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Assessing climate change impacts on open sandy coasts: A review

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ABSTRACT

The world's coastlines are shaped by mean sea level, wave conditions, storm surge, and riverflows. Climate change (CC) driven variations in these environmental forcings will inevitably have a profound effect on the coastal zone. Given the continued growth of coastal communities and extremely high value of coastal assets worldwide, effective adaptation measures underpinned by reliable coastal CC impact assessments are essential to avoid massive future coastal zone losses. This review aims to promote the adoption of best practice in local scale assessments of potential physical impacts of CC on open sandy coasts by (a) summarising the potential first order physical impacts of CC, (b) suggesting a standard modelling framework for local scale CC impact assessments, (c) identifying future research needs to facilitate the effective implementation of the prescribed modelling framework, (d) suggesting ways to address the identified research needs, and (e) discussing how existing methods/tools may be used for CC impact assessments until more advanced methods/tools are developed.

Contents

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1. Introduction

Projected climate change driven variations in mean sea level, wave conditions, storm surge, and riverflow will affect the coastal zone in many ways (Nicholls et al., 2007; Fitzgerald et al., 2008; Ranasinghe and Stive, 2009; Nicholls and Cazenave, 2010; Cazenave and Le Cozannet, 2013; Wong et al., 2014). As the coastal zone is the most heavily populated and developed land zone in the world (Small and Nicholls, 2003; Valiela, 2006), any negative physical impacts of climate change (hereafter CC) on the coastal zone are certain to have massive socio-economic impacts at global scale (Stern, 2007; Hallegate et al., 2013; Arkema et al., 2013; Kron, 2013, Hinkel et al., 2013; McNamara and Keeler, 2013; Johnson et al., 2015; Brown et al., 2016).

Increased awareness of the potential socio-economic damage associated with CC is now resulting in numerous coastal CC impact assessments around the world, specifically to support on-the-ground decision making at local scale (<10 km). However, these local scale assessments adopt widely varying modelling approaches to quantify the various coastal CC impacts, leading to results that are of rather variable quality. Given ever growing coastal communities and the extremely high value of coastal assets, poorly informed adaptation measures may have devastating effects, and in some situations, may even cause more damage than 'doing nothing' (Hoggart et al., 2014). It is therefore imperative that such local scale coastal CC impact assessments be undertaken using the best available coastal engineering practice. This review aims to facilitate best practice where assessments of physical impacts of CC on open sandy coasts are concerned by (a) summarising the potential first order physical impacts of CC, (b) formalising a modelling framework for local scale CC impact assessments, (c) identifying future research and development needs to facilitate the effective implementation of the proposed modelling framework, (d) suggesting ways to address the identified research and development needs, and (e) discussing how existing methods/tools may be effectively used in CC impact assessments until more advanced methods/tools are developed.

2. Climate change driven physical impacts on open sandy coasts

The world's coastlines can be divided into two main sub-systems: *Open coasts* and *Deltaic coasts*. Open coasts comprise sandy coasts, cliffed coasts and gravel beaches as well as estuaries (i.e. inlet-interrupted coasts) while Deltaic coasts include estuaries and mostly consist of muddy or silt-sand coasts. Open sandy coasts, the subject of this review, comprise up to 40% of world's coastline (Bird, 1996) and are subject to a very high level of human utilisation. Sandy coasts may be further sub-divided into mainland and barrier island coasts, with some operating physical processes being common to both types of coasts (e.g. storm erosion, coastline recession, spit/barrier breaching due to elevated water levels) and some others being specific to one coast type or the other (e.g. seasonal closure of small tidal inlets on mainland sandy coasts; barrier rollover on barrier island coasts). Processes that are particular to barrier island coasts such as barrier rollover, thinning, breaching, elongation etc., potential CC impacts on these processes, and their quantification are extensively discussed by, among others, Moore et al. (2010), Fitzgerald et al. (2013), Moore et al. (2014), Carrasco et al. (2016) and Duran Vincent and Moore (2015). Therefore, to limit the scope of this review, these barrier island-specific processes are not discussed herein. This article focusses on the potential physical impacts (i.e. impacts affecting coastal morphology) of CC that may be felt on both mainland sandy coasts and barrier island coasts, or only on mainland sandy costs (but not those that may be felt only at barrier island coasts). For convenience, the target geomorphic setting of this review is hereon referred to simply as sandy beaches.

Sandy beaches are highly dynamic and continually adjust to subtle changes in hydrodynamic forcing, and the feedback between hydrodynamics and morphology (i.e. morphodynamics) is highly non-linear and scale dependent, both temporally and spatially. The exact response of a particular stretch of the coast to a given set of environmental forcing (e.g. mean water level, storm waves, storm surge) will depend to a large extent on site-specific geomorphic features. Therefore, the composite physical impact of CC at local scale is impossible to determine without a comprehensive local scale study which takes into account site specific non-linear forcing-response mechanisms and geomorphology. Nevertheless, the potential first order CC driven physical impacts that maybe felt along the world's sandy coastlines can be summarised as shown in Table 1. It should be highlighted at the outset that the various CC impacts listed in Table 1 will manifest themselves at different time scales (Stive et al., 2002). For the purposes of this review, the various impacts are classified into episodic (time scale ~ hours-days), medium-term (time scale ~ year - decade), and long-term (time scale ~ decades - century). As shown in Table 1, CC impacts on sandy coasts will be governed by CC driven variations in mean sea level (i.e. Sea level rise - SLR), wave conditions, storm surges and riverflow. The main potential CC impacts related to these four environmental drivers are briefly discussed below.

2.1. Sea level rise

Due to the very slow nature of SLR, all SLR driven physical impacts will manifest themselves as long-term impacts (~50–100 yrs. time scale). Along most sandy coasts, accelerated sea level rise is likely to result in the permanent inundation of unprotected low-lying land and more frequent/intense episodic coastal inundation when CC modified wave conditions and storm surge act in combination with SLR. Both permanent and episodic inundation will be exacerbated at locations that are subject to land subsidence.

Another well known impact of SLR is chronic (i.e. long-term) coastline retreat (recession). The commonly used Bruun rule (Bruun, 1962)

Table 1
Potential first order climate change driven physical impacts on open sandy coasts.

Potential impact	Process time scale*	Main drivers
More/less frequent and/or more/less severe episodic coastal inundation (see Section 4.2.1)	Episodic	Sea level rise, changes in intensity and/or frequency of storms, changes in storm surge
Increased/decreased episodic storm erosion of beaches and dunes (see Section 4.2.2)	Episodic	Changes in intensity and/or frequency of storms, changes in storm surge, changes in storm wave characteristics
More/less frequent (or previously unexperienced) episodic formation and closure of small tidal inlets (see Section 4.2.3)	Episodic	Changes in storm surge, changes in intensity/frequency of extreme riverflow events, changes in storm wave characteristics
Sustained erosion/accretion due to re-alignment of embayed beaches (see Section 4.2.4)	Medium-term	Changes in mean offshore wave direction
Sustained changes in inlet cross-section/inlet stability (see Section 4.2.5)	Medium/Long-term	Sea level rise, changes in mean offshore wave conditions, changes in annual riverflow
Permanent inundation of low lying land and increased flood height (see Section 4.2.6)	Long-term	Sea level rise
Chronic coastline recession (uninterrupted coasts) (see Section 4.2.7)	Long-term	Sea level rise, changes in mean offshore wave conditions
Chronic coastline recession (inlet interrupted coasts) (see Section 4.2.8)	Long-term	Sea level rise, changes in riverflow, changes in fluvial sand supply, changes in mean offshore wave conditions

* *Time scale definitions*: Episodic ~ hours-days, medium-term ~ year - decade, and long-term (~ decades - century).

predicts an upward and landward movement of the coastal profile (Bruun effect) in response to SLR, suggesting a recession of 50–100 times the SLR amount along most sandy coastlines, depending on the average shoreface slope (i.e. average slope of profile from beach/dune to depth of closure; also taking into account overwash plains/cliffs if beach overwash/cliff erosion might be relevant at the time scales and location considered). However, the exact nature of the local response will be governed by total sediment budgets (Cowell et al., 2003; Dean and Houston, 2016).

A relatively less well known SLR induced process driving chronic recession along inlet-interrupted mainland coasts is the SLR induced infilling of estuaries and lagoons (basin infilling). This phenomenon can occur at both of the main inlet-estuary types on mainland coasts: Geological origin systems (e.g. Golden Gate inlet, CA, USA; Botany Bay inlet, Sydney, Australia) and bar-built estuaries (also known as Barrier estuaries or Small Tidal inlets) which are found in their thousands along the tropical and sub-tropical coasts of the world (Duong et al., 2016) (*Note: For convenience,* this type of systems will be hereon referred to as Small Tidal Inlets - STIs). Basin infilling occurs due to the SLR driven increase in the basin volume below mean water level. This additional volume is known as 'accommodation space'. In response to this geomorphic change, the basin, which always tries to maintain an equilibrium volume, will start importing sediment from offshore to raise the basin bed level such that the basin volume remains at its pre-SLR value. Depending on sediment availability, the basin morphology will reach equilibrium when a sand volume equivalent to the SLR induced accommodation space is imported into the basin. The basin infill volume is usually borrowed from the adjacent coastline and/or the ebb tidal delta, leading to additional coastline recession (on top of the above described Bruun effect) and/or depletion of the ebb delta (Stive and Wang, 2003; Ranasinghe et al., 2013).

At estuaries/lagoons backed by extensive salt marshes, SLR will increase the estuary/lagoon surface area and thus the tidal prism. This will inevitably change the inlet cross-section area (O'Brien, 1931) and possibly inlet stability (Bruun, 1978), leading to profound changes in hydrodynamics and sediment transport in the nearshore zone and estuary/lagoon dynamics such as ebb/flood delta evolution and estuarine mixing, flushing, circulation and water quality. This is more likely to occur at larger Geological origin inlet systems than at STIs (Duong et al., 2016).

SLR may also decrease the efficacy of existing coastal protection structures (e.g. overtopping of breakwaters, groynes, seawalls, dykes). In extreme cases an existing effective coastal protection structure might turn into a coastal erosion hazard due to SLR. One example of such a situation is when a currently emerged structure (usually placed close to the shoreline for maximum beach widening) becomes submerged due to SLR. While an emerged breakwater placed closed to shoreline will almost guarantee coastal protection (Silvester and Hsu, 1997), a shallow submerged breakwater placed closed to the shoreline could result in significant erosion of the shoreline in the lee of the structure (Ranasinghe et al., 2006, 2010).

2.2. Average wave conditions

Following a comprehensive multi-model ensemble study, Hemer et al. (2013) have shown that CC will result in significant changes in the average annual wave climate around the world. These future variations in average wave climate could lead to significant coastal impacts.

Any CC driven variation in the average wave direction could lead to increased erosion on the downdrift side and comparable accretion on the updrift side of embayed beaches (Slott et al., 2006; Ratliff and Murray, 2014), resulting in permanent re-alignment of the mean orientation of these beaches (over and above the beach oscillation/rotation due to natural climate variability commonly experienced at embayed beaches). This impact will most likely manifest itself over a decade or two (medium-term). Of particular relevance to embayed beaches located along the Pacific coast is the ENSO phenomenon which has been firmly linked to the cyclic rotation of these beaches via the annual wave climate (Ranasinghe et al., 2004; Harley et al., 2011; Barnard et al., 2015). Thus, any CC driven variations in the ENSO phenomenon, and the associated variations of wave conditions, are likely to result in changes in the magnitude and frequency of this cyclic rotation phenomenon, possibly leading to more intense, more frequent erosion/accretion cycles on the many embayed beaches found on both sides of the Pacific Ocean.

Changes to average wave direction and/or height could have a medium-term effect on the stability of, especially, the thousands of STIs located in wave dominated, microtidal environments (O'Brien, 1931; Bruun, 1978; Duong et al., 2016). STIs may be permanently open and fixed in location, permanently open and migrating alongshore, or fixed in location but seasonally/intermittently closed. At such systems, for example, if CC driven changes in average wave characteristics are such that the longshore current due to oblique wave incidence increases (thus increasing longshore sediment transport rates), a presently permanently open STI may close off or turn into a seasonally/intermittently open inlet. This is particularly likely at river influenced systems (i.e. systems where mean tidal discharge (m3/s)/river discharge (m3/s) < 20 (Bruun, 1978; Powell et al., 2006) when a CC driven decrease in riverflow into the estuary/lagoon is combined with an increase in longshore current. Conversely, if the longshore current (and thus longshore sediment transport) decreases, a currently seasonally/intermittently open STI could turn into a permanently open STI, particularly if combined with a concurrent CC driven increase in riverflow. CC driven variations in longshore sediment transport could also result in inlet migration and their subsequent relocation (Duong et al., 2016).

2.3. Storms and Storm surge

CC is also expected to affect storm wave characteristics and storm surges (Nicholls et al., 2007; Sterl et al., 2009; Hemer et al., 2012). An increase in the frequency of storm occurrence and/or storm wave heights will undoubtedly result in more severe episodic coastal erosion (as storm erosion volume is proportional to wave power (Overton and Fisher, 1988; Larson et al., 2004; Callaghan et al., 2008)). The situation will be further exacerbated by a concurrent increase in storm surge. Indeed, increased storm erosion may well have a more damaging coastal impact than the slow gradual erosion due to SLR. Coastal setback lines that are presently based only on, for example, the 1 in 100 year storm event extrapolated from historical data, will need to be re-evaluated using future projected storm and surge characteristics. The combination of SLR, increased storm wave height, and increased storm surge will also result in more instances of episodic inundation due to dune overwash (either by runup overtopping or dune overflow). In extreme cases of dune overwash, the dune may breach and be completely destroyed (Donnelly et al., 2006). This will present major threats to coastal communities located in low lying coastal zones that depend on the stability of coastal dunes as a primary defense mechanism. Furthermore, increases in storm wave heights, storm occurrence frequency and/or storm surge might render existing coastal protection structures such as offshore breakwaters and seawalls ineffective.

CC driven changes in storm occurrence/storm wave heights and/or storm surges may either close existing STIs and/or create new inlets by breaching sand bars that separate the estuary/lagoon from the ocean. Breaching of new inlets is particularly likely when storm surges are combined with extreme riverflow events at river influenced STI systems. As CC is expected to result in intensifying both extreme storm surges and extreme rainfall/runoff events in some parts of the world, breaching of new inlets may become more frequent at such river influenced systems. Closing of an existing inlet and/or breaching of new inlets will have massive implications on the tidal prism and hence water exchange between the ocean and the estuary/lagoon, which in turn will affect all estuarine processes (mixing, flushing, circulation, water quality).

2.4. Riverflow

IPCC (2013) projections indicate that CC may result in significant increases/decreases of annual riverflows around the world, in some places exceeding 40%. At river influenced inlet-estuary systems (both Geological origin systems and STIs), when CC results in a decrease (increase) of riverflow and/or fluvial sand supply into the estuary/lagoon, the long-term recession of the coastline adjacent to the inlet will further increase (decrease) due to the additional (reduced) demand of sand by the basin to maintain equilibrium velocities within the estuary/lagoon (Ranasinghe et al., 2013). Furthermore, a decrease in annual riverflow may result in the medium-term effect of stable STIs becoming unstable (alongshore migration and/or intermittent closure) (Duong et al., 2016), while an increase in riverflow may have the opposite effect (Slinger et al., 1994; Elwany et al., 1998; Ranasinghe and Pattiaratchi, 1999; Walker, 2003; Duong et al., 2016).

3. Quantifying climate change driven physical impacts on coasts at local scale

Global and/or national scale assessments of CC impacts on coasts may be undertaken with scale aggregated (or reduced complexity) models forced directly by coarse grid output from IPCC Global Climate Models (GCMs, with typical spatial resolutions of about 200 km) (Hinkel et al., 2013). However, the development of effective CC adaptation strategies at local governance unit level requires the quantification of CC impacts at much higher spatial resolutions, typically at <10 km resolution. Technically, a carefully selected and validated suite of mathematical models, operating at various spatio-temporal resolutions, could be used to quantify all of the above mentioned CC impacts at local scale (<10 km length scales). However, there are large uncertainties associated with not only the various models, but also with the forcing (i.e. greenhouse gas (GHG) emissions scenario uncertainty). Any conscientious effort to assess CC impacts on coasts should therefore include the quantification of the range of uncertainty associated with model predictions. This can be achieved via ensemble modeling.

A thorough local scale coastal CC impacts study would ideally follow the broad structure shown in Fig. 1 (Ruessink and Ranasinghe, 2014). In the suggested structure, GHG emissions scenario uncertainty is accounted for by considering all or some of the four IPCC (2013) scenarios, or Representative Concentration Pathways - RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). If only some RCP scenarios are considered, it should be ensured that both low and high GHG emissions scenarios are included in the ensemble.

Global Climate Models (GCM) (e.g. *HADCM, GFDL, GISS, ACCESS*) are owned and operated by large research organizations around the world. These GCMs are forced in line with the various IPCC scenarios and provide output consisting of time series of numerous climate variables (e.g. surface temperature, ocean temperature, atmospheric pressure, precipitation, wind (*Note:* Mean sea level (MSL) is usually obtained by post-processing GCM output) on a global grid at a fairly coarse resolution of about 200 km. As different GCMs give somewhat different projections, there is a significant uncertainty associated with GCM output. In the suggested modelling framework, the uncertainty associated with GCMs is accounted for by considering output from several GCMs.

As GCM output is generally available at a resolution that is inappropriate for direct use in regional/catchment scale models, let alone local scale coastal impact models, this output needs to be downscaled to a finer resolution. This is best achieved via dynamic downscaling (although statistical downscaling is also possible in data rich areas), where the coarse grid GCM output is used to drive regional scale models (Regional Climate Models – RCMs). Typically RCM simulations are undertaken for 20–30 year long time slices and are nudged towards the parent GCM at regular intervals to ensure that RCM output is consistent with GCM output over long time scales. RCMs generally provide output at 2–50 km resolutions. As there is model uncertainty associated with RCMs also, the use of several RCMs is suggested in the modeling framework shown in Fig. 1.

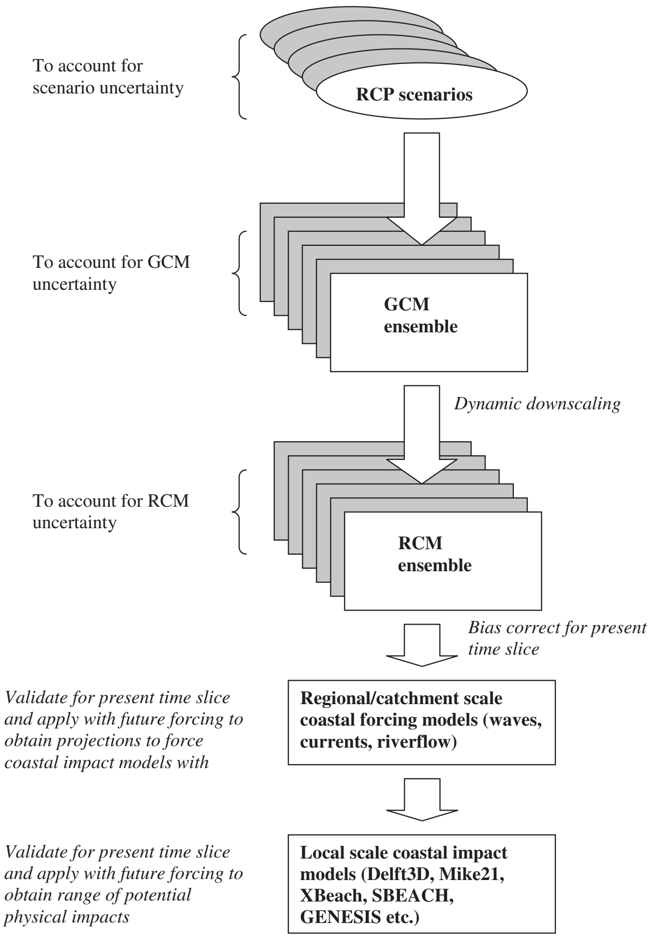

Fig. 1. Suggested standard modelling framework for a local scale climate change impact quantification study on sandy coasts (modified from Ruessink and Ranasinghe, 2014).

An important step prior to using RCM output as forcing for regional/catchment scale models is bias correction. This can be achieved by comparing RCM output for the present time slice (e.g. 1980–2010) with concurrent field measurements (or global re-analyses) of relevant climate variables (e.g. wind, air pressure, temperature, precipitation), and applying correction techniques to the RCM output as required. These corrections can then be applied to the RCM outputs for future time slices (e.g. 2081–2100), assuming that RCM biases stay the same at future times. The bias corrected RCM output for the future can be used to drive validated regional/catchment scale models to obtain future projections of forcing parameters (e.g. waves, currents, riverflow) that are relevant for coastal processes.

Finally, the projected forcing conditions thus obtained can be used to drive appropriate validated coastal impact models (e.g. *Delft3D, Mike21, CMS, GENESIS, SBEACH, XBeach*) to obtain projections of CC driven physical impacts on coasts at local scale.

The ensemble modelling approach suggested in Fig. 1 will provide a number of different projections of the coastal impact of interest. The range of projections will account for GHG scenario uncertainty, GCM uncertainty, and RCM uncertainty. If required, regional/catchment scale model and coastal impact model uncertainty can also be included in this approach, albeit at significant computing cost. The range of coastal impact projections thus obtained can then be statistically analysed to obtain not only a best estimate of coastal impacts (i.e. expected value) but also the range of uncertainty associated with the projections, which will enable coastal managers/planners to make risk informed decisions.

4. Available data, modelling methods and tools

The data and models required in the GCM, RCM and Regional scale coastal modelling components of the modeling structure shown in Fig. 1 are relatively well known. Hence, only very brief descriptions of these aspects are given below in Section 4.1. On the other hand, modelling methods and tools appropriate for the quantification of local scale CC driven coastal impacts are less well known, and are therefore comprehensively addressed in Section 4.2.

4.1. GCM output, RCMs and Regional scale coastal forcing models

The Program for Climate Model Diagnosis and Intercomparison (PCDMI) based at the Lawrence Livermore National Laboratory, California, USA is the primary entity that provides free access to IPCC GCM output. At present the GCM output from the Coupled Model Intercomparison Project 5 (CMIP5), which fed into the IPCC AR5 (2013) are available from http://www-pcmdi.llnl.gov. The CMIP5 data comprise output from 20 climate modelling centres around the world. Atmospheric and land surface data are available at 3 hourly to monthly resolutions, while ocean data is available at monthly temporal resolution. Data on 10 extreme indices (e.g. frost days, heat wave days) are also available. It should be noted that presently available projections of SLR are based not only on GCM output but also on semi-empirical scenarios (Rahmstorf, 2007) and expert opinion (Bamber and Aspinall, 2013; Church et al., 2013).

Despite the free availability of GCM output, the inappropriate format in which GCM output is provided, especially where local scale impact assessments are concerned, has been the subject of a robust debate for years. The crux of this debate lies in the disparity between what end-users need and what the scientific community generally provides; on-the-ground practitioners (managers, planners, engineers) generally require reliable ready-for-use predictions of climate variables, while the scientific community largely concentrates on quantifying the uncertainty associated with GCM projections (Brasseur and Gallardo, 2016). The uncertainty associated with GCM projections stems at least from four main sources; (1) future greenhouse gas emissions, (2) climate response to radiative forcing (also known as model spread), (3) inherent natural variability in the climate system, and (4) model initializing conditions (Kirtman et al., 2013; Bowyer et al., 2014). Furthermore, the GCM uncertainty issue is confounded by the fact that the relative importance of these different sources of uncertainty is dependent on the climate variable and timescales under consideration. As neither the IPCC nor the GCM operators provide direct advice on how these uncertainties should be accounted for in local scale impact studies, end-users are confronted with the daunting task of deciding how best to use GCM output to address the problem at hand. Recent developments in the sphere of Climate services at international, national and regional levels, however, have the potential to fulfill this urgent need felt by end-users of GCM projections (Brasseur and Gallardo, 2016).

Regional climate models (RCM) are usually operated at resolutions of about 50 km (as opposed to GCM resolution of about 200 km) and covers a limited area of the globe, typically 5000 km × 5000 km. RCMs, which are generally applied over a 20–30 yr time slice, are comprehensive physical models that describe the important processes in the climate system (e.g. clouds, radiation, rainfall, soil hydrology) as found in a GCM. Generally, RCMs do not include an ocean component, primarily because this would require significantly more computing power. RCM boundaries are driven by atmospheric winds, temperatures and humidity output from a GCM.

Numerous RCMs are being used around the world (e.g. *PRECIS* (Jones et al., 2004), *RegCM2* (Dickinson et al., 1989; Giorgi and Bates, 1989), *CCAM* (McGregor and Dix, 2008), *CRCM* (La Prise, 2008)). A major international initiative, *CORDEX*, aimed at producing improved multi-model RCM based high resolution climate information worldwide is currently underway (http://wcrp.ipsl.jussieu.fr/SF_RCMTerms.html). It should be noted, however, that RCMs invariably inherit the uncertainties associated with the parent GCMs and therefore RCM output may only be as reliable as the coarser resolution parent GCM projections (Xie et al., 2015).

Environmental forcings that are relevant for most coastal CC impacts studies are water levels (incl. mean sea level, tides, storm surge), offshore waves, coastal currents, and riverflow. Pre-determined water levels are usually specified as boundary conditions in coastal impact models. Commonly used models to simulate ocean waves at regional scale include (but are not limited to): *WAM* (Hasselmann et al., 1988), *SWAN* (Booij et al., 1999), *Mike21SW* (Sørensen et al., 2004), and *WaveWatch3* (Tolman, 2009). Widely used models to simulate regional scale coastal currents include (but are not limited to): *HAMSOM* (Backhaus, 1985), *ROMS* (Shchepetkin and McWilliams, 2003, 2005), *Delft3D* (Lesser et al., 2004), *Mike21HD* (DHI, 2005), and *NEMO-POA* (Madec, 2008). Land surface models (LSMs) commonly used to simulate riverflow include (but are not limited to): *Sacremento* (Burnash et al., 1973), *VIC* (Liang et al., 1994), *Noah* (Schaake et al., 1996), *SiB* variants (Dirmeyer and Zeng, 1999; Mocko and Sud, 2001), *Catchment* (Koster et al., 2000), and *ISBA* (Etchevers et al., 2001).

4.2. Coastal Impact models

As highlighted above in Section 2, CC impacts on sandy coasts will manifest themselves at various spatio-temporal scales (~10 m to ~100 km and days to centuries). It should also be noted that impacts manifesting themselves at different spatio-temporal scales may have profound inter-dependencies. For example, the coastal response to a given storm (episodic impact) will be quite different on a year 2100 coastal profile that has already adjusted to ~1 m of SLR (long-term impact) to that on a contemporary profile; or the rate of coastline recession (long-term impact) adjacent to an inlet with a depleted ebb delta (medium-term impact) will be different to that adjacent to a contemporary inlet with a large ebb delta. Thus, for CC impact assessment on sandy coasts, a coastal impact model should ideally be able to concurrently simulate the physical processes occurring at different spatio-temporal scales, including inter-scale morphodynamics. However, presently available models are generally only able to simulate processes occurring at one main spatio-temporal scale or the other (Le Cozannet et al., 2014). For example, the profile models *SBEACH* and *XBeach* are able to simulate beach/dune response to storms occurring at spatio-temporal scales of metres-days (Larson, 1988; Larson and Kraus, 1989; Roelvink et al., 2009); the coastal area model *Delft3D* is able to adequately simulate morphological change due to concurrent tides, waves and currents at spatio-temporal scales of about 5 km-5 yrs. (Lesser, 2009); the coastline models UNIBEST-CL (Szmytkiewicz et al., 2000; Ruggiero et al., 2010) and GENESIS (Hanson, 1989; Hoan et al., 2010) can simulate coastline change due to longshore transport gradients over length scales of ~100 km and time scales of ~100 yrs. While there are ongoing efforts to combine these different types of models to seamlessly simulate multi-scale coastal evolution, a generally applicable multi-scale model has not yet been successfully developed. However, even if/when a multi-scale process based model were to be available, the inevitably heavy computational costs of such a model will most likely preclude the multiple simulations required for robust quantification of the uncertainty cascade associated with CC impact assessments (see Fig. 1). Some thoughts on how these issues maybe overcome are presented in Section 5.

One interim solution for coastal CC impact assessments, until appropriate multi-scale coastal impact models and uncertainty quantification methods are developed, may be to adopt a systems modelling framework that sequentially applies systems mapping using empirical methods (French et al., 2010), physics based scale aggregated (or reduced complexity) models, data driven models, and process based models at gradually decreasing spatio-temporal scales In such an approach, the boundary conditions of the lower-level (finer resolution) model can be periodically adjusted with the output of the higher-level model at corresponding times to ensure the representation of some level of inter-scale behaviour in the modelled system response. An advantage of such a hybrid approach will be the significant reduction of computational cost, thus enabling the multiple realisations required for uncertainty quantification. This type of systems modelling framework is currently being developed and trialled at two sites in the UK via the ongoing iCOASST initiative which is expected to be completed in 2017 (Nicholls et al., 2012).

Another, more immediately applicable, approach to modelling CC impacts on sandy coasts is the strategic application of existing numerical models while accepting that, in most cases, scale-interaction effects will be absent from assessments thus obtained. In most situations, the results obtained in this fashion may suffice as a 'first-pass' assessment. To inform such an approach, the modelling methods and tools currently available to quantify the first order coastal impacts listed in Table 1 are described below.

4.2.1. Episodic coastal inundation

To quantify episodic coastal inundation, estimates of Relative Sea Level Rise (RSLR) (see 4.2.6), CC modified storm surge and wave runup height are required. RSLR estimates maybe derived using the detailed guidelines presented by Nicholls et al. (2014). CC modified storm surge estimates may be obtained by forcing a depth averaged (2DH) hydrodynamic model (e.g. *Mike21HD*, *Delft3D*, *ROMS*) with downscaled future wind and pressure fields (Sterl et al., 2009; Colberg and McInnes, 2012, Weisse et al., 2014). The model domain should be selected such that all major storm generating systems/regions are included. However, it is known that, in general, extreme events such as storm surge are not very well simulated by GCMs. Therefore, if long records of ocean water levels are available in the study are, a more reliable storm surge estimate could probably be obtained by using those data. This could be done by performing an extreme value analysis on the historical water level data to obtain an exceedance probability distribution of storm surge, and then extrapolating the distribution to determine the storm surge with the desired exceedance probability (commonly 0.01 exeedance probability is used in CC impact assessments). The storm surge height thus estimated could be used directly (assuming CC will not modify storm surge heights significantly), or with a reasonable adjustment based on expert judgement (to represent CC driven modifications of storm surge height), in the impact assessment.

Several empirical equations are available to estimate wave runup as a function of offshore wave conditions (Hunt, 1959; Holman, 1986; Nielsen and Hanslow, 1991; Larson et al., 2004; Stockdon et al., 2006). Of these, the most widely used approach is that presented by Stockdon et al. (2006).

The RSLR, storm surge and wave runup height estimates can then be used in conjunction with a Digital Elevation Map (DEM) to map the extent of episodic inundation at various return periods (i.e. 1 in 10 yr, 1 in 100 yr etc) as required. Where a high level of accuracy is desired, particularly very near the coast, the present-day DEM should be corrected to account for potential land losses from the coast due to storms and CC driven coastline recession (Lentz et al., 2016).

4.2.2. Episodic storm erosion

The method commonly used to estimate a given return period storm erosion volume is to force a calibrated and validated coastal profile model, including dunes where they are present, (e.g. *SBEACH* (Larson, 1988), *XBeach* (Roelvink et al., 2009)) with a storm comprising the same return period storm wave height (Callaghan et al., 2009). Technically, the same approach could be used to estimate CC modified storm erosion, with CC modified storm conditions as input. It should be noted however that, if CC modified wave conditions are very different to present day conditions (e.g. 50% increase/decrease of wave height), a profile model calibrated/validated for contemporary conditions might not strictly be applicable as some empirical constants/relationships, inevitably found in any coastal profile model, may not be valid when the forcing is very different to the conditions under which such constants/relationships had been derived (Callaghan et al., 2013). Fortunately, most wave downscaling studies undertaken to date indicate only moderate changes in the future CC modified storm wave conditions (Grabemann and Weisse, 2008; Debernard and Roed, 2008, Hemer et al., 2013).

However, this "standard" erosion volume estimation approach has several problems. First, it assumes that, for example, a 1:100 yr storm wave height results in a 1:100 yr storm erosion volume. This is a convenient but erroneous assumption (Callaghan et al., 2008, 2009). For example a 1:5 yr storm wave height event that occurred in Sydney, Australia in June 2007 resulted in a 1:10 yr storm erosion volume (Callaghan et al., 2009). However, in the absence of long term coastal erosion measurements, all that can be done is to ensure that front-line coastal zone managers/planners are aware that what this approach provides is *not the* (for example) 1:100 yr storm erosion volume, but the erosion volume *due to* a 1:100 yr storm wave height event.

Second, the calibration and validation of a process based coastal profile model requires comprehensive hydro-morphological data for at least 3 storms (including before and after bed profile measurements). This level of data is not readily available at most locations. Due to the large number (~10) of tunable parameters in these models, and due to the high level of sensitivity of the model predictions parameter values, a model that is not adequately calibrated/validated is more than likely to provide unreliable results. In situations where sufficient model calibration/validation data do not exist, or cannot be acquired within project constraints, it is therefore not advisable to use process based numerical models to obtain 'apparently reliable' estimates of storm erosion volumes.

Finally, one of the biggest shortcomings of this historical approach is its inability to provide probabilistic estimates of storm erosion which are now being required by contemporary risk based coastal management/planning frameworks (Kunreuther et al., 2013; Villatoro et al., 2014; Zanuttigh, 2014; Penning-Rowsell et al., 2014; Wainwright et al., 2015). Probabilistic estimates of storm erosion require multiple model simulations (thousands) which is simply computationally too expensive if sophisticated process based models were to be used. Callaghan et al. (2008) presented an approach to obtain probabilistic estimates of storm erosion volumes, which to a large extent, circumnavigates all of the above difficulties. The model (Joint Probability Model - JPM) essentially fits marginal, dependency and conditional distributions to long time series of forcing parameters (i.e. storm wave height, storm duration, storm wave period, storm wave direction, storm spacing, and tidal anomaly). These distributions are then used within a Monte Carlo simulation to derive a time series of storms and associated erosion volumes, which are subsequently statistically analysed to obtain exceedance probabilities of storm erosion volume.

The JPM model has been validated at the data-rich Narrabeen beach, Sydney (one of the few locations around the world with over 40 years of concurrent wave, water level and monthly beach profile data) using 3 different structural functions: Kriebel and Dean (1993), *SBEACH* and *XBeach*. The model/data comparisons (Fig. 2) show >90% of the data points falling within the 95% confidence limits when either *SBEACH* or *XBeach* is used as the structural function. A detailed description of this application is provided in Callaghan et al. (2013).

4.2.3. Episodic formation/closure of Small tidal inlets (STIs)

New inlets may be formed when (a) storm surge events breach sand bars that separate STIs from the ocean, and (b) high riverflow events carve out a hydraulically efficient new inlet through an existing sand

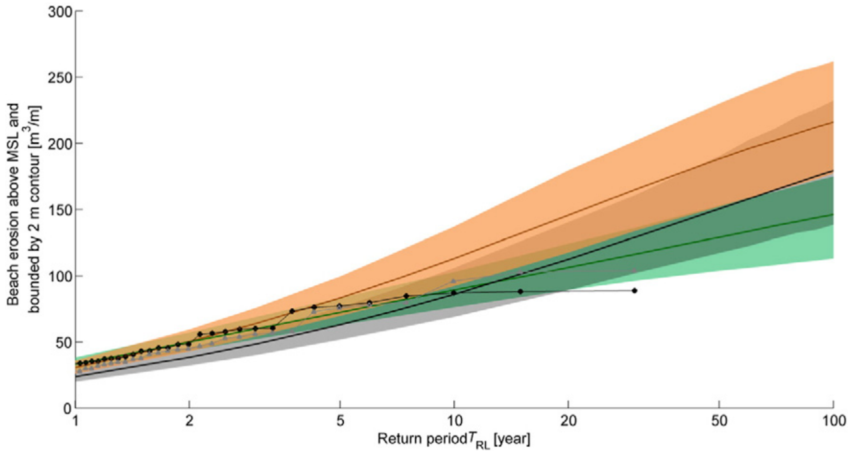

Fig. 2. The eroded sand volume above MSL at Narrabeen Beach from; profile measurements (empirical estimates by block averaging —▲— and consecutive volumes —●—); and simulating 1000 years of beach erosion repeated 2000 times to ensure convergent predictions for Kriebel and Dean (1993, continuous black line), *SBEACH* (Larson, 1988, continuous green line) and *XBeach* (Roelvink et al., 2009, continuous orange line). The respective shaded areas show the 95% confidence limits indicative of the uncertainty of the erosion estimates obtained using the 3 different structural functions (From Callaghan et al., 2013).

spit at river influenced STIs (i.e. mean tidal discharge (m3/s)/river discharge (m3/s) < 20 (Bruun, 1978; Powell et al., 2006)), especially when the existing inlet channel is long and sinuous (sometimes known as 'dog-leg' shaped channels). On the other hand, existing STIs may suddenly close off during high energy wave events with large and obliquely incident waves due to increased longshore sediment transport. This phenomenon is most likely to occur when riverflows are low.

Sand bar breaching due to elevated ocean water levels (e.g. storm surge) can be successfully modelled with a process based coastal area morphodynamic model (e.g. *Delft3D*, *Mike21, XBeach, TELEMAC2D, CMS*). A good example can be found in Roelvink et al. (2009) where the breaching of the Zwin inlet in Belgium is reproduced with *XBeach*. For coastal zone management/planning however, it is also important to know what happens after the initial breaching. For example, does a newly created inlet rapidly close off, migrate, or stay in place? Due to the inherent assumptions in presently available models, it is not advisable to continue model simulations after the initial breaching. Thus a continuous simulation of inlet breaching and subsequent evolution is not possible at present. However, it is possible to have one simulation until the breaching, and another after the breaching (initialised with the final morphology predicted by the pre-breach simulation).

Theoretically, a process based coastal area morphodynamic model should be capable of simulating new inlet formation due to high riverflows and the closure of STIs due to high energy wave events. However, no such model applications have been reported to date in the published literature.

4.2.4. Medium-term erosion/accretion due to re-alignment of embayed beaches

Embayed beaches commonly undergo oscillation and/or rotation (albeit with net zero change to mean beach orientation in the long term) as a result of climate variability effects (e.g. ENSO). These 2–5 year oscillation/rotation cycles are mainly driven by subtle changes in average and storm wave conditions which cause variations in longshore and/or cross shore sediment transport rates (Ranasinghe et al., 2004; Harley et al., 2011; Barnard et al., 2015). Such oscillation/rotation cycles will continue in the future, possibly with some adjustment due to CC induced modifications in the causative climate variability signals. However, on top of these net zero change cycles, CC driven changes in net longshore sediment transport (due to CC modified *average* wave heights and directions) could change the mean orientation of embayed beaches, resulting in their permanent re-alignment. Such permanent beach re-alignments due to changes in longshore sediment transport may be readily simulated with one-line models such as LITLINE, UNIBEST-CL, GENESIS and CEM (Slott et al., 2006; Ruggiero et al., 2006, 2010; Ratliff and Murray, 2014).

Alternatively, a simple one-line model could also be easily constructed using the Pelnard-Considere equation given by:

$$\frac{dy}{dt} = \frac{1}{d_c}\frac{dQ_{LST}}{dx} \tag{1}$$

where, y (m) = shoreline position along a cross-shore transect relative to a fixed datum, x(m) = alongshore coordinate, d_c (m) = depth of closure, Q_{LST} (m^3/s) = longshore sediment transport rate.

Q_{LST} maybe be estimated by using one of the several commonly used bulk longshore sediment transport (LST) equations such as CERC (1984), Kamphuis (1991), Bayram et al. (2007) (see also Milhomens et al., 2013 for recent improvements to these 3 bulk LST equations). The development and application of such a model to a schematised beach representing the coastline around Poole Bay, UK is described by Zacharioudaki and Reeve (2011).

As one-line models have very fast run-times, they may be applied over a centennial time scale. To obtain a single deterministic estimate of future coastline change due to CC driven variations in longshore sediment transport rates, a calibrated and validated one-line model maybe forced with gradually changing MWL (representing SLR) and wave conditions. i.e. the MWL and wave characteristics are gradually varied from their present values to the appropriate future projected values during the simulation. However, due to the uncertainty in CC projections and the contemporary shift towards risk informed coastal management/planning, it is more desirable to derive probabilistic estimates of coastline change via an ensemble of model simulations. Ruggiero et al. (2006, 2010) present a good example of this latter approach.

To develop effective management/planning decisions for embayed beaches, coastal zone managers/planners also need to take into account medium-term erosion/accretion signals (such as beach oscillation/rotation). As beach oscillation/rotation is governed by both longshore and cross-shore sediment transport (Ranasinghe et al., 2004; Harley et al., 2011), a fully 3D (or at least Quasi 3D) process based coastal area morphodynamic model which resolves the vertically non-uniform structure of cross-shore currents may be used to simulate these phenomena (e.g. *Delft3D* in 3D mode). However, presently available 3D or Quasi 3D coastal area models mostly concentrate on simulating bed level changes below MWL and do not incorporate the ability to accurately simulate coastline change.

Another approach to simulate beach oscillation/rotation is to link a one-line coastline change model with a 2DV coastal profile model. This approach was adopted by Huxley (2011) where a coastline model based on the CERC equation was coupled with Miller and Dean's (2004) cross-shore profile model. Huxley (2011) successfully applied this model to obtain projections of CC driven variations of the coastline at Wooli Wooli, Australia.

4.2.5. Medium/long-term changes in inlet cross-section/inlet stability

Inlet stability is governed by the delicate balance of ocean water levels, wave conditions, and riverflow, all of which will be modified by CC. The best approach to simulate medium or long-term CC impacts on inlet stability is via a multi-scale process based coastal area model. Ideally simulations would run continuously for the entire period of interest, which is typically 50–100 years for CC impact studies, and the model would concurrently simulate episodic events (e.g. storms, extreme riverflow events), medium-term phenomena (e.g. changes in average wave height/direction and annual riverflow), and long-term CC effects (e.g. SLR). However, as discussed above, such a model does not presently exist.

With present capabilities, it is however possible to gain qualitative insights into how CC may affect inlet stability via strategic ‘snap-shot’ simulations using process based coastal area models (Duong et al., 2016). In this approach, a model validated for present conditions may be applied with future forcing for simulation lengths of 1–2 years at the desired future times (e.g. 2050, 2100). Several studies have indicated that a simulation length of 1–2 years is sufficient for inlet morphology to reach near-equilibrium conditions following a perturbation in system forcing (Ranasinghe et al., 1999; Ranasinghe and Pattiaratchi, 2003; Bruneau et al., 2011), and therefore, this type of ‘snap shot’ simulation is likely sufficient to qualitatively assess the impact of CC on inlet stability.

In adopting this approach, the initial bathymetry of the future simulation should be adjusted such that long-term bathymetric changes that may be driven by phenomena such as basin infilling (landward bed load transport due to the SLR induced increase in accommodation space inside the estuary/lagoon) (Van Goor et al., 2003; Ranasinghe et al., 2013), changes in ebb delta morphology (due to CC driven variations in riverflows/longshore sediment transport) (Nicholls et al., 2007, 2012), and potential changes in inlet cross-section area (due to changes in tidal prism resulting from for e.g. SLR driven increases in the surface area in estuaries/lagoons backed by significant salt marshes) (Nicholls et al., 2007; FitzGerald et al., 2008). Such initial adjustments may be estimated via existing empirical relationships, reduced complexity models or strategic short-medium term process based modelling. However, estimates of long term morphological change obtained in this way are likely to be quantitatively less accurate than predictions that might be obtained from a continuous long term (50–100 yr) simulation of a (presently non-existent) robust multi-scale process based model. This is because the latter approach will not only encapsulate fundamental physical descriptions of governing processes but also (ideally) take into account gradual temporal shifts in mean forcing, chronology of extreme events and scale-interactions occurring over the entire simulation period. Furthermore, in areas where inter-annual and/or inter-decadal variability in system forcing (e.g. due to the temporal variation in climate variability indices such as ENSO, PDO, SAM etc.) is expected to result in significant net long-term effects on system morphology, this ‘snap-shot’ approach may not produce reliable results unless sufficiently long-term data of system forcing is available. If such data are available, synthetic forcing time series that adequately represent (albeit in an averaged sense) the temporal variability may be constructed to force the snap-shot simulations. It is anticipated that a minimum of 10/30 years of data would be required to reasonably represent inter-annual/inter-decadal variations in system forcing.

4.2.6. Permanent Inundation of low lying land

This is one of the easiest CC impacts to quantify, requiring only a detailed DEM and RSLR estimates. At the most primitive level, appropriate IPCC globally averaged SLR estimate(s) and a DEM can be used within ArcGIS to develop inundation maps. For more accurate local inundation estimates, regional variations in SLR and vertical land movements may also be taken into account. Nicholls et al. (2014) provide detailed guidelines for developing sea level scenarios that take into account all relevant contributors to RSLR. Where a high level of accuracy is desired, particularly very near the coast, the present-day DEM should be corrected to account for potential land losses from the coast due to CC driven coastline recession (Lentz et al., 2016) and land gains from SLR driven wetland accretion.

4.2.7. Long-term coastline recession (uninterrupted coasts)

The method most commonly used to estimate coastal recession due to SLR is the Bruun Rule (Bruun, 1962). Essentially, the Bruun Rule predicts a landward and upward displacement of the cross-shore profile (Eq. (2)) in response to SLR:

$$R = lS/(b + d_c) \tag{2}$$

where, d_c = the maximum depth of exchange of material between nearshore and offshore (depth of closure), l = horizontal distance from the shoreline to depth d_c, b = berm or dune elevation estimate for the eroded area, S = sea level rise, and R = horizontal extent of coastal recession.

More generalized versions of Eq. (2) that account for a range of physical process which may be relevant for coastline change over different time scales (e.g. dune overwash, cliff erosion, onshore sand transport (from beyond the depth of closure), alongshore sediment transport gradients) have been presented by Wolinsky and Murray (2009), Rosati et al. (2013) and Dean and Houston (2016).

While the underlying concept of the Bruun Rule is robust, its utility as a predictive tool has been a controversial issue for decades (Cooper and Pilkey, 2004; Pilkey and Cooper, 2004; Nicholls et al., 2007). Recent comprehensive reviews have concluded that while the Bruun Rule may be suitable for qualitative regional scale assessments, its relatively low quantitative accuracy and robustness renders the Bruun Rule unsuitable for local scale assessments in which reliable estimates are required (Ranasinghe and Stive, 2009; Stive et al., 2010).

Furthermore, the historical planning practice of adopting a single value of coastal recession due to a single SLR estimate is also proving inadequate with the emergence of risk informed coastal planning frameworks which require probabilistic estimates of coastal recession. Ranasinghe et al. (2012) presented an alternative physics based approach, which departs from the Bruun concept, to obtain probabilistic estimates of SLR driven coastline recession. The main strengths of this method (Probabilistic Coastline Recession (PCR) Model) are; (a) the physical processes governing coastal recession due to SLR are explicitly taken into account, and (b) estimates of coastal recession are provided within a probabilistic framework. The PCR model uses the above mentioned JPM model (Section 4.2.2) to obtain a synthetic storm time series; IPCC SLR projections to identify MSL at the time each storm occurs; and an analytical dune recession model (Larson et al., 2004) to estimate dune retreat due to each storm. This model train is executed within a Monte Carlo simulation to obtain exceedance probabilities of coastline recession. It is noteworthy that the PCR model is one model that does incorporate some level of inter-scale morphodynamic interaction as it concurrently simulates the effects of episodic storm events and long-term SLR on coastal profile evolution.

The model requires minimal computing effort and primarily requires as input long-term water level and wave data which are now available via widespread tide gauges and global hindcast models such as ERA40 (Uppala et al., 2005) and WaveWatch III (Tolman, 2009). Therefore, it is anticipated that the model should be widely and relatively easily applicable. The PCR approach, with a very slight modification, can also be used to quantify coastal risk and to determine economically optimal coastal setback lines (Jongejan et al., 2016) (Fig. 3).

4.2.8. Long-term coastline recession (inlet-interrupted coasts)

Coastline recession along inlet-interrupted coasts is driven by not only the above described recession due to SLR (i.e. Bruun effect), but also by SLR driven basin infilling (in the estuary/lagoon connected to the inlet), and, in systems with significant riverflows, also by CC driven variations in rainfall/runoff. As discussed above, using advanced process based models over CC time scales (50-100 yrs) with concurrent tide, wave and riverflow forcing is at present impractical. Ranasinghe et al. (2013) addressed this issue by developing a scale-aggregated model that is capable of providing very rapid, preliminary assessments of CC driven coastline change at local scale. The simplicity of the model enables multiple simulations to obtain probabilistic estimates of coastline change that take into account the range of uncertainty in CC projections as well as model parameters. In its present form, the model (Scale aggregated Model for Inlet interrupted Coasts - SMIC) is more suitable for STIs which are predominantly located in wave dominated, microtidal environments. The application of SMIC to four different inlet-estuary/lagoon systems in Australia and VietNam has shown that coastline change due to the Bruun effect represents only about 25–50% of the total potential coastline recession and hence inlet response is more relevant for coastline recession than previously thought (Fig. 4). Ongoing efforts are focussing on further developing SMIC to be generically applicable to any type of inlet/estuary system (e.g. barrier island inlets, tide dominated inlets).

5. Summary and the way forward

This review provides a summary of the potential first order climate change driven physical impacts on mainland open sandy coasts and suggests a standard modelling framework for the robust quantification of these impacts at local scale (<10 km), as required for the development of effective CC adaptation strategies at local governance unit level. Starting with IPCC Global Climate Model (GCM) output, the suggested standard modelling framework advocates the sequential ensemble application of Regional climate models (RCMs), Regional/catchment scale coastal forcing models, and finally, coastal impact models. The main obstacles that exist at present with regards to the robust quantification of CC impacts on sandy coasts are identified as the unavailability of: (a) multi-scale process based coastal impact models, and (b) efficient uncertainty quantification methods, particularly for coastal area morphodynamic models.

5.1. Multi-scale process based coastal impact modelling

As CC impacts on sandy coasts will manifest themselves at various different spatio-temporal scales (~10 m to ~100 km and days to centuries), ideally what is required for comprehensive CC impact assessments is a multi-scale coastal impact model that concurrently simulates the various physical processes occurring at different spatio-temporal scales, including inter-scale morphodynamics. To simulate coastal hydrodynamics relevant for episodic, medium-term, and long-term morpodynamics, such a model should incorporate both cross-shore (vertically non-uniform) and longshore (mostly vertically uniform) hydrodynamics. Thus, the model should be a coastal area model with at least quasi-3D hydrodynamics. Quasi-3D representation of nearshore hydrodynamics has already been achieved (see for example, Ranasinghe et al., 1999; Reniers et al., 2004). The challenge, however, lies in modelling morphological change due to the combined effect of waves and currents at time scales greater than a few years (De Vriend et al., 1993; Lesser, 2009). Since the 1990s, there have been numerous attempts, using very different approaches, to overcome this problem (De Vriend et al., 1993; Dabees and Kamphuis, 2000; Hanson et al., 2003; Roelvink, 2006). However, all of these attempts have only met with limited success. The main issue lies

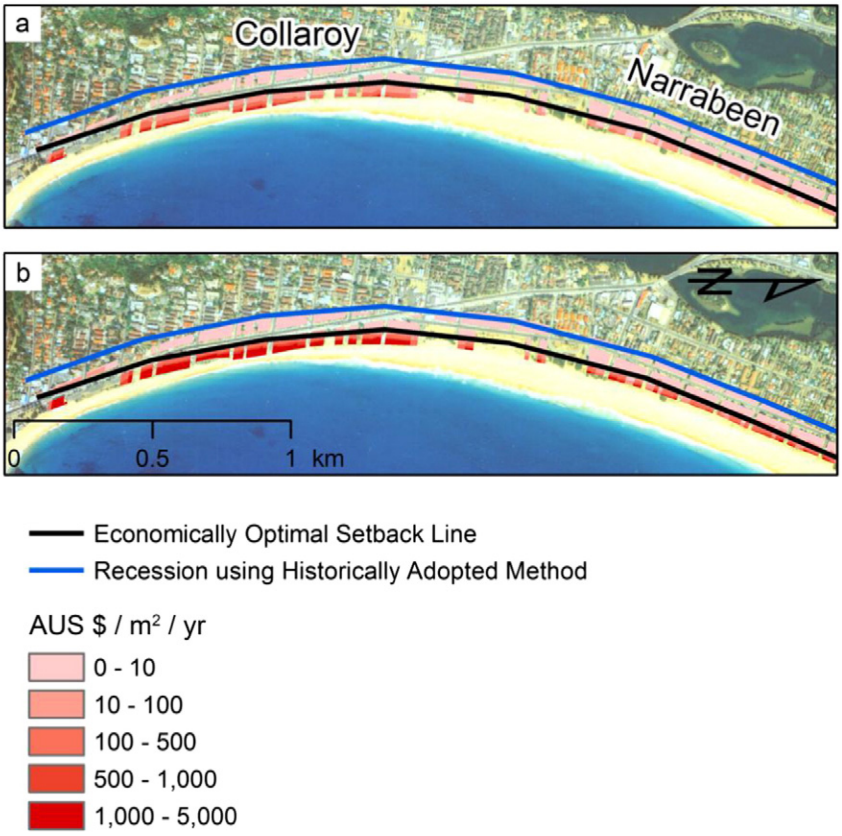

Fig. 3. Risk map and the economically optimal setback line (black line) obtained for Narrabeen beach, Sydney, Australia in 2010 (a) and 2100 (b) using a slightly modified version of the PCR model in conjunction with risk modelling techniques. A Sea level rise of 0.92 m by 2100 (relative to 1990) has been assumed. The setback line obtained using currently adopted methods is also shown (dark blue line). (From Jongejan et al., 2016).

Fig. 4. SMIC Model predicted coastline change at Swan River inlet, Australia by 2100 (red line) and coastline change due to the Bruun effect alone (blue line) (after Ranasinghe et al., 2013).

in using a gridded approach to simulate morphodynamics. While calculating hydrodynamics on a grid (be it triangular, rectangular, curvilinear, or hybrid) does produce robust and stable results, this is not the case for morphodynamics. Invariably, due to the accumulation of numerical errors within the domain and/or the propagation of boundary errors into the main computational domain, morphological instabilities (i.e. small morphological features that develop purely due to the accumulation of model errors and not due to correct representation of physical processes) do develop sooner or later in a long-term morphodynamic simulation, especially with wave forcing. When using currently popular morphological upscaling methods such as MORFAC (Roelvink, 2006; Ranasinghe et al., 2011) to accelerate morphodynamic evolution, such instabilities could grow rapidly in time, eventually leading to nonsensical model predictions. One solution would be to develop a totally new morphodynamic modelling concept where a non-gridded approach is adopted to simulate morphological change. For example, in such an approach, quasi-3D hydrodynamics calculated on a traditional grid may be spatially aggregated over the significant morphological features that are of interest (ebb deltas, sand bars, channels, mounds, trenches etc.), and subsequently, the aggregated hydrodynamic forcing may be used with an appropriate scale-factor to 'move' and 'change' those bed features, at say, the time scale of a few tidal cycles.

Another issue with present-day coastal area models is their inability to correctly simulate coastline change. Coastal managers/planners faced with developing CC adaptation strategies require not only a sound knowledge of how (submerged) nearshore morphology may change but also how the coastline may change. In fact, in most cases, the latter is more sought after than the former. A coastal area model with a good representation quasi-3D hydrodynamics should theoretically be able to simulate the coastline retreat that will occur under episodic storms. However, the simulation of coastline change that may occur in the medium or long-term due to subtle gradients in longshore sediment transport and/or onshore sediment transport (including bar welding to beach) with a coastal area model will require a detailed wave-by-wave representation of swash processes. A fully process-based description of swash processes (time scale ~5 s) is simply impractical in a multi-year (let alone multi-decade) coastal area model application. An aggregated approach where, for example, the slope of the general cross-shore profile (i.e. excluding significant bed features that may overlie the profile) is periodically (say, annually) adjusted every few metres alongshore (say, 25 m) to match an equilibrium profile (Dean, 1977) might be one way to address this issue. The profile adjustment would naturally move the coastline (i.e. mean land/water interface) seawards or landwards, thus simulating coastline progradation or retreat, respectively. Another approach may be to use a proxy, such as the Momentary Coastline (or MKL) used in the Netherlands for coastal management purposes (van Koningsveld and Mulder, 2004). Here the change in the proxy could be calculated, say over a spring-neap cycle, and the 0 m contour (i.e. mean land/water interface in the model) could be moved landwards or seawards by that amount (with some smoothing of the very nearshore slope) at the end of each simulated year.

New multi-scale modelling approaches such as that described above may well be several years in the making. Therefore, until such models are available, an interim approach for CC impact assessment may be found within a systems modelling framework that sequentially applies empirical methods, physics based scale aggregated (or reduced complexity) models, data driven models, and process based models at gradually decreasing spatio-temporal scales. Such a systems modelling framework is currently being developed via the ongoing iCOASST initiative in the UK.

For immediate needs, however, existing coastal impact models (which usually operate on a single spatio-temporal scale) may be strategically used to obtain reasonable CC impact assessments, while recognising that, in most cases, scale-interaction effects will be absent from such assessments.

5.2. Uncertainty quantification

Essentially, every step of the standard modelling framework suggested in Fig. 1 will introduce uncertainty, accumulating though the steps. Therefore, at the final step, multiple simulations of the coastal impact model are required to adequately account for the cascade of uncertainty from GHG emission scenarios, through GCMs, RCMs and Regional/

catchment scale coastal forcing models, to the Coastal impact model. Given the pyramid structure of the uncertainty cascade, when it comes down to this stage, a coastal impact model will probably need to be simulated with hundreds of different combinations of forcing variables to sufficiently quantify the uncertainty that accumulates through the multiple model tiers. This would ideally require a Monte Carlo approach within which the coastal impact model operates as the structural function, drawing random samples from appropriate distributions fitted to the range of values of the forcing variables obtained from Regional/catchment scale coastal forcing models (which would already account for the uncertainty introduced by GHG emissions scenarios, GCMs and RCMs). With present day computing facilities, a straightforward Monte Carlo approach, driven by random sampling, is feasible for inundation simulations using hydrodynamic models (Purvis et al., 2008), coastline evolution simulations with scale-aggregated models (Ranasinghe et al., 2013), one-line models (Ruggiero et al., 2006, 2010), and storm erosion simulations with cross-shore profile models (Callaghan et al., 2013). However, this type of straightforward Monte Carlo approach is presently impractical for simulations involving coastal area morphodynamic models. In these situations, methods such as importance sampling or stratified sampling maybe used to reduce the number of morphodynamic simulations required to quantify uncertainty.

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