Chapter 10: Climate change and the Knysna Estuary

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10.1 Introduction

Estuaries are shallow coastal environments that are influenced by both tidal action and freshwater inflow. As a result of the mixing of marine and fresh waters, estuaries are naturally dynamic, unstable environments with physico-chemical conditions oscillating on hourly, daily, seasonal, yearly and decadal scales[1]. Climate change is expected to modify the physical structure and biological functioning of estuaries, by changing the magnitude of these oscillations, as well as changing long-term average physico-chemical conditions (such as average temperature, salinity and dissolved oxygen levels). In addition to rising temperatures, climate change in the coastal and estuarine environment also incorporates changes in temperature variability (land and sea), winds and ocean currents, freshwater flow (rainfall), extreme weather events, sea level and ocean acidification; all of which will have profound consequences for species living in estuaries.

In this chapter these different drivers of change, such as temperature, rainfall and hydrology, floods and droughts, sea level rise, storm surges and ocean acidification are reviewed with a focus on the effectsof these drivers of change on the Knysna Estuary.

10.2 Temperature

Estuaries are affected by changes in air, river and sea temperatures. Globally, the average surface temperature has increased by 1.1°C compared to the average temperature in 1850 - 1900, which is the hottest level since 125 000 years ago[2]. Land-based air temperatures have been rising significantly over Africa; with temperature increases over subtropical southern Africa (which have increased by 3.2°C in the last 100 years) more than twice the global land-based air temperature increase[3]. Annual air temperatures over the coastline of South Africa are predicted to be between 2.5 and 4°C warmer in 2100 than they are today[3] (Figure 10.1).

A Representative Concentration Pathway (RCP) is a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC). For example, RCP 8.5 refers to

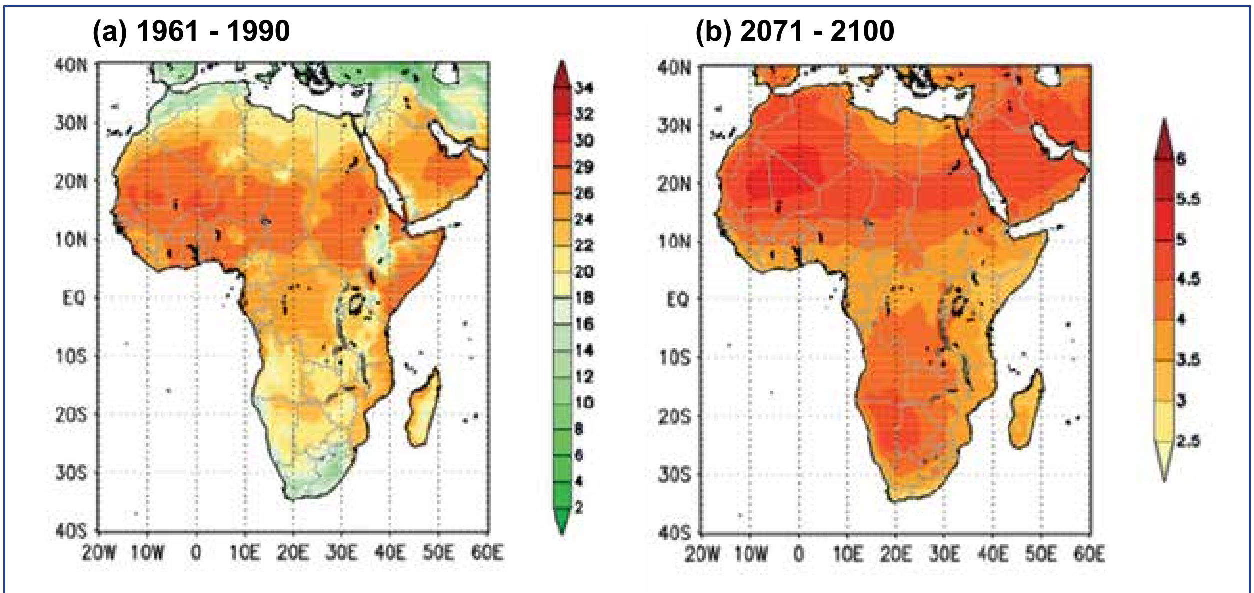

Figure 10.1 Modelled **(a)** average annual maximum air temperatures (°C) for 1961-1990 and **(b)** projected change in annual average temperature for 2071-2100 relative to 1961-1990 (after Engelbrecht et al.[3]).

the concentration of carbon that delivers global warming at an average of 8.5 watts per square meter across the planet. To provide some indication of the potential increase in temperatures predicted for the Knysna Estuary, Table 10.1 below summarises the findings for Representative Concentration Pathways 4.5 and 8.5 (RCP 4.5 and 8.5) downscaled for South Africa as part of the 'Green Book' project based on Englebrecht et al.[3]. The model simulations span the period 1960 - 2100, with the period 1960 - 1990 representing the baseline, 2021 - 2050 mid-future and 2070 - 2099 far-future. RCP 4.5 is a high mitigation scenario, whilst RCP 8.5 is a low mitigation scenario. These projections show that even under future scenarios with substantial climate mitigation interventions as represented here by RCP 4.5, predicted increases in average monthly land temperatures will vary between 1.1°C and 1.9°C in the mid-future, increasing further to between 1.3°C to 2.6°C in the far-future. While under the RCP 8.5 low mitigation scenario temperatures increase by between 1.4°C and 2.4°C for the mid-future and 3.4°C and 4.1°C for the far-future.

Rising air temperatures will likely be beneficial to some tidally inundated salt marsh species in estuaries, with their productivity predicted to increase in response to rising air temperatures until an upper threshold temperature is reached. In contrast, rising air temperatures may inhibit the germination of other plant species and thus cancel out the beneficial effect of increasing productivity[4].

As surface air temperatures increase, so do sea, estuary and river water temperatures and by the beginning of the next century, sea temperatures globally may have increased by 2°C relative to temperatures at the beginning of this century[5]. Temperature is one of the biggest drivers of change affecting marine animals, mainly because marine animals are ectotherms (their temperature regulation comes from outside their bodies), with water temperature determining their distribution on a global and regional scale. In South African estuaries, at a regional scale, the distribution of estuary-associated marine biota is strongly linked to marine water temperatures rather than estuarine water temperatures[6].

The coast of South Africa has four distinct biogeo graphic zones, a tropical transition zone, a subtropical zone, a warm-temperate zone and a cool-temperate zone[7]. Sea temperatures decrease from the tropical region (northern KwaZulu-Natal) to the cool-temperate region on the Atlantic west coast, with inshore water temperatures decreasing markedly southwest of Algoa Bay. In this region, the continental shelf broadens into the wide Agulhas Bank and the warm Agulhas Current (which flows along the edge of the continental shelf) is located further offshore (Figure 10.2).

Inshore waters in this region in summer can be substantially cooler than water in the warm Agulhas Current when upwelling occurs. Upwelling occurs when southerly winds drive cooler water from the deep towards the surface. Upwelling can result in rapid temperature changes, with inshore waters at least 5°C cooler than the surrounding Agulhas Current shelf water[8]. In contrast, water temperatures are often similar in estuaries throughout South Africa. For example, in mid-summer, temperatures in estuaries in Durban may be very similar to those recorded in the Knysna Estuary.

Few species occur in all estuaries in South Africa, with many species occurring within specific biogeographic zones. Harrison[9] recorded differences in the fish found in estuaries around the South African coastline, with a gradual decrease in the number of species recorded in estuaries from east to west, mainly as a result of the decreasing number of tropical marine species recorded in warm- and cool-temperate estuaries. Cool-temperate estuaries are mainly dominated by cool-water endemic (i.e. occur only in southern Africa) species and temperate species. Warm-temperate estuaries are dominated by warm-water endemic species that also extend their distribution into subtropical estuaries, as well as cool-water endemic species. Tropical and subtropical estuaries are dominated

Table 10.1 Predicted increase in ambient atmospheric average temperature (°C) for RCP 4.5 and 8.5 under mid- and far-future scenarios.

Average temperature increase	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RCP 4.5 Mid-future	1.6	1.3	1.3	1.7	1.1	1.8	1.4	1.3	1.5	1.5	1.3	1.9
RCP 4.5 Far-future	2.0	1.8	1.5	1.9	1.3	1.8	2.1	2.2	2.4	2.2	1.7	2.6
RCP 8.5 Mid-future	1.9	1.6	1.4	2.0	1.5	2.4	2.1	1.7	1.9	2.3	2.2	2.2
RCP 8.5 Far-future	4.0	3.5	3.6	3.6	4.1	4.1	3.8	3.4	3.6	3.7	3.8	3.7

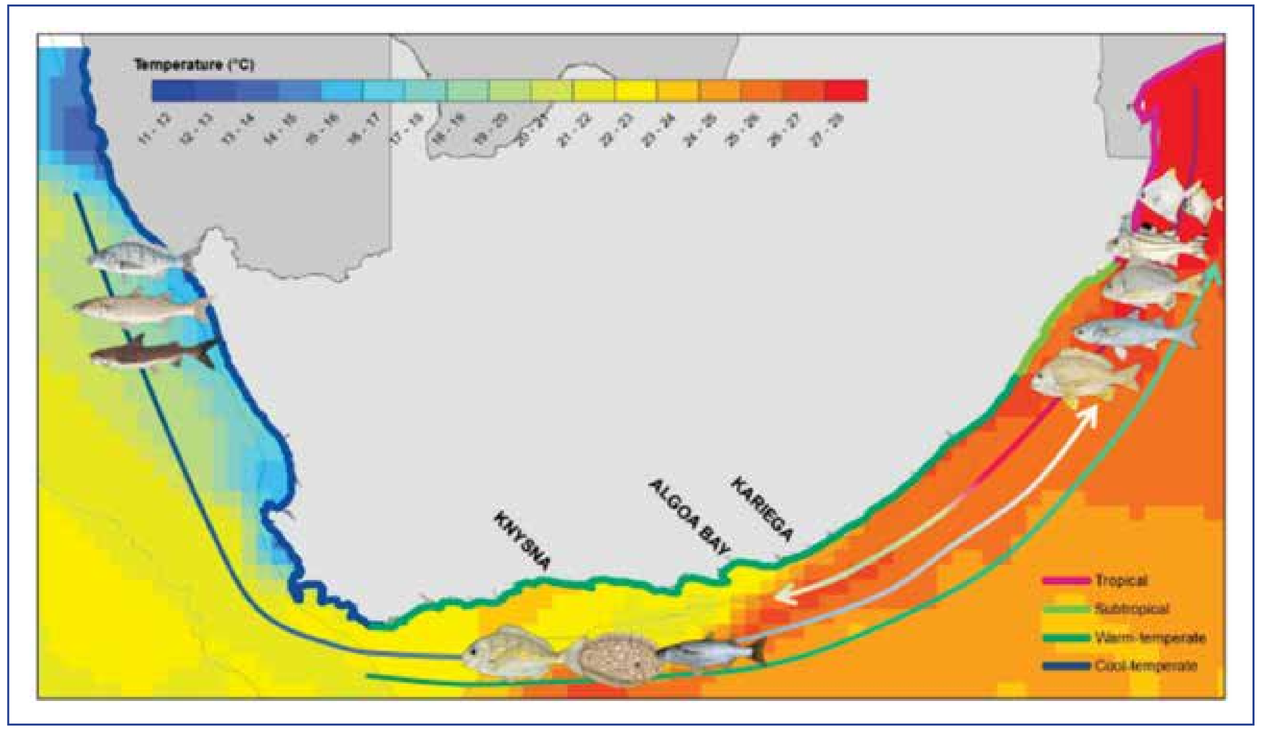

Figure 10.2 Summer sea temperatures, biogeographic regions and the distribution of tropical, warm-water endemic and cool-water endemic fish in South African estuaries (modified from James et al.[6]).

by subtropical species that occur in both subtropical and warm-temperate estuaries, as well as tropical Indo-Pacific species[10]. Prior to the past 30 years, tropical Indo-Pacific species were rarely recorded in temperate estuaries beyond Algoa Bay.

For most estuary-associated marine animals, larval development takes place in the marine environment, with the tolerance of biota to temperatures often being much lower during the adult and larval phase than during the hardy juvenile phase that occurs in estuaries. Warming marine temperatures associated with climate change have already resulted in an increase in the occurrence of tropical fish and invertebrate species in warm-temperate estuaries[1,11]. When tropical species extend their distribution into temperate estuaries, winter survival is often the bottleneck in the establishment of populations in these waters. Elevated winter temperatures associated with climate change may allow tropical species to overwinter and become established in these temperate systems.

The above said, we cannot associate all new occurrences or increases in abundance with rising temperatures. Many of the warm- and cool-temperate occurrences of tropical and subtropical estuarine associated species coincide with the unavailability of estuarine habitat in the subtropical region during extended drought periods and estuary mouth closure. More recently, extreme events such as floods and marine heatwaves seem to play a role in forcing fish and invertebrates southward.

Invertebrate species with a primarily tropical distribution (such as mud crab *Scylla serrata*, the peregrine paddler crab *Varuna litterata* and the mangrove snail *Cerithidea decollata*) are good indicators of global warming in the Knysna Estuary. Mud crabs occur in the Knysna Estuary but are absent from cool temperate estuaries (for biogeographic zones see Figure 10.2). Low water temperatures affect mud crabs, with feeding and movements stopping in temperatures lower than 12°C[11,12]. Warming water temperatures, particularly in winter in the Knysna Estuary, may increase the amount of habitat available for this species leading to an increase in the abundance of mud crab in the estuary—albeit confined to the areas of high mud distribution (e.g. Belvedere). The mangrove snail, as its name suggests, is associated with mangroves throughout its main range. This species has extended its distribution into the Knysna Estuary, where it escapes the high tide by climbing the rush *Juncus kraussi* rather than the trunks of mangrove trees[11]. On the other hand, the presence of *Varuna litterata* in Knysna Estuary does not seem to be primarily in response to rising temperatures. This crab has extended its range all the way to estuaries in the cool-temperate

False Bay, with an established population in the Zeekoeivlei Estuarine Lake. More recently, it has been recorded to the west of Cape Point in the Rietvlei Diep Estuary in Table Bay. Its occurrence in Knysna and estuaries to the west coincides with an increase in the frequency of eddies generated by the Agulhas Current, which carry and entrain warmer water species westwards to the cool-temperate coast.

An increase in the frequency and intensity of upwelling in the coastal nearshore in summer may, however, prevent range expansions of tropical species into the Knysna Estuary (by killing the larvae of tropical species before they can recruit into the mouth of the estuary). Duncan et al.[19] found that the intensity of upwelling has increased in recent years along the nearby Tsitsikamma coastline. Upwelling can affect water temperatures in the mouth and lower reaches of permanently open estuaries. Indeed, van der Walt et al.[14] measured thermal variability in the lower reaches of the Kariega Estuary on our southeast coastline (Figure 10.2) and found that when upwelling occurs in the marine environment the influx of cold upwelled water on the high tide can rapidly decrease water temperatures in this region of the estuary from 22°C to 17°C (difference of 5°C). In the middle and upper reaches of the estuary,temperatures did not drop below 24°C[14], with these reaches offering a refuge to animals from extreme temperature variability. The middle and upper reaches of the Knysna Estuary may also provide an important thermal refuge to species in the estuary as well as those from the marine environment, with fish such as baardman *Umbrina robinsoni* finding refuge inthe warmer waters of the estuary during upwelling events (Chapter 8).

During the estuarine phase of their life cycle, biota are able to tolerate both very high and very low temperatures and it is unlikely that warming will impact the distribution of biota already resident within the estuary. Temperatures within estuaries fluctuate hourly, with temperatures of up to 30°C recorded in the shallow littoral zone in the lower reaches of the warm-temperate Kariega Estuary in summer[14]. During their juvenile stage, when fish use estuaries as nurseries, fishes are very tolerant of high temperatures. Bennett[15] found that approximately 70% of juvenile tropical fishes (44 species) inhabiting shallow water nursery areas (mangroves, seagrass and tide pools) around Hoga Island in Indonesia are able to tolerate temperatures above 40°C. In the Kariega Estuary, juvenile mullet and sparids, with a predominantly temperate and subtropical distribution (e.g. southern mullet *Chelon richardsonii* and Cape stumpnose *Rhabdosargus holubi*) are able to tolerate temperatures up to 35°C, which is five degrees above the maximum water temperature recorded in the estuary[14] (Figure 10.3).

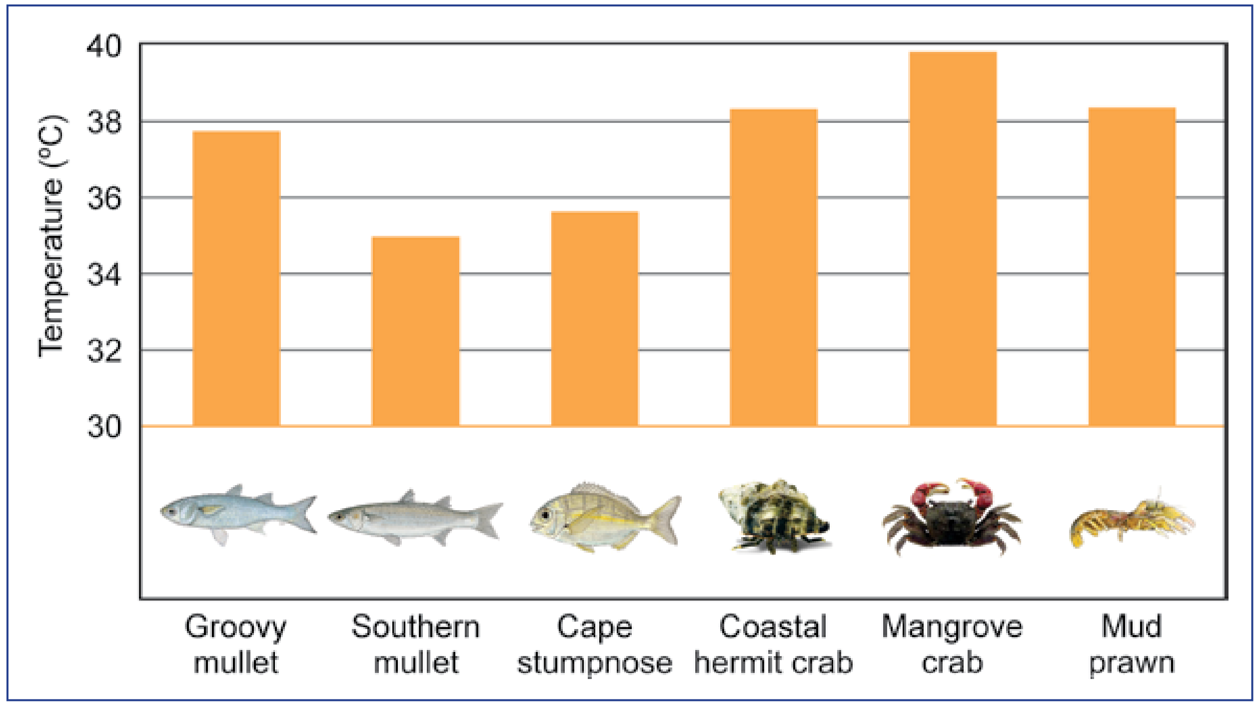

Figure 10.3 Critical thermal maxima (orange bars) limits of fish and invertebrates and maximum water temperature (orange line) in the warm-temperate Kariega Estuary.

These species, which are abundant in the Knysna Estuary, are also tolerant of low temperatures in winter and can tolerate temperatures as low as 5°C, which is well below the 12°C minimum winter temperature recorded in the estuary[14] (Figure 10.4). Resident estuarine species, such as clinids and gobies may be even more tolerant of extreme temperatures (e.g. above 40°C).

Van der Walt et al.[14] also found that the adults of three common estuearine-associated invertebrates; coastal hermit crab *Clibanarius virescens*, mangrove crab *Parasesarma catenatum* and mud prawn *Upogebia africanum* from the lower reaches of the Kariega Estuary are able to tolerate temperatures as high as 39°C in summer and as low as 4°C in winter (Figures 10.3 & 10.4). The broad temperature tolerance of many marine intertidal rocky shore invertebrates is well known, with several species able to depress their metabolism to cope with the stresses associated with tidal emersion and exposure[14]. However, similar information on estuarine intertidal invertebrates of mud and sand flats is much less well known.

Although estuarine water temperatures may continue to be within the temperature tolerance of estuarine biota, warmer water associated with global warming (and particularly extreme temperatures during heatwaves) may still be stressful for them when outside the temperature optima for that species and can lead to species declines. In the San Francisco Estuary in America, population declines in the endangered delta smelt (*Hypomesus transpacificus*), which is a small shoaling fish, have been linked in part to warm temperatures during summer heatwaves[16]. Warm water was associated with behavioral changes in delta smelt. Warm water increased the swimming speed of delta smelt and changed their schooling behaviour so that they swam further apart and were less protected in a group. These behavioural changes made these fish easier for predators to attack, with double the number of fish injured and preyed on in warmer water[16].

Similarly, Mvungi & Pillay[17] when working on the combined effects of warming and eutrophication on seagrass *Zostera capensis* from the Langebaan Lagoon in the Western Cape found that eutrophication and temperatures higher than 24°C negatively affected plant size, density and growth. They suggested that this was likely as a result of nutrient enrichment and warming induced bio-fouling (Figure 10.5), which negatively impacted photosynthesis. *Zostera capensis* is a temperate seagrass species that is widespread in South Africa and a particularly important habitat-forming species in Knysna. Studies have shown that temperatures higher than 25°C can also have negative effects on other temperate seagrass species[17].

It is extreme temperatures (rather than gradually

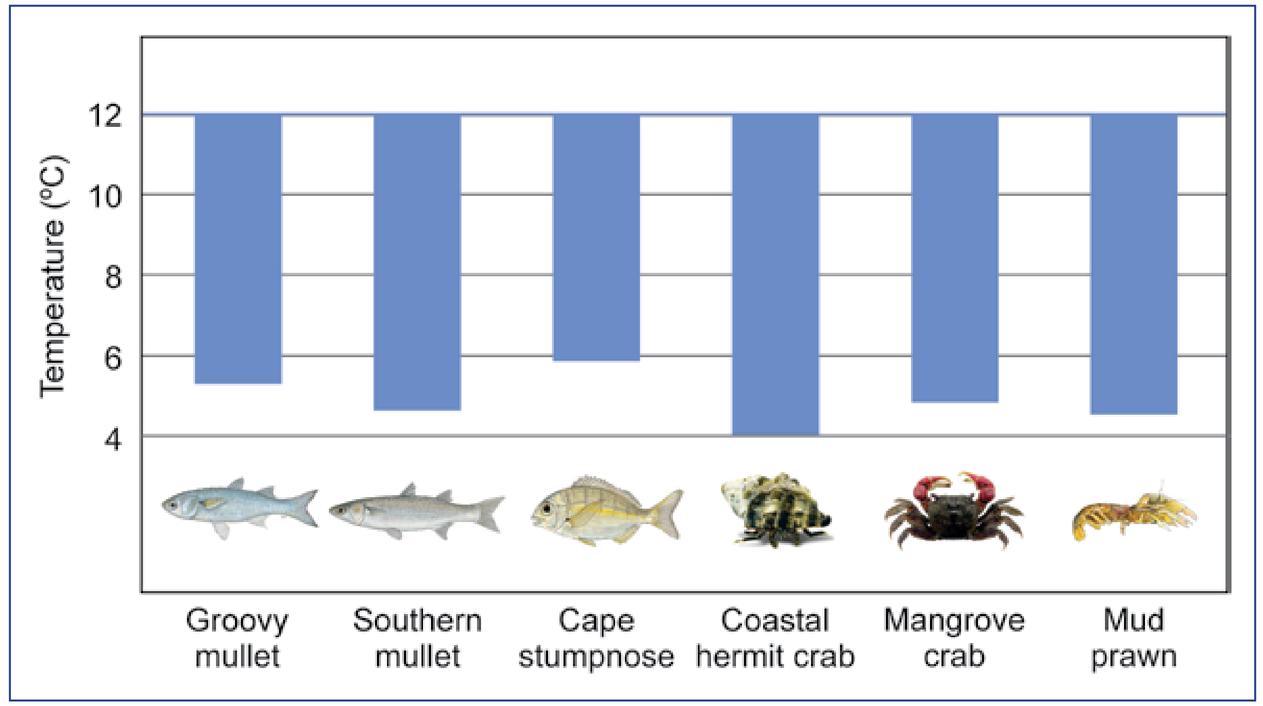

Figure 10.4 Critical thermal minima (blue bars) limits of fish and invertebrates and minimum water temperature (blue line) recorded in the warm-temperate Kariega Estuary.

Figure 10.5 Bio-fouled eelgrass *Zostera capensis* in the Swartkops Estuary (Photograph: ©Thembani Mkhize).

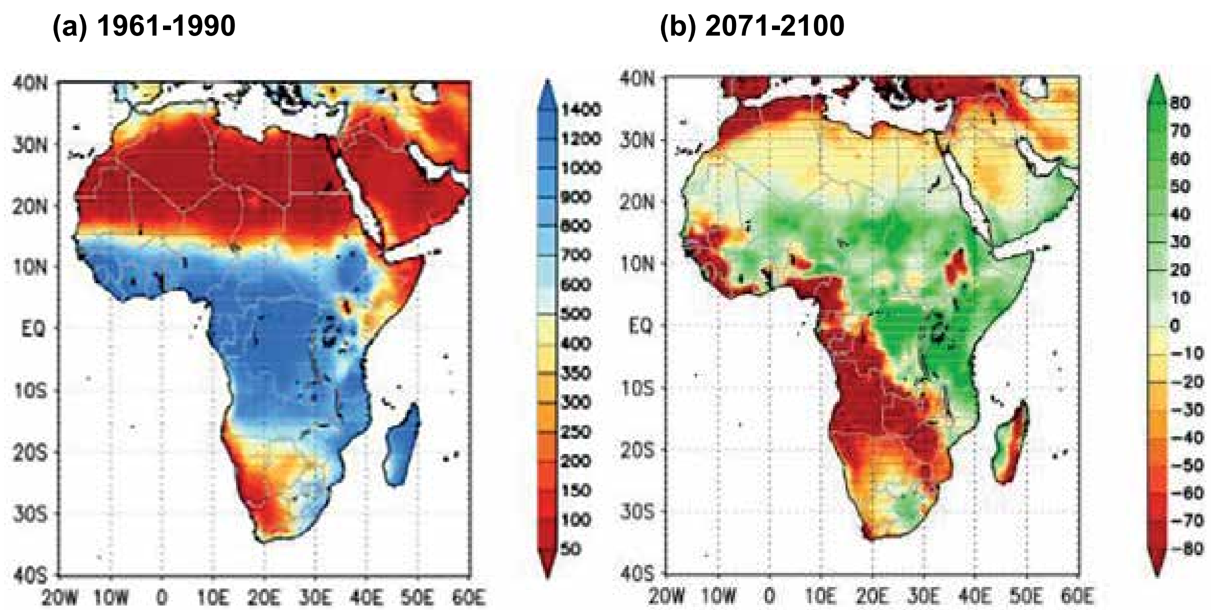

Figure 10.6 Modelled **(a)** annual average number of heatwave days for 1961-1990 and **(b)** projected change in annual average number of heatwave days for 2071-2100 relative to 1961-1990 (after Engelbrecht et al.[3]).

increasing average temperatures) that animals and plants do not cope with well. Southern Africa already has more heatwave days per year than the rest of Africa, with the number of heatwave days predicted to increase by the end of the century[3] (Figure 10.6). In the marine environment, marine heatwaves along the warm-temperate coastline (which includes Knysna) are more intense and of longer duration than those along the cool-temperate and subtropical coastline[18]. Marine heatwaves in this region arise from deviations in the Agulhas Current bringing warm water inshore, as well as the shape and extent of the shelf in the region. Within a recent five-year period (2013 – 2018), 16 marine heatwaves occurred in the inshore region of the warm-temperate Kenton-on-Sea, with the hottest marine heatwave attaining 28.4°C, and the longest heatwave lasting 18 days[19].

Extreme variability in temperatures is often lethal to fish. A recent regionally extensive marine heatwave event was recorded along the South African east coast at the end of summer 2021, coinciding with a >120 km meander of the Agulhas Current driving warm surface as well as cold upwelled water inshore. In this event, temperatures as high as 24.0 – 26.0°C occurred for several days, followed by an upwelling event, with temperatures rapidly decreasing to as low as 10°C. Thermal shock from the temperature difference, stunned fish and invertebrates, resulting in extensive fish and invertebrate washouts and kills[19,20]. There were also reports of aggregations of fish, sharks and rays finding refuge from both warm and cold water in estuaries and the nearshore.

The heatwave also resulted in dieback of the spined kelp *Ecklonia radiata* near Wavecrest on the Wild Coast and bleaching of red algae (*Plocamium corralorhiza*) in shallow rocky areas around Gqeberha (Figure 10.7). The latter species is also found in rocky areas of the Knysna Estuary. Although the effects of extended heatwaves have not been recorded in South African estuaries, an increase in these events may have severe consequences for estuarine plants and animals, especially in the extensive intertidal areas that are characteristic of the Knysna Estuary.

10.3 Rainfall and hydrology

Climate change is already altering rainfall patterns, with changes in rainfall affecting the amount and timing of freshwater entering estuaries. These changes are exacerbated in estuaries where humans have modified freshwater delivery through freshwater abstraction[1]. Average monthly rainfall in the Knysna region is between 600 and 700 mm per year, with this region predicted to be drier (an increase in dry days and rainfall variability) by the end of the century[3,21] (Figure 10.8). Historical estimates of flow reduction indicate that the natural mean annual runoff of 83.2 × 106 m^3 a^{-1} has been reduced by less than 20%, but of concern is that most of this impact resulted from a loss of baseflows[22]. This observation, and more recent data, indicate these global change impacts are greater than previously estimated[23]. This is concerning as freshwater inflow into the Knysna Estuary has shown a clear decreasing trend with time, with low flow conditions (<2.0 m^3 s^{-1}) occurring 80% of the time during the period 2005 - 2018.

While the estuary is naturally marine dominated (meaning that there is not much gradient between salty and freshwater) due to its extensive tidal amplitude, conditions in which there is no gradient are estimated to have increased from 6% to 45% of the time[23] (depicted in Figure 10.9). As the impacts of global and climate change intensifies, marine conditions may become the dominant state for the estuary. For example, Cullis et al.[24] indicate that the median flows are likely to decrease by about 10%, with low flows decreasing even more by between 12 and 15% and floods by about 5%. These predicted changes do not include the amplification effects of ongoing and escalating abstraction.

Largier et al.[25] defined three different water regimes in the estuary: the "bay regime" which is characterized by marine salinities above 34; the "estuary regime" which, although also marine dominated (salinities between 30 – 34), is warmer due to water retention in a shallow basin; and the "estuary regime" where river inflow influences salinity and temperature. This regime is characterized by lower salinity water (salinities <30). Further decreases in river inflow will further shrink the "estuary regime" and restrict it to just the uppermost region of the estuary during periods of river inflow. Under drought conditions, even this small gradient is lost and the system becomes an arm of the sea throughout, losing its estuarine character.

Effluent from the wastewater treatment works is discharged into the Ashmead Channel. In response to these growing discharges, water quality in the channel has been deteriorating over time, with eutrophication, low dissolved oxygen concentrations, and the development of nuisance macro and microalgal blooms becoming a more common occurrence[23]. A decrease in rainfall associated with climate change, as well as warming of estuarine waters, could also exacerbate poor water quality in this region of the system.

Further decreases in freshwater flow threaten

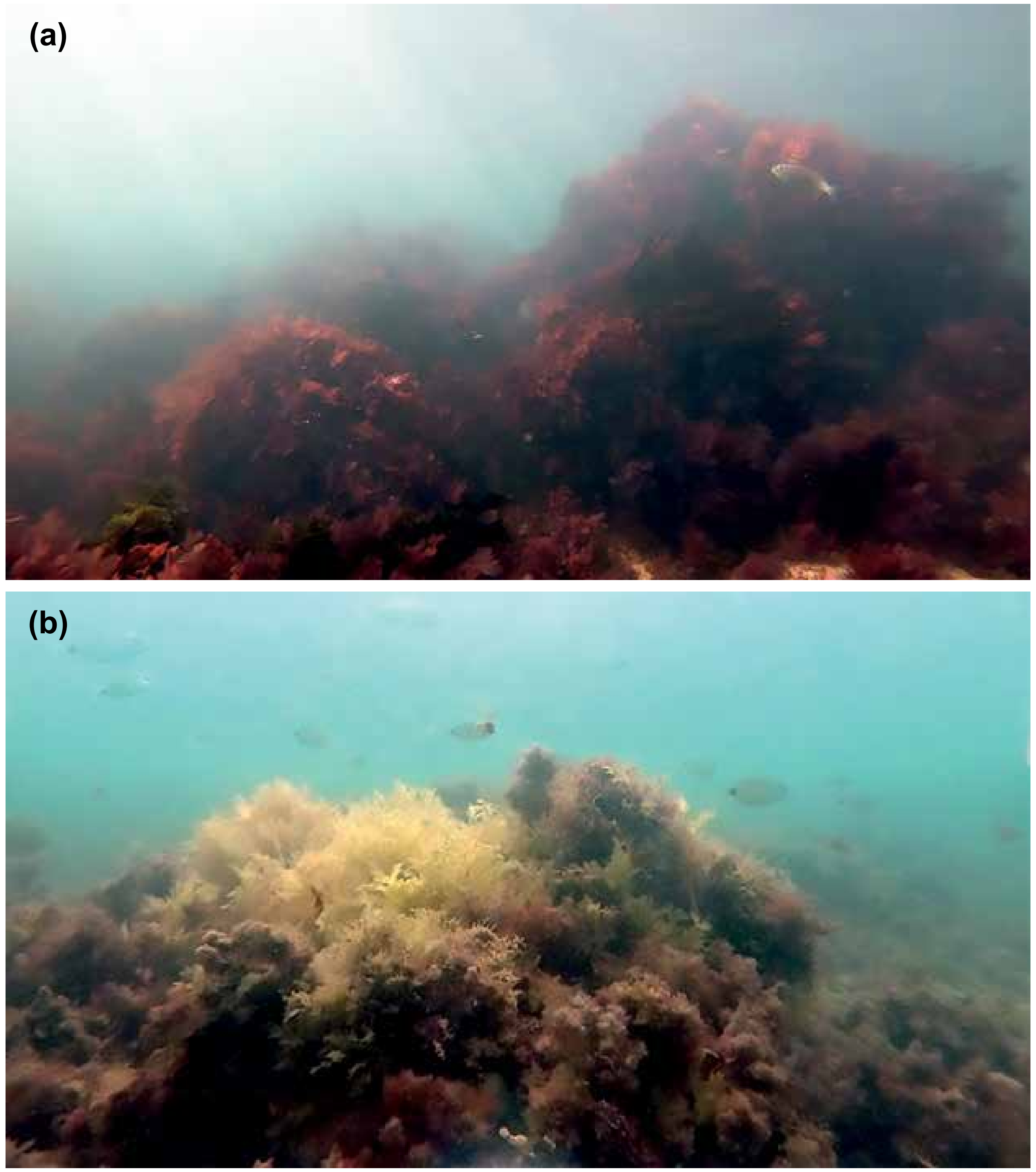

Figure 10.7 Healthy *Plocamium corallorhiza* **(a)** and bleached *P. corallorhiza* **(b)**. This red alga is found in The Heads region of the Knysna Estuary and may also be susceptible to bleaching due to extended heat waves in the future (Photographs: © Mihle Gayiza).

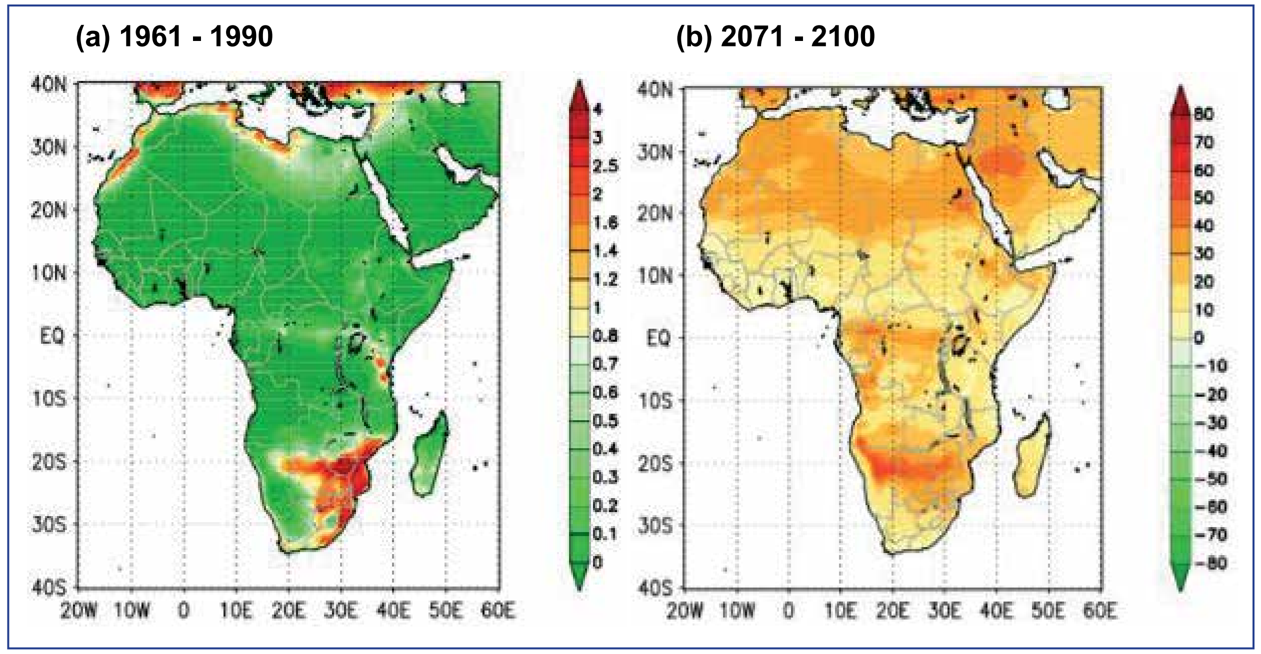

Figure 10.8 Modelled **(a)** annual average rainfall totals (mm) for 1961-1990 and **(b)** projected change in annual average rainfall (mm) for 2071-2100 relative to 1961-1990 (after Engelbrecht et al.[3]).

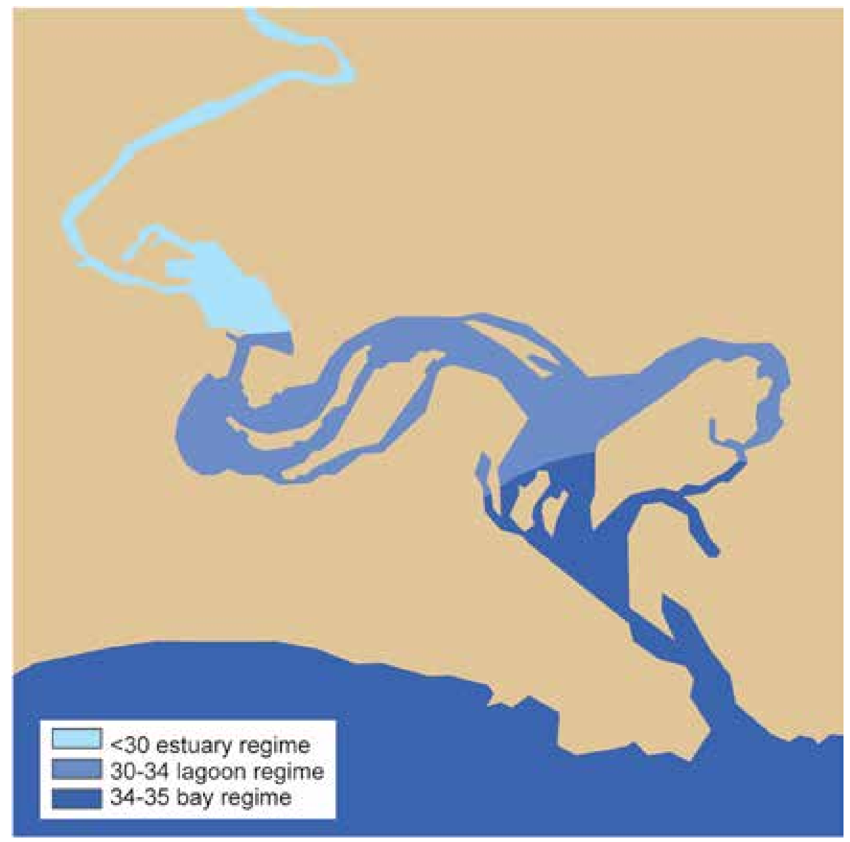

Figure 10.9 Average monthly surface salinity from 2016 to 2018 (data from Claassens et al.[21]).

the ecological functioning of the estuary, particularly in the upper reaches, where there is no longer a river estuary interface zone[23]. Salinity gradients in estuaries, that are directly dependent on freshwater flow, are regarded as one of the key determinants of estuarine species composition and productivity. The juveniles of marine fish species are adapted to a wide range of salinities and dominate estuaries throughout the salinity gradient, but are particularly abundant in the fresher middle and upper reaches. In contrast, marine stragglers that cannot tolerate the fluctuating salinities are confined to the lower reaches. Indigenous freshwater fish species such as Cape kurper *Sandelia capensis*, Cape galaxias *Galaxias zebratus* and redfins *Pseudobarbus* spp. occur in the river immediately above the estuary but only the non-native and salt tolerant mosquito fish *Gambusia affinis* has been recorded in the Knysna Estuary shallows.

A study of demersal fish assemblages in the marine-dominated Kariega Estuary following a major river flood event demonstrated the importance of adequate freshwater flow for estuarine productivity and functioning[26]. Similar to Knysna, the Kariega Estuary receives a proportionally limited amount of freshwater on a daily tidal basis, primarily because of both freshwater abstraction and prolonged drought conditions in the Kariega catchment. Although species richness is high in this estuary, with many marine straggler species recorded, the abundance of juvenile estuarine-associated species — particularly the important fishery species spotted grunter (*Pomadasys commersonnii*) and dusky kob (*Argyrosomus japonicus*) — is low. Following a major 1 in 100 year flood in the estuary, a normal estuarine salinity and turbidity gradient was re-established, and zooplankton productivity increased substantially in response. Euryhaline marine fish species responded to this increase in turbidity and productivity, particularly the early juveniles which prey on zooplankton. This led to a strong recovery in the populations of spotted grunter and dusky kob within the Kariega Estuary[26]. These results highlight the importance of maintaining river flow into the Knysna Estuary where these fishery fish species are also present.

10.4 Floods and droughts

The frequency and intensity of extreme events, such as droughts, sea storms and river floods is already increasing along the southern African coastline[1]. When large floods occur in the Knysna system, low salinity water extends all the way to the mouth and out to sea[25]. During floods, a considerable amount of polluted nutrient-rich stormwater discharge also enters the Ashmead Channel via the Bongani catchment[23]. An increase in the occurrence of extreme discharge events such as floods is likely to increase silt, nutrient input and turbidity to the system and could impact *Zostera capensis* beds in the estuary. Flooding can also result in the temporary loss of seagrass, which will have a direct impact on species using this important habitat such as crustaceans, gastropods and juvenile fish, including the critically endangered pulmonate limpet *Siphonaria compressa* and the Knysna seahorse *Hippocampus capensis*.

During droughts, river inflow is negligible and as a result, the estuary regime zone shrinks so that it occupies only a small proportion of the uppermost estuary[25]. The water residence times also increases in the estuarine and lagoon regime during drought conditions, potentially enhancing the effect of increased land surface temperatures and leaving the system more vulnerable to pollution and potentially resulting in warmer upper reaches.

In estuaries where sampling has been conducted after major flooding, recovery of the zooplankton, invertebrate and fish to pre-flood conditions (in terms of species composition and abundance) was fairly rapid. However, after consecutive flood events, recovery was less rapid[27]. Significantly, where floods and droughts result in prolonged loss of available habitat (habitat squeeze), species declines occur. In the much smaller intermittently open East Kleinemonde Estuary a decline in the abundance of marine species over a 20-year period was attributed to an increase in the intensity and duration of floods and droughts affecting the availability of subtidal habitat for fishes[28]. Similar responses (loss of subtidal habitat) can be expected in the Knysna Estuary under the increase in extreme events (drought and floods) predicted for a hotter climate.

10.5 Sea level rise and storm surges

Several climate models project an accelerated rate of sea level rise over the coming decades, with tide gauge data from the southern Cape showing that sea level has risen by approximately 1.57 mm per year[29]. Of all climate-induced changes sea-level rise, in combination with anthropogenic impacts on sediment supply, is seen as the greatest threat to salt marsh habitats in estuaries[30]. Salt marshes on a local scale are capable of responding to this threat by maintaining surface elevation using sediment accumulation. However, some salt marsh habitats fail to keep pace with changing sea-level when rates of subsidence (the sinking of the land) and sea-level rise are not balanced by accretion (sediment accumulation)[31]. In the absence of sediment inputs from

Figure 10.10 Salt marsh monitoring sites and vulnerability to sea level rise. Red stars indicate salt marsh habitat losing surface elevation and very vulnerable to sea level rise, orange stars indicate sites gaining surface elevation but not fast enough to keep pace with sea level rise (moderate risk), and yellow stars indicate salt marsh habitat gaining surface elevation at a rate fast enough to keep pace with sea level rise (low risk) (adapted from Raw et al.[28]).

catchments, salt marshes will move inland in response to rising sea level, retaining a constant position relative to the shifting tidal frame. This is how salt marshes have adapted to previous sea level rises. However, inland migration may be prevented by local topography, artificial embankments and infrastructure development, which thus cause a loss of salt marsh habitat (particularly supratidal salt marsh) through coastal squeeze[31].

Raw et al.[30] assessed surface elevation change and relative sea level rise experienced at salt marsh sites in the Knysna Estuary. Using tide gauge data for the period 1960 to 2017, they calculated relative sea level rise (the height of the sea relative to the land) of 2.19 mm per year. Salt marsh habitats in the middle reaches of the estuary (shown in red in Figure 10.10) are losing surface elevation, through either erosion or subsidence (sinking of the ground), and are not keeping pace with sea level rise. Worryingly, these habitats are surrounded by developed land, which will prevent landward migration of the supratidal salt marsh. Some salt marsh habitats in the upper and lower reaches (orange in Figure 10.10) are gaining surface elevation but not at a rate fast-enough to keep pace with sea level rise. These sites are also impacted by coastal squeeze (development around these sites is depicted in Figure 10.11), which will prevent local adaptation to sea level rise. However, two salt marsh sites in the upper and lower reaches (green in Figure 10.10) are gaining surface elevation at a rate faster than sea level rise and are adapting to the current rate of sea level rise[30].

Loss of salt marsh and other vegetated habitats in the estuary will ultimately affect the animals using these habitats as a food source or refugia, such as birds, fish and invertebrates. The effects of sea level rise will be exacerbated by increases in the frequency of severe storms and high tides. The South African coastline is at times affected by extreme swells and storm surges, which are predicted to increase in frequency and intensity[1] as the climate becomes hotter. These types of events cause estuarine habitat loss. For example, in the Mbhashe Estuary, a major storm surge deposited marine sediment in the lower reaches of the estuary that smothered the pneumatophores of some mangroves and resulted in dieback of a patch of mangrove trees[27]. Sediment deposition may temporarily or permanently cover sandprawn, mudprawn and other invertebrate burrows, resulting in a loss of habitat and refuge for gobies, shrimps and other burrow symbionts.

Figure 10.11 Developments on Thesen Island will prevent landward migration of salt marsh habitats during a rising sea-level scenario (Photograph: © Alan Whitfield).

10.6 Ocean acidification

From pre-industrial times (1750) to 2019, the atmospheric concentration of CO_2 has risen by 47%[2]. Approximately 30% of this man-made CO_2 has been absorbed by the oceans and one of the primary impacts of introducing huge amounts of CO_2 into the ocean is that water becomes more acidic (pH decreases), in a process referred to as ocean acidification. When CO_2 dissolves in seawater, a series of chemical reactions occur (referred to as the carbonate system). The addition of large amounts of dissolved CO_2 shifts the balance of the carbonate system, ultimately resulting in an increase in hydrogen ions (H^+) and HCO_3^-. Over time this lowers pH and uses up carbonate ions in the water column. Calcifying organisms, such as prawns and crabs, use carbonate ions to maintain and make calcium carbonate, which is the building block for the shells of many organisms.

The reduction in pH and carbonate ions that accompanies elevated CO_2 concentrations in seawater holds severe implications for some coastal organisms[32]. It is estimated that the pH of surface waters in the open ocean will decrease by 0.3 units (from a current average of 8.1) by 2100 as atmospheric CO_2 levels continue to increase[2]. Several laboratory-based studies where animals have been exposed to pH levels predicted for the open ocean at the end of the century have shown that both non-calcifying organisms (like fish) and calcifying organisms invertebrates) may be adversely impacted by ocean acidification[32]. The structures of calcifying organisms are made of calcium carbonate, which will start to dissolve and, as carbonate ions are reduced, it requires more metabolic energy for an organism to deposit calcium carbonate. Ocean acidification may also adversely affect the mortality and calcification of some fish species[33]. For example, when larval dusky kob *Argrosomus japonicus* were reared in low pH water (pH 7.78) the growth, bone development (ossification — shown in red in Figure 10.12) and survival of larvae was significantly lower in the low pH treatment compared to larvae reared in seawater with a pH of 8.1[34].

Changes in bone development can have severe implications for dusky kob and spotted grunter and other soniferous fish that rely on sound and

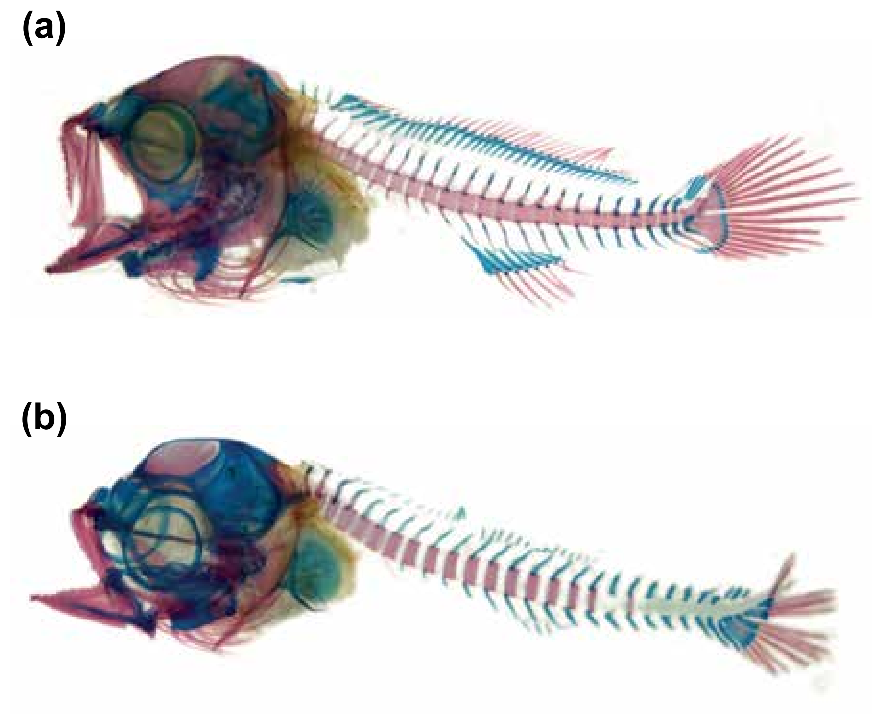

Figure 10.12 Bone (red) and cartilage (blue) development in larval dusky kob (*Argyrosomus japonicus*) reared in seawater with a pH of **(a)** 8.15 and **(b)** 7.78. Note that a small change in pH can result in major changes in cartilage and bone development in fish larvae (images from Erasmus[32]).

hearing for foraging and communication. Changes in earbone (otolith) structure results in hearing loss and may see fish switch from sound to visual foraging. Changes in sound-producing structures such as the pharyngeal teeth of spotted grunter, may cause complete loss of vocalization or sounds not familiar to others of the species. This and loss of hearing ability may play havoc with courtship and spawning.

The conditions predicted for the open ocean in 2100 may not, however, reflect what is going to happen in coastal ecosystems. Changes in pH in estuaries may be caused by ocean acidification (and the intrusion of CO_2 high seawater into the estuary) as well as a multitude of other (natural or anthropogenic) factors. These include nutrient enrichment, freshwater inflow, locally elevated atmospheric CO_2 from industry and agriculture, upwelling in the coastal environment and photosynthesis and respiration of plants and animals[35]. These factors cause much greater pH variability in estuaries than in the open ocean, and can result in greater fluctuation in pH and even more acidic conditions than in the open ocean[36]. This is a particular threat for the biota of the Knysna Estuary since the river water entering the estuary already has a low pH of approximately 5 and currently relies on the higher pH marine water in the system to act as a convenient buffer.

Nutrient enrichment can alter the pH of estuarine water through enhanced biological respiration and photosynthesis. Photosynthesis increases pH in the surrounding water and decreases dissolved carbon by taking up CO_2 and HCO^{3-} (bicarbonate). In contrast, respiration by marine animals and plants (at night) decreases pH and dissolved carbon because of the release of CO_2 in this process[37]. The pH of river inflow into estuaries is influenced by characteristics of the catchment such as geology and vegetation, as well as eutrophication and pollution in the river caused by anthropogenic activities such as the use of fertilisers, thus increasing natural pH variability[38]. The Knysna catchment comprises mainly Table Mountain Group sandstone and the dominant vegetation of temperate forest and fynbos can make the incoming river water acidic (median pH = 5.3, range 3.6-8.4)[38]. An increase in the intensity of marine upwelling, which is linked to climate change, may further influence acidification of the Kynsna system.

It is difficult to predict the pH of coastal systems in the future because we do not know enough about average coastal and estuarine pH values and their variability[35]. Recent research programmes have started to shed light on just how variable pH and carbonate chemistry is in estuarine and coastal environments. Rosenau et al.[36] monitored pH in the lower region of seven estuaries along the coast of America. They found that pH in the lower reaches of the study estuaries varied between 7.16 and 8.32. In contrast, surface water open ocean pH typically varies < 0.1 inter-annually[35]. In shallow water with dense seagrass and seaweed beds pH can fluctuate daily by more than 1 pH unit[37]. The pH in the Knysna Estuary ranges between 6.6 and 8.1[39]. In the future, an increase in eutrophication in the estuary, along with the intrusion of low pH seawater (from upwelling) could result in an increase in pH variability and acidification in the lower and middle reaches of the estuary, which are strongly marine influenced. In addition, should the river baseflow be removed from the estuarine system due to increased abstraction, the natural pH gradient observed in Knysna Estuary may also be lost.

Under elevated atmospheric CO_2 scenarios dissolved CO_2 and HCO^{3-} will increase, while CO_3^{2-} is set to decrease. This change, coupled with increasing temperatures, is likely to benefit productivity in seagrass[40]. Elevated atmospheric CO_2 concentrations may also increase productivity of some salt marsh species[4]. While lowered seawater pH caused by ocean acidification can have substantial impacts on seagrasses and seaweeds, these species can in turn also affect seawater pH. For example, seagrass and seaweed can raise pH on a local scale by taking up carbon through photosynthesis[41]. These localised zones of elevated pH associated with seagrass and seaweed beds could potentially serve as ocean acidification refugia[42]. For example, Wahl et al.[43] found that dense beds of brown algae and seagrass in the Western Baltic increased the overall mean pH of the surrounding water by as much as 0.3 units relative to other similar habitats with no macrophytes and also imposed strong diurnal pH fluctuations (due to photosynthetic activity). This allowed mussels (*Mytilus edulis*) to maintain calcification even under acidified conditions, the impact of ocean acidification on organisms living in these habitats. Seagrass beds in the lower and middle reaches of the Knysna Estuary (Figure 10.13) may counteract the effects of ocean acidification (by raising the overall pH of the surrounding water) and serve as ocean acidification refugia for the animals living within them.

Figure 10.13 Extensive seagrass beds may raise the pH of the surrounding water in parts of the Knysna Estuary, thus protecting the associated biota from ocean acidification trends (Photograph: © Alan Whitfield).

10.7 Summary of climate change effects on the Knysna Estuary

Sea-level rise, shifting temperatures, changes in rainfall, extreme events and changes in currents and wind regimes may see biogeographical regions and habitats shrinking, subjecting estuarine plants, fish and invertebrates to one or more of coastal, habitat and temperature squeezes.

In the Knysna Estuary, climate change will exacerbate anthropogenic stressors, such that the estuary regime will be reduced. Poor water quality (eutrophication and acidification), nuisance algal blooms and reduced productivity in the upper reaches (estuary regime) may be exacerbated by warming, low rainfall and droughts. Remaining salt marshes in the warmer lagoon regime (middle reaches) are at the greatest risk of habitat loss due to sea level rise (and coastal squeeze) and floods. Warming in this region of the estuary may result in an increase in the abundance of tropical species. However, temperature changes in this regime may have negative consequences on the growth and health of important seagrass habitats and associated temperate species (summarized in Figure 10.14 and Table 10.2).

Decreased productivity (associated with low rainfall and habitat squeeze through a reduction in the estuary regime) may also affect the nursery function of the estuary for estuary-associated marine species. Increased floods may result in poor water quality and habitat loss in the estuary regime. The bay regime may be impacted by coastal storms, which are increasing in frequency and intensity, as well as an increase in temperature variability and the intrusion of low pH seawater associated with an increase in the frequency and intensity of upwelling events (Figure 10.14 and Table 10.2).

In summary, the Knysna Estuary faces an uncertain future under a hotter and dryer climate, with rainfall events being less evenly spread and more erratic, both in magnitude and periodicity. These changes will impact negatively on an already stressed biotic community that is having to cope with existing human pressures.

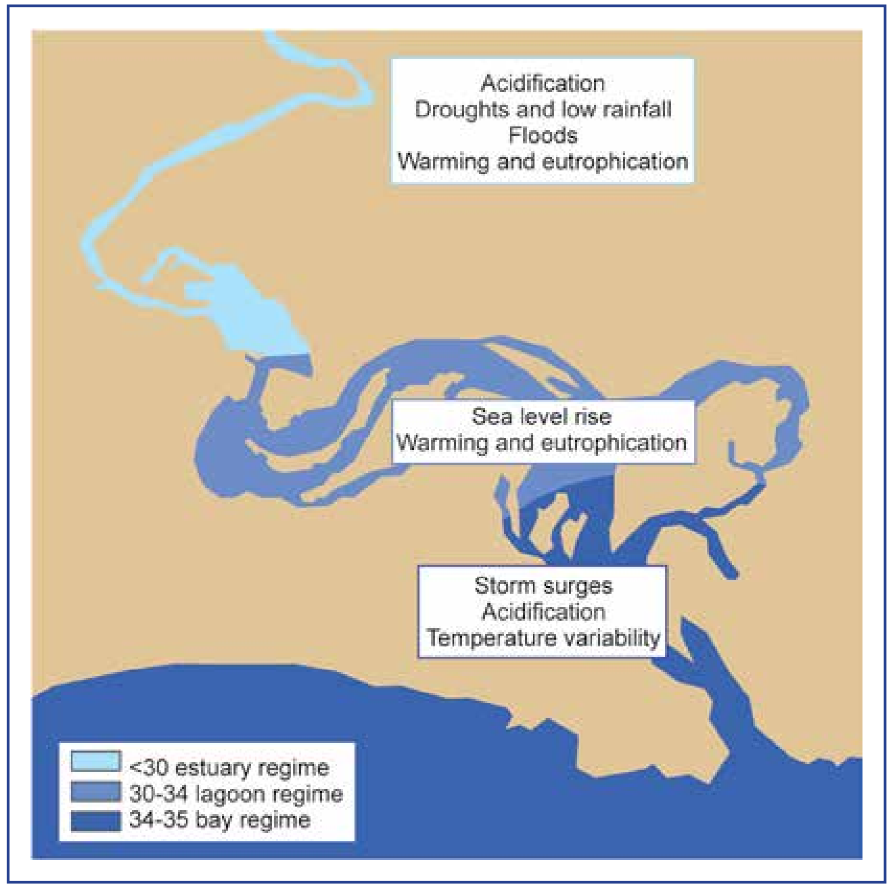

Figure 10.14 Categories of climate change impacts expected in the different sections of the Knysna Estuary. Surface salinity regime data from Claassens et al.[21].

Table 10.2 Summary of the expected intensity of climate change drivers and broad vulnerability of the Knysna Estuary to climate change. The more intense the colour, the greater is the expected intensity of change.

Intensity of change	Climate Change Driver	Marine zone	Lagoon Regime		Estuarine Regime
		Lower reaches	Middle Reaches	Ashmead Channel	Upper reaches
↑ Agulhas (off shore) ↓ Upwelling (inshore)	Sea Temperatures				
↑↑ 1 – 4 °C	Land Temperatures				
↑ Droughts ↓↓ Baseflows Flows ↓ Floods	Rainfall				
↑ 0.5 – 2.0 m	Sea level rise				
↓ pH ↑ pH	Acidification - Ocean - Catchment				
↑ Storms	Coastal storms				

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