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WATER RESEARCH COMMISSION

Response of South African coastal wetlands to climate change[1]

Janine Barbara Adams[1*], Johan Wasserman[1], Jacqueline Leoni Raw[1] and Lara Van Niekerk[1,2]

[1]DSI/NRF Research Chair in Shallow Water Ecosystems, Nelson Mandela University
[2]CSIR

The South African coastline has 290 estuaries that span over four biogeographic zones and support seagrasses, salt marshes and mangroves. These coastal wetland habitats provide a multitude of ecosystem services, but these services are threatened by the impacts of climate change. Predicted effects include sea level rise, increased sea storms and wave height, increased flood intensity, droughts, closure of estuary mouths salinisation, and increased atmospheric CO_2 and temperature. These impacts alter key abiotic stressors such as inundation patterns, salinity gradients and sediment biogeochemistry. Sea level rise raises concerns of habitat loss due to coastal squeeze and macrophyte dieback due to mouth closure and the associated changes in salinity and inundation regimes. Droughts may also increase mouth closure and salinity leading to changes in coastal wetlands. More intense sea storms and flooding can lead to increased deposition of sediments resulting in the smothering of mangroves and salt marsh. Increased temperatures are expected to facilitate the encroachment of mangroves into salt marsh habitats. The biogeographical patterns observed along the South African coastline present an important opportunity for climate change research as the transition between subtropical and warm temperate regions and between cool temperate and warm temperate regions are expected to be significantly influenced. Conservation and management plans need to include future changes in climate to ensure the protection of estuarine ecosystems at the southern tip of Africa.

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Introduction

The estuaries of South Africa host important coastal wetland habitats (seagrasses, salt marshes and mangroves) that provide a multitude of valuable ecosystem services. Estuaries are dynamic environments at the interface of the land and the sea, thus are subjected to multiple natural stressors. Coastal areas have also been historically heavily populated; thus estuaries are susceptible to anthropogenic activities associated with transformation and development. In South Africa, estuaries are under high anthropogenic pressure and most of the estuarine area has already been impacted to some extent [1]. The natural stressors acting on estuaries will be altered with climate change and acting synergistically with anthropogenic pressures, threaten estuarine habitats over a range of spatial extents and temporal periods [2,3]. An understanding of how climate change will affect coastal wetlands is necessary for producing realistic and achievable management and conservation strategies and plans.

The South African coastline, spanning roughly 3,000 km, covers four biogeographical regions. In the country's north-eastern corner lies the tropical region, which transitions into a subtropical region on the east coast, the warm temperate region on the southern coast, and the cool temperate region along the west coast. Furthermore, the variation in climatic, oceanographic and geological characteristics along the South African coast results in a diversity of estuarine ecosystems. The country's 290 estuaries have been classified into nine ecosystem types based on key ecological features and biogeographic settings [4,5]. The variation in estuary type and climate result in local and regional differences in abiotic stressors, which influences the distribution of macrophytes throughout South African estuaries [6]. The diverse climate and estuarine types of South Africa presents a unique opportunity to investigate the response of coastal wetland habitats to climate change.

Six distinct macrophyte habitat types occur in South African estuaries: submerged macrophytes, salt marsh, reeds and sedges, mangroves, swamp forests and macroalgae (Table 1, Figure 1) [6,7]. Submerged macrophytes such as the endangered seagrass ***Zostera capensis*** occur mainly in the country's permanently open estuaries [8]. The fresher and calmer conditions of temporarily closed estuaries (TCEs) and estuarine lakes often allow for the establishment of other submerged macrophyte species like ***Ruppia cirrhosa*** and ***Stuckenia pectinata*** [6]. Salt marshes occur in sheltered estuaries throughout South Africa with the greatest area occurring in the cool temperate and warm temperate regions, respectively [9]. Salt marsh plants occur in zones along a distinct tidal inundation gradient (Figure 2). Reeds and sedges (e.g. ***Phragmites australis***, ***Schoenoplectus scirpoides*** and ***Bolboschoenus maritimus***) are the most widespread and dominant (in terms of area cover) habitat type nationally and are typically found in fresh and brackish areas of estuaries across all biogeographical regions [6]. Mangroves grow in 32 sheltered estuaries along a 1800 km stretch of the east coast spanning from the warm temperate to the tropical bioregion [10]. Swamp forests are limited to the subtropical to tropical east coast [6]. Attached and free-floating macroalgae are common in estuaries throughout South Africa (Table 1), and filamentous macroalgal mats often form in nutrient-enriched systems in closed estuaries with calm and sheltered conditions [7]. Information on the extent and distribution of these various habitats have been collated and catalogued in a national Estuary Botanical Database [6,11].

Coastal wetland habitats will be influenced in multiple ways by anthropogenic climate change. Not only will the increased CO_2 levels directly influence the physiology of macrophytes, but the already dynamic abiotic environment of coastal wetlands will be changed by the multitude of consequent impacts. These impacts are not straightforward to predict, as they depend on the context of environmental conditions and anthropogenic activity, which can differ greatly among regions [12]. While many studies have speculated the response of estuaries to climate change in different parts of the world [2,13,14], local studies are needed that cover different region-specific contexts. This study aims to provide predictions on how climate change will impact seagrass, salt marsh and mangrove habitats in South African estuaries.

Study approach

This review synthesises available knowledge from peer-reviewed literature on the ecological responses of coastal wetland habitats to the predicted impacts of climate change. Focus was placed on increased atmospheric CO_2 concentrations, increased temperatures, changes in hydrological processes, floods, droughts, sea-level rise and increased sea storms and wave height. While the emphasis was on South African literature, studies from elsewhere in the world were also consulted.

Results and discussion

The key estuarine abiotic processes expected to be altered by climate change and the resultant biotic responses and expected habitat trends toward the year 2050 are summarised in Table 2. Salt marsh and mangrove area are expected to decrease overall. To date mangrove area has remained fairly stable due to increases and decreases in certain estuaries. Submerged macrophyte habitats are highly dynamic, but little overall change in habitat area is predicted, however, some increased fluctuations in biomass are expected in response to increased occurrence of extreme events such as floods and droughts.

Table 1. Summary of the biogeographical distribution of six macrophyte habitat types

Macrophyte habitat types	Biogeographical Region			
	Cool temperate	Warm Temperate	Subtropical	Tropical
Submerged Macrophytes	●	●	●	●
Salt Marsh	⬤	⬤	●	●
Reeds and Sedges	●	●	●	●
Mangroves		●	⬤	⬤
Swamp Forests			⬤	⬤
Macroalgae	●	●	●	●

Figure 1. Mangrove, salt marsh and seagrass habitats in the Nahoon Estuary.

Figure 2. Salt marsh zonation along a tidal inundation gradient at Knysna Estuary.

Table 2. Climate change stressors and predicted habitat trends by 2050 for submerged macrophytes, salt marsh and mangroves in South African estuaries (***italics*** indicate abiotic changes and responses in temporarily closed estuaries)

Abiotic change	Ecological responses		
	Submerged macrophytes	Salt marsh	Mangroves
↑CO_2 Higher C availability	Increase in plant growth and productivity ↑4%	Increase in plant growth and productivity ↑4%	Increase in plant growth and productivity ↑4%
↑Temperature Warming Higher aridity	Competition with more abundant macroalgae Decreased growth due to higher epiphyte cover ↓4%	Increase in plant growth and productivity, however distributional range shifts and change in habitat diversity, mangroves replace salt marsh Increase in invasive species. Change in salt marsh phenology and extinctions ↓3%	Increase in plant growth and productivity Distributional range shifts and change in habitat diversity, mangroves replace salt marsh. ↑4%
↑Floods ↑ Nutrient inputs & eutrophication ↑Sediment input *Scouring of estuary, decrease in salinity*	Submerged macrophyte loss due to scouring, sediment deposition and smothering ↓4%	Macroalgal growth, smothering of salt marsh *Loss of salt marsh cover, change in species composition* ↓4%	Mangrove loss due to scouring, sediment deposition and smothering ↓4%
↑Droughts ↑Salinity and aridity ↑*Closed mouth condition* ↑*Water level & inundation, loss of intertidal habitat*	Higher water level will allow an increase in submerged macrophyte cover Seagrass cover increases in response to higher salinity cover ↑4%	Change in species and community composition Decrease in productivity Loss of salt marsh cover. *Increase in water level, flooding and dieback of salt marsh. Loss of intertidal habitat and marine connectivity.* ↓5.5%	Decrease in productivity and cover *Flooding and die-back of mangroves* ↓5.5%
⇅ Stream flow ⇅ Closed mouth condition ⇅ Salinity penetration	Shift in water level will cause changes in submerged macrophyte cover Higher/lower salinity will increase/ decrease seagrass cover	Shifts in water level, flooding will cause an increase/decrease in intertidal habitat and marine connectivity. Changes in species composition NO OVERALL CHANGE	Changes in mangroves Inland / landward migration of mangroves Decrease/increase in productivity and cover
↑Sea level rise +1.5 – 2.7 $mm.yr^{-1}$ Inundation & waterlogging, coastal squeeze ↑*Open mouth condition* ↑*Saline conditions*	Increase in intertidal area for seagrass colonisation Seagrasses can become established further upstream ↑4%	Possible salt marsh subsidence or landward migration Die-back and loss Changes in species composition *Expansion of salt marsh on exposed sand/ mudflats* NO OVERALL CHANGE	Expansion of mangroves in intertidal areas Inland / landward migration of mangroves ↑4%
↑Sea storms & wave height Erosion ↑*Sediment deposition, constricted mouth*	Removal of seagrass and submerged macrophytes ↓4%	Smothering and loss of salt marsh *Increase in water level, flooding and dieback of salt marsh* ↓4%	Smothering e.g. of pneumatophores by marine sediment Loss of mangroves ↓4%
Ocean acidification	Possible increase in seagrass production and seagrass carbon storage	Not likely to cause significant impacts	

3.1. Increased atmospheric CO_2

Enhanced productivity due to higher CO_2 levels will occur for both mangroves and salt marshes as a result of increased photosynthetic efficiency and water use efficiency [17 and references therein]. Mangrove productivity will especially be favoured as these trees utilise the C3 photosynthetic pathway. Climate-related warming and an increase in CO_2 are positive conditions for mangroves to expand their distribution to higher latitudes but this will depend on propagule dispersal between estuaries and the availability of suitable habitats [25]. Many of the small estuaries are temporarily closed to the sea for different periods of time thus limiting recruitment [10]. Increased CO_2 concentrations are also expected to change the species composition of salt marshes. Higher CO_2 availability will favour the growth of C3 salt marsh species (e.g. ***Salicornia spp*** and ***Juncus spp***) over C4 species such as ***Spartina*** maritima. [74]. Elevated CO_2 concentrations will likely also increase the productivity of seagrasses and macroalgae, as they mostly appear to use the C3 photosynthetic pathway as well [37].

3.2. Increased temperature

Over the last 50 years, land-based air temperatures in southern Africa have been rising at twice the global average and are projected to continue increasing at 1.5 times that of the global rate. In general, South Africa will experience a warmer and drier climate in the future. Increased temperatures will directly affect the growth and reproduction of estuarine macrophytes. In salt marshes and mangroves, productivity will increase until an upper temperature threshold is reached [9,16]. However, increased temperatures can inhibit the germination of certain salt marsh species and this could counteract potential increases in productivity [17]. Seagrasses are also sensitive to increased temperatures and may die-back in response to warming [18]. Warmer temperatures will also alter plant phenological patterns and species composition in coastal wetlands [9,19].

Increased temperatures, in conjunction with elevated CO_2 levels, will also change the distribution of estuarine habitats. Rising temperatures are associated with the expansion of mangroves towards higher latitudes, often into salt marsh habitats, in a phenomenon known as 'tropicalisation'. Such range shifts have been described for different regions around the world [20-22], including for our subtropical east coast of South Africa [23,24]. Temperature is not a limiting factor in the poleward expansion of mangroves on South Africa's east coast; instead successful colonisation of new sites by mangroves will depend on the effectiveness of propagule dispersal between estuaries, the local geomorphology (including the estuary mouth being open), and the availability of suitable riparian habitats [10,25]. Mangrove encroachment into salt marshes will result in a decrease in salt marsh cover [26].

Rising temperatures and the associated evaporation can have dire impacts on the health of coastal wetlands. In extreme cases, estuaries can become highly desiccated and hypersaline leading to great declines or die-offs of flora and fauna [27]. The effects of warming will be most apparent in shallow estuaries, particularly those experiencing a prolonged phase of mouth closure [28]. South Africa's estuarine lakes will likely also be susceptible to increased evaporation. For example, St Lucia, the country's largest estuarine lake, persisted in a highly desiccated hypersaline state following an extended drought during a closed mouth phase, resulting in significant declines in biota [29]. Habitats such as submerged macrophytes and reeds and sedges are particularly susceptible to hypersalinity and desiccation [30-32]. Some salt marsh habitats can persist in extreme hypersaline environments, but increased evaporation would likely contribute to the threat of salt marsh desertification [9,33].

The effects of extended ocean heat waves have not been documented in South Africa but can have severe consequences. Above average temperatures for four months (2 - 4°C above average) caused 90% die-back of seagrass beds in Shark Bay, Western Australia [34]. In northern Australia the 2016 extreme El Niño event led to extensive dieback of mangroves in the Gulf of Carpentaria [35]. Ocean heat waves have increased notably in frequency and duration over the last century and are projected to become more common in the future [36]. These warming events will have profound impacts on species distributions and community structure [37,38]. In January to March 2021 South Africa's south and east coast experienced such a temperature anomaly due to meanders of the Agulhas current. Most of the impacts were only observed in the nearshore coastal environments, but should serve as a warning that could this become a more frequent occurrence in our estuaries.

3.3. Changes to hydrological process (streamflow)

The ecological functioning and health of estuaries depends strongly on freshwater inflows, which will change with climate change-driven alterations in rainfall patterns. The most widespread impact resulting from the predicted hydrological changes will be changes in the mouth dynamics of estuaries. Approximately 75% of South Africa's estuaries close to the sea for varying periods of time due to the formation of sand berms at the mouth resulting from high-wave energy, high sediment availability, and low tidal flows and fluvial inflows [4,27]. These temporarily closed estuaries will be susceptible to change in hydrological regimes, but in extreme cases even predominantly open estuaries can close to the sea as occurred at the Gamtoos Estuary, which closed for the first time in 49 years due to drought and freshwater abstraction [39]. Drier conditions and higher inter-annual variability in rainfall patterns are expected on the western coast of South Africa (Table 3) [41,42]. The frequency and duration of mouth closure are expected to increase in this region [42]. Along the rest of the coastline, extreme rainfall events are projected to increase in spring and summer but decrease in autumn and winter [40,41,43]. It is predicted that mouth dynamics will remain largely similar along the southern coast and that open mouth conditions will generally become more common further up the eastern coast due to increased freshwater flows and flooding [42].

Changes in mouth condition are likely to cause substantial changes in the extent and distribution of coastal wetland habitats and have been shown to cause shifts between macrophyte habitat types [44-46]. During periods of mouth closure, estuaries are unsuitable for the establishment of mangroves and intertidal salt marsh. Furthermore, extended periods of mouth closure can result in high water levels which cause inundation and die-back of intertidal salt marsh and mangroves [44,45,47]. Large mangrove die-back events have been recorded at the Kosi, Kobonqaba and St Lucia estuaries [48-50]. Elevated salinity levels during periods of mouth closure also lead to the loss of submerged macrophytes and the proliferation of opportunistic macroalgae [45,46]. Macroalgal blooms will be particularly concerning in closed estuaries susceptible to eutrophication as they can shade and smother submerged macrophytes and salt marsh habitats [51-53]. However, more frequent mouth closure may increase the resilience of salt marshes to sea level rise as these intertidal habitats have greater elevation gains and sediment accretion rates than those that maintain a permanent connection to the sea [54]. Increased open mouth conditions, in contrast, will facilitate the establishment of salt marshes and mangroves and create a favourable environment for the persistence of submerged macrophytes [8,10]. However, the periods of high productivity typical of closed mouth conditions will be decreased [55,56].

3.4 Droughts

In addition to altering mouth dynamics, changes in freshwater inflows (particularly extreme events like droughts and floods) will decrease the resilience of coastal wetlands to the impacts of climate change. Decreased freshwater inflows and drought will result in the salinisation and desiccation of macrophyte habitats. High salinity and low moisture content in sediments decrease salt marsh species composition, cover, and productivity [9]. Salinisation and desiccation will particularly place pressure on the country's arid west coast estuaries such as the Groot Berg, Olifants and Orange (Table 3) where the desertification of large areas of salt marsh has been recorded [9]. On the east coast, drought stress will affect the physiological processes in mangrove trees related to water uptake and water use efficiency, and will inhibit growth and expansion [57,58]. Recent large-scale mangrove die-back events have occurred in northern and western Australia under drought conditions in combination with low sea levels and low humidity as a consequence of an El Niño-Southern Oscillation (ENSO) event [35,59,60]. Prolonged droughts can lead to soil shrinkage, which would inhibit the ability of salt marshes and mangroves to maintain their elevation relative to rising sea levels [61,62]. Soil volumes, however, can recover after droughts have ended [62]. Droughts can also cause shifts in habitat type; for example, large scale drought-induced dieback of salt marsh at the Mississippi River Delta, USA resulted in mangrove encroachment until it became the dominant habitat type [63].

Lower freshwater inflows will also result in increased seawater penetration into estuaries, reducing the extent of the river-estuary interface and changing the distribution of habitats. Under these circumstances, a reverse estuary gradient is often formed. Increased salinity in the upper reaches of estuaries will facilitate an increase in seagrass biomass and distribution under clear-water conditions [64,65]. Prolonged periods of hypersalinity (salinity ≥ 75), however, will lead to the die-back of submerged macrophytes [30]. Reeds and sedges may die-back or persist only in brackish areas (salinity < 20) such as sites of freshwater seepage [32].

3.5 Floods

Flooding and increased freshwater inflows can also be detrimental to coastal wetlands in several ways. Floods will scour estuary banks, removing macrophytes in intertidal habitats. Such habitats may be able to re-establish, but this can take place slowly. For example, mangroves that were removed by flooding in the Mnyameni and Mzimvubu estuaries only re-established after 11 years [10]. Floods can also deposit sediments causing smothering and die-back of submerged macrophytes and mangroves. However, such deposition events can expand intertidal areas available for colonization by macrophytes. Submerged macrophytes respond particularly strongly to flooding – floods can completely remove them from estuaries as has occurred with ***Z. capensis*** habitats in Swartkops Estuary [66]. Recovery of submerged macrophytes after floods can have a lag period of up to three years [67]. Furthermore, increased siltation, turbidity and salinity changes associated with floods will influence the growth and distribution of submerged macrophytes [8]. Increased high intensity rainfall events and flooding will likely remove submerged macrophyte beds from estuaries, particularly along the east coast where floods are expected to increase (Table 3) [42]. The endangered ***Z. capensis*** is already absent from freshwater dominated estuaries in southern KwaZulu-Natal where flooding and highly turbid conditions are common [8].

Increased rainfall and runoff will contribute to the nutrient enrichment and eutrophication of estuaries, which is already a significant pressure on South African estuaries that will likely be exacerbated by climate change, especially in disturbed catchments [28,68]. Eutrophication can shift estuaries to an alternate state where algal blooms can outcompete, outshade and possibly exclude submerged macrophytes and smother salt marshes [51,52]. Nutrient enrichment leads to dense epiphytic growth on the leaves of submerged macrophytes reducing light availability and limiting growth, and epiphytic fouling will increase as temperatures rise [69]. Increased nutrient loading due to runoff, along with increased temperatures, will also result in the proliferation of invasive alien aquatic plants (IAAPs) which are already widespread in South African estuaries, especially along the KwaZulu-Natal coast [68]. Predictive models suggest that climate change over coming decades will facilitate the range expansion of several IAAP species along the South African coast [70]. The proliferation of IAAPs leads to the loss of native species and biodiversity with impacts across trophic levels, and alters aquatic environments by decreasing light penetration, flow and connectivity between rivers and estuaries [68,71]. IAAPs can also displace important nursery habitats, for example, the spread of water hyacinth along with turbid conditions displaced ***Z. capensis*** beds in the Swartkops Estuary [66]. Although increased freshwater inflow and floods will generally contribute to eutrophication, they will also be important in opening estuary mouths, flushing systems, reoxygenating the water column, re-establishing salinity gradients following periods of mouth closure, inundating floodplains and decreasing soil salinity, maintaining sediment structure and building habitat (accretion) [73].

3.6. Sea level rise

Current SLR rates differ along the South African coast, with an increase of 1.9 $mm.yr^{-1}$ on the west coast, 1.5 $mm.yr^{-1}$ on the south coast and 2.7 $mm.yr^{-1}$ on the east coast [80,81]. Sea-level rise will increase inundation and waterlogging altering sediment biogeochemistry, moisture and salinity. This is the predicted scenario; however, if salt marshes and mangroves build elevation at a sufficient rate then inundation and waterlogging may not increase [82]. Local topography and coastal development constrain the availability of areas for landward migration, but the rate of sedimentation determines the capacity of mangrove and salt marsh ecosystems to resist SLR through surface elevation gain [83,84]. Predictive models that incorporate landward migration and surface elevation processes have been used to estimate changes in blue carbon stocks under different SLR scenarios at the Knysna and Swartkops estuaries [85,86].

Higher sea levels would cause salt marshes to migrate landwards [87,88]. Plant ecophysiology studies have shown lower intertidal salt marsh species will be able to survive in upper intertidal zones, but upper intertidal species will not be able to persist in waterlogged conditions [47]. The tolerance of salt marsh species to inundation will determine their survival, and the availability of areas with suitable elevation will allow for the landward migration of salt marsh habitats [9,89]. However, many South African estuaries are impacted by development and urban encroachment, which leads to 'coastal squeeze' which limits the amount of suitable area for salt marsh migration [90]. Recent research has found that there is a deficit in elevation gain and local relative sea-level rise in South African intertidal salt marshes, and it will be necessary for accretion rates to increase for these salt marshes to persist in the long-term [91]. This is especially the case for the sediment starved estuaries fed by catchments dominated by Table Mountain Sandstone. Sea level rise modelling studies at the Swartkops Estuary have predicted that lower intertidal habitats characterised by the cordgrass ***Spartina maritima*** do not gain elevation at a rate sufficient to keep up with current and future sea-level rise, but these habitats would migrate landwards and replace habitats located higher in the tidal frame [85,92]. At the Knysna Estuary, the capacity of ***S. maritima*** habitats to build elevation is variable along the length of the estuary [86]. Most sites in the lower and middle reaches are subsiding and therefore will not persist under projected sea level rise without the potential for landward migration. This can only be facilitated by the removal of hard structures [86].

Sea-level rise may lead to an increase in open mouth conditions in temporarily closed estuaries creating favourable habitat for mangrove, salt marsh and seagrass colonisation in intertidal areas [10]. However, these positive effects may be counteracted by drought and a reduction in freshwater inflow that results in mouth closure, high water level flooding and die-back of mangrove and salt marsh. Nationally it is difficult to predict the future trajectory of change for the endangered seagrass ***Zostera capensis.*** Sea-level rise will increase salinity in estuaries and seagrass can expand upstream. However, an increase in high intensity rainfall events will likely remove submerged macrophyte beds [8].

3.7. Increased sea storms and wave height

South Africa's wave-dominated coast is sensitive to sea storminess that can result in erosion or sediment deposition and accretion [80]. More frequent and intense sea storms and wave action may further inhibit the ability of the mouth of estuaries to remain open [75]. The resultant increase in water levels within estuaries will cause prolonged inundation and waterlogging of intertidal areas, leading to the loss of macrophyte habitats. Sea storms can also deposit marine sediments onto habitats, smothering them and causing die-back. For example, a major storm at the Mbashe Estuary led to the die-back of mangroves, of which many died within three years and the area was subsequently colonised by salt marsh species [93]. However, increased wave action due to sea storms can erode the mouth area of estuaries increasing periods of open mouth conditions [76]. Salt marshes can be particularly sensitive to erosion, which has caused the loss of large areas of salt marsh in various parts of the world [94-96]. Salt marsh has already been lost to erosion in some South African estuaries and further losses are expected [97] (Figure 3). While some increase in the frequency and intensity of sea storms has been recorded along parts of the South African coast in recent decades, these have not yet been definitively linked to anthropogenically-driven climate change [98].

However, a global increase in sea storms has been projected [99], which will result in increased coastal erosion and the loss of estuarine habitats.

3.8. Ocean acidification

Ocean acidification is a concerning consequence of increased CO_2. Acidification will likely impact South Africa's permanently open estuaries, particularly those on the west coast where upwelling is prevalent (Table 3) [75]. Acidification impacts nutrient and carbon availability in aquatic environments, but the impacts of acidification on macrophytes are complex and requires species- and situation-specific investigations [76]. Acidification will impact calcifying fauna, possibly leading to indirect effects through species interactions – such changes in biotic controls – but these are also difficult to predict. Eutrophication and algal blooms, a widespread problem in South African estuaries, will exacerbate climate change-driven acidification [68]. This will particularly be an issue in eutrophic estuaries that are closed to the sea, especially since mouth closure is expected to increase with climate change in many of these systems in South Africa. During open mouth conditions, pH is regulated by tidal mixing but during closed mouth conditions, pH dynamics are dominated by ***in situ*** biological processes [78]. Closed estuaries that are susceptible to eutrophication will experience greater diurnal pH variability due to increased primary production by algal blooms [77]. When the algal blooms decay, remineralisation and aerobic respiration by bacteria decreases pH, particularly under the long water residence times experienced during a closed mouth phase [77,79]. These ***in situ*** processes are likely to be enhanced by increase temperatures.

Table 3. Summary of key processes that will be impacted by climate change stressors and the broad direction of change per biogeographical region (Solid ● = increase; Hollow ○ = decrease; Large ● = High degree of change, small ● small to moderate degree of change)

Key processes	Climate change stressors	**Biogeographical Region**			
		Cool temperate	Warm Temperate	Subtropical	Tropical
Atmospheric	CO_2	⬤	⬤	⬤	⬤
	Temperature	⬤	⬤	•	•
Hydrological	Floods	•	⬤	⬤	⬤
	Droughts	⬤	•	•	•
	Streamflow	◯	•	⬤	⬤
Oceanic	Sea level rise	⬤	⬤	⬤	⬤
	Sea storms & wave height	⬤	⬤	⬤	⬤
	Ocean Acidification	◯	○	○	○

Conclusions

Predicting the effect of multiple climate change stressors is difficult because of the natural variability of our coastal wetlands. Long-term monitoring is needed to support research findings. Monitoring of permanent plots and transects are necessary to identify changes such as salinisation and drying out of salt marshes. Synergistic interactions between climate change and human impacts need teasing out at a local scale so that we can understand the processes influencing the vulnerability and resilience of coastal wetlands. Long-term datasets are also needed to understand the change in the frequency and intensity of climatic cycles such as El Niño. Nationally we need policies and planning mechanisms to set aside buffers for landward migration of coastal wetlands in response to sea level rise. Estuary conservation and management plans need to include future changes in climate to ensure the protection of coastal wetlands. However successful management and restoration of coastal wetlands requires a socio-ecological systems approach to address the lack of alignment between ecosystem requirements, legislation, governance, implementation and social commitment.

Past research has identified patterns of change that allow for the prediction of potential future change. South Africa is an important outdoor laboratory as changes are occurring across different biogeographic zones i.e. subtropical to warm temperate and warm temperate to cool temperate. Our research makes an important contribution globally as little is known about the response of African coastal wetlands to climate change. Data sets inform range expansions of species at a southern continental limit and responses characteristic of a wave-dominated high-energy coastline.

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