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REVIEW

Coastal erosion and climate change: A review on coastal-change process and modeling

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Abstract Coastal erosion is a normal process of nature. However, the rate of coastal erosion, and the frequency and intensity of coastal flooding events, are now on the rise around the world due to the changing climate. Current responses to coastal erosion are primarily determined by site-specific factors, such as coastal elevation, coastal slope, coastal features, and historical coastline change rate, without a systematic understanding of the coastal-change processes in the context of climate change, including spatiotemporal changes in sea level, regional changes in wave climate, and sea ice coverage. In the absence of a clear understanding of the coastal-change processes, most of the current coastal responses have been built upon a risky assumption (i.e., the present-day coastal change will persist) and are not resilient to future climate change. Here, we conduct a literature review to summarize the latest scientific understanding of the coastal-change processes under climate change and the potential research gaps towards the prediction of future coastal erosion. Our review suggests that a coupled coastal simulation system with a nearshore wave model (e.g., SWAN, MIKE21, etc.) can play a critical role in both the short-term and long-term coastal risk assessment and protective measure development.

Keywords Climate change · Coastal-change process · Coastal erosion · Coastal Vulnerability Index · Nearshore wave · Wave model

INTRODUCTION

The landward displacement of the coastline caused by oceanic activities (i.e., waves and currents) is termed as coastal erosion. Nowadays, around 40% of the world's population live in the coastal regions (United Nation 2007; Maul and Duedall 2019). As the population density and economic activities in coastal zones have reached a significant stage, pressures on the coastal environment are being unprecedentedly tremendous. Previous studies have found that the coastal areas have presently become more sensitive and vulnerable to natural and human-made hazards that lead to coastal erosion (Zacharias and Gregr 2005; Luo et al. 2018; Li et al. 2021; Meijles et al. 2021). The risk of coastal erosion and coastline retreat could become increasingly serious because of global climate change and other anthropogenic activities that alter the natural processes of coasts (Prasad and Kumar 2014; Alves et al. 2020).

Coastal erosion mainly occurs when wind, waves, and longshore currents move sediments from shore and deposit it somewhere else, including to other coastal regions, to the deeper ocean bottom, or into an ocean trench. The removal of the sediment from the sediment sharing system results in permanent changes in the shape and structure of the coasts (Prasad and Kumar 2014). One of the most direct consequences of coastal erosion is the coastline retreat, which has been causing considerable damage to the property and infrastructure in coastal communities (Hapke et al. 2009; Ghionis et al. 2013). Accordingly, coastal erosion prediction and adaptation have become significant topics worldwide. Multiple factors have been enrolled in the assessment of coastal erosion, motivational and resultant, oceanic and terrestrial, describing the acting forces and force conditions of the coastal erosion (e.g., Orford 2007; Goldbach 2017; Kupilik et al. 2019). However, the current studies are mainly based on the geographic conditions (i.e., geological, oceanic, and meteorological conditions) of specific sites, of which the emphases vary dramatically due to environmental differences among relatively small areas. Moreover, climate change, as a globally-focused challenge, has also

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been regarded as an accelerator worsening the coastal erosion processes by raising mean sea-level (Bagheri et al. 2022), damaging coastal ecosystems (James et al. 2023), bringing extreme weather events (Wolanski and Hopper 2022), and increasing wave forces and storm surges (Toimil et al. 2021). While with the scientific focuses on different subjects, the influence of climate change on coastal erosion has rarely been systematically summarized with any processes in common or interaction in the coastal environmental systems. Therefore, the effectiveness of present coastal erosion prediction leaves unstandardized uncertainty with different focuses. The uncertainty in prediction may finally lead to hysteresis and inaccuracy in the adaptation to coastal erosion.

Facing the increasing pressure on coastal environments and the vagueness in previous research, it is meaningful to review the recent methodologies and findings of the coastal erosion studies. Therefore, the objective of this review is to reveal the mechanism about how different factors affect the erosion process and their respective importance in coastal erosion assessment, and to suggest the breakthrough among them. In particular, this review aims to investigate the major drivers for coastal-change processes throughout various coastal environments and reveal the potential research gaps towards coastal erosion prediction under a changing climate.

COASTAL VULNERABILITY ASSESSMENT

The Coastal Vulnerability Index (CVI) has been regarded as the most commonly-used method to assess the coastal vulnerability to erosion (Gornitz 1991), which is also utilized for the analysis on the roles of different components in the coastal system (e.g., Addo 2013; Djouder and Boutiba 2017; Kantamaneni et al. 2019; Brandes et al. 2021). Accordingly, seven parameters of CVI include: (1) coastal feature, (2) coastal elevation, (3) coastal slope, (4) coastline change rate, (5) wave height, (6) tidal range, (7) sea level rise, which are commonly selected as the key indicators of the coastal vulnerability assessment (Fig. 1). The coastal feature describes the landform and texture of coasts, such as different topographic categories and elements along the coastline. The coastal morphology can be expressed by coastal elevation and coastal slope, which are the heights of some parts of the coast or overall of coastal land to the water level and the slopes along coastal line. The coastline change rate is mainly calculated from observed data in different scale periods (Purkis et al. 2016; Wu et al. 2018), which provides the empirical eroding velocity of a specific coast. The oceanic conditions are coupled with wave height, tidal range, and sea-level rise. The wave height represents the wave energy in waters. The tidal range and sea-level rise suggest the change of sea-level height for different time scales in which tidal range is in specific periods while sea-level rise is accumulated from the long-term increase in fluctuations. The interaction of these seven parameters defines the comprehensive situation of coastal environments.

Indicators of coastal geological characteristics

Recently, the criteria of geological components are the most frequently applied in the CVI assessment (Saengsupavanich 2021). One main reason could be their relatively low difficulty for the investigation, compared to the oceanic factors.

For coastal features, different geographical types of coasts and different textural types of coasts have different susceptibilities about coastal erosion (Saengsupavanich 2013; Winterwerp et al. 2020). For example, muddy coasts and sandy beaches are more vulnerable to erosion than gravel beaches and rocky shores because of the more unconsolidated texture (Vousdoukas et al. 2020, Winterwerp et al. 2020). And bays are less vulnerable to erosion than capes because of wave divergence (Kamphuis 2010). Basically, the difference of erosion at different types of coasts is related to the combination of hydraulic conditions of the ocean-land interaction and sediment budget in a specific region, which can be affected by its topography and texture.

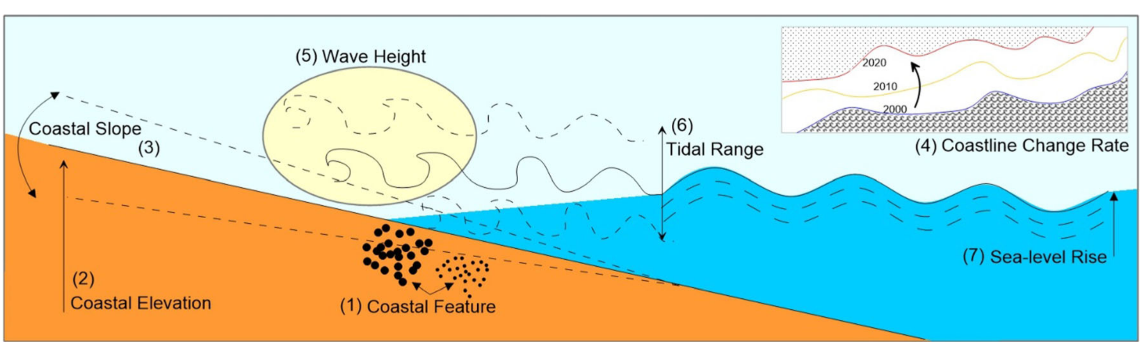

Fig. 1 Illustration of the seven key parameters of CVI

Coastal elevation is regarded as a key factor in defining and predicting areas that are threatened by the dangers posed by waves and rapid climate change (Hoque et al. 2018). Their correlation to coastal vulnerability has high similarity, that the low coastal elevation can be seen as highly vulnerable, while coastal areas with higher elevation are considered less vulnerable (Yin et al. 2012; Djouder and Boutiba 2017; Obu et al. 2017; Rani et al. 2018). The possible explanation for the result could be that the lower coast is easier to be inundated and overwhelmed than the higher one, especially facing the high water level caused by storm surges or wave set-up. Meanwhile, there is the existing problem on the definition of coastal elevation in the previous research, that different standards have been selected as the reference datum, such as mean sea-level, chart datum, or lowest low water, which may lead to significantly different results in the vulnerability assessment (Hoque et al. 2019; Shetty et al. 2019).

Coastal slope plays an important role in impacting flooding and dictates wave breaking on the beach face (Pantusa et al. 2018; Mahmood et al. 2020). A number of previous research (e.g., Gaki-Papanastassiou et al. 2010; Djouder and Boutiba 2017) found flatter coasts would suffer more from washing and erosion during sea-level rising or storm surge, while some others (e.g., Rani et al. 2018; Ružić et al. 2019; Tătui et al. 2019; Al-Awadhi et al. 2020) believed steeper slopes would be more vulnerable because of the dissipation of the hydraulic forces on the milder slopes. Similar to the coastal elevation, the coastal slope also has problems of standardization, that the common method of using the digital elevation model (DEM) doesn't reflect the accurate slope at the surfing zone (Mavromatidi et al. 2018; Rani et al. 2018; Mahmood et al. 2020), which directly face the effect of oceanic force. Meanwhile, the slope of the coast diversifies widely not only spatially but also temporally, even at a specific coast (Ariffin et al. 2018; Ismail et al. 2020), which may result in consequences at opposite poles through the analysis.

Indicators of oceanic force

Compared to the abundant investigation of the coastal geological factors for CVI assessment, the criteria of oceanic forces (i.e., waves, tides, sea-level rises) are relatively less focused (Al-Awadhi et al. 2020; Saengsupavanich 2021). At the same time, the quantification of their impact on the coastal erosion hasn't proceeded as well as geological ones.

For tidal range, it's regarded as a key parameter indicating the water level with coastal flooding and coastal erosion (Mavromatidi et al. 2018). Two opposing opinions exist on its effect on coastal vulnerability. On the one hand, larger tidal range creates wider buffer zones for surges on a tide-dominated coastline. A macro-tidal region, compared to micro- or meso-tidal environments, has more capacity to accept storm surges for half a tidal cycle (Mahmood et al. 2020). On the other hand, the wider intertidal area of macro-tidal region improves the possibility of erosion on the beaches and cliffs with long-term sea-level rises (Tragaki et al. 2018). Meanwhile, the collected tidal statistics could not avoid the ignorance of the impact on different coastal features, and the wave- and wind-setup of seawater levels (Saengsupavanich 2021), which reduces the reliability of the assessment of its role in coastal erosion.

Sea-level rise shows significance in the CVI assessment for the long-term scenario but causes a relatively mild impact in the instant response from the coast (Gutierrez et al. 2011; Yates et al. 2011; Pramanik et al. 2015), compared to the tidal range and wave height. For example, one previous research shows the sea-level change rate in Krishna–Godavari delta region (east coast of India) with hundreds of kilometers scale remains several millimeters per year even in the climate change scenario (Pramanik et al. 2015). Like tidal range, sea-level rise, as an indicator of oceanic forces, mainly brings the effect of inundation to the coast, but with longer impacting periods over decades scale, which makes it not the most important parameter in relatively shorter-term applications.

Wave height is the indicator directly reflecting the wave energy and expresses the energy as a function of its square value (US Army Corps of Engineers 2002). Among all the types of waves, including wind waves, infra-gravity waves, tsunamis, and other waves with longer wave periods (Holthuijsen 2007), the wind wave is most frequently applied in the coastal vulnerability assessment, as it contains the most energy and happens the oftenest in the ocean. Although most researchers have categorized coasts with lager waves as more vulnerable (e.g., Djouder and Boutiba 2017; Rani et al. 2018; Ružić et al. 2019), there was still no common-used standard for the global assessment of wave's impact on coastal erosion (Saengsupavanich 2021). Even some studies which selected sea-level rise as their research object have ignored the impact of wave height, whether big or small (Al-Awadhi et al. 2020).

Challenges and future directions

The review of previous research on the coastal erosion controlling factors reflects that the current stage of relevant scientific topics puts more emphasis on the geological side. However, the criteria for each factor have conflicts and non-unification (Table 1), mainly based on the specific situations of the study areas. In another words, the standardization of the coastal geological criteria is hard to reach due to the different geographic conditions. At the same time, the lack of understanding of coastal processes (e.g., hydrodynamic effect, multi-factor processes) has

Table 1 Review of coastal vulnerability indicators

Parameter	Description	Criteria	References
Coastal Feature	Finer and looser texture with higher vulnerability: e.g., clay, silt, fine sand; coarser and firmer texture with higher vulnerability: e.g., bedrock, gravel, coarse sand	Qualitative description (5-level grading: very low, low, medium, high, very high)	Saengsupavanich (2013), Vousdoukas et al. (2020) and Winterwerp et al. (2020)
	More convergent geography with higher vulnerability at headland, lower at bay	Qualitative description (no grading)	Kamphuis (2010)
Coastal elevation	Lower elevation with higher vulnerability	Below 10 m range and below 3-m isometric gaps	Behera et al. (2019), Rajasree and Deo (2020) and Shetty et al. (2019)
		Over 10 m range and over 3-m isometric gaps	El-Shahat et al. (2021) and Jana and Hegde (2016)
		Below 10 m range and non-isometric gaps	Hoque et al. (2019) and Mullick et al. (2019)
		Over 10 m range and non-isometric gaps	Chaib et al. (2020), Djouder and Boutiba (2017) and Imran et al. (2020)
Coastal slope	Flatter slope with higher vulnerability from inundation	Vulnerabilities decrease with increasing slopes in below 5% ranges	El-Shahat et al. (2021), Hoque et al. (2019), Jana and Hegde (2016), Mahmood et al. (2020), and Mullick et al. (2019)
		Vulnerabilities decrease with increasing slopes in over 5% ranges	Djouder and Boutiba (2017), Mavromatidi et al. (2018), and Tragaki et al. (2018)
	Flatter slope with lower vulnerability from wave dissipation	Vulnerabilities increase with increasing slopes in below 5% range	Tătui et al. (2019)
		Vulnerabilities increase with increasing slopes in over 5% range	Al-Awadhi et al. (2020), Rani et al. (2018), and Ružić et al. (2019)
Coastline change rate	Larger retreat rate with higher vulnerability; Empirical equilibrium prediction model with few processes considered	5 levels vulnerabilities with symmetric retreat-advance rates	Hoque et al. (2019), Jana and Hegde (2016), Rajasree and Deo (2020), Sahoo and Bhaskaran (2018) and Tătui et al. (2019)
		5 levels vulnerabilities with unsymmetric retreat-advance rates or decreasingly from retreats to balanced	Behera et al. (2019), Mahmood et al. (2020) and Shetty et al. (2019)
Wave height	Larger wave height with higher vulnerability	5 levels increasing vulnerabilities from low heights to high heights	Al-Awadhi et al. (2020), Djouder and Boutiba (2017), Holthuijsen (2007), Rani et al. (2018), Ružić et al. (2019), Saengsupavanich (2021), US Army Corps of Engineers (2002)
Sea-level rise	Rising sea-level with higher vulnerability from inundation	Qualitative description (no grading)	Gutierrez et al. (2011), Pramanik et al. (2015) and Yates et al. (2011)
Tidal range	Low possibility of storm surge happening in high-tide region, leading to lower vulnerability	5 levels decreasing vulnerabilities from narrow ranges to wide ranges	Djouder and Boutiba (2017), Hoque et al. (2019), Mahmood et al. (2020), Mavromatidi et al. (2018) and Rajasree and Deo (2020)
	Possibility of erosion happening at the top of cliff or beach in high-tide region, leading to higher vulnerability	5 levels increasing vulnerabilities from narrow ranges to wide ranges	Jana and Hegde (2016), Mullick et al. (2019), Sahoo and Bhaskaran (2018) and Tragaki et al. (2018)

limited the effectiveness of the assessment (Saengsupavanich 2021). Therefore, it has been revealed that only in the situation where geological parameters are more efficient to the CVI analysis they can be set as the major drivers of coastal erosion (Pramanik et al. 2015). This means the geological parameters have more limited impacts on the coastal erosion processes, though their investigations are relatively more mature than oceanic parameters.

Previously, the historical coastline change has been regarded as one of the most important parameters for coastline prediction and coastal vulnerability assessment, on which many empirically based equilibrium coastline models have been proposed (Splinter et al. 2013). However factually, the selection of the length of historical record was different, longer (over 40 years, e.g., Jana and Hegde 2016; Hoque et al. 2019), or shorter (around 20 years, e.g., Rani et al. 2018; Sahoo and Bhaskaran 2018), while the different time spans would no doubt lead to different change rates (Saengsupavanich 2021). Therefore, this traditional methodology of coastline prediction has its original flaw. Meanwhile, climate change brought more uncertainty to this methodology. It has been proved in some research that the frequency of extreme weather events happening along the coastal regions has grown rapidly in the twenty-first century (Griggs and Reguero 2021), which brings coastal erosion into a critical situation under the coast floods and inundations (Jia et al. 2016; Liu et al. 2020). Therefore, the more serious coastal erosion caused by more frequent extreme weather signifies one part of the consideration of climate change adaptation (Schliephack and Dickinson 2017). Under the growing natural pressure, the focus of coastline retreat and coastal erosion studies should be moved from the empirical history-based method to the process-based one.

Focusing on the oceanic processes, the wave affecting the coastal region, as well as the nearshore wave, plays the most direct and frequent role in washing the shore, and flooding at the extreme situations, while the tidal range and sea-level rise only locate the elevation of nearshore wave effect. Whereas, the criterion of the tidal range remains questionable, with conflicting conclusions (Table 1), and it is proven that the wave height intensity plays a significantly more important role than the sea-level rise in the rate of coastal erosion (Hackney et al. 2015). Therefore, according to the considerations of direct and frequent impact onto coastline, the relative great lack in the previous research, and the existence of inconsistencies from other criteria, the nearshore wave effect should be regarded as the major driver of the coastal erosion and coastline reshape, with its tremendous potential to be revealed at the current stage. A new modeling system based on coastal processes (i.e., combining the waves, tides, and sea-level with geological conditions) can be highly suitable for the vulnerability assessment compared to the former experience based on quantities of status, especially under the pressure of climate change. To start this innovative technical route, the concepts and current applications of wave monitoring and models are worthy of being reviewed.

OCEAN WAVE MODELING

Ocean waves export energies onto coastal environments physically. It has been proved that during the erosion processes, wave conditions mainly control the sediment and morphological variations along coastlines (El Mrini et al. 2012). Considering the review of all CVI parameters, a quantitative analysis of the wave effects become the central step of process-based erosion modeling.

Concept about waves and wave models

As mentioned in "Indicators of oceanic force" section, the most frequent-applied type of wave in the vulnerability assessment is the wind wave, because it is the most energetic wave that occurs most often in the ocean and most possibly affects the coastline, compared to others, including infra-gravity waves, tsunamis, and other waves with longer wave periods. To express the wave energy acting on the coastal environment, the wave height is commonly used as the key parameter, because the wave energy can be regarded as a function of its square value. Together with the wave direction and period, the wave climate can be described in a specific sea area. Among all the factors of CVI assessment, waves have the major impact on the coastal erosion, while the others interact to form the environmental conditions where the nearshore wave effect locates.

Instead of in-situ observations, due to the excessive cost and difficulty of large coverage of nearshore wave measurement, the wave models are widely used for the wave height simulation in the coastal vulnerability assessment (Bagdanavičiūtė et al. 2019; Ružić et al. 2019). The information on the ocean and derived wind and wave characteristics are generally available in open oceanic settings, which can be derived from buoy measurements and physical models, and ship observations, and more recently through satellite altimetry products (Musa et al. 2015; Guisado-Pintado 2020). However, the increased differences from the deep-water environment occur as waves travel landward with shallower conditions, such as changes in their behaviour and structure, and appearances of transformational phenomena (e.g., shoaling, refraction, diffraction, and wave breaking, among others; Guisado-Pintado 2020). Therefore, the numerical simulations have currently often complemented the assessment, in addition to the previous single parameter, the significant wave height.

The wave models can be defined as the numerical approaches used to depict the sea state and to predict the evolution of the wind-generated waves (Cavaleri et al. 2007). Nowadays, wave simulation techniques can provide the statistics of wave characteristics (wave heights, periods, and propagation directions) and derived parameters (e.g., dissipation, set-up, diffraction parameter) under the conditions of atmospheric wind forcing and non-linear wave interactions (Guisado-Pintado 2020), which have been utilized in multiple fields with coastal environments.

Categories of wave models

The wave models can be mainly categorized by their complexity, their applicability to offshore or nearshore waters, and the use of parametric or spectral wave data. Two broad groups of shallow water wave models could be generalized, the phase-resolving model and the phase-average model (equally the spectral model; Battjes 1994).

The phase-resolving models work based on conservation laws of mass and momentum, which can describe the waves in detail with rapid variations. This kind of model resolves individual waveforms by functionalizing the sea surface with time, which requires very fine grids to resolve all relevant wavelengths (Guisado-Pintado 2020). However, in order to provide spatial and temporal detailed hydraulic information of waves, phase-resolving model at the same time requires demanding settings to compute the wave processes. Therefore, phase-resolving models have been usually applied in engineering studies focused on a small coastal region (e.g., a harbour entrance), studies of lower frequency motions (e.g., infra-gravity waves, tsunamis, and tides) or short-duration dynamics (Buckley et al. 2014). Currently, there are two most representative models, time-dependent, non-linear models based on the Boussinesq equation (Boussinesq models), and stationary, linear phase-resolving wave models based on the Mild-Slope Equation (MSE). They overall incorporate processes of shoaling, refraction, diffraction, reflection, wave generation, bottom friction, wave–current interactions, wave breaking, and run-up and wave-induced currents.

The phase-averaged models are based on the energy or action balance equation and describe the evolution of the wave energy spectrum in both space and time (Monbaliu 2003), which means they simulate the wave in a stochastic manner, usually based on the linear wave of Airy wave theory (Airy 1985). Different from the computation for the full range of waves from the phase-resolving model, the phase-averaged model calculates the wave energy spectrum at every grid point of the computational domain, therefore, representing the wave field. Accordingly, it regards the waves as a combination of local wind and far-field swells, and assumes the wave conditions change slowly both spatially and temporally in the wave fields with given frequencies and energy levels. Hence, phase-averaged models usually have the weakness of describing rapid time-varying changes of waves. Also based on the relative randomness of spectral model, some research has found significant difference between the observed wave height and the simulated one in areas with complex submarine topography (Gorrell et al. 2011). While for the applicability limitations, spectral models often do not have limitations on grid resolution or time steps, and therefore computational areas can vary from one meter scale to many kilometers ($\sim$ 100 km). This allows a range of longer and wider research to utilize it without having huge computational costs (Guisado-Pintado 2020).

From the review, phase-resolving and phase-averaged wave models have their strengths respectively (Table 2). Facing specific scientific or applied questions, the selection or combination of phase-resolving or spectral model depends on the conditions of the specific situation, including wave types, grid scales, and time steps. Relevant research (Ardhuin and Roland 2013) has provided a consideration in the increasing order of importance of the water level, the currents, and the accuracy of forcing factors (wind and the offshore boundary conditions), to finally determine the accuracy of the specific model in use.

Currently, as the higher applicability in general, the phase-averaged model, or the coupled model based on spectral framework added some phase-resolving procedures, is more commonly used in the coastal environmental assessment. Nowadays, the widely used numerical wave spectral models basically belong to the third-generation wave models, which include the basic processes (from first-generation models) of wind input and dissipation and additional processes of wave–wave interaction, directional spreading, refraction and shoaling, bottom friction, and wave–current interaction (from the second-generation) (Monbaliu 2003), and the non-linear wave interactions (i.e., Discrete Interaction Approximation) (Hasselmann and

Table 2 Comparison of phase-resolving and phase-averaged wave models

Model types	Principle	Calculation amount	Output information	Scope of application	Examples
Phase-resolving	Laws of mass and momentum	Requiring fine grids to resolve all relevant wavelengths	Waves in detail with rapid variations	Small-region engineering studies, studies of low-frequency motions or short-duration dynamics	MIKE21-Boussinesq waves; FUNWAVE; SWASH
Phase-averages	Energy or action balance equation	Calculating wave energy spectrum at grid point of computational domain	Wave fields with given frequencies and energy levels	Any wave field simulation varying from meters to hundreds of kilometers scales	WAM; WWIII; SWAN; MIKE21-SW

Hasselmann 1985; Hasselmann et al. 1985). For this type of model, two groups can be divided by the applied water-depth conditions, as well as offshore models and nearshore models. The most representative offshore models are WAM (WAMDI Group 1988) and WAVEWATCH III (WWIII) (Tolman et al. 2002), and the nearshore one is Simulation Wave Nearshore (SWAN) (Ris et al. 1999). Landward, the offshore model provides the information of swells for the nearshore ones as the boundary conditions; and the nearshore model can be coupled with phase-resolving ones (e.g., FUNWAVE, a Boussinesq model) to predict surf zone and swash processes or morphodynamic models (e.g., XBeach).

As for the assessment of coastal erosion and coastal vulnerability, the modeling of nearshore waves and surf-zone washing becomes the focus, because the erosion processes happen in influencing area of nearshore and surf-zone waves. Accordingly, current applications of different models from relevant fields in nearshore or coastal environment can be the experience featuring an applicable modeling tool for coastal vulnerability assessment.

Current applications of nearshore wave models

Throughout reviewing, it has been found that the papers utilizing wave models to study coastal erosion are limited. In this case, the relevant recent research utilizing nearshore wave modeling and outputting these parameters become the emphasis of reviewing. As mentioned in "Concept about waves and wave models" section, the significant wave height (H_s), mean wave period (T_m) and mean wave direction (MWD) have been regarded as the key parameters of wave effects on coastal erosion. In addition to these three main parameters, the peak wave height (H_p) is also a commonly-used parameter when considering the extreme sea state towards inundation or overtopping. Research articles related to 'nearshore wave model application' have been searched and reviewed, of which twenty representative ones have been collected. The complexities of the model constitution (such as, output and scale) vary widely and are highly related to their area of study, including wave dynamic study, navigation and dredging, natural hazards prevention, and coastal sedimentary dynamics study (Fig. 2b; Table 3). All the collected case studies fully or partly contain the essential parameters (i.e., H_s, T_m, H_p, MWD), and are applied in a nearshore environment, as well as small-area, local, or regional scales (specific coastal sites are regarded as small area scale, such as beaches, harbours, channels; coastal regions of a city/county, or specific morphogenetic regions are regarded as local scale, such as deltas, bays or city/county-coasts; named sea areas are regarded as regional scale, such as Gulf of Mexico and Mediterranean sea).

From the statistics of reviewing, eight of the total twenty cases choose it to simulate the nearshore wave (Fig. 2a). Meanwhile, the wave module of the third most chosen Delft 3D model is also based on SWAN. Furthermore, there are many of articles introducing SWAN as the representative nearshore wave model together with the offshore ones of WAM and WWIII, whether they use it or not (e.g., Atan et al. 2017; Bellotti et al. 2021; Makris et al. 2021; Lira-Loarca et al. 2022). All of these records prove that SWAN can be regarded as the most popular nearshore wave modeling tool. Other than SWAN, it is also noteworthy that MIKE21, Delft3D, ADCIRC, and TELEMAC are applied for over one single time in collected case-studies (Fig. 2). Specially, ADCIRC are all nested with other models in the applications (i.e., Melby et al. 2018; Kang et al. 2019; Siverd et al. 2019).

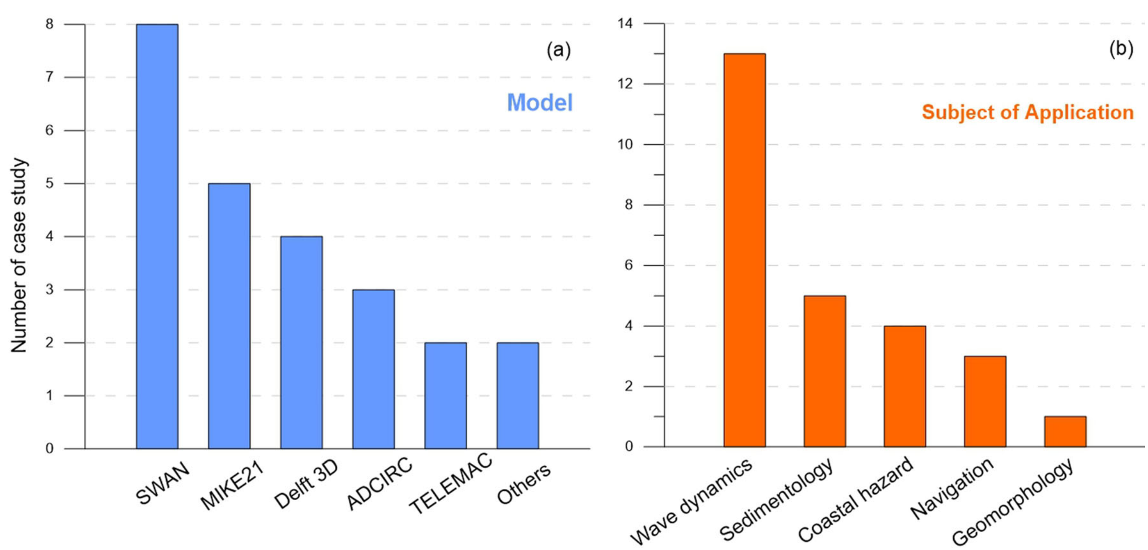

Fig. 2 Models (**a**) and subjects of application (**b**) in the collected case-studies

Table 3 Applications of nearshore wave models

Model	Region	Subject	Output	Scale	References
SWAN, XBeach	Perranporth Beach, UK, and Xago Beach, Spain	Sedimentology, Oceanography	H_s, MWD	Local scale	Abanades Tercero (2017)
SWAN	North Gulf of Mexico	Oceanography (Wave dynamics)	H_s, H_p	Regional scale	Arab et al. (2022)
SWAN	Galway Bay, Ireland	Oceanography (Wave dynamics)	H_s, T_m, MWD, etc.	Local-regional scale	Atan et al. (2017)
SWAN	North-central Tyrrhenian Sea, Italy	Oceanography (Wave dynamics)	H_s, T_m, etc.	Local scale	Bellotti et al. (2021)
MIKE21-SW	Nhat Le coastal zone, Vietnam	Oceanography (Wave dynamics)	H_s, MWD	Local scale	Dinh et al. (2018)
SWAN and SWASH	Navigation channel to harbour (general)	Navigation	H_s, T_m, MWD, etc.	Small area (channel/ harbour) scale	Dusseljee et al. (2014)
Delft 3D	Yellow River Delta, China	Oceanography (Wave dynamics), Sedimentology	H_s	Local scale	Fan et al. (2020)
Delft 3D	Kalutara coastal zone, Sri Lanka	Sedimentology, Geomorphology	H_s, MWD	Local scale	Gunasinghe et al. (2021)
ADCIRC-UnSWAN (Unstructured SWAN), FLOW-3D, XP-SWMM	Busan, Korea	Coastal hazard	H_p	Local scale	Kang et al. (2019)
WWIII	Mediterranean Sea	Oceanography (Wave dynamics), Coastal hazard	H_s, T_m	Regional scale	Lira-Loarca et al. (2022)
HiReSS, TOMAWAC (TELEMAC), WAVE-L	Sites in Mediterranean Sea	Navigation	H_s, T_m, MWD, etc.	Small area (harbour) scale	Makris et al. (2021)
ADCIRC-STWAVE, ADCIRC-SWAN	Gulf of Mexico	Oceanography (Wave dynamics), Coastal hazard	H_p	Local scale	Melby et al. (2018)
Boussinesq Model	Experimental simulation	Oceanography (Wave dynamics)	H_s	Small area (beach/ breakwater) scale	Metallinos et al. (2021)
Delft 3D	Major coastal towns in South Africa	Oceanography (Wave dynamics)	H_s, T_m, MWD	Local scale	Rautenbach et al. (2020)
TELEMAC, MIKE21-SW	Selected coasts in South Italy	Oceanography (Wave dynamics)	H_s, T_m, MWD	Local scale	Samaras et al. (2016)
MIKE21-SW	China East Adjacent Seas	Oceanography (Wave dynamics)	H_s, MWD	Regional scale	Shi et al. (2022)
ADCIRC-SWAN	Mississippi River Delta	Coastal hazard, Oceanography, Sedimentology	H_s, H_p	Local scale	Siverd et al. (2019)
Delft 3D	Bohai Bay, China	Oceanography (Wave dynamics)	H_s, H_p, MWD	Local-regional scale	Song et al. (2020)
MIKE21-SW	6 coastal sites in Karnataka, India	Oceanography (Wave dynamics)	H_s, T_m, MWD	Local scale	Upadhyaya et al. (2021)
MIKE21-SW	Santos Bay, Brazil	Sedimentology, Navigation (Dredging)	H_s	Local scale	Venancio et al. (2020)

SWAN model is developed by Delft University of Technology (DUT). It is a third-generation wave-phased averaged spectral model for simulating and propagating waves from offshore to nearshore based on the action balance equation, which implicitly considers the interaction between waves and currents (Ris et al. 1999). Many previous scientific studies have proved the validity of its simulation of nearshore waves, explaining the physical processes (Cavaleri and Sclavo 2006; Rogers and Wang 2007; Inghilesi et al. 2012; Gallagher et al. 2014), including the growth by wind, the interaction between individual waves, and the dissipation and decay by wave breaking and bottom friction. Due to its ideal performance, many coastal models are produced under the nesting of SWAN or are derived from it, such as the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST) (USGS 2020), and Delft 3D Wave module (D-Waves) (Deltares, n.d. a).

MIKE21 is a software package for 2D modelling of hydrodynamics, waves, sediment dynamics, water quality and ecology developed by Danish Hydraulic Institute (DHI) (DHI 2017). It is a modular product and includes simulation engines that are aimed at a very wide range of applications, including modelling of tidal flows, storm surge, advection-dispersion, oil spills, water quality, mud transport, sand transport, harbour disturbance and wave propagation. The MIKE21-SW (Spectral Wave) is a state-of-the-art third generation spectral wind-wave model developed by DHI, as well as the spectral wave model of MIKE21 (DHI 2012). The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. It has been regarded as one major widely-used nearshore wave model other than SWAN in some research (e.g., Atan et al. 2017), and has been applied successfully in various coastal environment (Upadhyaya et al. 2021).

Delft3D is a world leading 3D modeling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine, and coastal environments, including open-source modules the Delft3D flow (FLOW), morphology (MOR) and waves (WAVE) (Deltares, n.d. b). Based on SWAN, the wave module computes the non-steady propagation of short-crested waves over an uneven bottom, considering wind action, energy dissipation due to bottom friction, wave breaking, refraction (due to bottom topography, water levels and flow fields), shoaling and directional spreading (Deltares, n.d. b). Similar to MIKE21, Delft3D contains multiple modules focusing on different coastal physical environmental components, including wave, flow sediment and morphology.

Both TELEMAC and ADCIRC use finite-element method to calculate free-surface flows (Open TELEMAC 2022; University of North Carolina at Chapel Hill, n.d.). TELEMAC is developed by the Laboratoire National d'Hydraulique (National Hydraulic Laboratory), France. Like MIKE21 and Delft3D, it contains different modules solving flow, wave, sediment transportation questions. The TOMAWAC, one TELEMAC's module, is used to model wave propagation in coastal areas. It solves a simplified equation for the spectro-angular density of wave action under steady-state conditions, outputting parameters including significant wave height, mean wave frequency, mean wave direction. ADCIRC is a multi-program system formulated using the traditional hydrostatic pressure and Boussinesq approximations. It is developed by Dr. Rick Luettich at the University of North Carolina at Chapel Hill and by Dr. Joannes Westerink at the University of Notre Dame, usually applied in the fields of prediction of storm surge and flooding modeling, tides and wind-driven circulation, and near shore marine operations. Both TELEMAC and ADCIRC weigh more on the calculation of flows rather than wave. In this case, the wave modeling from TELEMAC's nearshore wave module, while the ADCIRC is usually coupled with other wave models like SWAN in the application dependently (Table 3).

Looking into the features of collected models, all the models meet the requirements of coastal vulnerability assessment from nearshore wave effects, which are the inputs to express wind-driving in nearshore region, and the outputs describing significant wave height, wave direction and wave period (Table 4). Meanwhile, one significant difference has been figured out among the different models. The most popular model SWAN, as a single program outputting wave climate information, need to nest with other coastal morphodynamic models when assessing wave impacts on coastal environments (e.g., XBeach, Abanades Tercero 2017). While the other modular models' (i.e., MIKE21, Delft3D, TELEMAC) wave module can be nested with their modules of flow, sediment transportation, or morphology, to analyze the wave–effect interaction with other coastal environmental components. As for the performances of different models, there has not been enough records found of their comparisons within the same sea area through reviewing, which suggests a future research direction for better applying wave models on coastal erosion assessment.

In general, wave models (especially the third-generation models, like SWAN, MIKE21-SW, TOMAWAC) have been commonly applied in a wide range of scientific or non-scientific industries (Table 3), which proves their potential applicability in coastal systems. The wave in nearshore zones has been revealed as one of the most critical variables, especially as a key indicator of the coastal processes; yet it has not been well studied before. Therefore, with the outputs of essential parameters for coastal erosion or vulnerability assessment, their successful applications in different fields appropriately meet the demand for the coastal erosion assessment, considering the impacts of climate change.

Table 4 Summary of key features of commonly-used wave models

Model	Model type	Input	Output	Modularization
SWAN	Phase-averaged	• Bathymetry • Current • Water level • Bottom friction • Wind speed • Wind direction Etc.	• One- and two-dimensional spectra • **Significant wave height and wave periods** • **Average wave direction and directional spreading** • One- and two-dimensional spectral source terms • Root-mean-square of the orbital near-bottom motion • Dissipation • Wave-induced force (based on the radiation-stress gradients) • Set-up • Diffraction parameter	Single program
MIKE21-SW	Phase-averaged	• Water level • Water depth • Current velocity • Wind speed • Wind direction • Ice concentration	• **Significant wave height** • **Peak wave period** • **Averaged wave period** • Zero-crossing wave period • Wave energy period • **Peak wave direction** • **Mean wave direction** • Directional standard deviation • Wave height with direction • Radiation stress tensor • Particle velocities • Wave power	MIKE21-SW is one of the modules of MIKE21 system, which contains other components for: • Flow Model • Boussinesq Waves • Sand Transportation • Mud Transportation • Shoreline Morphology • Flooding • Oil spill • Mooring analysis Etc.
Delft3D-Wave	Phase-averaged	Same as SWAN	In addition to SWAN, the flow effect on waves can be accounted for with Delft3D-Flow nested.	The FLOW module is defined as the core of Delft3D, with which the effect of flow on waves can be accounted for. Besides FLOW and WAVE, Delft3D contains other modules of: • Morphdynamic • Water Quality • Particle Etc.
TELEMAC (TOMAWAC)	Phase-averaged	• Water level • Bottom topography • Current velocity • Wind speed • Wind direction	• **Significant wave height** • **Mean wave frequency** • **Mean wave direction** • Peak wave frequency • Wave-induced currents • Radiation stresses	Besides the coastal wave module TOMAWAC, TELEMAC contains other modules including: • SISYPHE – Sediment transport and bed evolution • NESTOR—modeling dredging operations in the riverbed • MASCARET 1-Dimensionnal free surface flow modelling • ARTEMIS—numerical simulation of wave propagation towards the shore and agitation into harbours • TELEMAC-3D—3D Hydrodynamics • TELEMAC-2D—Two-dimensional hydrodynamic

CLIMATE CHANGE AND COASTAL EROSION

More and more evidences have been proving that the oceanic processes which directly impact the coastal erosion processes has been accelerated by ongoing climate changes, including the changes of mean and extreme wave conditions (Wong et al. 2014), extreme sea-level (ESL), storm surges (Toimil et al. 2020), and sea-ice coverage (Nielsen et al. 2020).

Generally, the changing climate directly impacts the meteorological conditions in nearshore regions, including sea surface temperatures (SST), regional atmospheric pressures, and wind speeds. These original variations then lead to the changes of coastal hydrodynamic conditions which intensify the coastal erosion (Walsh et al. 2020). As for each kind of climate impact, relevant processes play their specific role in the worsening of erosion.

Mean and extreme wave condition

As mentioned in "Concept about waves and wave models" section, wave conditions are mainly represented by wave height, wave period and direction. And it is the wind-driven waves in nearshore zones that mainly output oceanic energy on coastal erosion processes, as described in "Indicators of oceanic force" section. Hence, the generator of wind-wave becomes the major focus to assess the impact of climate change on wave condition. Correlatively, recent research has pointed out that with the variation of sea-surface pressures and wind speeds will create more energetic wave conditions in the future (Walsh et al. 2020). Meanwhile, it has been widely reported that regional wind speed and frequency of high-wind events will significantly increase under a changing climate (e.g., Rolph et al. 2018; Hong and Zhang 2021; Rusu 2023). It is also noteworthy that the more frequent high-wind events are more likely to occur in high-latitude regions. (Walsh et al 2020). The increase of wind speed or high-wind events may come from the regional enhancement of pressure gradient (Redilla et al. 2019). Impacting on the wave conditions, the statistical projections consistently indicated that the occurrence frequency of the present-day 1-in-10-year extreme wave heights is likely to double or triple in many coastal regions around the globe (Wong et al. 2014). Furthermore, the wave period and wave direction may also be changed in more unstable wind fields, which will convert the coastal sediment transport pattern and then lead to more severe erosion and landward retreat (Castelle et al. 2015; Harley et al. 2017).

Extreme sea-level and storm surge

ESL and storm surges usually happen at the same time of extreme storm events, during which extreme regional atmospheric pressures (i.e., the inverse barometer effect) cause temporary high water levels (e.g., wave run-up effect) at shorefront (Tsoukala et al. 2016; Walsh et al. 2020). In addition to the energetic wave actions during storm events, storm surges raise the water level onto higher elevations or further inland areas. The temporal ESL in a storm event can make erosion processes happen at the locations which barely have ocean-land interaction in ordinary oceanic status (Stockdon et al. 2023), such as backshore of sandy beaches as upper sea cliffs. At the same time, relevant research has reported that storm events have become increasingly frequent in the past several decades (Zahn and von Storch 2010; Rinke et al. 2017; Zahn et al. 2018), which is likely to raise the appearances of high ESL and storm surges. It has been found that by the end of this century, the 1-in-100-year ESL is on average projected to increase by 81 cm for the highest radiative forcing scenario (Toimil et al. 2020). Another relevant research has indicated a highly likely increase in the global average 1-in-100-year ESL of 58–172 cm under the highest radiative forcing scenario (Vousdoukas et al. 2018). The rise of ESLs and increase of storm surge events could result in an unprecedented frequency of extreme coastal erosion events and seawater intrusion flooding along many parts of the world (Vousdoukas et al. 2018; Hendry et al. 2019; Fang et al. 2021).

Sea-ice coverage

High-latitude coastal erosion is primarily limited by the presence of sea ice (Nielsen et al. 2020), because it attenuates wave energy thereby reducing sediment transport (Manson 2022). With the increase of SST in high-latitude regions, sea-ice concentration (SIC) reduces significantly, leaving a higher possibility of coastal erosion. More and more research outcomes have commonly revealed the SSTs in high-latitude regions have significantly increased from the past period (e.g., Moore 2016; Overland et al. 2018; Kanno et al. 2019). The duration of open-water season (OWS) (i.e., sea-ice free season) has been regarded as a good estimator of high-latitude coastal erosion and coastal vulnerability (Overeem et al. 2011; Barnhart et al. 2014), which has been extending with higher SSTs. It has been observed that the OWSs have increased at similar rates between 1979–2002 and 2002–2007 (1.5-fold and 1.6-fold, respectively) in Southern Laptev Sea (Overeem et al. 2011), which has shown the acceleration of warming. To the effect on coastal erosion, a case study based on Prince Edward Island north shore suggests that if SIC decreases from high (> 60%) to moderate (36%–60%) or from moderate to low (10%–35%), sediment transport is expected to increase 23–24; if SIC decreases from low to open water (< 10%) conditions, sediment transport is expected to abruptly increase a further 85% (Manson 2022). Generally, within the OWS in winter, more frequent and more intense storms are likely to occur, resulting in coastal erosion by causing storm surges and extreme waves (Jones et al. 2009). Hence, longer OWSs can be regarded as the worsening of potential erosion by extending the period of erosive oceanic dynamics.

Summary of climate change effects

Higher and more frequent ESL and storm surges, more extreme wave conditions, and more limited sea-ice coverage, resulted from warmer SSTs, more unstable atmosphere pressures, and more extreme wind speeds, have been showing worsened signs of climate change. Moreover, these phenomena all belong to the uncertain variation of oceanic processes related to coastal erosion. Therefore, it strongly suggests that the emphasis of the assessment of coastal vulnerability and erosion needs to switch to the oceanic processes, especially ocean waves and extreme storms which have greater potential in accelerating erosion processes. At the same time, the traditional equilibrium simulation and prediction of coastline change, based on the empirical model, have been added plenty of uncertainties due to the changing meteorological conditions. As the reliability of previous methods has been highly limited, the significance of wave modeling in coastal erosion study reaches a prior stage. By utilizing the observed or simulated wind data, nearshore wave models like SWAN, MIKE21, Delft3D, TELEMAC, etc. can provide more accurate wave parameters, such as significant wave height and set-up, wave period, and wave direction, for the dynamic estimation of coastal erosion.

APPLICABILITY OF NEARSHORE WAVE MODELS

Through the reviews of the application of the wave models, several models with their mature application outputting key parameters for coastal vulnerability assessment are expected as an appropriate fundamental tool for the analysis of the impact of the wave on coastal erosion and coastline reshape, including SWAN, MIKE21, Delft3D, TELEMAC, etc. Meanwhile, several challenges of its application also need to be solved in the following exploration.

Benefits of nearshore wave models

For all the parameters which constitute the CVI, those of the coastal characteristics (i.e., slope, elevation, feature, and change rate) have already had a significant influential pattern. Meanwhile, the coastal characteristics have relatively stable impacts on the coastal erosion and vulnerabilities of the coastal system. At the same time, the impact of tidal range and mean sea-level rise belongs to the non-instant and long-term effect on the coastal system, which means they will indeed, but not immediately, affect the coastal system under the changing climate. However, the changing climate has resulted in the worsening of extreme wave conditions, extreme sea-level and storm surge, and sea-ice coverage by influencing sea-surface temperature, regional atmospheric pressure, and wind speed, which accelerate the coastal erosion processes globally. Therefore, among all the factors of CVI assessment, the exploration of the wave impact on the coastline has both a huge blank in the previous relevant research, and great significance now and future.

Regarding the different zones of the application of wave models, offshore waves don't play the direct role in the coastal hydraulic conditions, but only transmit the swell to the nearshore zones, which have been considered in the third-generation nearshore wave models. In general, nearshore regions are the key zones for the assessment of the wave impact on the coast, where the hydraulic force is the most strongly driven by the wind and directly affects the sedimentary environment. Accordingly, nearshore wave models usually require the input of the data of water level, wind, current and ice at the study area, which can reflect climate change; the parameters of significant wave height, wave direction and wave period can be output from the application of listed nearshore wave models, which have been summarized as key indicators of nearshore wave impact on the coastal vulnerability of erosion (as mention in "Coastal vulnerability assessment" and "Climate change and coastal erosion" sections). After nesting the coastal geological conditions, an innovative coupled coastal system can be established (Fig. 3). Because the drivers of the designated model will dynamically reflect the changing meteorological conditions, the lack of considering oceanic process will be avoid comparing to previous research.

Gaps of the application of nearshore wave model

One of the commonly existing problems of all the simulations would be the authenticity examination. As for the wave model, the authenticity examination is performed in the form of accuracy, that how accurately the model can simulate the waves in real-time environments. Among the relevant experiences, the accuracy of the wave simulation varies from millimeters high to meters low (Guisado-Pintado 2020), which remains the challenge for the following development to improve the accuracy of the model. In this case, the observation of the natural wave height becomes one of the difficulties for the comparison between real waves and simulated ones. Potentially, another technical route would be making the designated wave model component of the coastal system simulation into a black-box model, which focuses on the correlation between the meteorological condition and the coastal sedimentary variation regardless of the detailed description of the wave process. In addition to the accuracy examination, the performance of different wave models also needs to be compared, because the oceanic processes assessment (as mentioned in "Current applications of nearshore wave models" section) and the coastal vulnerability assessment based on it has not reached a uniform standard (as mentioned in "Challenges and future directions" section), which leaves preparation procedures for future wave-model applications.

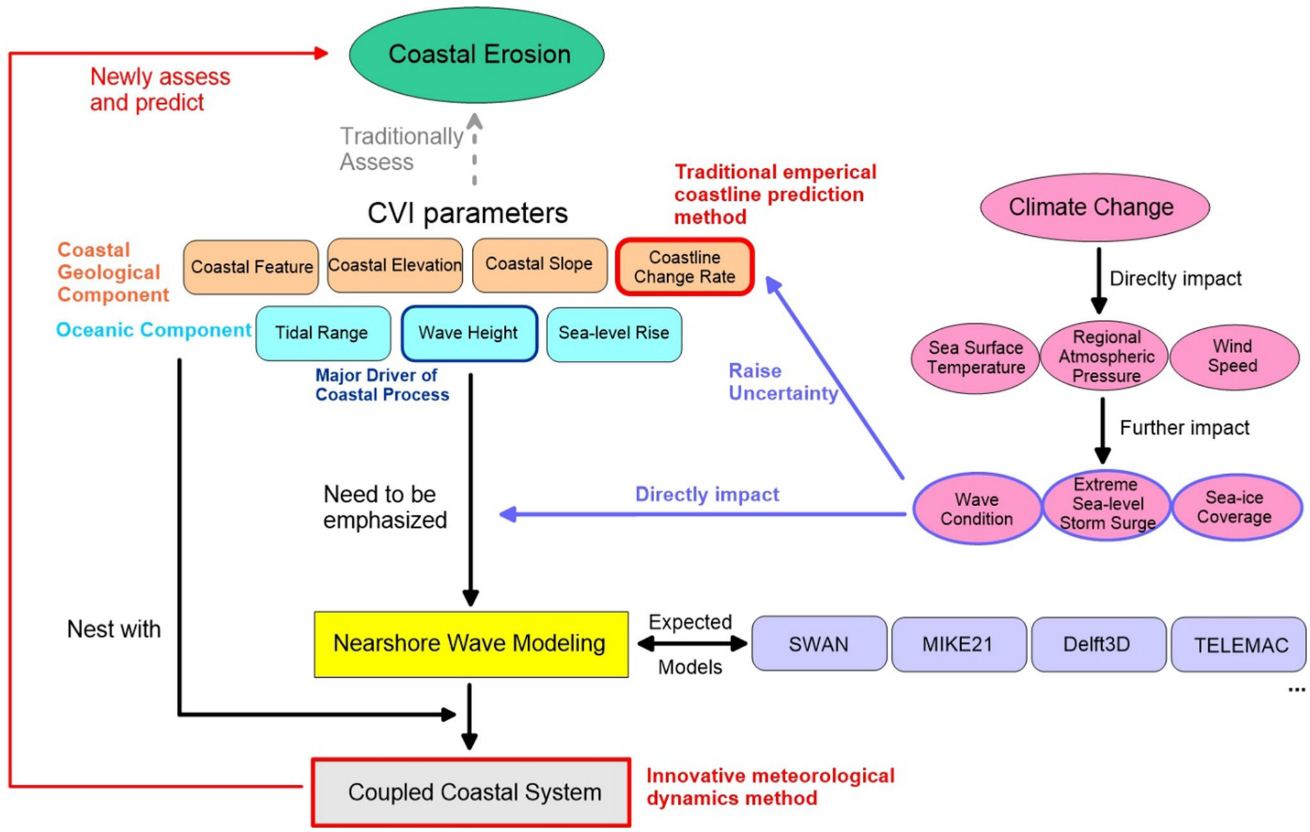

Fig. 3 Conceptualization of the review progress and the coupled coastal model

In order to apply the designated model to the coastal erosion study, a coupled system needs to be established combining the meteorological conditions, hydraulic conditions, and geological components (Fig. 3). According to the review of current nearshore wave model applications, the wave model needs to nest with other geomorphology models (e.g., Abanades Tercero 2017) or to be used together with morphology or sediment transportation modules under the same system (e.g., Fan et al. 2020; Venancio et al. 2020; Gunasinghe et al. 2021) if considering the sedimentological or geomorphological impacts. Following this route, the key point of this coupled system would be to set up the quantitative correlation between different variables existing in the same natural environment, which relies on field investigation of the specific study area and a large amount of testing through multiple linkages of all the components. This coupled coastal is expected to provide more reliable near-term predictions and long-term projections of coastline reshape due to erosion based on oceanic processes in designated coastal regions, which will support policymakers of coastal environmental management, owners of near-water properties, and planners of coastal infrastructures. With assumptions of coastal geographic changes, this model can also help to simulate the performance of coastal protection or adaptation designs.

CONCLUSIONS AND RECOMMENDATIONS

Nowadays, coastal erosion study has been reaching more and more mature stages with the analyses of multiple factors, among which the seven parameters of CVI assessment are the most commonly-used. However, the geological components of CVI assessment are weighed more, while the oceanic processes lack enough attention from the scientific community. With impacts from a changing climate, the oceanic processes are directly affected and easier to get into a more energetic status, which has not been sufficiently considered. Accordingly, more uncertainty is brought into the prediction of the coastline reshapes empirically based on the historic change rate. Therefore, to assess the impact of oceanic hydrodynamics in the coastal system has become unprecedentedly significant. Among the ocean processes, sea-level rise (both long-term and extreme) and tidal range determine the water level of inundation and wave action, and the wave height expresses the intensity of wave energy in the coastal erosion processes. In particular, the wave effect is the most vital oceanic factor, which responds to climate change and extreme weather instantly but intensely.

Due to the difficulty in the operation, and low efficiency in covering a relatively large area, the real-time observation of wave height is not considered as an appropriate method for the wave investigations. Instead, according to the wide range applications of wave models, wave simulations can be expected to be utilized for the assessment of the wave impact on the coastal environment. Meanwhile, as nearshore regions have been regarded as the key zones considering wave effect on coastal erosion and climate change, nearshore wave should be selected as the major research object in ocean process-based coastal erosion assessment. Therefore, the reviewed nearshore wave models have considerable potential to predict nearshore wave effects in the context of climate change, with correlated input parameters reflecting climate change and output parameters indicating coastal vulnerability of erosion.

To sum up, there are a few gaps in current studies on coastal erosion:

1. Coastal vulnerability assessment weighs more on coastal geological components, while oceanic processes, especially ocean waves, play a more significant role in coastal erosion, which relatively lacks relevant research experience. Thus, the focus on coastal vulnerability and erosion study should transit from geological investigation to oceanic processes simulation, especially nearshore wave conditions, which is the actual major driver of erosion processes.
2. Climate change has been accelerating the intensity of oceanic processes, making the traditional empirical prediction methods lose accuracy with growing meteorological uncertainties. Correlatively, wind-driven ocean wave modeling can be applied on the object of study related to climate change, which is the variation of oceanic meteorological conditions.

Furthermore, a coupled coastal simulated system (Fig. 3) should be established with multiple components combined, both geological factors and oceanic ones. Meanwhile, the accuracy of the nearshore wave simulation and the effectiveness of specific technical routes need to be examined. With the mature running of the system, policymakers and the public are expected to benefit from information of future coastal erosion.

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