5SM

Changing Ocean, Marine Ecosystems, and Dependent Communities

Supplementary Material

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SM5.1 Ocean Heat Content

The assessed rate of increase in ocean heat content is given in Section 5.2.2 (Table 5.1). Table SM5.1 is the supplementary information to support the new observational assessment in the two depth layers 0–700 m and 700–2000 m and their *very likely* ranges. Fluxes in W m^{-2} are averaged over the Earth's entire surface area. The four periods cover earlier and more recent trends; the 2005–2017 period has the most complete interior ocean data coverage and the greatest consistency between estimates, while longer trends are better for distinguishing between forced changes and internal variability. These observationally-estimated rates come from an assessment of the recent research.

Section 5.2.2 (Table 5.1) also has estimates of the spread of the ocean heat content change for the same periods as the observational assessments and the background for that part of Table 5.1 is in the second table below (Table SM5.2). The Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Model (ESM) estimates are based on a combined 28-member ensemble of historical, Representative Concentration Pathway (RCP)2.6 and RCP8.5 simulations.

Table SM5.1 | NaN means missing value, in effect the depth layer is unavailable for this ocean heat content product. The data sets are drawn from range of websites or other sources and are estimates of ocean heat uptake that have been updated from published methods. The references are from Palmer et al. 2007; Domingues et al. 2008; Roemmich and Gilson, 2009; Hosoda et al. 2010; Levitus et al. 2012; Lyman and Johnson, 2014; Von Schuckmann et al. 2014; Cheng et al. 2017; Ishii et al. 2017; and Johnson et al. 2018.

Ocean Heat Content Changes																					
W m^{-2} Earth surface (averaged over Earth's surface: 5.1 × 10^{14} m^2)																					
Paper on Ocean Heat Content	**Units**	**Long-term trend period (1970–2017)**	**Ocean Heat Content estimate (0–700) m layer**	**90% confidence level or range**	**Ocean Heat Content estimate (700–2000) m layer**	**90% confidence level**	**Short or near term trend period (2005–2017)**	**Ocean Heat Content estimate (0–700) m layer**	**90% confidence level or range**	**Ocean Heat Content estimate (700–2000) m layer**	**90% confidence level**	**Period (1993–2017)**	**Ocean Heat Content estimate (0–700) m layer**	**90% confidence level or range**	**Ocean Heat Content estimate (700–2000) m layer**	**90% confidence level**	**Period (1969–1993)**	**Ocean Heat Content estimate (0–700) m layer**	**90% confidence level or range**	**Ocean Heat Content estimate (700–2000) m layer**	**90% confidence level**
(Cheng et al. 2017) (from Cheng website, latest version)	W m^{-2} Earth surface	1970–2017	0.28	0.06	0.14	0.03	2005–2017	0.32	0.05	0.2	0.02	1993–2017	0.39	0.04	0.18	0.01	1969–1993	0.15	0.05	0.05	0.03
(Ishii et al. 2017) (from Ishii website, latest version)	W m^{-2} Earth surface	1970–2017	0.26	0.03	0.16	0.04	2005–2017	0.35	0.05	0.28	0.05	1993–2017	0.36	0.04	0.25	0.04	1969–1993	0.19	0.04	0.09	0.02
(Domingues et al. 2008) (updated to present and updated after 2018)	W m^{-2} Earth surface	1970–2017	0.3	0.05	NaN	NaN	2005–2017	0.35	0.05	0.28	0.05	1993–2017	0.41	0.05	NaN	NaN	1970–1993	0.29	0.08	NaN	NaN
(Ishii et al. 2017; Johnson et al. 2018) (BAMS SoC) MRI/JMA	W m^{-2} Earth surface											1993–2017 (use the values above, Ishii et al. most updated version)	0.36	0.06	0.22	0.06					
(Domingues et al. 2008; Johnson et al. 2018) (BAMS SoC) CSIRO/UTAS	W m^{-2} Earth surface											1993–2017 (use the values above, Domingues et al.)	0.4	0.07	NaN	NaN					
(Lyman and Johnson, 2014; Johnson et al. 2018) (BAMS SoC) PMEL/JPL/JMAR	W m^{-2} Earth surface											1993–2017	0.4	0.07	0.35	0.03					

Ocean Heat Content Changes

W m^{-2} Earth surface (averaged over Earth's surface: 5.1×10^{14} m^{2})

Paper on Ocean Heat Content	Units	Long-term trend period (1970–2017)	Ocean Heat Content estimate (0–700) m layer	90% confidence level or range	Ocean Heat Content estimate (700–2000) m layer	90% confidence level	Short or near term trend period (2005–2017)	Ocean Heat Content estimate (0–700) m layer	90% confidence level or range	Ocean Heat Content estimate (700–2000) m layer	90% confidence level	Period (1993–2017)	Ocean Heat Content estimate (0–700) m layer	90% confidence level or range	Ocean Heat Content estimate (700–2000) m layer	90% confidence level	Period (1969–1993)	Ocean Heat Content estimate (0–700) m layer	90% confidence level or range	Ocean Heat Content estimate (700–2000) m layer	90% confidence level
(Levitus et al. 2012; Johnson et al. 2018) (BAMS SoC) NCEI	W m^{-2} Earth surface	1970–2016 (Pentadal time series used, end at 2016)	0.23	0.05	0.11	0.04	2005–2016 (Pentadal time series used, end at 2016)	0.33	0.05	0.26	0.02	1993–2017	0.38	0.07	0.19	0.07	1969–1993 (from NCEI website, Pentadal time series)	0.18	0.09	0.05	0.04
(Johnson et al. 2018) (BAMS SoC) Hadley Centre. (Palmer et al. 2007)	W m^{-2} Earth surface											1993–2017	0.4	0.18	NaN	NaN					
(Cheng et al. 2017; Johnson et al. 2018) (BAMS SoC) ICCES	W m^{-2} Earth surface											1993–2017 (use the values above, Cheng et al. most updated version)	0.4	0.06	0.19	0.01					
Argo product: (Roemmich and Gilson, 2009)							2005–2017	0.3	0.06	0.2	0.03										
Argo product: JAMSTEC: (Hosoda et al. 2010)							2005–2017	0.32	0.03	0.27	0.02										
Argo product: (Schuckmann and Traon, 2011) (update)							2005–2017	0.35	0.1	0.28	0.1	1993–2017									
Copernicus Marine Service (von Schuckmann et al. 2018), http://marine.copernicus.eu/science-learning/ocean-monitoring-indicators/catalogue/												1993–2017	0.6	0.2							

Table SM5.2 | The CMIP5 ESM estimates are based on a combined 28-member ensemble of historical, RCP2.6 and RCP8.5 simulations to make times series that cover all of the periods in Table 5.1. The mean value of the ensemble models with the half range of the 90% certainty spread was used in Table 5.1 because this presentation of the ensemble models spread is most similar to the presentation of the mean observed heat content change and their associated confidence intervals. The models are CESM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3, CanESM2, FGOALS-S2.0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INM-CM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M. Up to 3 ensemble members or variants were included per model, and all changes are relative to a control run with an identical initial condition but with pre-industrial forcing. A table with a description and citations for each of these models, along with more detailed discussion of the use of Earth System Model (ESM) output, can be found in Flato et al. 2013). RCP is Representative Concentration Pathway.

Global Ocean Heat Content Change (ZJ/yr)
From combined RCP2.6 and RCP8.5 ensemble

		0–700 m					700–2000 m						
Time Period	**Ens size**	**5th pct.**	**95th pct.**	**50th pct.**	**Mean**	**5–95% half-range**	**5th pct.**	**95th pct.**	**50th pct.**	**Mean**	**5–95% half-range**		
1969–1993	28	1.71	5.54	3.78	3.6	1.915	–0.38	2.6	1.31	1.32	1.49		
1993–2017	28	5.39	9.57	7.34	7.37	2.09	1.08	3.9	2.89	2.72	1.41		
1970–2017	30	3.74	7.54	5.66	5.64	1.9	0.32	3.34	1.94	1.99	1.51		
2005–2017	27	4.97	10.38	8.04	7.85	2.705	1.12	4.61	3.47	3.33	1.745		

Global Ocean Heat Uptake average over Earth's surface (W m^{-2})
From combined RCP2.6 and RCP8.5 ensemble

		0–700 m					700–2000 m						
Time Period		**5th pct.**	**95th pct.**	**50th pct.**	**Mean**	**5–95% half-range**	**5th pct.**	**95th pct.**	**50th pct.**	**Mean**	**5–95% half-range**		
1969–1993		0.106	0.344	0.235	0.224	0.119	–0.024	0.162	0.081	0.082	0.093		
1993–2017		0.335	0.595	0.456	0.458	0.130	0.067	0.242	0.180	0.169	0.088		
1970–2017		0.232	0.468	0.352	0.350	0.118	0.020	0.208	0.121	0.124	0.094		
2005–2017		0.309	0.645	0.500	0.488	0.168	0.070	0.286	0.216	0.207	0.108		

Assessed Real-world Global Ocean Heat Uptake from Observational Estimates (ZJ/yr)

		0–700 m					700–2000 m					**8-Values RMS:**	**1.194**
Time Period		**Mean**	**5–95% half-range**		**Squared CMIP-OBS diff.**		**Mean**	**5–95% half-range**		**Squared CMIP-OBS diff.**			
1969–1993		3.22	1.61		0.1444		0.97	0.64		0.1225			
1993–2017		6.28	0.48		1.1881		3.86	2.09		1.2996			
1970–2017		4.35	0.8		1.6641		2.25	0.64		0.0676			
2005–2017		5.31	0.48		6.4516		4.02	0.97		0.4761			
					RMS:	1.5369				**RMS:**	0.701		
Earth's surface area	5.10E + 14	Second per year	**31557600**	J to ZJ	1E + 21		6.21E-02						

Table SM5.3 | Compiled information on the rate of pH change from various time series, ship reoccupations and Pacific Ocean moorings. Modified after Table in Williams et al. (2015) with additional datasets.

Region	pH change (pH units per decade)	Uncertainty	Study	Study period	Study type
Irminger Sea	–0.026	0.006	(Bates et al. 2014)	1983–2012	Time series
North Atlantic (BATS)	–0.017	0.001	(Bates et al. 2014)	1983–2012	Time series
North Atlantic (BATS)	–0.018	0.002	(Takahashi et al. 2014)	1983–2010	Time series
Iceland Sea	–0.023	0.003	(Olafsson et al. 2009)	1985–2008	Time series
North Pacific (ALOHA)	–0.018	0.001	(Dore et al. 2009)	1988–2007	Time series
North Pacific (HOT)	–0.016	0.001	(Bates et al. 2014)	1988–2012	Time series
North Pacific (HOT)	–0.018	0.001	(Takahashi et al. 2014)	1988–2009	Time series
Northwest Pacific	–0.02	N/A	(Ishii et al. 2017)	1994–2008	Time series
Mediterranean (Dyfamed)	–0.03	0.01	(Yao et al. 2016)	1995–2011	Time series
Mediterranean (Gibraltar)	–0.044	0.0006	(Flecha et al. 2015)	2012–2015	Time series
North Atlantic (ESTOC)	–0.018	0.002	(Bates et al. 2014)	1995–2012	Time series
North Atlantic (ESTOC)	–0.017	0.001	(González-Dávila et al. 2010)	1995–2004	Time series
Caribbean (CARIACO)	–0.025	0.004	(Bates et al. 2014)	1995–2012	Time series
North Atlantic (ESTOC)	–0.02	0.004	(Takahashi et al. 2014)	1996–2010	Time series
Southwest Pacific (Munida)	–0.013	0.003	(Bates et al. 2014)	1998–2012	Time series
Atlantic Ocean	–0.013	0.009	(Kitidis et al. 2017)	1995–2013	Merged ship occupations
East Equatorial Indian	–0.016	0.001	(Xue et al. 2014)	1962–2012	Merged ship occupations
Polar Zone Southern Ocean	–0.02	0.003	(Midorikawa et al. 2012)	1963–2003	Merged ship occupations
Northwest Pacific	–0.015	0.005	(Midorikawa et al. 2010)	1983–2007	Merged ship occupations
North Pacific	–0.017	N/A	(Byrne et al. 2010)	1991–2006	Merged ship occupations
Pacific Southern Ocean (S4P)	–0.022	0.004	(Williams et al. 2015)	1992–2011	Merged ship occupations
South Pacific	–0.016	N/A	(Waters et al. 2011)	1994–2008	Merged ship occupations
Pacific Southern Ocean (P16S)	–0.024	0.009	(Williams et al. 2015)	1995–2011	Merged ship occupations
Southern Ocean (SR03)	–0.031	0.004	(Pardo et al. 2017)	1995–2011	Merged ship occupations
Drake (PZ)	–0.015	0.008	(Takahashi et al. 2014)	2002–2012	Merged ship occupations
Drake (SAZ)	–0.023	0.007	(Takahashi et al. 2014)	2002–2012	Merged ship occupations
WHOTS (23N, 158W)	–0.02	0.003	(Sutton et al. 2017)	2004–2013	Mooring
Stratus (20S, 86W)	–0.02	0.003	(Sutton et al. 2017)	2006–2015	Mooring
KEO (32N, 144E)	–0.01	0.005	(Sutton et al. 2017)	2007–2014	Mooring
Papa (50N, 145W)	–0.01	0.005	(Sutton et al. 2017)	2007–2014	Mooring

Table SM5.4 | Models and variables used. Black crosses indicate data over the period 1861–2100 following the Representative Concentration Pathway (RCP)8.5 scenario, black circles indicate data following the RCP2.6 scenario, and numbers indicate the length of the control simulation. The models are also used in Frölicher et al. (2016). SST is sea surface temperature, NPP is net primary production.

Model	Surface pH	SST	O_2 (100–600)	NPP (0–100 m)	NO_3 (0–100 m)	References
CanESM2	xo996	xo996				(Arora et al. 2013)
CNRM-CM5		xo850				(Voldoire et al. 2013)
IPSL-CM5A-LR	xo1000	xo1000	xo1000	xo1000	xo1000	(Dufresne et al. 2013)
IPSL-CM5A-MR	xo300	xo300	xo300	xo300	xo300	(Dufresne et al. 2013)
IPSL-CM5B-LR	x300		x300	x300	x300	(Dufresne et al. 2013)
MIROC-ESM					xo630	(Watanabe et al. 2011)
MPI-ESM-LR	xo1000		xo1000	xo1000	xo1000	(Giorgetta et al. 2013)
MPI-ESM-MR	xo560	xo1000	xo650	xo1000	xo1000	(Giorgetta et al. 2013)
CCSM4		xo1051				(Gent et al. 2011)
NorESM1-ME		xo252				(Bentsen et al. 2013)
GFDL-ESM2G	xo500	xo500	xo500	xo500		(Dunne et al. 2012)
GFDL-ESM2M	xo500	xo500		xo500		(Dunne et al. 2012)
GISS-E2-H		xo281				(Shindell et al. 2013)
GISS-E2-R		xo531				(Shindell et al. 2013)
CESM1-CAM5		xo319				(Meehl et al. 2011)
BCC_CSM1-1		xo500				(Wu et al. 2014)
BCC-CSM1-1-m		x400				(Wu et al. 2014)
Total	**8/7/8**	**14/13/14**	**6/5/6**	**7/6/7**	**6/5/6**	

Table SM5.5 | Table of evidence of observed effects and projected impacts of climate hazards on cold water corals (in support of Box 5.2 (Cold water Corals and Sponges)).

Species	Locations	Evidence type	Key findings	Reference
*Lophelia pertusa** *Note recently renamed to Desmophyllum pertussum*	Northeast Atlantic	Experiment	Acidification exposure over 12 months will cause the biomineralised aragonite skeleton of *L. pertusa* to exhibit less organisation, a longer and thinner growth form, and reduced structural integrity of the exposed skeletal framework which forms the base of cold water coral reefs and a significant proportion of the habitat	(Hennige et al. 2015)
Desmophyllum dianthus	Fjords of Northern Patagonia	Observations	Thrives under natural low pH conditions (down to 7.4)	(Fillinger and Richter, 2013)
Desmophyllum dianthus	Mediterranean Sea	Experiment	Elevated pCO_2 (750 ppm CO_2) when combined with elevated temperatures (from 13°C–15°C) reduces calcification and respiration rates and shifts metabolic substrates from a mixture of protein and carbohydrate/lipids to a less efficient protein-dominated catabolism	(Gori et al. 2016)
Desmophyllum spp., *Lophelia pertusa*, *Madrepora oculata*, *Acanella arbuscula*, and *Paragorgia arborea*	Northwest Atlantic	Habitat suitability model	Habitat suitability analyses suggest that food supply (particulate organic carbon (POC) flux) is a critical variable	(Morato et al. 2006; Levin, 2018)
Desmophyllum spp., *Lophelia pertusa*, *Madrepora oculata*	Northwest Atlantic	Habitat suitability model	Dissolved oxygen is critical in defining habitat suitability	(Morato et al. 2006; Levin, 2018)
Lophelia pertusa, *Madrepora oculata*	Mediterranean Sea	Experiment	Net calcification and respiration of both species was unaffected by the levels of pCO_2 of 350–1000 µatm during both short and long-term (9 months) exposure	(Maier et al. 2013)
Madrepora oculata	Mediterranean Sea	Experiment	Energy demand to maintain calcification at 800 µatm is 2 times that required for calcification at ambient pCO_2, but only 1% of that of respiratory metabolism	(Maier et al. 2016)
Lophelia pertusa	Northeast Atlantic	Experiment	Capable of calcifying under elevated CO_2 (800 µatm) and temperature (12ºC), its condition (fitness) is more strongly influenced by food availability rather than changes in seawater chemistry	(Büscher et al. 2017)
Lophelia pertusa	Gulf of Mexico	Experiment	Some genotypes were able to calcify at pH 7.6 and aragonite undersaturation for 2 months but all exhibited reduced calcification after 6 months exposure	(Kurman et al. 2017)
Desmophyllum dianthus	Global ocean	Paleo record	Populations waxed and waned over the last 40,000 years as the global ocean was influenced by glacial advances and retreats and changing concentrations of CO3-2, O_2, and surface productivity	(Thiagarajan et al. 2013)
Desmophyllum dianthus	Seamounts in the North Atlantic and Southwest Pacific Oceans	Paleo record	Populations on altered their depth distribution in response to changes in the aragonite saturation depth	(Thiagarajan et al. 2013)
Lophelia pertusa and Madrepora oculata	Mediterranean Sea	Experiment	No effect of pH 7.81 on skeletal growth rate, microdensity and porosity after 6 months exposure	(Movilla et al. 2014)
Probably *Solenosmilia* and *Enalopsammia*	North Pacific	Observation	Live scleractinian reefs persist on six seamounts at depths of 535–732 m and aragonite saturation state (Ωarag) values of 0.71–1.33, suggesting little influence of the aragonite saturation horizon	(Baco et al. 2017)
Antipathes fiordensis (black coral)	New Zealand fjords	Observation	Shallow occurrence in a low salinity fjord	(Jiang et al. 2015)
Lophelia pertusa	Northwest Atlantic Gulf of Mexico	Experiment *In situ* observation	Upper lethal limit is 15ºC	(Brooke et al. 2013)
Lophelia pertusa, *Madrepora oculata*	Mediterranean Sea	Experiment	Species-specific thermal adaptations may regulate tolerance to future conditions. *L. pertusa* shows thermal acclimation in respiration and calcification but *M. oclulata* does not	(Naumann et al. 2014)
Lophelia pertusa	North Atlantic	Experiment, Model	The long planktonic duration (8 to 9 weeks) and upward swimming of larvae make connectivity of cold water coral populations likely to be sensitive to future changes in the state of North Atlantic Oscillation (NAO) in the northeast Atlantic	(Larsson et al. 2014; Fox et al. 2016)
Geodia barrette	North Atlantic	Experiment	Sponge and its microbiome tolerate a 5ºC increase in temperature, accompanied by rise in respiration, nitrogen efflux and cellular stress	(Strand et al. 2017)
Radiella sp., *Polymastia sp*	Northwest Atlantic	Experiment	Ocean acidification (pH 7.5) reduces the feeding of demosponge taxa	(Robertson et al. 2017)
Solenosmilia variabilis	Southern Australia, Seamounts	Observation, Habitat Suitability Modelling	Limited to Ωarag) of >2.5 and temperature >7ºC. By the end of the century low carbonate saturation levels and upper temp. limit eliminates all areas with a habitat suitability >40%; at RCP8.5	(Thresher et al. 2015)

SM5.2 Risk Assessment of Open Ocean Ecosystems in Support of Section 5.2.5

The deep seafloor and pelagic embers are generated based on earth system model projection of climate variables to the seafloor under RCP2.6 and RCP8.5 scenarios, and then translated to RCP associated change in sea surface temperature (SST). The assessed confidence in assigning the levels of risk at present day and future scenarios are *low, medium*, *high* and *very high* levels of confidence. A detailed account of the procedures involved in the ember for each type of ecosystem, such as their exposure to climate hazards, sensitivity of key biotic and abiotic components, natural adaptive capacity, observed impacts and projected risks, and regional hotspots of vulnerability is provided in Table SM5.6 and Table 5.5.

Table SM5.6a | Shows the main factors in the assessment of the deep seafloor and pelagic embers. RCP is Representative Concentration Pathway, POC is particulate organic carbon, EBUS is Eastern Boundary Upwelling Systems, NPP is net primary production, DO is dissolved oxygen, BI is benthic invertebrates, F is fishes, EF is export flux, P is phytoplankton, Z is zooplankton, HSM is historical simulation, CWC is cold water corals, MM is marine mammals, SST is sea surface temperature, obs is observation, exp is experiment, palaeo is paleontological data and proj is projection.

Deep Sea Floor Ecosystem	Water Depth (m)	Ecosystem Component	Main Climate Hazard	Sensitivity	Adaptive Capacity	Vulnerability (Risk)	Other Hazards	Impacts and Risks	Hotspots
Cold water corals	200–1600 m (forming reefs)	BI, F, CWC, sponges	**warming, acidification (especially aragonite undersaturation), deoxygenation, POC flux**	**SST>** CWC – moderate (obs., exp, HSM, proj) **pH/CO$_2$/ omega(arag)>** CWC – medium (obs, exp, proj) **POC flux>** CWC (proj) **DO>** CWC, BI – high (obs, exp, proj)	Moderate: Corals can survive for kyr and appear tolerant of elevated CO$_2$, but not significant warming or loss of oxygen. Genetic variability underpins adaptation to current conditions.	Moderate/High under RCP85: Tolerance to declining pH and omega. Drastic reduction in fitness under combined T, DO and pH/omega stress. Aragonite undersaturation weakens CWC skeletons and increases vulnerability to bioerosion by sponges, annelids, fungi.	Physical disturbance from fishing (bottom trawling and longlining), oil spills, potential for minerals mining disturbance.	Loss of CWC habitat through dissolution of non-living components of reefs under aragonite undersaturation, loss of fish habitat. Loss of resilience through changes in food supply (as POC flux decline) or mediated by migrating plankton.	Greatest vulnerability to aragonite undersaturation and loss of habitat suitability in the north Atlantic, and on south Australia seamounts.
Bathyal features: Seamounts, canyons, slopes	200–3000 m	BI, F, Protozoa	**deoxygenation, acidification, warming, POC flux**	**DO>** BI, F, Protozoa – moderate/high (obs. palaeo, exp. proj) **pH/CO$_2$, omega (arag)**. BI, F – l ow/moderate (obs., palaeo, exp. proj) **SST>** BI, F – low (obs., proj) **POC flux>** BI low (proj)	Moderate: Mostly unknown. Adults are exposed to wide range of conditions naturally. Fish and BI can migrate upslope or downslope to reach suitable conditions.	Moderate under RCP8.5, low under RCP2.6. Tolerance to declining DO and omega on upwelling margins but not everywhere. Lack of studies on sublethal responses.	Coincident human activities on seamounts, canyons and slopes such as cable laying, bottom fishing, oil and gas extraction/spills, waste disposal/debris accumulation can create cumulative stress. Altered precipitation and winds on land can alter bentho-pelagic coupling.	Loss of biodiversity, changes in trophic pathways and carbon cycling, reduction in biomass and habitat compression of Fish and BI under declining DO. Effects of acidification are poorly known for deep water species, but some hypoxia and acidification-tolerant taxa will expand distributions. Protozoan and metazoan meiofauna show different responses in different regions, but more tolerant than macro- or megafauna.	Largest declines in pH and POC flux in the northeast Atlantic may lead to alteration of canyon and seamount ecosystems; expanding oxygen minimum zone (OMZs) will create biodiversity loss and habitat compression at suboxic thresholds on EBUS slopes (northeast Pacific).

Deep Sea Floor Ecosystem	Water Depth (m)	Ecosystem Component	Main Climate Hazard	Sensitivity	Adaptive Capacity	Vulnerability (Risk)	Other Hazards	Impacts and Risks	Hotspots
Epipelagic (low-latitude)	0–200 m	P, Z, F, MM, NPP, EF	**warming, stratification, acidification, deoxygenation, nutrient concentration**	**SST>** P, Z, F (high), MM (moderate) *high confidence* (obs., proj.) **pH/CO$_2$** – P, Z, F, (low/moderate) *medium confidence* (obs, exp, proj) **EF>** (low) *low confidence* (proj) **DO>** Z, F, (moderate) *medium confidence* (obs, exp, proj) **NPP>** (low) *low confidence* (proj) **Nut>** P, Z, F (high), MM (moderate) *medium confidence* (obs., proj.)	Moderate: Plankton, F and MM can migrate poleward, following thermal and productivity gradients to reach suitable conditions. Poleward shifts of Z may be limited by the seasonality of light cycle at high latitudes that drives the P cycle. Geographic barriers such as land boundaries, or barriers related climate driven processes (e.g., low oxygen waters), may limit the range shift and migration patterns of F and MM. P may genetically adapt to changing climate conditions. Marine ectotherms have some capacity for physiological adjustment and evolutionary adaptation that lowers their sensitivity to warming and decrease in oxygen, but adaptation not always suffices to mitigate projected impacts.	High under RCP8.5, moderate under RCP2.6. Uncertain effects and tolerance of planktonic organisms (calcified vs non-calcified) and fishes on declining oxygen and pH, with temperature exacerbating acidification and deoxygenation. Major risk on declining productivity and fish biomass in low latitudes (tropical waters), as well as lower export flux in subtropical and tropical waters.	Enhanced decline of fish biomass due to overfishing with extended impact on large-bodied animals.	Poleward shifts of plankton and fish organisms, following expanding thermal gradients, with changes in community structure towards small size organisms in low latitudes. Earlier timing of spring phenology in Z and F, with cascading effects on the ecosystem. Enhanced stratification due to surface warming leads to reduced nutrient availability and lower NPP, with moderate to high Z and F biomass declines, and lower carbon export production to the deep ocean. The combined effects of warming, ocean deoxygenation and acidification in the 21st century are projected to exacerbate the impacts on the growth, reproduction and mortality of fishes, and consequently increases their risk of population decline.	Greatest impact on decline of NPP in equatorial regions. Projections from multiple fish species distribution models show hotspots of decrease in species richness in the Indo-Pacific region, and semi-enclosed seas such as the Red Sea and Arabian Gulf.
EBUS	0–200 m	P, Z, F, NPP	**warming, upwelling intensification, acidification (especially aragonite undersaturation), deoxygenation, nutrient concentration**	**SST>** P, Z,(low/moderate) *medium confidence* (obs., proj.) **pH/CO$_2$/omega (arag)** BI none/low (obs) **POC flux>** BI – low (obs) **DO>** BI – moderate (obs, proj)	Moderate: Plankton and F are exposed to large natural variability, so would be able to adapt to changing climate conditions. Calcified plankton species (e.g., pteropods, forams) unable to adapt to undersaturated carbonate (calcite and aragonite) thresholds, will be under serious risk of disappearance.	Moderate under RCP8.5, low under RCP2.6. High resilience of EBUS to changing climate conditions. Uneven effects on the four EBUS. Major risk on deoxygenation (expansion of OMZ) and acidification (carbonate undersaturation) in the two Pacific EBUS.	Non climatic stressors like overfishing and coastal pollution alter ecosystems' resilience. Changes in wind intensification and coastal precipitation alter upwelling intensity and local oceanographic conditions.	EBUS are rather close to a number of important thresholds in terms of increasing deoxygenation and ocean acidification, enhanced by ocean warming. Regional fisheries highly sensitive to local upwelling projected to increase due to wind intensification in three of the four EBUS (except the Canary Current EBUS). The direction and magnitude of observed changes vary between and within EBUS with mechanisms explaining these variabilities not fully understood yet. Given the high sensitivity of the coupled human-natural EBUS to oceanographic changes, the future sustainable delivery of key ecosystem services (fisheries, aquaculture, coastal tourism and climate regulations) is at risk under climate change.	Model projections for the end of the century suggest strong effects of deoxygenation and reduced pH in the Humboldt Current and the California Current EBUS under RCP8.5, the Humboldt Current transitioning toward widespread undersaturated conditions with regard to aragonite within a few decades. Observed and projected warming in the Canary Current EBUS, with a strong dependence on EBUS services and low adaptive capacity.

Figure SM5.6b | The global mean Sea Surface Temperature (SST) at which transitions in the level of risk occur for coastal ecosystems in response to climate-related hazards, from expert judgement and updated literature since IPCC AR5 and IPCC SR1.5. The corresponding Global Mean Surface Temperature (GMST), calculated by multiplying a scaling factor of 1.44 based on changes in an ensemble of RCP8.5 simulations, is provided in parentheses; there is an uncertainty of ~4% in this scaling factor based on differences between the RCP2.6 and RCP8.5 scenarios. (White: no detectable risks from climate-related hazards; Yellow: Moderate levels of risk; Red: High level of risk; Purple: Very high level of risk). * Low confidence; ** Medium confidence; *** High confidence; **** Very high confidence.

Ecosystems	Risk – colour	Transition	SST (GMST) (oC)	Confidence
Epipelagic	White to Yellow	Begin	0.5 (0.7)	
		End	0.8 (1.2)	***
	Yellow to Red	Begin	1.6 (2.3)	
		End	2.0 (2.9)	**
	Red to Purple	Begin	2.1 (3.0)	
		End	3.0 (4.3)	**
Eastern boundary upwelling systems	White to Yellow	Begin	0.8 (1.2)	
		End	2.0 (2.9)	*
	Yellow to Red	Begin	2.1 (3.0)	
		End	3.0 (4.3)	*
	Red to Purple	Begin	3.1 (4.5)	
		End	4.0 (5.8)	*
Cold water corals	White to Yellow	Begin	1.5 (2.2)	
		End	2.0 (2.9)	**
	Yellow to Red	Begin	2.1 (3.0)	
		End	2.7 (3.9)	**
	Red to Purple	Begin	2.8 (4.0)	
		End	3.5 (5.0)	*
Seamounts, canyons, slopes	White to Yellow	Begin	0.9 (1.3)	
		End	1.3 (1.9)	*
	Yellow to Red	Begin	1.4 (2.0)	
		End	2.5 (3.6)	*
	Red to Purple	Begin	N/A	
		End	N/A	
Abyssal plain	White to Yellow	Begin	2 (2.9)	
		End	2.5 (3.6)	**
	Yellow to Red	Begin	2.7 (3.9)	
		End	3.2 (4.6)	**
	Red to Purple	Begin	N/A	
		End	N/A	
Vents and seeps	White to Yellow	Begin	2 (2.9)	
		End	2.8 (4.0)	*
	Yellow to Red	Begin	3.2 (4.6)	
		End	4 (5.8)	*
	Red to Purple	Begin	N/A	
		End	N/A	

Table SM5.7 | A summary of available evidence to document the potential effects of climate change in Western and Eastern American sandy beach macrobenthic communities. Based on the theoretical framework detailed in Parmesan et al. (2013). Adapted from McLachlan and Defeo (2017). The numbers indicate the source references.

Lines of evidence	Attribution process	References
Long-term observations and resurveys	– Mass mortality events of *Mesodesma* clams in South America consistently follow warm sea surface temperature events (e.g., El Niño)[1] in the Pacific (*M. donacium* in Perú and Northern Chile) and occurred sequentially in a north-south direction in the Atlantic (*M. mactroides* in Brazil, Uruguay and Argentina), following oceanographic shifts, increasing sea surface temperature (SST) and isotherms moving poleward.[2] – 30 years of systematic sampling in Uruguay[2] and resurveys in Brazil and Argentina[3] across the distribution range of the clam *M. mactroides* document declines and local extirpations related to increasing SST and associated factors.	1. (Riascos et al. 2009) 2. (Ortega et al. 2013; Ortega et al. 2016) 3. (Herrmann et al. 2009; Adams et al. 2011; Herrmann et al. 2011)
Fingerprints	– Population extirpations along the northern (trailing) range edge and lowest levels of impact along southern (leading) range boundaries,[1, 2, 4] uniquely consistent with regional warming in the Pacific and Atlantic oceans and not with local human-caused stresses. – Drastic long-term demographic changes in the population of *M. mactroides* in sandy beaches from Uruguay are associated with changes in primary production driven by a climatic shift from a cold to a warm phase and increasing offshore winds, where reduced harvesting allow the population recovery.[11] – Mass mortalities of the yellow clam *Amarilladesma mactroides* occurred during warmer seasons throughout its entire distribution range,[5] concurrently with accelerating SST warming.	4. (Riascos et al. 2011) 5. (Fiori et al. 2004; Vázquez et al. 2016)
Meta-analyses: global coherence of responses across taxa and regions	– Mass mortalities observed across Pacific and Atlantic sandy beaches of South America, particularly during El Niño events and recorded oceanographic shifts.[1, 2] – Drastic changes in the composition of the suspension-feeder assemblages, with coherent responses across taxa and regions. *Mesodesma* clams were virtually extirpated at their northern range edges, being partially replaced by *Donax* clams and *Emerita* mole crabs (tropical affinities) in both Pacific[6, 7] and Atlantic[8, 9, 10] sandy beaches. Impoverished macrofaunal communities and *Mesodesma* species never reached biomasses at pre-mortality levels.[6, 9, 15] – Species introduction from adjacent areas in benthic macrofauna communities of surf zones driven by storm surges.[12] – Changes in spatial zonation of benthic macrofauna along the profile of mesotidal sandy beaches due to sediment movement in response to winds and storm surges.[13] – Parasites were found in clams, and also necrosis in gills and stomachs, during mortality events in the Atlantic (Argentina[4] and Uruguay[2]) and in the Pacific during strong El Niño events.[6] – Mass mortality events of the yellow clam *Amarilladesma mactroides* (considered a vulnerable species since the mid-1990s) likely in response to high population densities and pathogenic infections by *Vibrio* sp.[5] – Body downsizing towards warmer latitudes was consistently observed for the guilds of intertidal suspension feeders and benthic crustaceans including isopods, crab and amphipod species in sandy beaches from the southwest Atlantic[2, 8] and the northeast and southeast Pacific (USA and Chile).[1, 4, 14]	6. (Riascos et al. 2011) 7. (Arntz et al. 1987; Arntz et al. 2006) 8. (Celentano and Defeo, 2016) 9. (Dadon, 2005) 10. (Herrmann et al. 2009) 11. (Lercari et al. 2018) 12.(Carcedo et al. 2015; Carcedo et al. 2017)
Experiments	– Controlled in-vitro experiments showed that *D. obesulus* (tropical affinities) was tolerant to El Niño temperatures, whereas *M. donacium* (temperate) was sensitive to both El Niño and La Niña extreme conditions, with sublethal and lethal effects.[15]	14. (Jaramillo et al. 2017) 15. (Carstensen et al. 2010)

SM5.3 Risk Assessment of Coastal Ecosystems

The level of vulnerability to climate hazards of each type of coastal ecosystem assessed in Sections 5.3.1 to 5.3.6 depends on their sensitivity and adaptive capacity. The ecosystem sensitivity is assessed by discriminating the distinct responses to climate hazards of the main biotic and abiotic components that define each ecosystem, such as vegetation, benthic fauna, plankton, biogeochemical gradients (e.g., salinity, nutrients) and geomorphology. The level of exposure of each type of coastal ecosystem to climate hazards depends on the ecosystem (1) geographical distribution and (2) topographic characteristics, such as, intertidal or submerged, and (3) the level of local human impacts, for example, eutrophication, aquaculture and coastal infrastructure. For example, estuaries (Section 5.3.1) and sandy beaches (Section 5.3.3) are distributed all across the global coastlines that are experiencing diverse range of changes in climate hazards, while mangroves (Section 5.3.2) are restricted to temperate and tropical/subtropical regions (Figure 5.14) where their exposure to climate hazards is generally similar in nature. Likewise, kelp forests (Section 5.3.6) and most seagrass meadows (Section 5.3.2) are submerged ecosystems, while all the other ecosystems defined here are intertidal, except rocky reefs (Section 5.3.5) and coral reefs (Section 5.3.4) that can be both, intertidal and submerged. Intertidal ecosystems are more threatened by flooding and erosive processes due to sea level rise (SLR) and marine heat waves. Furthermore, the pervasive anthropogenic habitat degradation exacerbates climate vulnerabilities of coastal systems. Common examples of these compounding effects are the expansion of hypoxic zones enhanced by eutrophication in estuaries, and the reduction of the adaptive capacity of wetlands to flooding and salinisation by coastal squeezing, which constrains the landward migration of vegetated forms.

The common ecosystem responses to global warming (Sections 5.3.1 to 5.3.6) are habitat contraction, migration and loss of functionality and biodiversity. At the species level, the main biological responses are similar to those in pelagic ecosystems (Section 5.2.3), including shifts in species distribution towards the poles or specific physicochemical gradients (e.g., salinity and type of substrate) that result in species range expansions and local extinctions. Unique biological responses in coastal areas include the potential for inland migration of benthic fauna and littoral vegetation in response to increased sea water intrusion. Consequently, the restructuring of coastal ecosystems will negatively affect their functioning and services such as carbon storage, sediment stability, storm protection and provisioning of foraging and nursery sites (Section 5.4.1).

Table SM5.8a | Tidal exposure: IT: intertidal; S: submerged. Ecosystem component: R-S is river-sea transition. GM is geomorphology. BGQ is biogeochemistry. BI is Benthic invertebrates. P is Plankton. V is Vegetation. F is Fishes. MM is Marine mammals. SB is Sea birds. SE is Soil elevation, T is turtles, MA is macroalgae, HABS is harmful algal blooms, SLR is sea level rise, SST is sea surface temperature, RCP is representative Concentration Pathway.

Coastal Ecosystem	Ecosystem component	Main climate hazard	Sensitivity	Adaptive capacity	Vulnerability (Risk)	Other hazards	Impacts and risks	Hotspots
Estuaries	R-S IT BGQ BI P V F MM	**SLR, warming, deoxygenation**	**SST** > BGQ, BI, P, V, F, MM- medium (obs+proj) **pH/CO$_2$** > BI, F- low (proj) **SLR** > BGQ, GM, V- high (obs+proj) **DO** > BGQ, P, F – medium (obs+proj) **Precipitation/river runoff (droughts/floods)** > BGQ, BI, V (obs+proj).	**Moderate/High** (High resilience, especially deep, macrotidal estuaries with high exchange with the open ocean).	**Moderate** (*medium confidence*)	Habitat degradation due to human activities: aquaculture, agriculture, urbanisation. Eutrophication. Pollution. Overfishing. Shipping/dredging. Sedimentation/ mouth closure.	Salinisation, increase in nutrient and sediment loads. Changes in circulation patterns. Upstream redistribution of brackish and marine benthic and pelagic species, depending on their tolerance range to salinity and substrate type. Organic matter accumulation. Increased bacterial respiration. Hypoxia and anoxia. Occurrence of HABS) and pathogenic outbreaks. Increased mortality of invertebrates and fishes. Poleward migration of low latitude flora and fauna species between estuaries.	Microtidal, shallow and eutrophic estuaries in mid and high latitudes are more vulnerable to SLR, warming, deoxygenation and acidification. Salinisation due to SLR and warming will intensify in estuaries in drought regions.
Salt marshes	V IT SE F SB	**SLR, warming**	**SST** > V, F- medium (obs+exp+proj) but positive/negative effects **pH/CO$_2$** > V- low (obs+proj+exp) but positive/negative effects **SLR** > V, SE, SB- high (obs+proj) **Increased storm disturbance** (but positive/ negative effects depending on sediment supply) > V, SE (obs+proj).	**Moderate** (Salt marshes are initially resilient to SLR due to soil accretion (biomass accumulation and sediment deposition) but system will not be able to withstand SLR after 60 years under RCP8.5.	**High** (*medium confidence*)	Coastal development causing squeeze and altered flushing regimes. Species invasions. Mangrove encroachment. Eutrophication. Land use change for agriculture. Dredging. Overfishing.	Reduction in above- and belowground plant biomass, carbon storage and soil elevation. Tolerance to inundation and salinisation depends on plant species and organic accretion. Shifts in plant species, local extinctions. Habitat restructuration from salt marshes to mudflats, biodiversity loss. Reduction in sediment stability. Reduction in foraging and nursery services. The projected loss in global coastal wetlands (20–60%) is in part counterbalanced by some increase in arid and sub-tropical marshes (3–6%) under low SLR scenario and lateral re-accommodation of sediments (if not constricted by human constructions).	Salt marshes in microtidal estuaries in dry areas, with low sediment supply and low soil accretion capacity, are exposed to high salinisation due to SLR and warming. Salt marshes in sub-tropical areas are threatened by expansion of mangrove forests. Migration inland of salt marshes is limited in areas with coastal human development.
Mangrove forests	V IT SE F SB	**SLR, warming, deoxygenation**	**SST** > V, F- low/medium (obs+proj) but positive/ negative effects **pH/CO$_2$** > V- low (obs+exp+proj) but positive/negative effects **SLR** > V, SE, SB- high (obs+proj) **Increased storm disturbance** (but positive/ negative effects depending on sediment supply) > V, SE (obs+proj).	**Low/Moderate** (Long-living, large-size plants. Initially resilient to SLR due to soil accretion. Ecosystem under intense human impacts. Rehabilitation practices can stimulate soil elevation).	**Moderate** (*medium confidence*)	Coastal development causing squeezing. Habitat degradation due to human activities: Deforestation, aquaculture, agriculture, urbanisation.	Hydro-geomorphological settings play important role in mangrove responses to SLR. Soil accretion can cope with low SLR scenario (RCP2.6) throughout the 100 years projection period, but only up to mid-century under RCP8.5. Fringe mangroves are more vulnerable to SLR than basin mangroves. Mangroves under microtidal regime with low soil accretion capacity are also more vulnerable.	Mangrove forests in low-lying coastal areas with low soil accretion capacity are highly vulnerable to SLR. Migration inland of mangrove forests is limited in areas with coastal human development.
Seagrass meadows	V F IT MM SB T	**Warming and heat-waves**	**SST** > V, F, MM, T- high (obs+exp+proj) **pH/CO$_2$** > V- high but positive/negative effects (obs+exp+proj) **SLR** > V, SB- low (obs+proj) **Increased storm disturbance** > V (obs+proj).	**Low/Moderate**	**Very high** (*very high confidence*)	Eutrophication, habitat degradation, biological invasions.	Reduction in plant fitness due to temperature stress and reduction in underwater light levels due to turbidity and SLR. Mass mortality events due to heatwaves. Spread of invasive tropical species. Severe habitat loss of the endemic *Posidonia oceanica* in the Mediterranean, 70% by 2050 and potential extinction by 2100 under RCP8.5. Warming will lead to significant reduction of *Cymodosea nodosa* meadows (46%) in the Mediterranean, and expansion into the Atlantic. Increased herbivory by tropical consumers on temperate seagrasses, ecosystem biodiversity loss.	Seagrasses meadows in low latitudes and in coastal seas with limited expansion capacity of endemic species (e.g., Mediterranean), and those exposed to extreme temperature events and invasion of tropical herbivorous species.

Coastal Ecosystem	Ecosystem component	Main climate hazard	Sensitivity	Adaptive capacity	Vulnerability (Risk)	Other hazards	Impacts and risks	Hotspots
Sandy beaches	GM IT BI V P T	**SLR, warming, storms**	**SST** > BI, P, T- high (obs+proj) **pH/CO_2** > BI, P-low (obs+proj) **SLR** > GM, BI, V, T-high (obs+proj) **Increased storm disturbance, runoff** > GM, BI, V (obs+proj).	**Moderate**	**Moderate** (***medium confidence***)	Infrastructure development causing squeezing, habitat degradation.	Increasing erosion/sediment loss related to storms, waves and SLR. Changes in beach morphology, dune scarping, vegetation loss, reduction in beach area and turtle nesting sites. Poleward shifts in macrobenthic communities, reduction in body size with warming, mass mortality of clams. Limitation in the landward migration of the beach profile due to human development.	Sandy beaches in the southwest Atlantic and southeast Pacific: Chile, South Brasil, Uruguay and Argentina are exposed to compound effects of SLR, storm surges, warm phases of El Niño and changes in tidal amplitudes.
Coral reefs	BGQ IT S BI P F	**Warming, acidification, SLR, storms**	**SST** > BGQ, BI, P, F-high (obs+exp+proj) **pH/CO_2** > BGQ, BI, P-high (obs+exp+proj) **SLR** > GM, BI- high (obs+exp+proj) **Increased storm disturbance** > GM, BI (obs+proj).	**Low/Moderate** (some populations seem adapted to climate changes)	**Very high** (***very high confidence***)	Habitat degradation, eutrophication, overfishing, pollution.	Species-specific responses to multiple climate drivers. Coral bleaching, mass mortality. Drastic reduction in coral fitness (growth, reproduction) due to combined effects of warming, acidification and SLR. Spread of invasive species. Reef dissolution and bioerosion. Shift in habitat structure from calcified corals towards algal or soft, slow growing coral dominated reefs. Ecosystem biodiversity loss. Only a few reefs worldwide have shown resilience to recent global change impacts. Limitation in the dispersal of organisms due to, for example, ocean currents, enhances the alterations in coral reef communities driven by climate warming.	The highest probability of coral bleaching occurs at tropical mid-latitude sites (15–20 degrees north and south of the Equator). However, coral bleaching is less common in localities with a high variance in SST anomalies and ecological settings. Reduced calcification and enhanced SLR render few reefs with the capacity to track SLR projections.
Rocky shores	BI S IT MA F SB	**Warming, acidification, SLR.**	**SST** > BI, MA, F-high (obs+exp) **pH/CO_2** > BI, MA-high (obs+exp) **SLR** > BI, MA, SB-medium (proj)	**Uncertain**	**High** (***medium confidence***)	Eutrophication. Coastal development causing squeezing.	Poleward shifts of benthic fauna and algal species due to warming. Heat exposure during low tide and SLR constrict the area for relocation of the intertidal benthic communities. Simplification of the food web structure at low trophic levels due to warming and acidification. Dissolution of calcareous species and increased grazing on them. Reduction in habitat complexity (shift from calcareous species to weedy algae). Macroalgae responses to acidification and warming depend on light and nutrient levels. Ecosystem biodiversity loss.	Local extinctions at the equatorial or warm edge of species ranges, and mass mortality of intertidal rocky reef organisms due to heatwaves. This vulnerability to heat stress will be exacerbated in areas where coastal acidification will reduce the biodiversity of intertidal and rocky reef ecosystems dominated by calcareous species.
Kelp forests	MA S MM F	**Warming, heat-waves.**	**SST** > MA, MM, F-high (obs+exp+proj) **pH/CO_2** > MA-low (exp+proj) **SLR** (nd) **Increased heatwaves and storm disturbances** > MA- high (obs+exp+proj).	**Low** (kelps are highly sensible to warming and have low dispersal capacity)	**Very High** (***very high confidence***)	Habitat degradation by human activities. Overgrazing by sea urchins.	Mass mortality of kelps due to heatwaves combined with high irradiance; eutrophication delays the re-establishment. Global range contractions of kelps at the warm end of distributional margins and expansions at the poleward end, spread of invasive species. Reduction in habitat complexity (from kelps to turfs). Macroalgae responses to acidification and warming depend on light and nutrient levels. Ecosystem biodiversity loss. In polar fjords, kelp fitness is reduced by warming and increased turbidity due to ice melting.	Kelp forests in the higher rage of temperature distribution will experience the larger reduction due to warming, and those exposed to increased heatwaves events, such as kelp forests in Australia.

Figure SM5.8b | The global mean Sea Surface Temperature (SST) at which transitions in the level of risk occur for coastal ecosystems in response to climate-related hazards, from expert judgement and updated literature since IPCC AR5 and IPCC SR1.5. The corresponding Global Mean Surface Temperature (GMST), calculated by multiplying a scaling factor of 1.44 based on changes in an ensemble of RCP8.5 simulations, is provided in parentheses; there is an uncertainty of ~4% in this scaling factor based on differences between the RCP2.6 and RCP8.5 scenarios. (White: no detectable risks from climate-related hazards; Yellow: Moderate levels of risk; Red: High level of risk; Purple: Very high level of risk). * Low confidence; ** Medium confidence; *** High confidence; **** Very high confidence.

Ecosystems	Risk – colour	Transition	SST (GMST) oC	Confidence
Estuaries	White to Yellow	Begin	1.2 (1.7)	
		End	1.8 (2.6)	**
	Yellow to Red	Begin	2.3 (3.3)	
		End	3.0 (4.3)	**
	Red to Purple	Begin	N/A	
		End	N/A	
Salt marshes	White to Yellow	Begin	0.7 (1.0)	
		End	1.2 (1.7)	***
	Yellow to Red	Begin	1.8 (2.6)	
		End	2.7 (3.9)	**
	Red to Purple	Begin	3.0 (4.3)	
		End	3.4 (4.9)	**
Mangrove forests	White to Yellow	Begin	1.2 (1.7)	
		End	2.0 (2.9)	**
	Yellow to Red	Begin	2.3 (3.3)	
		End	3.0 (4.3)	**
	Red to Purple	Begin	N/A	
		End	N/A	
Seagrass meadows	White to Yellow	Begin	0.5 (0.7)	
		End	0.8 (1.2)	****
	Yellow to Red	Begin	1.5 (2.2)	
		End	1.8 (2.6)	***
	Red to Purple	Begin	2.2 (3.2)	
		End	3.0 (4.3)	***
Sandy beaches	White to Yellow	Begin	0.9 (1.3)	
		End	1.8 (2.6)	**
	Yellow to Red	Begin	2.3 (3.3)	
		End	3.0 (4.3)	*
	Red to Purple	Begin	N/A	
		End	N/A	
Warm water corals	White to Yellow	Begin	0.2 (0.3)	
		End	0.4 (0.6)	***
	Yellow to Red	Begin	0.4 (0.6)	
		End	0.6 (0.9)	****
	Red to Purple	Begin	0.6 (0.9)	
		End	1.2 (1.7)	****
Rocky shores	White to Yellow	Begin	0.8 (1.2)	
		End	1.3 (1.9)	**
	Yellow to Red	Begin	1.8 (2.6)	
		End	2.7 (3.9)	**
	Red to Purple	Begin	2.9 (4.2)	
		End	3.4 (4.9)	*
Kelp forests	White to Yellow	Begin	0.6 (0.9)	
		End	1.0 (1.4)	***
	Yellow to Red	Begin	1.2 (1.7)	
		End	1.8 (2.6)	***
	Red to Purple	Begin	2.2 (3.2)	
		End	2.8 (4.0)	***

SM5.4 Additional Information Relating to 'Ocean Solutions' in Section 5.5.1.1

Details are given in Tables SM5.9a and SM5.9b on ten potential ocean-based actions that provide the rows of Figure 5.23, and on the associated five benefits and four constraints that provide the columns of that figure. Additional information, including more than 500 supporting references, is given in Gattuso et al. (2018).

Table SM5.9a | Descriptions of ocean-based actions assessed in Figure 5.23. Global scale assumes worldwide implementation (at maximum theoretical level); local scale is based on implementation at less than ~100 km^2. Three global-scale actions considered by Gattuso et al. (2018) are excluded here: land-ocean hybrid methods, marine cloud brightening, and increased surface ocean albedo.

Action	Description	Scale
Marine renewable energy (physical processes)	The production of energy using offshore wind turbines and harvesting of energy from tides, waves, ocean currents, and thermal stratification. This action is included for comparison of its benefits and constraint to those of others.	Global
Ocean fertilisation (open ocean)	The artificial increase in the ocean's primary production and carbon uptake by phytoplankton, achieved primarily by adding soluble iron to surface waters where it is currently lacking.	Global
Enhanced weathering (alkalinisation)	The addition of a variety of minerals or other alkaline substances that consume CO_2 and/or neutralise acidity, usually involving raising the concentration of carbonate or hydroxide ions.	Global and local
Restoring and conserving coastal vegetation	Management of coastal 'blue carbon' ecosystems, primarily salt marshes, mangroves and seagrasses, to enhance their carbon sink capacity and avoid emissions from the degradation or loss of their existing carbon stocks.	Global and local
Marine protected areas	The conservation of habitats and ecosystems, in order to increase the abundance of marine species and thereby help protect natural populations against climate impacts.	Local
Reducing pollution (including nutrients)	The decreased release of harmful substances that increase the sensitivity of marine organisms and ecosystems to climate-related drivers, or those that can directly exacerbate ocean acidification and hypoxia.	Local
Restoring hydrological regimes	The maintenance and restoration of marine hydrological conditions, including the tidal and riverine delivery of water and sediments, to alleviate local changes in climate-related drivers.	Local
Eliminating over-exploitation	Management action to ensure that living resources are sustainably harvested (within biologically safe limits and maintaining ecosystem function) and that the extraction of non-living resources (e.g., sand and minerals) is at levels that avoid irreversible ecological impacts.	Local
Assisted evolution	The large-scale genetic modification, captive breeding and release of organisms with enhanced stress tolerance.	Local
Relocation and restoration (reef systems)	The restoration and/or active relocation of degraded coral and oyster reefs, with the potential creation of new habitats and use of more resilient species or strains.	Local

Table SM5.9b | The scoring schemes for the benefits and constraints relating to ocean-based actions described in Table SM5.9a and summarised in Figure 5.23, assuming worldwide implementation for global scale actions, and implementation at less than ~100 km^2 for local scale. The 1 to 5 (very low to very high) scoring scale is based on combined assessments of the positive or negative consequences relating to four marine ecosystems and habitats (coral reefs, mangroves and salt marshes, seagrass habitats and Arctic biota) and four marine ecosystem services (fin fisheries, finfish aquaculture, bivalve fisheries and aquaculture and coastal protection) arising from deployment of each action at its maximum physical capacity, with quantification based on a comprehensive literature review combined with expert judgement. Scores for benefits indicate the potential for reducing the difference in climatic impacts on between emissions scenarios Representative Concentration Pathway (RCP)8.5 and RCP2.6 by 2100. Scores for constraints indicate the potential for adverse consequences or other issues that would need to be addressed for full-scale implementation. These scoring schemes follow those used in Gattuso et al. (2018), although the scores for constraints are reversed in scale. SLR is sea level rise.

Benefits	Scoring scheme	Scale
Impact reduction: warming	Scoring scale: 1, cumulative carbon mitigation (reduction or removal) potential of 0–250 GtC to 2100; 2, mitigation potential of 250–500 GtC; 3, mitigation potential of 500–750 GtC; 4, mitigation potential of 750–1000 GtC; 5, mitigation potential of >1000 GtC. Scale based on cumulative emission difference of 1400 GtC between RCP2.6 and RCP8.5, over the period 2012–2100.	Global
	Scores from assessment of effectiveness of local impact reduction, based on comparing projected warming impacts to 2100 of RCP8.5 and RCP2.6.	Local
Impact reduction: ocean acidification	Scores based on carbon mitigation, allowing for specificities of actions with regard to their effects on seawater carbonate chemistry, and assuming a difference of 0.25 pH units between RCP2.6 and RCP8.5 for mean global surface seawater.	Global
	Scores from assessment of effectiveness of local impact reduction, based on comparing projected ocean acidification impacts of RCP8.5 and RCP2.6 to 2100.	Local
Impact reduction: SLR	Scores as for global warming mitigation less 1, to allow for inherent inertia of sea level response.	Global
	Scores from assessment of effectiveness of local impact reduction, based on comparing projected SLR impacts of RCP8.5 and RCP2.6 to 2100.	Local
Impact reduction: warming, ocean acidification and SLR combined	Mean score of mitigation for all three drivers of climate change.	Global
	Scores from assessment of effectiveness of local impact reduction, based on comparing projected warming, ocean acidification and SLR impacts of RCP8.5 and RCP2.6 to 2100.	Local
Co-benefits	Scores for literature-based expert judgement of potential non-climatic benefits at global scale, including improvement of ecosystem status and the generation of ecosystem services.	Global
	Scores for literature-based expert judgement of potential non-climatic benefits at local scale, including improvement of ecosystem status and the generation of ecosystem services.	Local

Constraints	Scoring scheme	Scale
Trade-offs	Scores for literature-based expert judgement of potential adverse impacts for ecosystems and ecosystem services arising as a result of the action. Societal effects (e.g., inequity) that depend on socioeconomic scenarios are excluded. (Note that trade-offs are considered as 'dis-benefits' in Gattuso et al. (2018)).	Global
	As above, considered at local scale.	Local
Technical issues to overcome	A combined score for technological readiness (with range between fully ready for deployment and conceptual-only); lead time for full potential effectiveness (days/months to decades), and (im)permanence of effect (duration of effect once implemented), each assessed on 1–5 scale with higher scores indicating greater technological barriers.	Global
	As above, considered at local scale.	Local
Cost (for warming mitigation)	Mean values for carbon removal or emission reduction determined from the range of literature costs for implementation of actions. Scoring scale: 1, <10 USD per tonne CO_2 removed; 2, 10–60; 3, 60–110; 4, 110–160; 5, >160.	Global
	Mean values on a per unit area basis determined from the range of literature costs for implementation of actions. Scoring scale is for USD per ha: 1) <100; 2) 100–200; 3) 200–300; 4) 300–400; 5) >400.	Local
Governability challenges	Assessment of the capability of the global community of nation states and other international actors to implement actions through co-operation and coordination, based on semi-quantified biophysical factors (e.g., distribution of benefits and dis-benefits) and occurrence of formal and informal institutional arrangements. Sub-national governance challenges were also recognised as important by Gattuso et al. (2018), but were not scored.	Global
	As above. For actions considered at both global and local scales, the same score was applied.	Local

SM5.5 Supplementary Information Supporting Table 5.7

Summary of reported Adaptation responses (A), the Impacts (I) they aimed to address, and the expected Benefits (B) in coastal ecosystems within Physical, Ecological, Social, Governance, Economic and Knowledge categories. The summary is presented in Table 5.7 and the papers used to support the assessment are found below.

A. Ecosystem: Coral Reefs

A.1 Climate and other CO_2-related drivers

SLR, Increased storm wave energy and frequency, ocean acidification

A.2 Anthropogenic co-drivers

A.2.1 Physical

Dense urban development (Osorio-Cano et al. 2017; Beck et al. 2018; Gattuso et al. 2018) with coastal built infrastructure (Perkins et al. 2015) to accommodate population growth (Beck et al. 2018)

Physical damage from shipping (van Oppen et al. 2017), mining (Beck et al. 2018), dredging (Wynveen and Sutton, 2015), sedimentation (Wynveen and Sutton, 2015; Elliff and Silva, 2017) and destructive fishing techniques (van Oppen et al. 2017; Gattuso et al. 2018)

Pollution (Gallagher et al. 2015; Elliff and Silva, 2017; van Oppen et al. 2017; Gattuso et al. 2018)

A.2.2 Ecological

Overharvesting (Wynveen and Sutton, 2015; van Oppen et al. 2017; Gattuso et al. 2018)

A.2.3 Social

Marine tourism (Wynveen and Sutton, 2015)

A.3 Impact

A.3.1 Physical

Coastal physical processes disrupted

Loss of coastal protection services (Lirman and Schopmeyer, 2016) resulting in coastal flooding (Perkins et al. 2015; Beetham et al. 2017; Elliff and Silva, 2017; Beck et al. 2018; Comte and Pendleton, 2018)

Habitat loss (Perkins et al. 2015; Gattuso et al. 2018) via increased wave energy (Beetham et al. 2017)

A.3.2 Ecological

Ecosystem degradation and loss

Decreasing hydrodynamic roughness (Osorio-Cano et al. 2017)

Deteriorating quality of reef habitat (Lirman and Schopmeyer, 2016; van Oppen et al. 2017) including coral bleaching (Wynveen and Sutton, 2015; Elliff and Silva, 2017; Osorio-Cano et al. 2017; van Oppen et al. 2017; Beck et al. 2018; Comte and Pendleton, 2018; Gattuso et al. 2018)

Biodiversity and genetic diversity loss

Loss of reef-building taxa (Lirman and Schopmeyer, 2016) and biodiversity impacts (Lirman and Schopmeyer, 2016)

Habitat range shifts

Habitat range shifts (Gallagher et al. 2015; Miller et al. 2017)

Sub-lethal species impacts

Species level impacts (growth and reproduction) (Gallagher et al. 2015)

A.3.3 Social

Local decline in agriculture and fisheries

Declining fisheries (Lirman and Schopmeyer, 2016)

A.4 Adaptation responses

A.4.1 Physical

Supporting physical processes

Pollution reduction (Gattuso et al. 2018)

Restoring hydrology (Gattuso et al. 2018)

Hard engineering responses

Watershed management (Lirman and Schopmeyer, 2016)

A.4.2 Ecological

Ecosystem restoration and protection

Protection and maintenance of coral reefs (Elliff and Silva, 2017; Comte and Pendleton, 2018; Gattuso et al. 2018)

Coral gardening and reef restoration (Lirman and Schopmeyer, 2016)

Bioengineering

Bioengineering by increasing habitat complexity on coastal structures (Perkins et al. 2015)

Assisted evolution and relocation

Assisted colonisation (Gallagher et al. 2015; Lirman and Schopmeyer, 2016) and evolution (van Oppen et al. 2017; Gattuso et al. 2018)

Relocation (Gattuso et al. 2018)

A.4.3 Social

Switching livelihoods

Fisheries engaging in alternative livelihoods (Miller et al. 2017)

Stakeholder involvement, including access to information, technology and funding (Miller et al. 2017)

Community participatory programmes

Building trust through community participation to increase buy-in for adaptation response (Wynveen and Sutton, 2015)

Sustainable resource use

Eliminating overexploitation (Gattuso et al. 2018)

Sustainable fishing practices (Lirman and Schopmeyer, 2016)

A.4.4 Governance

Horizontal/vertical integration of governance

Horizontal and vertical integration of organisations and policies (Miller et al. 2017)

Developing partnerships and building capacity

Engaging in tourism partnerships with other industries (Miller et al. 2017)

Improving implementation and coordination of policies

Interdisciplinary and cross-jurisdictional approaches (Miller et al. 2017)

Improving Integrated Coastal Management (ICM)/ Marine Protected Areas (MPAs)

MPA establishment (Lirman and Schopmeyer, 2016)

Multiple adaptation responses used

Synergistic application of multiple responses supported (van Oppen et al. 2017)

Coral gardening and reef restoration need to be used with other tools such as watershed management, sustainable fishing practices, MPA establishment (Lirman and Schopmeyer, 2016)

A.5 Benefits

A.5.1 Physical

Physical processes supported

Coastal protection (Perkins et al. 2015; Elliff and Silva, 2017; Comte and Pendleton, 2018) from flooding (Beetham et al. 2017; Beck et al. 2018)

A.5.2 Ecological

Ecosystem/ecological resilience supported

Improved ecosystem functioning (Perkins et al. 2015; Miller et al. 2017; Comte and Pendleton, 2018)

Restoration of coral reefs (Lirman and Schopmeyer, 2016; van Oppen et al. 2017) with increased reef resilience (Gattuso et al. 2018)

Increased biodiversity

Increased biodiversity (Gallagher et al. 2015; Perkins et al. 2015)

Improved organismal fitness

Increased reef resilience (Gattuso et al. 2018) including inter-habitat connectivity (Perkins et al. 2015; Lirman and Schopmeyer, 2016), vertical reef accretion (Beetham et al. 2017), stress tolerance (van Oppen et al. 2017)

A.5.3 Social

Access to sustainable ecosystem services

Reduced social vulnerability (through provisioning services) (Beck et al. 2018)

Improved ecosystem service provision (Perkins et al. 2015; Miller et al. 2017; Comte and Pendleton, 2018)

Improved employment and livelihoods

Improved livelihoods (Lirman and Schopmeyer, 2016)

Increased adaptive capacity

Reduced social vulnerability (through provisioning services) (Beck et al. 2018)

Improved coping and adaptive capacity (Beck et al. 2018)

A.5.4 Governance

Developing partnerships and building capacity

Stakeholder-management trust encourages adoption of pro-environmental behaviour (Wynveen and Sutton, 2015)

A.5.5 Economic

Increased revenue/income

Revenue from tourism (Lirman and Schopmeyer, 2016; Comte and Pendleton, 2018)

A.5.6 Knowledge

Improved education and outreach

Provide scientific information, education and outreach opportunities (Lirman and Schopmeyer, 2016)

A.6 Constraints and limitations

A.6.1 Physical

Site availability (Gallagher et al. 2015)

Reefs with low resilience from anthropogenic drivers are less likely to adapt to climate change impacts. (Elliff and Silva, 2017)

Tools not developed yet for large-scale implementation (van Oppen et al. 2017)

Ocean acidification as a limiting factor in warm water adaptation (Lirman and Schopmeyer, 2016; Miller et al. 2017)

A.6.2 Ecological

Failure of some species to colonise restored reef (Gallagher et al. 2015)

Sea level rise may outpace reef vertical accretion (Beetham et al. 2017; Elliff and Silva, 2017)

Restoration efforts may not support intertidal communities (Perkins et al. 2015)

Natural systems with organismal thermal tolerance and limits with biochemical characteristics (Miller et al. 2017)

Coral predator abundances, disease impacts on out planted populations and nurseries and genetic impacts on extant nurseries (Lirman and Schopmeyer, 2016)

A.6.3 Social

Social and cultural norms with conflicting and competing values (Miller et al. 2017), including loss of local support (Lirman and Schopmeyer, 2016) and vandalism and physical damage to nursery resources (Lirman and Schopmeyer, 2016)

Public lack of knowledge on climate change and distrust of information sources (Wynveen and Sutton, 2015)

A.6.4 Governance

Effective implementation challenges (Comte and Pendleton, 2018)

Cross border coordination challenges (Gallagher et al. 2015)

Inadequate governance and institutional structures (Miller et al. 2017)

Turnover on personnel (Lirman and Schopmeyer, 2016)

A.6.5 Economic

Economic undervaluation of ecosystems and the services they provide (Perkins et al. 2015)

Financial costs of design (Gallagher et al. 2015)

Lack of finances (Miller et al. 2017), including sustained funding beyond nursery stage (Lirman and Schopmeyer, 2016)

A.6.6 Knowledge

Absence of baseline data may undermine coastline management (Perkins et al. 2015)

Knowledge gap on restoration of coral reef systems as an adaptation tool (Comte and Pendleton, 2018)

Public knowledge gaps and distrust of information sources (Wynveen and Sutton, 2015)

A.7 Costs

A.7.1 Physical

Site availability (Gallagher et al. 2015)

Reefs with low resilience from anthropogenic drivers are less likely to adapt to climate change impacts (Elliff and Silva, 2017)

Tools not developed yet for large-scale implementation (van Oppen et al. 2017)

Ocean acidification as a limiting factor in warm water adaptation (Miller et al. 2017)

Coastal protection from flooding reducing annual expected costs by 4 billion USD (Beck et al. 2018)

A.7.2 Social

Social and cultural norms with conflicting and competing values (Miller et al. 2017)

A.7.3 Ecological

Failure of some species to colonise restored reef (Gallagher et al. 2015)

SLR may outpace reef vertical accretion (Beetham et al. 2017; Elliff and Silva, 2017)

Restoration efforts may not support intertidal communities (Perkins et al. 2015)

Natural systems with organismal thermal tolerance and limits with biochemical characteristics (Miller et al. 2017)

A.7.4 Economic

Economic undervaluation of ecosystems and the services they provide (Perkins et al. 2015)

Financial costs of design (Gallagher et al. 2015)

Lack of finances (Miller et al. 2017)

A.7.5 Governance

Effective implementation challenges (Comte and Pendleton, 2018)

Cross border coordination challenges (Gallagher et al. 2015)

Inadequate governance and institutional structures (Miller et al. 2017)

A.7.6 Knowledge

Absence of baseline data may undermine coastline management (Perkins et al. 2015)

Knowledge gap on restoration of coral reef systems as an adaptation tool (Comte and Pendleton, 2018)

B. Ecosystem: Mangrove Forests

B.1 Climate drivers

SLR, Increased storm wave energy and frequency, Extreme high tide events, Changed ocean circulation patterns, Drought and changes in rainfall patterns and intensity, Rising global temperatures in oceans and air

B.2 Anthropogenic co-drivers

B.2.1 Physical

Dense urban development due to human population growth (Sierra-Correa and Cantera Kintz, 2015; Feller et al. 2017; Romañach et al. 2018)

Habitat transformation through coastal reclamation (Triyanti et al. 2017), mangrove in-filling (Gilman et al. 2008), conversion for agriculture, such as rice farming (Romañach et al. 2018) and aquaculture (Gilman et al. 2008; Feller et al. 2017; Nguyen et al. 2017; Romañach et al. 2018)

Over-exploitation of resources (Sierra-Correa and Cantera Kintz, 2015) such as timber (Nanlohy et al. 2015; Romañach et al. 2018) causing deforestation (Alongi, 2015), groundwater extraction (Triyanti et al. 2017), salt harvesting (Romañach et al. 2018)

Pollution (Gilman et al. 2008; Romañach et al. 2018)

B.2.2 Ecological

Invasive species (Romañach et al. 2018)

B.2.3 Governance

Poorly planned development (Sierra-Correa and Cantera Kintz, 2015)

Weak governance controls (Sierra-Correa and Cantera Kintz, 2015)

B.3 Impact

B.3.1 Physical

Coastal physical processes disrupted

Coastal flooding (Alongi, 2015; Sierra-Correa and Cantera Kintz, 2015; Triyanti et al. 2017) causing increased erosion (Gilman et al. 2008)

Saline intrusion (Ward et al. 2016)

Loss of mangroves with releases of greenhouse gases (Gilman et al. 2008), decreased accretion rates of inorganic sediments (Gilman et al. 2008), peat collapse and soil compression (Gilman et al. 2008) and reduced estuarine and coastal water quality (Gilman et al. 2008)

Increased sulphide soil toxicity (Gilman et al. 2008)

B.3.2 Ecological

Ecosystem degradation and loss

Mangrove migration constrained by coastal squeeze (Feller et al. 2017)

Loss of mangroves (Nitto et al. 2014; Nanlohy et al. 2015; Sierra-Correa and Cantera Kintz, 2015; Feller et al. 2017)

Decreased habitat quality (Sierra-Correa and Cantera Kintz, 2015) including nursery habitats (Gilman et al. 2008), with changes in community composition (Gilman et al. 2008) including local extinctions (Gilman et al. 2008) due to salinity (Ward et al. 2016)

Biodiversity and genetic diversity loss

Biodiversity (Gilman et al. 2008; Alongi, 2015) and mangrove species genetic structure (Gilman et al. 2008) impacts

Habitat range shifts

Mangrove migration across a latitudinal gradient (Gilman et al. 2008; Alongi, 2015; Miller et al. 2017; Romañach et al. 2018) and landwards (Gilman et al. 2008; Nitto et al. 2014; Alongi, 2015; Nanlohy et al. 2015; Romañach et al. 2018)

Sub-lethal species impacts

Changes in reproduction and dispersion (Miller et al. 2017; Romañach et al. 2018), seedling survival (Gilman et al. 2008) and changes to propagule dispersal

Higher temperatures are likely to increase growth, reproduction, phenology (Gilman et al. 2008; Miller et al. 2017), photosynthesis and respiration rates (Alongi, 2015) with potential species richness and inter-specific interactions increasing (Miller et al. 2017)

Increased salinity causing decreasing net primary productivity and growth (Nanlohy et al. 2015)

Mangrove species specific differences in resilience to climate change due to morphology and anatomy (Alongi, 2015) including leaf anatomy, vascular vessel densities, diameter, grouping and length and fibre wall thickness (Alongi, 2015)

B.3.3 Social

Loss of ecosystem services

Impacts on coastal protection (Ataur Rahman and Rahman, 2015; Ahmed and Glaser, 2016)

Local decline in agriculture and fisheries

Agricultural (Nanlohy et al. 2015) and fisheries production impacts through declines in catch and size of catch (Nanlohy et al. 2015)

Increased community vulnerability

Increased community vulnerability (Sierra-Correa and Cantera Kintz, 2015)

B.4 Adaptation responses

B.4.1 Physical

Supporting physical processes

Ensure sediment supply to mangroves to support elevation (Sierra-Correa and Cantera Kintz, 2015)

Managing catchment activities that affect mangrove sediment elevation (Gilman et al. 2008)

Support mangrove sediment deposition and erosion processes to adjust to sea level change (Ward et al. 2016; Romañach et al. 2018)

Hard engineering responses

Hard engineering infrastructure to halt erosion (Gilman et al. 2008) including backlines to reduce flooding from sea (Sierra-Correa and Cantera Kintz, 2015)

Improving drainage systems (Sierra-Correa and Cantera Kintz, 2015)

Managed retreat and coastal realignment

Managed retreat allowing mangroves to migrate and retain their natural functional processes (Gilman et al. 2008)

B.4.2 Ecological

Ecosystem restoration and protection

Eliminate conversion and support reclamation of wetlands (Romañach et al. 2018)

Protection and maintenance of mangroves (Sierra-Correa and Cantera Kintz, 2015; Romañach et al. 2018) and mangrove restoration (Feller et al. 2017)

Ecosystem management interventions supporting positive surface elevation gains compared to SLR and salinity (Ward et al. 2016; Romañach et al. 2018)

B.4.3 Social

Sustainable resource use

Sustainable resource use through harvesting only mature trees (Nguyen et al. 2017)

Community participatory programmes

Improved community participation in mangrove management programmes (Nanlohy et al. 2015)

Mangrove planting programmes (Triyanti et al. 2017) using contracts with local community members (Nguyen et al. 2017)

B.4.4 Governance

Adopting/mainstreaming sustainability policies

Increased political will to conserve (Gilman et al. 2008)

Improving implementation and coordination of policies

Interactive governance (Triyanti et al. 2017)

Better synergism between monitoring and implementation programmes (Gilman et al. 2008)

B.4.5 Finance

Improving financial resources availability

Improve mangrove bonding social capital (Triyanti et al. 2017)

B.4.6 Knowledge

Better monitoring and modelling

Regional monitoring networks (Gilman et al. 2008), improving data collection. (Romañach et al. 2018) and use of technologies and innovation (Nanlohy et al. 2015)

Improving planning processes

Improving site and land use planning (Gilman et al. 2008) using buffer areas (Sierra-Correa and Cantera Kintz, 2015) for managed retreat

Improving decision support frameworks

Establishing baselines (Gilman et al. 2008)

Improving scientific communication

Improving communication between scientists (Romañach et al. 2018) in multi-disciplinary teams (Nanlohy et al. 2015)

Stakeholder identification, outreach and education

Outreach and education to empower decisions makers and communities to make informed decisions (Gilman et al. 2008; Nanlohy et al. 2015; Romañach et al. 2018)

Multiple adaptation responses used

Addressing climate change impacts by reducing anthropogenic co-drivers (Gilman et al. 2008; Sierra-Correa and Cantera Kintz, 2015; Romañach et al. 2018)

B.5 Benefits

B.5.1 Physical

Physical processes supported

Mangrove restoration may delay or buffer climate impacts (Romañach et al. 2018) by providing shoreline protection (Gilman et al. 2008; Alongi, 2015; Sierra-Correa and Cantera Kintz, 2015; Doughty et al. 2017; Nguyen et al. 2017; Sheng and Zou, 2017; Romañach et al. 2018), erosion protection (Triyanti et al. 2017) through shoreline stabilisation (Nanlohy et al. 2015), raising sediments heights (Hayden and Granek, 2015) and inundation protection (Triyanti et al. 2017; Romañach et al. 2018) from storm surge and tsunamis through wave attenuation (Romañach et al. 2018)

Improved water quality (Gilman et al. 2008)

Vertical sediment accumulation may allow mangroves to outpace SLR (in areas of higher elevation and relatively low tidal range) (Romañach et al. 2018)

Sediment trapping (Kamal et al. 2017) including sequestration of nutrients and contaminants (Alongi, 2015) and carbon storage (Alongi, 2015; Nanlohy et al. 2015; Kelleway et al. 2016; Yando et al. 2016; Romañach et al. 2018)

B.5.2 Ecological

Ecosystem/ecological resilience supported

Increased structural heterogeneity (Romañach et al. 2018)

Improved biodiversity and ecological functioning (Triyanti et al. 2017) of nursery grounds (Sierra-Correa and Cantera Kintz, 2015; Miller et al. 2017; Romañach et al. 2018) and breeding sites (Alongi, 2015) supporting improved fisheries (Benzeev et al. 2017; Goecke and Carstenn, 2017)

Increased mangrove resilience and recovery (Romañach et al. 2018)

Improved organismal fitness

Increased primary production (Triyanti et al. 2017)

B.5.3 Social

Access to sustainable ecosystem services

Improved fisheries (Benzeev et al. 2017; Goecke and Carstenn, 2017)

Sustained ecosystem services, including timber and fuelwood (Alongi, 2015; Nanlohy et al. 2015; Palacios and Cantera, 2017)

Improved cultural services (Triyanti et al. 2017; Romañach et al. 2018) including recreation and aesthetic experience (Triyanti et al. 2017)

Human systems supported

Supporting aquaculture (Huxham et al. 2015; Ahmed and Glaser, 2016)

Improved employment and livelihoods

Supporting coastal livelihoods (Triyanti et al. 2017) providing a source of income for communities (Nanlohy et al. 2015; Nguyen et al. 2017)

Increased adaptive capacity

Reduced vulnerability in communities (Gilman et al. 2008; Sierra-Correa and Cantera Kintz, 2015)

B.6 Co-benefits

B.6.1 Social

Supporting coastal livelihoods (Triyanti et al. 2017) providing a source of income for communities (Nanlohy et al. 2015; Nguyen et al. 2017)

B.7 Constraints and limitations

B.7.1 Physical

Insufficient mitigation of greenhouse gases will make adaptation more difficult. (Sierra-Correa and Cantera Kintz, 2015)

Mangroves occupy a range of tidal settings making it difficult to offer simple solutions (Alongi, 2015)

B.7.2 Social

People are increasingly distanced from nature and may be less concerned about nature conservation (Romañach et al. 2018)

B.7.3 Governance

Ineffective mangrove protection due to poor implementation of maintenance programmes (Nguyen et al. 2017)

Poor law enforcement and technical guidance (Nguyen et al. 2017)

Administrative and settlement boundaries do not always align with natural boundaries (Triyanti et al. 2017)

Human adaptation response has not been keeping pace with SLR (Gilman et al. 2008)

Inadequate governance and institutional structures, lack of finances, lack of information access, social and cultural norms, conflicting and competing values (Miller et al. 2017)

B.7.4 Economic

Replanting and restoration communities may be more motivated by financial reward than ecological interest (Romañach et al. 2018)

B.7.5 Knowledge

Perception of exclusion from resource harvesting due to poor understanding of mangrove protection services (Romañach et al. 2018)

Translating good science and strong community engagement into effective policy can be difficult due to disconnect between scientific, community and decision making processes (Waite et al. 2015; Romañach et al. 2018)

Lack of data, funding and institutional trust (Torres and Hanley, 2017; Romañach et al. 2018)

Knowledge gaps in mangrove ecological and human management response to climate change (Ward et al. 2016)

C. Ecosystem: Salt Marshes and Wetlands

C.1 Climate drivers

SLR

Ocean warming and changes in wave regimes

Changes in precipitation and storm patterns

Increased frequency and intensity of extreme events

C.2 Anthropogenic co-drivers

C.2.1 Physical

Increase in human populations, development and infrastructure (Schuerch et al. 2018) and anthropogenic threats (Ondiviela et al. 2014)

Eutrophication (Watson et al. 2017; Wigand et al. 2017)

Mechanical damage of wetland meadows (e.g., dredging) (Ondiviela et al. 2014)

C.3 Impact

C.3.1 Physical

Coastal physical processes disrupted

Increased coastal flooding (Wigand et al. 2017), changing sediment dynamics (Schaeffer-Novelli et al. 2016) with decreased sediment inputs (Watson et al. 2017), shoreline erosion (Ondiviela et al. 2014; Wigand et al. 2017) and salt water intrusion (Ondiviela et al. 2014; Miloshis and Fairfield, 2015; Schaeffer-Novelli et al. 2016)

Deterioration of water quality (nutrient loading, pollution and suspended material) (Ondiviela et al. 2014)

C.3.2 Ecological

Ecosystem degradation and loss

Loss of wetlands (Schuerch et al. 2018), wetland degradation (Miloshis and Fairfield, 2015) and destruction of vegetation cover (Schaeffer-Novelli et al. 2016; Watson et al. 2017) including loss of root biomass (Schaeffer-Novelli et al. 2016)

Biodiversity and genetic diversity loss

Loss of biodiversity (Schuerch et al. 2018) including IUCN extinction list of four species (Ondiviela et al. 2014)

Increased rates of edge erosion (Watson et al. 2017)

Sub-lethal species impacts

Seasonal and geographic changes in abundance and distribution (Ondiviela et al. 2014; Schaeffer-Novelli et al. 2016), declines in macrophyte productivity (Watson et al. 2017), impacts on sea grass metabolism (Schaeffer-Novelli et al. 2016) and decreased crab herbivory (Watson et al. 2017) resulting in increased marsh vulnerability (Wigand et al. 2017)

Increased dissolved CO_2 concentrations promote growth (Ondiviela et al. 2014)

Increase in water velocity may contribute to plant productivity in some areas (Ondiviela et al. 2014)

Invasive alien species

Invasive species (Ondiviela et al. 2014)

C.3.3 Social

Decreased access to ecosystem services

Loss of ecosystem services (Schuerch et al. 2018), including shoreline protection (Ondiviela et al. 2014)

C.4 Adaptation responses

C.4.1 Physical

Supporting physical processes

Shoreline protection by raising the elevation of the marsh (Ondiviela et al. 2014) and increasing marsh drainage (Watson et al. 2017)

Dam removal (Wigand et al. 2017) allowing hydrologic remediation with restoration of sediment supplies (Watson et al. 2017)

Sediment diversion to reduce land conversions on flood plains and deltas (Miloshis and Fairfield, 2015)

Integrated hard and soft engineering

Artificial measures (construction of structures, beach nourishment or coastal realignment, hard structures), vegetation fields (mangroves or willow forests) and restoration of bay areas (Ondiviela et al. 2014)

Managed retreat and coastal realignment

Facilitating marsh upland migration (Schaeffer-Novelli et al. 2016; Wigand et al. 2017)

C.4.2 Ecological

Ecosystem restoration and protection

Bioengineering

Eco-engineering using organisms (Ondiviela et al. 2014; Miloshis and Fairfield, 2015)

Reductions in edge losses using biomaterials (Watson et al. 2017)

C.4.3 Economic

Improving financial resources availability

Interventions such as sediment subsidies (Watson et al. 2017)

C.4.4 Knowledge

Improving planning processes

Spatial planning for wetland protection and management (Schuerch et al. 2018)

C.5 Benefits

C.5.1 Physical

Physical processes supported

Vertical sediment accretion, which may outpace SLR (Schuerch et al. 2018)

Coastal flood protection (Miloshis and Fairfield, 2015; Wigand et al. 2017) through wave attenuation (Ondiviela et al. 2014; Schaeffer-Novelli et al. 2016)

Water quality improvement (Schaeffer-Novelli et al. 2016; Wigand et al. 2017; Schuerch et al. 2018) including improved water transparency, increased light availability and quality through trapping and sorting solid particles and dissolved nutrients (Ondiviela et al. 2014)

Sequestering carbon dioxide through burial or exporting offshore (Schaeffer-Novelli et al. 2016)

C.5.2 Ecological

Ecosystem/ecological resilience supported

Ecosystem engineers facilitating trophic transfer to adjacent habitats (Ondiviela et al. 2014)

Habitat sustainability providing support for species of concern (Wigand et al. 2017)

Improved primary productivity (Ondiviela et al. 2014) and a source of carbon to the detrital pool (Ondiviela et al. 2014)

Increased biodiversity

Increased biodiversity (Ondiviela et al. 2014; Miloshis and Fairfield, 2015)

Habitat range shifts accommodated

Facilitated marsh-upland migration (Watson et al. 2017)

C.5.3 Social

Access to sustainable ecosystem services

Support for fisheries (Ondiviela et al. 2014; Miloshis and Fairfield, 2015; Schaeffer-Novelli et al. 2016; Schuerch et al. 2018)

Improved ecosystem services like carbon sequestration (Schuerch et al. 2018) and climate regulation (Miloshis and Fairfield, 2015), nutrient sequestration (Wigand et al. 2017) and cycling (Miloshis and Fairfield, 2015), sediment and biomatter accumulation and the provision of a vegetative buffer to reduce flow velocities during tidal and storm surges (Miloshis and Fairfield, 2015)

C.6 Constraints and limitations

C.6.1 Physical

Constraints on the inland migration of coastal wetlands due to adverse human-modified soil conditions, unsuitable geomorphological characteristics or elevation constraints (Schuerch et al. 2018)

Areas with high sediment input from riverine sources are likely to accommodate a 1m rise in sea level (Miloshis and Fairfield, 2015)

C.6.2 Ecological

Genetic diversity could help the plants adapt to higher temperatures through individual thermal tolerances if changes occur at a slow enough rate (Ondiviela et al. 2014)

C.6.3 Governance

Balancing adaptation expenses against pervasive marsh loss (Watson et al. 2017)

C.6.4 Knowledge

Inherent uncertainties in models (Schaeffer-Novelli et al. 2016)

D. Ecosystem: Estuaries

D.1 Climate drivers

SLR

Increased ocean temperature

Changes in wave action and storm surge

Increased storm frequency and severity

Changes in rainfall and evapotranspiration patterns

Ocean acidification

D.2 Anthropogenic co-drivers

D.2.1 Physical

Increasing coastal populations (Runting et al. 2017) combined with inappropriate development and infrastructure (Barbier, 2015b;

Peirson et al. 2015; Wigand et al. 2017), resulting in habitat loss and alteration (Peirson et al. 2015)

Dam emplacement (Wigand et al. 2017), freshwater diversions (Peirson et al. 2015), catchment agriculture (Robins et al. 2016; Sheaves et al. 2016), deforestation (Wigand et al. 2017) and dredging (Peirson et al. 2015)

Poorly planned and managed aquaculture and shellfish fisheries (Robins et al. 2016), fisheries over-exploitation (Peirson et al. 2015)

Organic carbon loading (Peirson et al. 2015), nutrient enrichment (Peirson et al. 2015) and eutrophication (Thorne et al. 2017; Wigand et al. 2017)

D.2.2 Ecological

Alien invasive species (Peirson et al. 2015)

D.3 Impact

D.3.1 Physical

Coastal physical processes disrupted

Increased coastal flood risk (Monbaliu et al. 2014; Robins et al. 2016; Wigand et al. 2017) with extreme water levels and changes in flood current velocity (Seiffert and Hesser, 2014), increased tidal range (Monbaliu et al. 2014; Peirson et al. 2015) and tidal dynamics (Seiffert and Hesser, 2014)

Shoreline erosion (Robins et al. 2016; Wigand et al. 2017) increased due to wetland loss

Decreased freshwater flow (Peirson et al. 2015), salinity intrusion (Robins et al. 2016; Seiffert, 2014), nutrient enrichment and eutrophication (Robins et al. 2016) resulting in deteriorating water quality (Robins et al. 2016)

Increased hypoxia (Robins et al. 2016)

Coastal infrastructure damage

Damage to coastal infrastructure (Thorne et al. 2017) and property with increased vulnerability (Barbier, 2015b; Robins et al. 2016)

D.3.2 Ecological

Ecosystem degradation and loss

Wetlands lost through inundation (Runting et al. 2017; Wigand et al. 2017)

Habitat modification (Robins et al. 2016) including vegetation type changes and soil moisture reductions (Robins et al. 2016) resulting changes in coastal wetland distribution (Runting et al. 2017) and marsh vulnerability (Wigand et al. 2017)

Habitat range shifts

Habitat modification (Robins et al. 2016) including vegetation type changes and soil moisture reductions (Robins et al. 2016) resulting changes in coastal wetland distribution (Runting et al. 2017) and marsh vulnerability (Wigand et al. 2017) causing changes in breeding grounds (Peirson et al. 2015) and species composition (Peirson et al. 2015; Thorne et al. 2017)

Sub-lethal species impacts

Changes in breeding grounds (Peirson et al. 2015) and species composition (Peirson et al. 2015; Thorne et al. 2017)

Invasive alien species

Increased invasive species (Robins et al. 2016)

D.3.3 Social

Public health risks

Harmful algal blooms (Robins et al. 2016)

D.4 Adaptation responses

D.4.1 Physical

Supporting physical processes

Adaptive sediment management (Seiffert and Hesser, 2014)

Catchment dam removal (Wigand et al. 2017) supported by appropriate built infrastructure (Barbier, 2015b)

Hard engineering responses

Hydraulic engineering structures, including barriers narrowing the estuaries mouth to dampen storm surge (Seiffert and Hesser, 2014)

Catchment dam removal (Wigand et al. 2017) supported by appropriate built infrastructure (Barbier, 2015b)

Managed retreat and coastal realignment

Facilitate landward migration (Runting et al. 2017; Wigand et al. 2017)

D.4.2 Ecological

Ecosystem restoration and protection

Restoration (Barbier, 2015b; Wigand et al. 2017)

Expanding the coastal reserve network to accommodate wetlands response (Runting et al. 2017)

D.4.3 Governance

Adopting/mainstreaming sustainability policies

Local planning authorities pre-emptively limit development in dry land areas that are likely to transition to wetlands under climate change (Runting et al. 2017)

Development controls

Local planning authorities pre-emptively limit development in dry land areas that are likely to transition to wetlands under climate change (Runting et al. 2017)

D.4.4 Knowledge

Better monitoring and modelling

Improve estuarine modelling (Monbaliu et al. 2014) and long-term monitoring effort (Robins et al. 2016)

Improve monitoring of estuary hydrology and dynamics (Wigand et al. 2017)

Stakeholder identification, outreach and education

Improve stakeholder identification and engagement to improve systems knowledge (Peirson et al. 2015)

D.5 Benefits

D.5.1 Physical

Physical processes supported

Protection (Wigand et al. 2017) against storms and coastal floods (Robins et al. 2016), mainly through wave attenuation (Barbier, 2015b; Runting et al. 2017)

Nutrient retention (Runting et al. 2017; Wigand et al. 2017) and cycling of organic (Robins et al. 2016; Runting et al. 2017) and suspended particulate matter (Robins et al. 2016)

Water quality maintenance (Peirson et al. 2015)

D.5.2 Ecological

Ecosystem/ecological resilience supported

Water quality improvement (Peirson et al. 2015) supporting habitat for wildlife (Wigand et al. 2017), including improving nursery areas (Sheaves et al. 2016; Runting et al. 2017) for commercial fisheries (Peirson et al. 2015) or breeding areas for terrestrial animals like birds (Robins et al. 2016)

Increased biodiversity

Support optimal biodiversity (Sheaves et al. 2016)

D.5.3 Social

Access to sustainable ecosystem services

Improved water supply for agriculture (Peirson et al. 2015) and aquaculture (Peirson et al. 2015)

Human systems supported

Improved water supply for tourism, heritage and recreational water uses (Peirson et al. 2015; Robins et al. 2016)

Improved health

Healthy human living environments (Sheaves et al. 2016)

D.5.4 Knowledge

Improved education and outreach

Social learning during vulnerability assessments can play a key role in climate change adaptation planning through stakeholder engagement, learning and sharing of best practices (Thorne et al. 2017)

D.6 Constraints and limitations

D.6.1 Physical

Landward estuarine migration constraints (Robins et al. 2016)

Inherent complexity of coastal systems and climate change make it difficult to predict specific shoreline changes (Wigand et al. 2017) and requires an adaptive management strategy (Wigand et al. 2017)

D.6.2 Ecological

Physical and ecological constraints on restoration actions (Wigand et al. 2017)

Biodiversity and community composition changes and the emergence of novel ecosystems will make protecting some species and ecosystems difficult (Wigand et al. 2017)

D.6.3 Governance

Opportunity costs associated with retreat are borne immediately whereas the benefits take much longer to materialise (Runting et al. 2017)

Time, money and staff resources (Thorne et al. 2017)

Complex governance landscape (Sheaves et al. 2016)

Barriers include lack of funding, policy and institutional constraints and precise information on climate change projections (Wigand et al. 2017)

D.6.4 Knowledge

Scale-relevant information for local decision making (Thorne et al. 2017)

Continuously evolving and large body of scientific publications about climate change (Thorne et al. 2017)

Rural areas require local adaptation strategies that rely on soft engineering and improved community awareness (Robins et al. 2016)

D.6.5 Costs

Additional resources are required to expand the wetlands reserve network to allow for wetland migration depending on future climate scenario (Runting et al. 2017). Despite these higher costs, payments for ecosystem services have the potential to substantially reduce the net cost of expanding. (Runting et al. 2017)

E. Ecosystem: Multiple Ecosystems

E.1 Climate drivers

SLR

Ocean warming

Storm frequency and intensity

E.2 Anthropogenic co-drivers

E.2.1 Physical

Habitat loss (Williams et al. 2016) or fragmentation (Hernández-González et al.) due to urbanisation (Hernández-González et al.; Williams et al. 2016) and development, including conversion of estuarine land to agriculture, compounded by poor agricultural practices (Hernández-González et al.) or aquaculture (Hernández-González et al.)

Agricultural, industrial and tourist activities impact aquaculture species composition (Williams et al. 2016)

Unsustainable exploitation of resources (Jiao et al. 2015; Williams et al. 2016) including mangrove harvest (Hernández-González et al.), overfishing and destructive fishing (Hernández-González et al.)

Intensive irrigation and dams (Hernández-González et al.)

Pollution (Jiao et al. 2015) including eutrophication (Williams et al. 2016), effluent from aquaculture (Williams et al. 2016)

E.3 Impact

E.3.1 Physical

Coastal physical processes disrupted

Coastal erosion (Hernández-González et al.) causing increased flooding of low-lying lands and salinisation of groundwater (Hernández-González et al.)

Coastal infrastructure damage

Impacts on shoreline developments (Williams et al. 2016) compounded by coastal squeeze (Hernández-González et al.)

E.3.2 Ecological

Ecosystem degradation and loss

Degradation of marine and coastal ecosystems (Jiao et al. 2015), causing impaired ecosystem functioning (Williams et al. 2016), shifts in ecological communities (Williams et al. 2016) and loss of biodiversity (Williams et al. 2016)

E.3.3 Social

Increased food insecurity

Food security impacts (Williams et al. 2016)

E.4 Adaptation responses

E.4.1 Physical

Integrated hard and soft engineering

Ecosystem-based coastal defines structures, green: coastal defences selecting more tolerant species or strains and protecting key habitats under expanding aquaculture (Williams et al. 2016)

Incorporate proven management interventions (such as hybrid engineering structures) (Hernández-González et al. 2016)

Managed retreat and coastal realignment

Incorporate proven management interventions (such as managed realignment) (Hernández-González et al. 2016)

E.4.2 Ecological

Ecosystem restoration and protection

Marine EbA: maintaining the balance and health of ecosystems (Jiao et al. 2015)

Incorporate proven management interventions (such as habitat restoration) (Hernández-González et al. 2016)

E.4.3 Social

Sustainable resource use

Building resilience of socioeconomic and ecological systems through sustainable management of natural resources (Hernández-González et al. 2016)

Building socioecological resilience

Building resilience of socioeconomic and ecological systems through sustainable management of natural resources (Hernández-González et al. 2016)

E.4.4 Governance

Adopting/mainstreaming sustainability policies

Implement policies to support environmental integrity (Hernández-González et al. 2016)

Bring ecosystems into mainstream decision making processes (Hernández-González et al. 2016)

Incorporate proven management interventions (such as MPAs, habitat restoration, managed realignment and hybrid engineering structures) (Hernández-González et al. 2016)

Improving ICM/MPAs

Incorporate proven management interventions (such as MPAs) (Hernández-González et al. 2016)

Developing partnerships and building capacity

Build capacity for implementation (Hernández-González et al. 2016)

E.4.5 Economic

Economic diversification

Building resilience of socioeconomic and ecological systems through economic diversification (Hernández-González et al. 2016)

E.4.6 Knowledge

Better monitoring and modelling

Develop regional, fine scale databases to identify possible winners or losers species for use in green coastal defences (Williams et al. 2016)

Developing evidence of climate related declines in foundational species and their associated marine ecosystems (Williams et al. 2016)

Improving decision support frameworks

Consider ecosystems in vulnerability assessments of coastal communities (Hernández-González et al. 2016)

Improving participatory processes

Engage stakeholders (Hernández-González et al. 2016)

Integrating knowledge systems

Evidence for improving application of ecosystem-based adaptation (EbA) responses through integrating traditional infrastructure (Perkins et al. 2015; Sutton-Grier et al. 2015; Sánchez-Arcilla et al. 2016; van der Nat et al. 2016)

Multiple adaptation responses used

EbA and community-based adaptation (CbA) (Hernández-González et al. 2016)

E.5 Benefits

E.5.1 Physical

Physical processes supported

Protection from storms surge (Williams et al. 2016) and coastal erosion prevention (Williams et al. 2016) by reducing wave energy (Hernández-González et al. 2016)

Increasing sedimentation and movement of sediment (Hernández-González et al. 2016) and contaminant filtration (Williams et al. 2016)

E.5.2 Ecological

Ecosystem/ecological resilience supported

Improved nursery grounds (Williams et al. 2016)

E.5.3 Social

Increasing resilience in human systems

Aquaculture benefits providing food security (Williams et al. 2016)

E.6 Co-benefits

The co-benefits of ‘soft’ engineering options common for the ecosystems assessed include increasing ecological complexity, with multiple services provided, many economic benefits, and resilience to climate change (Perkins et al. 2015; Perry, 2015; Moosavi, 2017; Scarano, 2017)

The application of synergistic combinations of ecosystems can provide a range of co-benefits, and this approach is strengthened when combined with socioinstitutional approaches (Kochnower et al. 2015; MacDonald et al. 2017)

E.7 Constraints and limitations

E.7.1 Ecological

Multiple simultaneous stressors induce highly variable species responses impacting upon effectiveness of EbA response (Williams et al. 2016)

Coastal habitats such as salt marshes and mangroves may have an advantage over engineered coastal defences if they increase in elevation and grow with SLR

E.7.2 Knowledge

There is a need to advance coastal protection science by quantifying ecosystem services (Hernández-González et al. 2016)

Developing scenarios and tools to model complex combined risks to build decision-support systems for communities (Hernández-González et al. 2016)

Few syntheses of the context-specific application and cost-effectiveness of EbA approaches are to be found in the literature (Narayan et al. 2016)

Further research evaluating natural infrastructure is required (Roberts et al. 2017)

E.8 Costs

E.8.1 Physical

Green coastal defence structures are expensive to maintain (Williams et al. 2016)

E.8.2 Ecological

Coastal ecosystems can play an important and cost-effective role in reducing vulnerability (Hernández-González et al. 2016)

F. Ecosystem: Sandy Beaches and Dune Systems

F.1 Climate drivers

SLR

Increased storminess and storm surge

Extreme winds

Changes in rainfall

F.2 Anthropogenic co-drivers

F.2.1 Physical

Increasing human coastal populations (Poumadère et al. 2015; Ranasinghe, 2016; Sánchez-Arcilla et al. 2016) leading to coastal development (Onaka et al. 2015; Ranasinghe, 2016; Ciccarelli et al. 2017; MacDonald et al. 2017; Pranzini, 2018; Salgado and Martinez, 2017; Vikolainen et al. 2017; Gracia et al. 2018) with vegetation clearing (Ciccarelli et al. 2017; Magnan and Duvat, 2018) and loss of sediment (Salgado and Martinez, 2017)

Unsustainable resource exploitation (Nehren et al. 2017)

F.2.2 Social

Tourism (Onaka et al. 2015)

F.2.3 Governance

Mismanagement practices (Carro, 2018)

Lack of integrated coastal management (Nehren et al. 2017)

F.3 Impact

F.3.1 Physical

Coastal physical processes disrupted

Coastal squeeze (Villatoro et al. 2014) and erosion (Onaka et al. 2015; Poumadère et al. 2015; Ranasinghe, 2016; Sánchez-Arcilla et al. 2016; Goreau and Prong, 2017; Nehren et al. 2017; Pranzini, 2018; Salgado and Martinez, 2017; Vikolainen et al. 2017; Gracia et al. 2018) of sandy beaches, dunes and bluffs (MacDonald et al. 2017; Shumack and Hesse, 2018; Carro, 2018; Magnan and Duvat, 2018)

Flooding (Villatoro et al. 2014; Poumadère et al. 2015; Sutton-Grier et al. 2015; Sánchez-Arcilla et al. 2016; Goreau and Prong, 2017; Nehren et al. 2017; Salgado and Martinez, 2017; Vikolainen et al. 2017)

F.3.2 Ecological

Ecosystem degradation and loss

Fire and vegetation removal (Shumack and Hesse, 2018)

F.3.3 Social

Decreased access to ecosystem services

Reduced ecosystem services (Nehren et al. 2017)

F.4 Adaptation responses

F.4.1 Physical

Supporting physical processes

Recovery of natural buffer (100 m unbuilt strip of vegetation) (Magnan and Duvat, 2018)

Hard engineering responses

Hard defences, including submerged breakwaters and groins (Sutton-Grier et al. 2015; Pranzini, 2018)

Soft engineering responses and buffers

Soft sand engineering (sandscaping) (Sutton-Grier et al. 2015; Vikolainen et al. 2017)

Artificial dune/beach sand replenishment (Pranzini, 2018)

Vegetation planting (Magnan and Duvat, 2018)

Integrated hard and soft engineering

Hybrid hard and soft engineering solutions (Sutton-Grier et al. 2015; Martínez et al. 2017)

Sustainable drainage systems (Salgado and Martinez, 2017; Carro, 2018)

Managed retreat and coastal realignment

Shoreline natural readjustment and coastal managed realignment (MacDonald et al. 2017)

F.4.2 Ecological

Ecosystem restoration and protection

Recovery of natural buffer (100 m unbuilt strip of vegetation) (Magnan and Duvat, 2018)

Shoreline protection (Salgado and Martinez, 2017) through the creation and restoration of coastal ecosystems (e.g., dunes, sandy beaches and bluffs (Carro, 2018) and re-vegetation for dune regeneration (Salgado and Martinez, 2017; Carro, 2018)

Conserving, sustainably managing, and restoring (Nehren et al. 2017)

F.4.3 Social

Sustainable resource use

Reduction of human use pressures (Salgado and Martinez, 2017; Carro, 2018)

Sustainable coastal management where old railways were transformed into walking and cycling routes and the railway embankment became a promenade (Pranzini, 2018)

F.4.4 Governance

Adopting/mainstreaming sustainability policies

Integrate management of ecology, recreation and land use with other aspects of coastal management (Vikolainen et al. 2017; Gracia et al. 2018)

Developing partnerships and building capacity

Capacity development in coastal protection and rehabilitation in Mauritius (Onaka et al. 2015)

F.4.5 Knowledge

Improving decision support frameworks

Conceptual assessment design of the ecosystem (Gracia et al. 2018)

Integration of indicators and tools (Gracia et al. 2018)

Development of decision support systems (Gracia et al. 2018)

Multiple adaptation responses used

Physical

Reduction of human use pressures (Salgado and Martinez, 2017; Carro, 2018)

F.5 Benefits

F.5.1 Physical

Physical processes supported

Reduced coastal erosion (Sánchez-Arcilla et al. 2016; Goreau and Prong, 2017; Vikolainen et al. 2017; Carro, 2018; Gracia et al. 2018) through maintaining dunes (Pranzini, 2018) as natural buffers to wave energy (Nehren et al. 2017), reducing flood risk (Onaka et al. 2015; MacDonald et al. 2017; Nehren et al. 2017) and increasing resilience to climate change impacts (Sutton-Grier et al. 2015; Gattuso et al. 2018)

Carbon sequestration (Gracia et al. 2018)

F.5.2 Ecological

Ecosystem/ecological resilience supported

Stimulate natural dune growth (Vikolainen et al. 2017)

Secure sustainable natural resources (Vikolainen et al. 2017; Gracia et al. 2018; Magnan and Duvat, 2018) like dunes (Onaka et al. 2015) to improve ecosystem capacity to cope with climate change impacts (Gracia et al. 2018)

Increased biodiversity

Stimulating biodiversity conservation (Gracia et al. 2018)

Natural infrastructure provides additional goods and services to humans, as opposed to built infrastructure which only provides coastal flood protection (Sutton-Grier et al. 2015)

Strengthened socioecological system

Strengthening resilience of both natural and human systems to coastal erosion effect (Gracia et al. 2018)

F.5.3 Social

Access to sustainable ecosystem services

Secure ecosystem services (Nehren et al. 2017)

Improved community participation

Encouraging community participation (Gracia et al. 2018)

Improved socioeconomic services

Socioeconomic services maintained (MacDonald et al. 2017) with increase in nature-based recreation (MacDonald et al. 2017)

F.5.4 Governance

Political and institutional capacity developed

Capacity building of municipal staff and stakeholders (Carro, 2018)

Improved adaptive management

Incorporation of EbA by subnational-level coastal governments (Carro, 2018)

Improved implementation and policies

Policy gaps addressed (Pranzini, 2018)

F.5.5 Knowledge

Improved co-production of knowledge

Knowledge development and innovation (Pranzini, 2018; Vikolainen et al. 2017)

Improved education and outreach

Knowledge exchange with national decision makers and scientists (Carro, 2018)

Opportunity for ecological and conservation scientists to interact with social, economic and political scientists on EbA research (Scarano, 2017)

F.6 Co-benefits

F.6.1 Ecological

Stimulating biodiversity conservation (Gracia et al. 2018)

Natural infrastructure provides additional goods and services to humans, as opposed to built infrastructure which only provides coastal flood protection (Sutton-Grier et al. 2015)

F.7 Constraints and limitations

F.7.1 Physical

Space requirements (Sutton-Grier et al. 2015; Sánchez-Arcilla et al. 2016; Salgado and Martinez, 2017)

Natural vegetation cannot always protect shorelines in every location and/or situation (Salgado and Martinez, 2017)

Level of flood and erosion protection is limited by the condition of the dune system (Nehren et al. 2017)

Natural and hybrid infrastructure can take a lot longer to build than hard infrastructure (Sutton-Grier et al. 2015)

F.7.2 Ecological

Slow recovery periods of natural systems (Gracia et al. 2018) and for ecological succession (Salgado and Martinez, 2017)

F.7.3 Governance

Policy (Sánchez-Arcilla et al. 2016) and regulations can constrain this kind of restoration (Vikolainen et al. 2017)

Public and policy need to redefine dune protection in the context of sustainable development (Nehren et al. 2017)

Lack of expertise to implement hybrid solutions (Sutton-Grier et al. 2015)

F.7.4 Economic

Economic constraints include cost of implementation and high cost of coastal land (Gracia et al. 2018)

Cheaper than man-made structures. (Nehren et al. 2017; Salgado and Martinez, 2017; Vikolainen et al. 2017; Gracia et al. 2018)

F.7.5 Knowledge

Local conditions-compliant design requirement (Vikolainen et al. 2017)

Knowledge of which plant species to use (Salgado and Martinez, 2017)

EbA research takes place within the socioecological systems framework, which is often carried out in isolation from sociotechnical systems research. These should be integrated (Scarano, 2017)

Lack of data for cost-benefit analysis (Sutton-Grier et al. 2015)

F.8 Costs

Net annual provision of services is 262,935 GBP (1460.75 GBP per ha) at Hesketh Outmarsh West and 93,216 GBP (574.70 GBP per ha) at Inch of Ferryton (MacDonald et al. 2017)

Natural resilience larger for more energetic coasts, lower for littorals with milder drivers (Poumadère et al. 2015)

SM5.6 Supplementary Information Supporting Table 5.8

Summary of reported Adaptation responses (A), the Impacts (I) they aimed to address, and the expected Benefits (B) in human systems within Physical, Ecological, Social, Governance, Economic and Knowledge categories. The Summary is presented in Table 5.8 and the papers used to support that assessment is found below.

A. Human System: Coastal Communities

A.1 Climate drivers

SLR

Coastal Flooding

Saline intrusion

Drought

Extreme rainfall events and rainfall variability

Ocean warming

Increased frequency of climate change disasters

Increased monsoon intensity

A.2 Anthropogenic co-drivers

A.2.1 Physical

Population growth (Marfai et al. 2015; Nursey-Bray et al. 2015; Wise et al. 2016) and rapid coastal urbanisation (Abedin et al. 2014; Lieske et al. 2014; Ataur Rahman and Rahman, 2015; Karlsson and Hovelsrud, 2015; Hobday et al. 2016; Betzold and Mohamed, 2017; Hagedoorn et al. 2019), including increases in daytime populations (Esteban et al. 2017), industrialisation (Ataur Rahman and Rahman, 2015)

Landscape land use change, including hardened impermeable surfaces (with poor drainage and low infiltration) (Broto et al. 2015) and reclaimed agricultural land (Jones and Clark, 2014)

Settlement location in low-lying areas (Linkon, 2017), for example, the majority of people in small island developing states (SIDS) live below the 4 m contour, which is 2 m above the present day high tide mark (Hagedoorn et al. 2019)

Poorly planned (Ataur Rahman and Rahman, 2015) and inappropriately located (Abedin et al. 2014) construction and poorly maintained infrastructure (Abedin et al. 2014) including land reclamation (Betzold and Mohamed, 2017), land use change (Nagy et al. 2014; Marfai et al. 2015), embankments, polderisation and unplanned afforestation (Ataur Rahman and Rahman, 2015) and coastal squeeze (Betzold and Mohamed, 2017)

Pollution (DasGupta and Shaw, 2015; Marfai et al. 2015; Bennett et al. 2016; Hobday et al. 2016; Betzold and Mohamed, 2017; Hagedoorn et al. 2019), including solid waste (Broto et al. 2015; Marfai et al. 2015; Bennett et al. 2016; Betzold and Mohamed, 2017) and contamination of ground and surface water (Ataur Rahman and Rahman, 2015), for example, arsenic contamination (Abedin et al. 2014)

Increased waste (Dhar and Khirfan, 2016; Betzold and Mohamed, 2017) and pollution (Ataur Rahman and Rahman, 2015; Betzold and Mohamed, 2017)

Reduction of freshwater flow due to abstraction (Ataur Rahman and Rahman, 2015); Groundwater extraction (leading to land subsidence) (Marfai et al. 2015)

Fire damage (Bennett et al. 2016)

Informal settlements (located in areas with high flood risk; unregulated; lack infrastructural services; poor sanitation and drainage) (Broto et al. 2015; Marfai et al. 2015)

Geographic remoteness of islands (DasGupta and Shaw, 2015; Karlsson and Hovelsrud, 2015)

Impacts on sea ice and Artic ecology (Ford et al. 2016)

A.2.2 Ecological

Unsustainable exploitation (Cinner et al. 2018) of mangroves (Ataur Rahman and Rahman, 2015) and dependence on natural resources (Cinner et al. 2018)

Habitat transformation (Hobday et al. 2016; Cinner et al. 2018) including forests and wetlands for rice agriculture (Ataur Rahman and Rahman, 2015; Marfai et al. 2015), mangrove forests (DasGupta and Shaw, 2015; Leon et al. 2015), reefs, sea grass and mangroves (Dhar and Khirfan, 2016), traditionally managed floodplains and coastal ecosystems (Ataur Rahman and Rahman, 2015) causing biodiversity loss (Nursey-Bray et al. 2015; Hagedoorn et al. 2019)

Low sand production (due to damaged ecosystems) impacting beach erosion (Dhar and Khirfan, 2016)

Illegal farming and deforestation in the Morass, which is slowly drying out (losing its basic functions, including flood alleviation, filtering nutrients and chemicals) (Dhar and Khirfan, 2016) causing increasing ecosystem vulnerability (Dhar and Khirfan, 2016)

Removal of coastal vegetation (Barbier, 2015a)

A.2.3 Social

Socioeconomic conditions (Smith and Rhiney, 2016; Jamero et al. 2018), including poverty (Jurjonas and Seekamp, 2018) food insecurity; housing shortage and poverty (Jamero et al. 2018), aging demographics (Jurjonas and Seekamp, 2018) and out-migration (Nursey-Bray et al. 2015; Jurjonas and Seekamp, 2018), for example, in Inuit communities (Ford et al. 2016)

Growing exposure of marginalised communities with limited power and agency (Wise et al. 2016)

Increased vulnerability on coastal floodplains from growing populations and industrialisation (Ataur Rahman and Rahman, 2015), high levels of dependency on agriculture and fishing (Nagy et al. 2014; DasGupta and Shaw, 2015; Hobday et al. 2016; Smith and Rhiney, 2016) and over-fishing (Ataur Rahman and Rahman, 2015; Hobday et al. 2016)

Excessive use of resources (Dhar and Khirfan, 2016), including groundwater for irrigation (prime reason for arsenic contamination) (Abedin et al. 2014) and shrimp farming (Abedin et al. 2014), compounded by community reliance on groundwater for drinking, resulting in groundwater depletion (Abedin et al. 2014)

Unregulated sand mining (Ataur Rahman and Rahman, 2015; Karlsson and Hovelsrud, 2015; Betzold and Mohamed, 2017), including marine sand (Betzold and Mohamed, 2017) and weak enforcement measures (Betzold and Mohamed, 2017) compounded by a heavy dependency upon sand mining as an important source of income in Comoros (Betzold and Mohamed, 2017)

Social, political, economic, demographic and environmental changes occurring at local and national scales compound these changes. Some coastal communities are struggling to adapt to these changes with an increase in their vulnerability (Bennett et al. 2016)

Low access to health sustaining resources (Ford et al. 2016)

Livelihoods in coastal communities have shifted away from subsistence fishing and agriculture towards dependence upon employment in the fisheries, agriculture, plantation and tourism sectors (Bennett et al. 2016)

Lack of loss of traditional practices and knowledge (Ataur Rahman and Rahman, 2015), for example in disaster and risk management (Audefroy and Sánchez, 2017)

Loss of ecosystem services means that these communities cannot respond to crises (DasGupta and Shaw, 2015)

Social fragmentation (Petzold and Ratter, 2015)

Modernisation of villages (become reliant on capitalist activities) (Sakakibara, 2017)

Inability of different socioeconomic groups to anticipate and respond to climate threats (Smith and Rhiney, 2016)

A.2.4 Governance

Misuse of resources (Ataur Rahman and Rahman, 2015)

Coastal Zone Policy does not include integrated coastal zone management (ICZM) (Ataur Rahman and Rahman, 2015) and is not informed by local knowledge (Ataur Rahman and Rahman, 2015) or local ecosystems (Ataur Rahman and Rahman, 2015) and is poorly implemented (Ataur Rahman and Rahman, 2015)

There is a disconnect between the national agencies and local level implementation in communities (Ataur Rahman and Rahman, 2015) with top-down decision making (Ataur Rahman and Rahman, 2015), political institutional barriers (Ataur Rahman and Rahman, 2015) and centralised risk and disaster policies (Audefroy and Sánchez, 2017), resulting in local communities, who are poorly adapted to climate change impacts

Poor enforcement (Marfai et al. 2015) of coastal setbacks, settlement planning and land use guidelines (Dhar and Khirfan, 2016)

Wide-ranging institutional challenges in community planning and health care provision (Ford et al. 2016)

Legacy of colonisation transforming traditional practices (Ford et al. 2016)

Poor government services provision (Jamero et al. 2018)

Gap between policy development and implementation (Karlsson and Hovelsrud, 2015)

Limited institutional support for local communities (Smith and Rhiney, 2016)

A.2.5 Economic

Increasing reliance on erratic markets, facilitating foreign investment in national and local markets and liberalisation of national economic policies have led to the development of new technologies that change behaviour away from traditional harvest practices, affect market productivity and influence consumption demands (Bennett et al. 2016)

High levels of poverty (DasGupta and Shaw, 2015)

Economic disadvantages on the global market (Petzold and Ratter, 2015)

Assets in flood prone areas (Marfai et al. 2015)

Possibilities of maladaptation (due to poor governmental coordination and lack of stakeholder awareness) (Wise et al. 2016)

Development planning is often captured by political elites and governmental officials (community needs are not met, lack of procedural justice and corruption) (Wise et al. 2016)

A.2.6 Knowledge

Insufficient focus on the mapping of social and financial vulnerabilities at the local level (Audefroy and Sánchez, 2017)

Low levels of awareness of vulnerability (Esteban et al. 2017)

Lack of general awareness of adaptation efforts (Lieske et al. 2014; Smith and Rhiney, 2016)

Mismatches between top-down interventions and local cultural practices (Wise et al. 2016)

A.3 Impacts

A.3.1 Physical

Coastal physical processes disrupted

Coastal erosion (Jones and Clark, 2014; Lieske et al. 2014; DasGupta and Shaw, 2015; Karlsson and Hovelsrud, 2015; Leon et al. 2015; Marfai et al. 2015; Nursey-Bray et al. 2015; Petzold and Ratter, 2015; Betzold and Mohamed, 2017; Hagedoorn et al. 2019) compounds saltwater intrusion (Abedin et al. 2014; Jurjonas and Seekamp, 2018) through soil loss (Ataur Rahman and Rahman, 2015) and buffering (Betzold and Mohamed, 2017)

Flooding (Jones and Clark, 2014; Nagy et al. 2014; DasGupta and Shaw, 2015; Marfai et al. 2015; Nursey-Bray et al. 2015; Dhar and Khirfan, 2016; Hobday et al. 2016; Jamero et al. 2018; Linkon, 2017; Hagedoorn et al. 2019) and breached embankments (with livelihood impacts) (Lieske et al. 2014; DasGupta and Shaw, 2015; Jamero et al. 2018)

Saline intrusion (Leon et al. 2015; Marfai et al. 2015; Petzold and Ratter, 2015; Jurjonas and Seekamp, 2018; Linkon, 2017) and variation (causing a reduction of mangrove diversity) (DasGupta and Shaw, 2015)

Sediment transportation processes affected (Karlsson and Hovelsrud, 2015)

Coastal infrastructure damage

Loss of infrastructure and housing (Nursey-Bray et al. 2015; Hobday et al. 2016; Jurjonas and Seekamp, 2018; Linkon, 2017), including world heritage sites (Perry, 2015)

Communal toilets damaged (Jamero et al. 2018)

Disruption of urban systems

Disruption to roads (Leon et al. 2015) and transportation processes (Ataur Rahman and Rahman, 2015)

Interruptions to electricity supply (Jamero et al. 2018)

Rainwater supply depleted (Jamero et al. 2018)

Recreation or tourism opportunities supported by reef ecosystems or regional fisheries (Cooley et al. 2016)

Land subsidence

Land subsidence caused by groundwater extraction, loading of buildings and other constructions on compressible soils, natural consolidation of the alluvial soil or tectonic subsidence (Esteban et al. 2017)

A.3.2 Ecological

Ecosystem degradation and loss

Loss of ecosystems (Ataur Rahman and Rahman, 2015; Petzold and Ratter, 2015; Dhar and Khirfan, 2016) including mangroves (Ataur Rahman and Rahman, 2015; DasGupta and Shaw, 2015; Leon et al. 2015) (e.g., the world heritage Sundarbans mangroves), wetlands (Leon et al. 2015; Marfai et al. 2015), beaches (Dhar and Khirfan, 2016; Betzold and Mohamed, 2017), and degradation of medicinal plants (Abedin et al. 2014) , a reduction in soil fertility (Abedin et al. 2014) and coral bleaching (Petzold and Ratter, 2015; Hagedoorn et al. 2019) leading to a loss of reefs and beach erosion (Dhar and Khirfan, 2016)

Climate change impacts on Artic residents includes transformed homelands (Sakakibara, 2017)

Biodiversity and genetic diversity loss

Loss of biodiversity (Abedin et al. 2014; Jones and Clark, 2014; Ataur Rahman and Rahman, 2015)

Habitat range shifts

Shifts in distribution, abundance and seasonal migrations of commercially valuable marine species (changes harvested fish abundance) (Hobday et al. 2016)

Sub-lethal species impacts

Shifts in reproductive patterns of commercially valuable marine species (changes harvested fish abundance) (Hobday et al. 2016)

Reduced growth and survival of species (Cooley et al. 2016) and loss of fish stocks (Hagedoorn et al. 2019)

Lack of predator avoidance of several finfish (Cooley et al. 2016)

Bivalve shellfish impacts caused by ocean acidification (Cooley et al. 2016)

Likely to enhance the biological effect of other simultaneous global changes (temperature increase, deoxygenation) (Cooley et al. 2016)

A.3.3 Social

Decreased access to ecosystem services

Loss of marine ecosystem services (Cooley et al. 2016)

Reduced access to freshwater (Abedin et al. 2014; Dhar and Khirfan, 2016; Smith and Rhiney, 2016)

Coastline protection by coral reefs (Cooley et al. 2016)

Local decline in agriculture and fisheries

Impaired food production (Abedin et al. 2014), with impacts on fisheries and agriculture (Abedin et al. 2014; Nagy et al. 2014; Ataur Rahman and Rahman, 2015; Jamero et al. 2018; Jurjonas and Seekamp, 2018)

Fishing days and jobs lost due to rough seas (Ataur Rahman and Rahman, 2015)

Movement of fishing vessels into other areas (Hobday et al. 2016)

Ocean acidification impacts marine harvests (Cooley et al. 2016)

Fisheries closures (Bennett et al. 2016)

MPAs may impact communities through fisheries closures (Bennett et al. 2016)

Increasing living costs

Communities forced to buy food they normally produce (Smith and Rhiney, 2016) and increases in food prices (Smith and Rhiney, 2016)

Increases in price of imported water (Jamero et al. 2018)

Livelihoods impacts

Livelihood impacts (Abedin et al. 2014; Nagy et al. 2014; Leon et al. 2015; Dhar and Khirfan, 2016; Smith and Rhiney, 2016)

Livelihoods have shifted away from fishing and rice farming towards agriculture and tourism (Nagy et al. 2014; Bennett et al. 2016)

Increased food insecurity

Damage to crops and infrastructure (Cinner et al. 2018), food security (Smith and Rhiney, 2016; Hagedoorn et al. 2019)

Public health risks increased

Health problems (Abedin et al. 2014), for example, diarrhoea and skin infections (Marfai et al. 2015), prevalence of diseases (Ataur Rahman and Rahman, 2015)

Mental health (Ford et al. 2016)

Cultural and traditional knowledge impacts

Increases in infrastructure and technology (communications, media, social services, disaster warning systems and transportation modes) have changed traditional communities (Bennett et al. 2016), with changing demographics in communities due to an influx of outside organisations and migrants and efflux of youth (Bennett et al. 2016)

Gender related impacts

Gender bias due to water collection by females (Abedin et al. 2014), including harassment (Abedin et al. 2014)

Increased social vulnerability

Vulnerability (Broto et al. 2015; Bennett et al. 2016) to tropical cyclones and floods (Ataur Rahman and Rahman, 2015), especially within low-lying (Ataur Rahman and Rahman, 2015; Broto et al. 2015; Leon et al. 2015) settlements (Marfai et al. 2015), resulting in loss of lives (Ataur Rahman and Rahman, 2015; Linkon, 2017)

Serious socioeconomic and cultural impacts (weakening of social fabric, marginalisation, unemployment and destruction of property by erosion) (Ataur Rahman and Rahman, 2015)

Decreased access to local government services

Impacts on education (Abedin et al. 2014) including closure of schools (Marfai et al. 2015)

Socioeconomic entrapment and decline

Affecting mostly poor developing communities through poverty-environment trap (Barbier, 2015a)

Through an increase in government and outside organisation supporting communities, there is a perception that the collective have limited control over changes (locus of power is outside of individuals) (Bennett et al. 2016)

Habitat loss compounds damage to infrastructure and weakens the social fabric of coastal communities (Bennett et al. 2016)

Decline in perceived value of human systems

Decrease in sea ice impacting culture and economy of Inuit (Sakakibara, 2017)

Conflict and migration

Social conflict (Abedin et al. 2014)

Large-scale migration (Abedin et al. 2014)

Impacting mostly rural areas (Abedin et al. 2014)

Conflicts between coastal resource users (Ataur Rahman and Rahman, 2015)

A.3.4 Governance

Increased geopolitical tensions

Increased economic and geopolitical tensions and instabilities (Abedin et al. 2014)

Economic

Increased business and living costs

Financial costs for infrastructure repair and loss of archaeological sites (Sakakibara, 2017)

Rising prices of goods and declining incomes (Bennett et al. 2016)

Business disruptions and losses

Increasing financial losses (Audefroy and Sánchez, 2017)

Economic loss (Linkon, 2017) of tourism revenue from beach erosion (Dhar and Khirfan, 2016)

Increases in coastal flooding causing economic losses (Esteban et al. 2017)

Disruption of economic activities (price increases) (Marfai et al. 2015)

A.4 Adaptation responses

A.4.1 Physical

Hard engineering responses

Includes seawalls, breakwaters and land reclamation (Jamero et al. 2018), coastal dykes (Esteban et al. 2017) and artificial reefs (Bennett et al. 2016)

Coastal defence structures (Betzold and Mohamed, 2017) are often poorly designed and constructed increase erosion and reducing long-term sustainability of beaches (Betzold and Mohamed, 2017)

(Location specific knowledge) including orientation of houses for sunlight (Ataur Rahman and Rahman, 2015), housing design (raising floors, natural windbreaks and bamboo in houses for wind protection) (Ataur Rahman and Rahman, 2015)

Building design, location, orientation, elevation, construction materials and reinforcement measures implemented (Linkon, 2017)

Adaptation responses included Raising the level of the house and building of houses with additional floors, building small dykes (using low quality building materials were cost was a factor, development of communal works systems to clear drainage around settlements and access to micro-finance (Marfai et al. 2015)

Paper focuses on perceptions of seawalls, which have been favoured, but implemented in an ad hoc manner. Communities favour these with little awareness of alternative approaches, despite problems caused by seawalls (Betzold and Mohamed, 2017)

Soft engineering responses and buffers

Beach nourishment, reef conservation or relocation (Betzold and Mohamed, 2017)

Planting design and selection of trees (raising of crops to prevent water-logging, seasonal planting for wet and dry season) (Ataur Rahman and Rahman, 2015)

Monitoring of beach profiles and coastal erosion along the Uruguayan coastal and incorporation of climate issues in the lagoon's management plan (Nagy et al. 2014)

Integrated hard and soft engineering

Traditional landscaping (building homesteads on a raised mound) (Ataur Rahman and Rahman, 2015), wooden platforms on excavated earth with 2 or 3 ponds (conservation of floodplain) (Ataur Rahman and Rahman, 2015)

Hard engineered and soft ecological adaptation responses (Dhar and Khirfan, 2016)

A.4.2 Ecological

Ecosystem restoration and protection

Habitat conservation (Petzold and Ratter, 2015) and restoration (Barbier, 2015a) in savannah (Bennett et al. 2016), mangroves (Bennett et al. 2016; Jamero et al. 2018), beach nourishment (Dhar and Khirfan, 2016) and coral reef management (Jamero et al. 2018)

Sundarbans mangrove forest provides protection from storms (Ataur Rahman and Rahman, 2015)

Community EbA measures identified include the establishment of marine and terrestrial protected areas (Hagedoorn et al. 2019)

Restoring coastal forests (Hagedoorn et al. 2019) through a participatory mangrove plantation programme (Ataur Rahman and Rahman, 2015)

Monitoring protected areas (Hagedoorn et al. 2019)

EbA (favouring no or low regret adaptation options) (Dhar and Khirfan, 2016)

Nature based solutions

Invasive species management (Hagedoorn et al. 2019)

Implementing a riparian buffer (Hagedoorn et al. 2019)

Planting trees (Hagedoorn et al. 2019)

Compile a list of migratory birds and endangered species, use of soft coastal biophysical protection measures such as beach and dune vegetation, and wind fencing (Nagy et al. 2014)

A.4.3 Social

Improving access to/storage of natural resources

Water conservation practices (Abedin et al. 2014), including rainwater harvesting and storage (Abedin et al. 2014; Ataur Rahman and Rahman, 2015; Bennett et al. 2016; Jamero et al. 2018), personal filtration devices (for arsenic) (Abedin et al. 2014), water boiling (Abedin et al. 2014) and collection from distant, but safe sources (Abedin et al. 2014)

Stop groundwater extraction in Jakarta suggested to stop land subsidence (Esteban et al. 2017)

Improving agricultural or fisheries practices

Improving animal husbandry, increasing agricultural and seafood production and processing to improve livelihoods (Bennett et al. 2016)

Improving fishing community adaptation efforts by predicting future coastal-marine food resources, and co-developing adaptation options (Hobday et al. 2016)

Introduction of climate resistant crops (Hagedoorn et al. 2019)

Crop diversification (Hagedoorn et al. 2019) and changing harvesting techniques (Hagedoorn et al. 2019)

Screening of tube well water for contamination (Abedin et al. 2014)

Sustainable resource use

Waste management (Bennett et al. 2016)

Improved waste management to reduce pressure on ecosystems. (Hagedoorn et al. 2019)

Reducing resource extraction (Hagedoorn et al. 2019)

Sustainable technologies (Ataur Rahman and Rahman, 2015)

Sustainable household management

Cleaning community areas and the prevention of weeds/pests (Hagedoorn et al. 2019)

Local foods, materials and structures were used to strengthen housing, provide alternative food sources, adopt adapting practices (like stilts), mangrove restoration for protection and observations of the environment for storm prediction (Hiwasaki et al. 2015)

Small-scale response strategies by communities to flooding included moving household possessions to higher levels, evacuation of children and elderly to mosques, (but this was uncoordinated), receiving food parcel support (but lacked medicines) (Marfai et al. 2015)

Maintaining or switching livelihoods

Maintaining traditional fisheries livelihoods and supporting alternative livelihoods (Bennett et al. 2016) like nature based tourism (Bennett et al. 2016)

Community participatory programmes

Common currency or time banking systems where individuals are incentivised to volunteer (Cinner et al. 2018)

Empowering communities through participatory processes such as adaptive co-management (Cinner et al. 2018)

Use of adaptive, participatory, and transformative methods (Perry, 2015)

Participatory urban planning in Maputo incorporating highly technical knowledge from climate scenarios focussing on informal settlements (Broto et al. 2015)

Adaptation responses were based on top-down and bottom-up knowledge (Nagy et al. 2014)

Using participatory methods and community-based approaches so they are useful and implementable (Bennett et al. 2016)

Multi-stakeholder, participatory planning process prioritising rural livelihood adaptation strategies (Wise et al. 2016)

Developing adaptive networks

Formation of community water committees to address drought (Abedin et al. 2014)

Access to networks (Cinner et al. 2018)

Improving access to community services

National government: Providing construction materials for housing repair and acquisition of new water tanks, build new seawalls; Municipal: relocate island residents to mainland, provide funds for road maintenance; Non-governmental organisations: build temporary classrooms, donate stilted houses, elevate floors of classrooms, create rice cooperatives, establish microfinance; Barangay Council: elevate and extend roads, repair and elevate damaged infrastructure like seawalls, acquire large evacuation boats, increase electricity supply; Community: clean shared spaces after tidal flooding (Jamero et al. 2018)

Empowering communities and addressing inequality

Societal organisation to enable (or inhibit) cooperation, collective action and knowledge sharing (Cinner et al. 2018)

Empowering communities through removing barriers that may inhibit people's ability to exercise agency (Cinner et al. 2018)

Building socioecological resilience

Build capacity of tropical coastal communities to adapt to climate change (Cinner et al. 2018)

Factors contributing to higher vulnerability included a lack of coordination, poor environmental conditions, poor infrastructure maintenance and lack of public concern.

Building social capital (Cinner et al. 2018)

A.4.4 Governance

Adopting/mainstreaming sustainability policies

Improving disaster response programmes

Increased focus on vulnerability (looking at stressors, sensitivity to change and adaptive capacity) (Bennett et al. 2016)

Improving implementation and coordination of policies

Switching between adaptation strategies through flexibility in policies and the removal of barriers (Cinner et al. 2018)

Developing partnerships and building capacity

Institutional support to legitimise and sustain adaptation through capacity building (Broto et al. 2015)

Social investments for sustaining livelihoods (Cinner et al. 2018)

Design of an agreed participatory multi-criteria model to manage a lagoon sand bar(Nagy et al. 2014)

Improving access to community services

Government programme to improve tap water (Bennett et al. 2016)

Pursuing climate justice

Adoption of a climate justice framework (Smith and Rhiney, 2016)

Factors driving vulnerability within communities are a function of centuries of economic neglect and political marginalisation (Smith and Rhiney, 2016)

A.4.5 Economic

Improving financial resources availability

Engaging with economic programmes, for example, the King of Thailand's sufficiency economy (Bennett et al. 2016)

Improving access to insurance products

Building assets could improve access affordable credit and insurance (Cinner et al. 2018)

A.4.6 Knowledge

Improving planning processes

Increased focus on vulnerability (looking at stressors, sensitivity to change and adaptive capacity) (Bennett et al. 2016)

Spectrum of adaptive capacity (from vulnerable to resilient) (Jurjonas and Seekamp, 2018)

Improving forecasting and early warning systems

Improved planning for disasters (Bennett et al. 2016)

Improving decision support frameworks

Consideration of 'futures' planning methodologies (visioning, backcasting and scenario planning) (Bennett et al. 2016)

Resilience assessment framework for coastal rural communities in low-lying Asian mega-deltas (DasGupta and Shaw, 2015)

Coordinating top down and bottom up approaches

Combine top-down scientific models and bottom-up approaches involving community participatory action research using design charrettes

Framework to foster resilience dialogue during community conversations, spark adaptive capacity from the bottom-up

Integrating top down with bottom-up approaches (Hagedoorn et al. 2019)

Top-down and bottom-up approaches to identify adaptation options (Nagy et al. 2014)

Integrating knowledge systems

Observations using traditional knowledge to forecast extreme events may increase the resilience of coastal communities (Audefroy and Sánchez, 2017)

Integrating scientific and Indigenous knowledge (Cinner et al. 2018)

Local and Indigenous knowledge related to climate-related hazards, including folklore, rituals and ceremonies that reinforce religious, customary and traditional beliefs, which can strengthen community resilience (Hiwasaki et al. 2015)

Integration of local knowledge and traditional practices with scientific approaches in disaster risk reduction (Audefroy and Sánchez, 2017)

Humanistic research and community based projects in rural and indigenous communities often produce understandings of climate and climate change that are incompatible with statistical finds of climate science (Sakakibara, 2017)

Participatory model integrates traditional/local and scientific knowledge (Leon et al. 2015)

Increasing vulnerability assessments incorporating local and scientific knowledge (Bennett et al. 2016)

Vulnerable Arctic communities confront uncertainty through reinforcing traditional cultural practices and cultural response (Sakakibara, 2017)

Individual adaptation during building of dwelling units using Indigenous knowledge (Linkon, 2017)

Building agency in communities by incorporating local or customary knowledge, skills and management into both science and policy (Cinner et al. 2018)

Call for indigenous people to be primary actors in the monitoring of and adaptation to climate change (Smith and Rhiney, 2016)

Improving location and context specific knowledge

Need to understand structural inequalities (Broto et al. 2015)

Developing and understanding alternative community adaptation options (Hobday et al. 2016)

Improved use of local knowledge and traditional practices to strengthen the resilience of communities to climate change (Audefroy and Sánchez, 2017)

Perceptions of measures to increase resilience in Jakarta include build stronger and bigger dykes or a giant sea wall, plant mangroves, elevate districts adjacent to dykes and relocation of properties (Esteban et al. 2017)

Improving scientific communication

Access to information/knowledge (Cinner et al. 2018)

Stakeholder identification, outreach and education

Building regional skill sets to understand, predict and communicate coastal vulnerability (Hobday et al. 2016)

Improving education (Bennett et al. 2016), in environment (Bennett et al. 2016), English language training (Bennett et al. 2016)

Ocean acidification responses include education/outreach to inform policymakers, evidence-based action and policy (Cooley et al. 2016)

Multiple adaptation responses used

A.4.7 Synergistic adaptation responses

Combines natural and traditional adaptation practices and defence mechanisms (Ataur Rahman and Rahman, 2015)

Complementary actions for managing the environment, community livelihoods and adapting to climate change (Bennett et al. 2016)

Synergise EbA with CbA (Scarano, 2017) to capitalise on the experiential knowledge of local communities in adapting to climate change (Dhar and Khirfan, 2016).

Fisheries management interventions and CBA (Hobday et al. 2016)

Multiple adaption pathways (Wise et al. 2016)

A.5 Benefits

A.5.1 Physical

Physical processes supported

Protection from wind, saltwater intrusion, landslides and erosion (Hiwasaki et al. 2015)

Coastal infrastructure resilience increased

Flood protection (Betzold and Mohamed, 2017)

A.5.2 Ecological

Physical processes supported

Coastal forests attenuate wave and wind speed and bind soils for erosion protection) (Ataur Rahman and Rahman, 2015)

Increased biodiversity

Morass (wetland as a biodiversity resource, protects species) (Dhar and Khirfan, 2016)

A.5.3 Social

Access to sustainable ecosystem services

Traditional disaster reduction methods and location specific knowledge (Ataur Rahman and Rahman, 2015) helps secure protection against tidal surges and strong winds; landsides (Ataur Rahman and Rahman, 2015)

Improved water security (when in drought) (Hiwasaki et al. 2015)

Plants for medicinal purposes (Ataur Rahman and Rahman, 2015)

Improved access to resources

Provide alternative food sources (Hiwasaki et al. 2015)

Improved socioeconomic services

Building social capital (bonding, bridging and linking) (Cinner et al. 2018)

Creation of social capital (trust building, creation of social norms) (Hagedoorn et al. 2019)

Strengthening of social capital to improve community resilience (Smith and Rhiney, 2016)

Improved community participation

Promotes participatory discussion making and agency (Jurjonas and Seekamp, 2018)

Better informed communities

CbA benefits include practical information and benefits; future focus; evaluation; accountability across scales (Ford et al. 2016)

Better prediction of natural hazard events (Hiwasaki et al. 2015)

Identified barriers to capacity building (Jurjonas and Seekamp, 2018)

Improved integration of knowledge systems

Traditional disaster reduction methods and location specific knowledge (Ataur Rahman and Rahman, 2015) helps secure protection against tidal surges and strong winds; landsides (Ataur Rahman and Rahman, 2015)

Empowering women and children

Empowerment of women and children in a male dominated society (Leon et al. 2015)

Increased adaptive capacity

Increased community perception of resilience (Jurjonas and Seekamp, 2018)

Social learning helps communities adapt to change (Nursey-Bray et al. 2015)

Improved disaster preparedness

Communities are better prepared for disasters and are improved in their risk management (Audefroy and Sánchez, 2017)

Improved community cohesion

Strengthening networks, building trust, enhanced volunteerism, social cohesion (Cinner et al. 2018)

Strengthen social relations to build community resilience (Hiwasaki et al. 2015)

Community consensus on climate threats (Jurjonas and Seekamp, 2018)

Reduced inequality

Building socially just and robust coastal management strategies (Nursey-Bray et al. 2015)

A.5.4 Governance

Political and institutional capacity developed

Build capacity (Ford et al. 2016; Hobday et al. 2016)

Strengthened participatory governance

Promotes citizenship and collective rights, empowerment and decentralising power (promotes the co-construction of knowledge) (Broto et al. 2015)

Better planning processes supported

Participation in development planning (Wise et al. 2016)

Improved coordination and decision making

Building political and institutional relationships (Broto et al. 2015)

Improved implementation and policies

Initiated discussions on other things like service provision (Broto et al. 2015)

Climate justice advanced

Climate justice below the national scale (linked to developmental context) (Smith and Rhiney, 2016)

Improved adaptive management

Can improve efforts in disaster risk reduction – as it can help develop coping mechanisms for inhabitants in flood-prone areas (Marfai et al. 2015)

A.5.5 Economic

Increased revenue/income

Assets can improve market accessibility and catalyse other types of development (Cinner et al. 2018)

A.5.6 Knowledge

Informed decision making tools

Promotes adaptive co-management (Nagy et al. 2014)

Improved co-production of knowledge

Communities identified what is important to them (local knowledge). The process led to co-learning with potential to lead to more localised action (Bennett et al. 2016)

Co-production of knowledge to empower low income communities (Broto et al. 2015; Hobday et al. 2016)

Co-production of knowledge (Nagy et al. 2014)

Utilise Indigenous/local knowledge (Ford et al. 2016)

Local knowledge included community engagement (Leon et al. 2015)

Improved awareness

Better understanding of structural inequalities in relation to climate change (Broto et al. 2015)

Better understanding of risk and acceptance of adaptation response (Lieske et al. 2014)

Empowers stakeholders (Nagy et al. 2014)

Addressing the climate knowledge gap (Smith and Rhiney, 2016)

A.6 Co-benefits

Co-benefits for human development and adaptive capacity (Wise et al. 2016)

A.7 Constraints and limitations

A.7.1 Physical

Seawalls were typically poorly designed and constructed, and when compounded by sand winning, disrupted dynamic beach processes, and in so doing increased coastal erosion and the ability of the beach processes to respond to changing ocean conditions (Betzold and Mohamed, 2017)

Engineering solutions in SIDS are sometimes problematic, being characterised by poor design and construction, especially in rural areas, limited access to human, technical and financial capacity and a lack of data on site-specific conditions resulting in failure after short time periods (Betzold and Mohamed, 2017)

Seawalls negatively affect beach erosion within increased erosion at edges or bottom of seawalls leading to collapse and abandonment, while increasing or displacing beach erosion (Betzold and Mohamed, 2017)

Impacts are increasingly complex and unpredictable through direct and downstream effects of climate change (Bennett et al. 2016)

Dykes as hard defences in Jakarta are threatened by continual subsidence and possible but communities underestimate the level of vulnerability (Esteban et al. 2017)

A.7.2 Ecological

Species selected (exotic) for mangrove plantations have not always been appropriate for location, and combined with poor planting methods have exacerbated damage (Ataur Rahman and Rahman, 2015)

Beach nourishment disturbed natural processes and adversely affected beach ecosystems (Betzold and Mohamed, 2017)

Undermining the long-term sustainability of coastal ecosystems trade-offs in adaptation strategies catalysing socioecological (Cinner et al. 2018) and poverty-environment (Barbier, 2015a) traps

Lack of synergy between EbA and CBA at regional scales (especially in practice) (Dhar and Khirfan, 2016)

A.7.3 Social

Thick shelter beds protect the coastal zone but have shifted wind damage to interior regions (Ataur Rahman and Rahman, 2015)

Factors that impede individual or community response to coastal erosion and flooding include lack of resources, knowledge and capacity (Betzold and Mohamed, 2017)

Lack of capacity and resources impedes alternative measures that are adapted to local conditions, or the enforcement of rules and regulations such as a ban on sand mining (Betzold and Mohamed, 2017)

Considerable socioeconomic barriers to adaptation at various scales (Ford et al. 2016)

CbA is not a panacea: Not all communities want to have the level of engagement implied by CbA, there may be general participation problems with entrenchment of personal views and local power dynamics may shape the process causing tensions, resistance and withdrawal (Ford et al. 2016)

Maintaining a climate adaptation focus (communities have more other pressing issues that require attention (Ford et al. 2016)

Younger generation are abandoning rituals and practices (Hiwasaki et al. 2015)

Low levels of participation in planned measures, addressing symptoms and not causes and lack of local consultation (Jamero et al. 2018)

Existing communities' traditional coping mechanisms may be overwhelmed and not be able to respond (Smith and Rhiney, 2016)

Multi-level participatory approach limitations include: the structured social learning process failed to expose and address the systemic causes of vulnerability, stakeholders may have recognised systemic issues, but were unwilling to challenge them due to lack of confidence or capacity or gave precedence to meeting immediate livelihood needs (Wise et al. 2016)

A.7.4 Governance

Lack of enforcement of rules (Betzold and Mohamed, 2017)

New environmental management measures, for example, MPAs may impact communities through fisheries closures (Bennett et al. 2016)

Limitation like systemic issues, power relations and elite capture persisted despite participatory process (Broto et al. 2015)

Institutional support dwindled after the project finished (Broto et al. 2015), but participatory processes require support (Broto et al. 2015)

Lack of flexibility in governance processes (Jamero et al. 2018)

Planned measures were not enough (Jamero et al. 2018)

Maladaptation in autonomous measures include negative environmental consequences for elevating floors of classrooms using coral stones and using trash as foundation for new houses (Jamero et al. 2018)

The Belize national climate adaptation policy has not been implemented. With typically top-down hard and soft engineering measures such as sea-walls, land use planning, ecosystem conservation, building codes, insurance schemes and managed retreat of settlements, the strategies were ineffective; individual properties were submerged; the communal beach area reduced and tourism development area destroyed (Karlsson and Hovelsrud, 2015)

The implementation of proactive, planned adaptation to reduce community vulnerability is strongly dependent upon people's perception of the threat posed to their communities at the local scale (Lieske et al. 2014)

Uncoordinated responses during flood events produces greater exposure to hazards, and notes that community responses remain below the ideal with a risk of maladaptation (Marfai et al. 2015)

Very few transformative strategies were identified to address deeper systemic issues (Wise et al. 2016)

A.7.5 Economic

Limited local resources, therefore important role of donors (Betzold and Mohamed, 2017)

Access to a significant amount of financial resources and the transfer of technologies (Smith and Rhiney, 2016)

A.7.6 Knowledge

A persisting perception exists that traditional knowledge is socially constructed and difficult to integrate with scientific and institutional information. It is reinforced by communication in a top-down manner (Audefroy and Sánchez, 2017)

Scenario planning capacity limitations related to local understanding of climate change and its local implications (Bennett et al. 2016)

Data availability (Broto et al. 2015)

People underestimate the severity of vulnerability due to their regular exposure (Esteban et al. 2017)

Conflict at the interface of Western and local/Indigenous knowledge within a specific cultural context, which may compromise long-term sustainability (Ford et al. 2016)

The multifaceted role of the researcher to go beyond standard academic practice (Ford et al. 2016)

Potential for tokenistic engagement of communities, consultation fatigue, and imbalance between Western and Indigenous knowledge in this work (Ford et al. 2016)

Developing comparative approaches across regions that differ in political institutions, socioeconomic community demographics, resource dependency and research capacity is challenging (Hobday et al. 2016)

Social learning has not made the transition from theory to practice (Nursey-Bray et al. 2015)

A.8 Costs

Economic costs due to acute ocean acidification events in the Pacific Northwest, USA have jeopardised the 270 million USD, 3200 jobs yr^{-1} shellfish aquaculture industry in Washington State (Cooley et al. 2016)

Large projected economic costs associated with ocean acidification include 75–187 million USD yr^{-1} for shellfish harvests in the USA; global shellfish harvests at 6 billion USD yr^{-1}; coral reef impacts at 0–900 billion USD yr^{-1} (Cooley et al. 2016)

Costs associated with management options for the coastline: accommodating SLR and flooding include tax burdens on citizens, high maintenance costs and possible biodiversity loss and with management retreat include loss of properties without compensation, flooding of agricultural land, loss of species and recreational activities (Jones and Clark, 2014)

Risk of maladaptation from substitution of materials to build additional floors by low income households, which were structurally weak (Marfai et al. 2015)

B. Human System: Built Infrastructure

B.1 Anthropogenic co-drivers

B.1.1 Physical

Growing coastal populations (Perkins et al. 2015; Moosavi, 2017; Carter, 2018), urbanisation (Kabisch et al. 2017)

Hard engineering structures (Gracia et al. 2018)

Hardening of surfaces and run-off impacts (Kabisch et al. 2017)

Pollutants (Zikra et al. 2015; Peng et al. 2017) including nitrogen and sulphur (Kaja and Mellic, 2017)

Industrial activities (Martínez et al. 2018)

Fires (Martínez et al. 2018)

B.1.2 Ecological

Loss and degradation of natural areas (Kabisch et al. 2017)

B.1.3 Social

Social vulnerabilities (Woodruff, 2018)

B.1.4 Governance

Insufficient or inappropriate planning and policy (Becker et al. 2015)

Poor governance (Vikolainen et al. 2017) and less public participation (Martínez et al. 2018)

B.2 Impacts

B.2.1 Physical

Coastal physical processes disrupted

Coastal flooding (Villatoro et al. 2014; Shope et al. 2016; Kaja and Mellic, 2017; Brown et al. 2018; Elshorbagy et al. 2018)

Urban land use changes (Carter, 2018)

Coastal erosion (Moosavi, 2017; Martínez et al. 2018), including accelerated bottom erosion in front of the structure and down drift scouring (Gracia et al. 2018)

Large morphological changes to island coastlines (Shope et al. 2016)

Disturbance of sediments supply and beach reduction (Gracia et al. 2018) in communities down drift (Vikolainen et al. 2017)

Alteration of alongshore sediment transport (Gracia et al. 2018)

Ground water saline intrusion (Shope et al. 2016)

Coastal infrastructure damage

Damage to infrastructure (Villatoro et al. 2014; Shope et al. 2016; Asadabadi and Miller-Hooks, 2017), including transport (Colin et al. 2016; Forzieri et al. 2018), freight, and equipment (Becker et al. 2015), energy (Brown et al. 2018), hydropower generation (Forzieri et al. 2018; Mikellidou et al. 2018) and water infrastructure (Friedrich and Kretzinger, 2012; Elshorbagy et al. 2018)

Salt mobilisation and crystallisation in buildings (Kaja and Mellic, 2017)

Wind damage (Kaja and Mellic, 2017)

Deterioration of marine steel (Peng et al. 2017)

Disruption of urban systems

Flooding can affect the quality of coal (Mikellidou et al. 2018)

Biological infestation in buildings (Kaja and Mellic, 2017)

Systemic disruptions (relate to system function, capability or capacity) (Rahimi et al. 2014)

Land subsidence

Landslide/debris (Jeong et al. 2014)

B.2.2 Social

Decreased access to ecosystem services

Hydropower generation impacts through reduced flow (Antwi-Agyeia et al. 2018)

Local decline in agriculture and fisheries

Shortened growing season with implications for the agricultural and fisheries sectors (Forzieri et al. 2018)

Extensive damage to crops and livestock leading to famine (Antwi-Agyeia et al. 2018)

Increased food insecurity

Food insecurity (Elshorbagy et al. 2018; Martínez et al. 2018)

Extensive damage to crops and livestock leading to famine (Antwi-Agyeia et al. 2018)

Public health risks increased

Potential risk to bathers (Gracia et al. 2018)

Health (Martínez et al. 2018)

Cultural and traditional knowledge impacts

Increased social vulnerability

Increased social vulnerabilities (inequality) (Woodruff, 2018)

Decreased access to local government services

Restricted public access (Gracia et al. 2018)

B.2.3 Economic

Increased business and living costs

Clean up costs (Becker et al. 2015)

Business disruptions and losses

Loss of business and delays in commerce (Becker et al. 2015)

Reduced hydropower generation efficiency (Mikellidou et al. 2018)

Loss of economic activity due to damaged/destroyed infrastructure (Mikellidou et al. 2018)

B.3 Adaptation responses

B.3.1 Physical

Supporting physical processes

Erosion control system/framework (Jeong et al. 2014)

Hard engineering responses

Construction of groins, seawalls, revetments, gabions and breakwaters (Friedrich and Kretzinger, 2012; Moosavi, 2017; Vikolainen et al. 2017; Wadey et al. 2017)

Elevating infrastructure and improving drainage (Perkins et al. 2015; Becker et al. 2016; Colin et al. 2016; Asadabadi and Miller-Hooks, 2017; Brown et al. 2018)

Construction of an artificial island named Hulhumale (Wadey et al. 2017)

Soft engineering responses and buffers

Integrated hard and soft engineering

Ecologically enhanced hard engineered infrastructure (Perkins et al. 2015; van der Nat et al. 2016; Moosavi, 2017)

Hard engineering structures with EbA approaches (Jeong et al. 2014; Perkins et al. 2015; Gracia et al. 2018)

Managed retreat and coastal realignment

Relocation of infrastructure (Friedrich and Kretzinger, 2012; Colin, 2016 #27; Wadey et al. 2017)

B.3.2 Ecological

Ecosystem restoration and protection

Land banking to secure spaces to implement green infrastructure (Carter, 2018)

Bioengineering

Sandscaping (Vikolainen et al. 2017) with EbA approaches (Jeong et al. 2014; Perkins et al. 2015; Gracia et al. 2018)

Nature-based solutions

Nature-based solutions (urban green infrastructure and EbA) (van der Nat et al. 2016; Kabisch et al. 2017; Gracia et al. 2018)

Landscape-based approach (Kaja and Mellic, 2017)

Developing approaches to empower local communities to adopt and manage green infrastructure sites (Carter, 2018)

B.3.3 Social

Community participatory programmes

Stakeholder involvement (Becker et al. 2015)

Developing adaptive networks

Adaptation networks (Woodruff, 2018)

Empowering communities and addressing inequality

Developing approaches to empower local communities to adopt and manage green infrastructure sites (Carter, 2018)

B.3.4 Governance

Adopting/mainstreaming sustainability policies

Policy development (Becker et al. 2015), including zoning policies (Carter, 2018) and government adaptation policies (Woodruff, 2018)

Consolidate a system of environmental governance (Martínez et al. 2018)

ICM (Rosendo et al. 2018)

Developing partnerships and building capacity

Increase adaptive capacity (Martínez et al. 2018)

B.3.5 Knowledge

Better monitoring and modelling

Assessing model and solution frameworks (Asadabadi and Miller-Hooks, 2017) and simulation models (Jeong et al. 2014), scenario development and land use modelling methods (Carter, 2018)

Data-model integration approach. The multi-hazard risk framework includes climate sensitivity of critical infrastructures, risk integration and adaptation scenarios (Forzieri et al. 2018)

Coupled Model Intercomparison Project Phase 5 (CMIP5) and global climate models (GCMs) (Shope et al. 2016)

Improving planning processes

Infrastructure Planning Support System (Espinet et al. 2016)

Climatic design for critical infrastructure (Mikellidou et al. 2018)

Hindcasting and climate modelling (Villatoro et al. 2014)

Hydro-economic models. Intensity–duration–frequency curves and design storms in various regions (Elshorbagy et al. 2018)

Improving decision support frameworks

Risk (Colin et al. 2016) and vulnerability assessment tools, for example, ARCoES Decision Support Tool (DST) (Brown et al. 2018)

Minimum assumption credible design (Becker et al. 2016)

A standard climate narrative is essential to assess port risk, vulnerability and resilience (Mutombo and Ölçer, 2016)

Sustainable engineered systems and early warning systems (Rahimi et al. 2014)

Integrating knowledge systems

Local communities understanding the local knowledge systems (Kaja and Mellic, 2017)

A consistent analysis framework, provided by the Sources Pathways Responses Consequences (SPRC) approach (Villatoro et al. 2014)

B.4 Benefits

B.4.1 Physical

Physical processes supported

Increase mitigation and coastal erosion co-benefits (Gracia et al. 2018)

Coastal infrastructure resilience increased

Protection of waste water infrastructure (Friedrich and Kretzinger, 2012)

Critical infrastructure is resilient to climate change impacts (Moosavi, 2017; Wadey et al. 2017; Mikellidou et al. 2018)

Engineered systems are built, maintained and eventually recycled within its larger embodied ecological systems (ecosystems) (Rahimi et al. 2014)

Improved infrastructure functionality

Improve the functionality of critical infrastructure (Mikellidou et al. 2018)

B.4.2 Ecological

Ecosystem/ecological resilience supported

Stimulate the resilience of natural systems (Gracia et al. 2018)

Improves ecosystem-based management (van der Nat et al. 2016)

Physical processes supported

Providing ecological defines against coastal erosion (Gracia et al. 2018)

Increased biodiversity

Stimulate biodiversity conservation (Perkins et al. 2015; Gracia et al. 2018)

Creating habitat and protection of biodiversity (Vikolainen et al. 2017)

B.4.3 Social

Access to sustainable ecosystem services

Important ecosystem services secured (Perkins et al. 2015)

Improved health

Improved health and social benefits (Kabisch et al. 2017)

Empowered communities

Cultural change and higher empowerment of society around urban problems related to ecosystems and nature (Martínez et al. 2018)

Inspiring and encouraging community participation in coastal erosion management processes

Increased adaptive capacity

Stimulate the resilience of human society to coastal erosion effects (Gracia et al. 2018)

Improved community cohesion

Develop common goals (Woodruff, 2018)

Improved community cohesion (Woodruff, 2018)

Reduced inequality

Reduction of health inequalities (Kabisch et al. 2017)

B.4.4 Governance

Political and institutional capacity developed

Help governments with lack of technical expertise, staff time and funding (Woodruff, 2018)

Better planning processes supported

Greater emphasis on resilience planning (Becker et al. 2015)

B.4.5 Economic

Increased revenue/income

Increased tourism (Vikolainen et al. 2017)

Increased financial resources available

Attract investment (Woodruff, 2018)

Reduced operational and capital costs

Reduce damage costs from future extremes (Jeong et al. 2014)

Reduced costs of adaptation (Woodruff, 2018)

B.5 Knowledge

Informed decision making tools

Make resource forecast for adaptation projects more transparent, widely accessible, highlights shortfalls of current engineering (Becker et al. 2016)

Monitors future coastal vulnerabilities (SLR and storms) (Brown et al. 2018)

Scenario planning can support decision makers in understanding and responding to the implications of divergent development pathway and contrasting future land use patterns on urban adaptive capacity (Carter, 2018)

Help managers and planners with tools to develop adaptation strategies (Colin et al. 2016)

Provides stakeholders with a roadmap for planned investments in building resilience to future change in sea level and extreme events (Brown et al. 2018)

Significant guidance for design engineers when factoring climate change in infrastructure design calculations (Mutombo and Ölçer, 2016)

improved coastal storm predictions such that the timing, intensity and other important storm variables can be forecast quite accurately up to approximately three days in advance (Villatoro et al. 2014)

The hydrometeorological research community has made significant strides in the direction of quantifying possible climate change impacts on precipitation, stream flow, temperature, reservoir operation, flood risks and droughts (Elshorbagy et al. 2018)

Hydroeconomic models assess the economic impacts of climate change and water shortage on society (Elshorbagy et al. 2018)

Improved co-production of knowledge

Shared learning (Woodruff, 2018)

Improved education and outreach

Increase awareness and facilitate information flow (Woodruff, 2018)

B.6 Constraints and limitations

B.6.1 Ecological

Ecosystems demand space to flourish, and sometimes require more space than conventional hard structures (Gracia et al. 2018)

Furthermore, development of the ecosystem and its functionality depends on the coastal setting, hydrodynamics, structure, and habitat dimensions, together with the severity of coastal erosion (Gracia et al. 2018)

Nature-based solutions still need to be developed, but they do have a strong action focus (problem rooted in climate change solving) (Kabisch et al. 2017)

The science of sustainability requires a deep understanding of ecological complexity. In addition, others believe ecological systems to be the prototypical complex adaptive systems with emergent behaviours and feedback that influences subsequent interactions (Rahimi et al. 2014)

B.6.2 Economic

Multiple benefits of sandscaping are hard to calculate and link to funding paths, so the project partners focus on what would help to attract more money and make the project possible (Vikolainen et al. 2017)

B.6.3 Governance

This alone leaves municipalities with unanswered questions regarding the translation of the estimated change (e.g., 15% increase in extreme rainfall) to the urban storm water management infrastructure and its temporal storage capacity. Therefore, till such issues are addressed, it is difficult to convince decision makers of the real impacts of climate change on water resource systems and infrastructure (Elshorbagy et al. 2018)

B.6.4 Knowledge

Does not account for other social benefits derived from preventing flooding occurrences, such as property damage averted and reductions in lives lost on flooded roadways, lower risk to emergency personnel, avoided evacuations, reduced utility service losses and dampened local or regional, short- and long-term economic losses (Asadabadi and Miller-Hooks, 2017)

The sample size looked at in the study was relatively small, making it difficult to compare how different sectors of stakeholders felt concern about different types of impacts or how different types of stakeholders perceived strategies differently (Becker et al. 2015)

Pathway that the design follows does not consider any other variables outside of optimisation of materials. Thus, it is most likely not an optimal alignment to mitigate local wave dynamics and may cut through other important infrastructure, densely populated areas, critical habitat or historic landmarks (Becker et al. 2016)

Detailed understanding of the local processes also allows the limitations of the ‘static’ morphology within the Decision Support Tools (DST) to be put in context through the identification of how uncertainty within the mapped results could occur (Brown et al. 2018)

This study does not account for important climate change related factors including SLR, flooding, and other extreme events (Espinet et al. 2016)

The assumptions used in the case study are rather simple in approach due to data limitations (Jeong et al. 2014)

knowledge of coastal erosion management by means of ecosystems is, in part, little known and less applied and very few studies exist (Gracia et al. 2018)

Requires longer time frames to establish and needs research to understand dynamic processes (Moosavi, 2017)

While successful at increasing biodiversity, as neither baselines nor additional ecological parameters (e.g., ecosystem functions) were quantified for these systems, proportional and absolute ecological gains through mitigation remain unknown and mitigation effectiveness unquantified. For soft engineering options where mitigation outcomes have far greater potential, before-and-after quantifications are limited (Perkins et al. 2015)

Ecological criteria used are rather general and based only on the literature on ecosystem-based management. Moreover, the method presented here evaluates flood protection systems based on ecological and engineering parameters alone. Lacking financial, political and social aspects, the method can only contribute to part of the total evaluation needed to choose a certain design concept. The method ignores the potential negative effects of the inherently large footprint of some design concepts (van der Nat et al. 2016)

Adaptation networks may be limited in their ability to distribute knowledge and resources to cities that need the greatest support (Woodruff, 2018)

Each port is unique and located in distinctive geographical locations therefore it is difficult to develop a climatic representation using GCMs that fit all port geographical and climatic conditions (Mutombo and Ölçer, 2016)

Understanding of long-term climate risks is limited by the lack of in-depth knowledge on the impacts of climate hazards, due to the absence of harmonised loss data recording. Also subject to bias (Forzieri et al. 2018)

Diffraction and wind interruption from the small islands within the model domain were not resolved due to the coarse spatial resolution of the WW3 domain. Additionally, the effects of El Niño Southern Oscillation (ENSO) were not considered (Shope et al. 2016)

This study lacks a detailed and up-to-date scientific assessment that considers sea levels, waves and coastal floods (Wadey et al. 2017)

Due to the short time scales covered by the majority of the available records, this often meant ignoring longer term trends, such as those resulting from climate variability and human induced SLR (Villatoro et al. 2014)

B.7 Costs

B.7.1 Ecological

Construction based protection system in coastal erosion have proven to be more costly than ecosystem-based approaches (Moosavi, 2017; Gracia et al. 2018)

Economic loss of intertidal ecosystem functions and services can outweigh reclamation (Perkins et al. 2015)

Sandscaping is the most cost-effective compared to other adaptation measures (Vikolainen et al. 2017)

B.7.2 Governance

Adaptation measures put in place can result in high costs in public services especially water and electricity (Martínez et al. 2018)

Cities participate in adaptation networks if transactional costs are outweighed by benefits

B.7.3 Economic

Different approaches vary in costs but sea walls have proven to be much more costly (Asadabadi and Miller-Hooks, 2017)

The assessment of flooding and erosion risk on the coast is a complex problem, due to the large spatial variability of marine dynamics, geological, ecological and urban coastal environments, defences and protection measures, etc. (Villatoro et al. 2014)

C. Human System: Fisheries and Aquaculture

C.1 Adaptation responses

C.1.1 Physical

Supporting physical processes

Prevent ocean mining (Jones et al. 2018)

Manage catchment vegetation to reduce sedimentation (Bell et al. 2018)

Hard engineering responses

Construction of earthen dams and coastal embankments to protect shrimp farms (Ahmed and Diana, 2015)

Netting, fencing and higher dikes around shrimp farms (Ahmed and Diana, 2015)

C.1.2 Ecological

Ecosystem restoration and protection

Retention of marine wilderness (Jones et al. 2018)

EbA measures (Heenan et al. 2015; Hobday et al. 2015; Cheung et al. 2018), including restoration of essential habitats (Roberts et al. 2017; Cheung et al. 2018)

Mangrove plantation and conservation of the Sundarbans for breeding grounds of shrimp (Ahmed and Diana, 2015)

Precautionary ecosystem-based integration measures (Ho et al. 2016)

Improving fishery management through the incorporation of traditional strategies and ecosystem management into fisheries management strategies (Weng et al. 2014)

Mangrove rehabilitation (Harkes et al. 2015)

Assisted evolution and relocation

Human assisted evolution (Harvey et al. 2018)

Nature based solutions

Afforestation of greenbelt in shrimp farming communities (Ahmed and Diana, 2015)

Maintain the structural complexity of fish habitats (Bell et al. 2018)

C.1.3 Social

Improving access to/storage of natural resources

Develop water irrigation facilities with proper drainage systems (Ahmed and Diana, 2015)

Flexible arrangements to allocate more of the tuna resources to local food security (Dunstan et al. 2018)

Improving agricultural or fisheries practices

Sustain recruitment and production of demersal fish (Bell et al. 2018)

Introduction of coastal fish breeding programs and sea ranching to enhance diversity of key species (Dasgupta et al. 2017)

Improvements in fishery management (Hobday et al. 2015; Gaines et al. 2018), including harvest policies that are adaptive to changing demographics (Gaines et al. 2018), reduced fishing effort and catch (Cheung et al. 2018; Jones et al. 2018), adopting precautionary principle (Hobday et al. 2015).

Diversify fishing methods (Ho et al. 2016) by transferring fishing efforts from reefs to large pelagic fish (Bell et al. 2018), implement near shore fish aggregating devices (Valmonte-Santos et al. 2016; Dunstan et al. 2018; Bell et al. 2018), develop fisheries for small pelagic species (Bell et al. 2018), improving post-harvest methods (Bell et al. 2018)

Improved post-harvest methods and food storage systems to stockpile tuna and small pelagic when good catches are made (Dunstan et al. 2018)

Coastal fisheries: targeting of coastal pelagic (but this is difficult for small-scale fishermen) (Weng et al. 2014)

Culture of prawn, shrimp, and fish with salt-tolerant and drought-resistant rice varieties (Ahmed and Diana, 2015)

Dike cropping (fruits and vegetables) and social forestation (Ahmed and Diana, 2015)

Increasing the diversity of seafood commodities (Ho et al. 2016)

Increasing aquaculture productivity (Ho et al. 2016)

Creating diverse marketing channels (Ho et al. 2016)

Promote sustainable growth of fisheries (Valmonte-Santos et al. 2016)

Reduce operational costs (Valmonte-Santos et al. 2016)

Development of aquaculture (Valmonte-Santos et al. 2016)

Responsive management to reflect changes in stock distribution (Pinsky et al. 2018)

Flexible management practices (no-take areas, gear restrictions) (Dunstan et al. 2018)

Restoration of deserted shrimp farms (Harkes et al. 2015)

Supporting natured-based industries

Sustainable resource use

Adjusting the scale of the fisheries (Ho et al. 2016)

Maintaining or switching livelihoods

Implementation of alternative livelihood programs for small-scale coastal communities (Dunstan et al. 2018)

Facilitating the fishing community's learning of alternative skills (Shaffiril et al. 2017)

Encouraging community-based entrepreneurship of small-scale shrimp farmers (Galappaththi et al. 2017)

Community participatory programmes

Stakeholder participation (Harvey et al. 2018)

Increased stakeholder participation and community-based grass-root planning (Salim et al. 2014)

Better communication with communities (through facilitators, appropriate mediums, appropriate times; and pictures) (Cvitanovic et al. 2016; Dunstan et al. 2018)

Participatory climate change adaptation planning for fishermen (Shaffiril et al. 2017)

Scenario-based stakeholder engagement (Finkbeiner et al. 2018)

Participatory conservation strategies (Harvey et al. 2018)

Developing adaptive networks

Effective use of social networks (Cvitanovic et al. 2016)

Strengthening social relationships (Shaffiril et al. 2017) for disaster preparation and cooperation within networks (Shaffiril et al. 2017)

Strengthening local social networks (Cvitanovic et al. 2016)

Sustainable household management

Strategies that build certain high-risk groups' networks (Novak Colwell et al. 2017)

Improving access to community services

Strengthening early warning systems in fisheries (Ho et al. 2016)

Increase investment in transportation and other infrastructural needs (Valmonte-Santos et al. 2016)

Empowering communities and addressing inequality

Develop capacity (Weng et al. 2014)

Autonomous and facilitative adaptation (Finkbeiner et al. 2018)

Guarantee access rights (Faraco et al. 2016) through recognition and protection of tenure (Gourlie et al. 2018)

Strategies that build certain high-risk groups' networks (Novak Colwell et al. 2017)

Building socioecological resilience

Enhancing societal adaption (Cvitanovic et al. 2016; Valmonte-Santos et al. 2016)

Sustainable socioecological systems (Harvey et al. 2018)

Multifaceted efforts that simultaneously tackle exposure, sensitivity and adaptive capacity (Islam et al. 2013)

Protection for local workers (Gourlie et al. 2018)

Community awareness and preparedness for disaster management (weather forecast and shelters) (Ahmed and Diana, 2015)

Strengthening civil society value in poor fishing communities (Cahaya, 2015)

C.1.4 Governance

Adopting/mainstreaming sustainability policies

Improve sustainable management of coastal fisheries through legislative action and regulatory implementation (Gourlie et al. 2018)

Sustainable conservation policies (Gourlie et al. 2018)

Design and implement management strategies that are robust to the uncertainties of changing marine ecosystems (Busch et al. 2016)

Climate compatible development (Harkes et al. 2015)

Improving disaster response programmes

Emergency preparedness programs (Dunstan et al. 2018)

Preparedness for disaster management (disaster warning and cyclone shelters) (Ahmed and Diana, 2015)

Strengthening early warning systems in fisheries (Hobday et al. 2015; Ho et al. 2016)

Community awareness and preparedness for disaster management (weather forecast and shelters) (Ahmed and Diana, 2015)

Improving implementation and coordination of policies

Greater attention to trade-offs in decision making regarding climate adaptation (Finkbeiner et al. 2018)

Improve sustainable management of coastal fisheries through legislative action and regulatory implementation (Gourlie et al. 2018)

Adaptively managing implementation strategies (Le Cornu et al. 2018)

Minimise conflicts between fishing nations (Asch et al. 2018) through support for co-management strategies (Gourlie et al. 2018)

Trading country-based allocations of fishing effort (Asch et al. 2018)

Strengthen international cooperation (Ho et al. 2016)

Flexible frameworks (Faraco et al. 2016)

Support for institutional coordination and policy cohesion (Gourlie et al. 2018)

Enabling policy and legislative environments (Heenan et al. 2015)

Aligning management measures (Heenan et al. 2015) with good governance and institutions (Heenan et al. 2015)

Resolve economic and political concerns that influence fisheries (Valmonte-Santos et al. 2016)

Empower actors to continuously learn and improve governance institutions (Nursey-Bray et al. 2018)

Lack of consistent frameworks and agreements across Pacific Islands (Cvitanovic et al. 2016)

Developing effective strategies and policy frameworks for managing adaptation of coastal communities to climate change (Colburn et al. 2016)

Application of international standards (Harkes et al. 2015)

Financial and regulatory mechanisms supporting aquaculture (Harkes et al. 2015)

Development controls

Adequate enforcement mechanisms (Gourlie et al. 2018)

Evidence-based implementation

Transparent resource management (Gourlie et al. 2018)

Improving ICM/MPAs

MPAs (Valmonte-Santos et al. 2016) to buffer against uncertainty in management, environmental fluctuations, directional change and extreme events, conserving biodiversity, repairing damaged fish stocks, creation of habitat forming areas, promote genetic diversity that provides raw material for adaptation to climate change (Roberts et al. 2017)

MPAs (Faraco et al. 2016; Dasgupta et al. 2017; Roberts et al. 2017; Asch et al. 2018; Jones et al. 2018) that include marine spatial planning for climate change (Le Cornu et al. 2018; Cheung et al. 2018; Harvey et al. 2018)

MPAs, positioning reserves in areas expected to warm less or not at all (Bruno et al. 2018)

Holistic adaptation planning using CbA and ICM (Ahmed and Diana, 2015)

MPAs may impact communities through fisheries closures (Bennett et al. 2016)

Identify appropriate climate-informed defence points for managing large marine reserves with appropriate strategies for management (Busch et al. 2016)

Horizontal/vertical integration of governance

Decentralisation and co-management (Harkes et al. 2015)

Developing partnerships and building capacity

Participatory conservation strategies (Harvey et al. 2018) and co-management of fisheries (Nursey-Bray et al. 2018; Pinsky et al. 2018)

Motivate stakeholders to self-organise, design and reform their institutions (Nursey-Bray et al. 2018)

Mobilise resources for decision making and implementations (Nursey-Bray et al. 2018)

Support for principles of fair governance, building relationships, two-way dialogues between government and industry, enhanced governance and leadership (Nursey-Bray et al. 2018)

Improving access to community services

Flexible arrangements to allocate more of the tuna resources to local food security (Dunstan et al. 2018)

Flexible licencing provisions (Dunstan et al. 2018)

Guarantee access rights (Faraco et al. 2016) through recognition and protection of tenure (Gourlie et al. 2018)

Pursuing climate justice

Increase allocation of area of the exclusive economic zone available to small-scale fishers (Dunstan et al. 2018)

C.1.5 Economic

Improving financial resources availability

Enhancing fishermen's access to credit (Shaffiril et al. 2017)

Includes fisheries agency budget planning to ensure funds are available for maintenance and repair of FADs (Dunstan et al. 2018)

Fuel and gear subsidies (Dunstan et al. 2018)

Improving access to insurance products

Creation of social safety nets, for example, insurance programs for small scale fisheries (SSF), community insurance banks for communities (Dunstan et al. 2018)

Reducing fishing risks through affordable insurance policies (Shaffiril et al. 2017) and innovative context-appropriate insurance practices (Shaffiril et al. 2017)

Economic diversification

Diversifying incomes for subsistence shrimp farmers (Galappaththi et al. 2017)

Increasing access to international funding programmes

C.1.6 Knowledge

Better monitoring and modelling

Scientific needs: ecosystem modelling to social science, economics, international politics and conflict resolution (Weng et al. 2014)

Monitoring, verification and management (Weng et al. 2014)

Effective monitoring and evaluative mechanisms (Le Cornu et al. 2018; Gourlie et al. 2018)

Climate model literacy training for marine biological researchers (Payne et al. 2017)

Better understanding climate stressors through enhanced social indicator modelling (Colburn et al. 2016)

Integrated end-to-end models that explore trade-offs (Hobday et al. 2015)

Improving planning processes

Identify areas of high risk and factors contributing to risk (Salim et al. 2014)

Improved adaptation science (Cvitanovic et al. 2016)

Improving forecasting and early warning systems

Improved marine ecological forecasting (Payne et al. 2017)

Develop effective prediction tools (Dunstan et al. 2018)

Community awareness and preparedness for disaster management (weather forecast, shelters) (Ahmed and Diana, 2015)

Seasonal forecasting of fisheries (Asch et al. 2018)

Improved forecasting (Ho et al. 2016)

Predicting productivity, spatial distribution and phenological changes (Payne et al. 2017)

Predicting human elements of the system (Payne et al. 2017)

Considering trade-offs in forecasting (Payne et al. 2017)

Horizontal and vertical range shifts in coastal fishes, eastward shifts of tuna stocks in the tropical Pacific, improved habitat in the east and declines in the Warm Pool region

Improving decision support frameworks

Acquiring reliable data to base decisions on and data sharing (Pinsky et al. 2018)

Use of a vulnerability indices to inform adaptation planning (Johnson et al. 2016)

Holistic adaptation planning using CbA and ICM (Ahmed and Diana, 2015)

Establishing mechanisms of food security classification management (Ho et al. 2016)

Appropriate design (Le Cornu et al. 2018)

Avoidance measures of climate risk and production uncertainty (Ho et al. 2016)

Develop tools to incorporate social vulnerability indicators into policy making (Colburn et al. 2016)

Improving participatory processes

Scientists working with communities (Cvitanovic et al. 2016) through participatory research approaches (Cvitanovic et al. 2016)

Engaging key actors in relevant forms of knowledge exchange (Cvitanovic et al. 2016; Faraco et al. 2016; Le Cornu et al. 2018; Payne et al. 2017; Finkbeiner et al. 2018)

Incorporating science with community needs and decision making at all scales (Cvitanovic et al. 2016) and participatory (Valmonte-Santos et al. 2016; Nursey-Bray et al. 2018) research approaches (Cvitanovic et al. 2016)

Co-producing knowledge with subsistence shrimp farmers (Galappaththi et al. 2017)

Coordinating top down and bottom up approaches

Bottom up approach to fisheries management (Salim et al. 2014)

Co-ordination with existing on-ground activities (Cvitanovic et al. 2016)

Integrating knowledge systems

Collecting and integrating diverse sources of information (Le Cornu et al. 2018)

Improving fishery management through the incorporation of traditional strategies and ecosystem management into fisheries management strategies (Weng et al. 2014)

Traditional knowledge (Johnson et al. 2016)

Recognition and support for local communities and traditional management (Gourlie et al. 2018)

Improving location and context specific knowledge

Increased investigation of natural resource management issues through a gendered lens (Novak Colwell et al. 2017)

Adaptive management strategies based on market intelligence (Rodríguez-Rodríguez and Bande Ramudo, 2017)

Improving scientific communication

The use of mobile technology to warn fishermen of threats (Shaffiril et al. 2017)

Information for improved fisheries management strategies (Weng et al. 2014)

Data, research and information sharing (Gourlie et al. 2018)

Information exchange between stakeholders (Heenan et al. 2015)

Stakeholder identification, outreach and education

Community training programmes with sharing of technical knowledge and awareness (Salim et al. 2014)

Informing fishermen of the value and importance of having insurance (Shaffiril et al. 2017)

Education of a marine fish-eating culture (Ho et al. 2016)

Support and train stakeholders to use forecast models effectively, engaging end-users (Payne et al. 2017)

Provide technical assistance to subsistence fishers (Valmonte-Santos et al. 2016)

Multiple adaptation responses used

Reduction in local anthropogenic stressors (Harvey et al. 2018)

EbA measures which respond to local vulnerability context (Faraco et al. 2016)

CbA and ICM (Ahmed and Diana, 2015)

Improving fishery management through the incorporation of traditional strategies and ecosystem management into fisheries management strategies (Weng et al. 2014)

Synergistic responses addressing social, governance and knowledge responses (Dunstan et al. 2018)

Synergistic social adaptation strategies should be applied (Shaffiril et al. 2017)

Holistic adaptation planning using CbA and ICM (Ahmed and Diana, 2015)

C.2 Benefits

C.2.1 Ecological

Ecosystem/ecological resilience supported

Reduction of human stressors in MPAs promotes ecosystem recovery and prevents biodiversity loss (Roberts et al. 2017)

Maintain healthy reefs (Harvey et al. 2018)

Supports development of shrimp industry with less damage to mangroves and salt marshes (Harkes et al. 2015)

Physical processes supported

High abundance of mesopelagic fish in open ocean MPAs may enhance CO_2 absorption and buffer acidification near the surface through excretion of gut carbonate, protect apex predators that confer increased stability to coastal habitats that buffer climate-induced instabilities (Roberts et al. 2017)

Reduced fishing pressure on reef resources (Valmonte-Santos et al. 2016)

Increased biodiversity

Reduction of human stressors in MPAs promotes ecosystem recovery and prevents biodiversity loss (Hobday et al. 2015; Roberts et al. 2017)

Preserve species with large home ranges (Jones et al. 2018)

Habitat range shifts accommodated

MPAs provide steppingstones for dispersal and safe landing zones for climate migrants (Roberts et al. 2017) maintaining high levels of ecological and evolutionary connectivity (Jones et al. 2018)

Improved organismal fitness

Increased reproductive outputs (Cheung et al. 2018)

Genetic heterogeneity supported

Increased genetic variability (Cheung et al. 2018; Jones et al. 2018)

Strengthened socioecological system

Promotion of socioecological resilience (Ahmed and Diana, 2015; Harkes et al. 2015)

C.2.2 Social

Access to sustainable ecosystem services

Improved ecosystem services (Faraco et al. 2016)

Preservation of marine resources (Cahaya, 2015)

Reduction of human stressors in MPAs enhances livelihoods and ecosystem services (Roberts et al. 2017)

Increases in maximum catch potential (Asch et al. 2018) and global fishery yield (Gaines et al. 2018)

Helps sustain the contribution of coastal fisheries to food security (Bell et al. 2018)

Ensure food security (Heenan et al. 2015; Asch et al. 2018; Finkbeiner et al. 2018) by replenishing depleted stocks (Bell et al. 2018)

Higher fish production (Valmonte-Santos et al. 2016)

Increased catch per unit of effort (Valmonte-Santos et al. 2016)

Reduction in reliance on fish imports (Valmonte-Santos et al. 2016)

Supports development of shrimp industry with less damage to mangroves and salt marshes (Harkes et al. 2015)

Improved socioeconomic services

Enhanced food security (Cvitanovic et al. 2016; Le Cornu et al. 2018; Gaines et al. 2018) and nutritional status of Pacific Island countries (Valmonte-Santos et al. 2016)

Healthier shrimp industry (Harkes et al. 2015)

Improved employment and livelihoods

Reduction of human stressors in MPAs enhances livelihoods and ecosystem services (Roberts et al. 2017)

Sustaining livelihoods (Harkes et al. 2015; Harvey et al. 2018) through securing employment (Le Cornu et al. 2018)

Uplifting the living standard of fishermen (Cahaya, 2015) by supporting local livelihoods (Heenan et al. 2015; Faraco et al. 2016; Payne et al. 2017; Finkbeiner et al. 2018; Gourlie et al. 2018), well-being (Gourlie et al. 2018), culture (Finkbeiner et al. 2018) and sovereignty (Finkbeiner et al. 2018)

Prevent and reduce poverty (Faraco et al. 2016; Payne et al. 2017)

Facilitates diversification of effort (Gourlie et al. 2018)

Supports livelihoods and contributes to food security and well-being of coastal and freshwater systems (Galappaththi et al. 2017)

Improved health

Reduces disease through lower use of chemicals (Harkes et al. 2015)

Increased adaptive capacity

Increased adaptive capacity (Cvitanovic et al. 2016)

Social transformation towards sustainability (Galappaththi et al. 2017)

Empowered communities

Empowerment of communities (capacity building) (Ahmed and Diana, 2015)

Empowering small-scale fishers (Bell et al. 2018)

Facilitates community-level ownership of adaptation (Gourlie et al. 2018)

Improved community cohesion

Incentivises collective action (Faraco et al. 2016)

Reduced inequality

Increases equity (shared benefits) and productivity (Harkes et al. 2015)

C.2.3 Governance

Strengthened participatory governance

Co-management enhances ownership over decision making processes (Nursey-Bray et al. 2018)

Better planning processes supported

Co-management promotes greater sensitivity to socioeconomic and ecological constraints (Nursey-Bray et al. 2018)

Ensures measures are appropriate for the local context (Le Cornu et al. 2018)

Address complex issues like climate change by contributing to reduce uncertainty and by

Avoiding or, at least limiting, the unbalance of pre-existing governance systems (Rodríguez-Rodríguez and Bande Ramudo, 2017)

Improved implementation and policies

Sustainable fisheries management (Gourlie et al. 2018)

Better communication

Improved communication (Cvitanovic et al. 2016)

Improved transparency and trust

Co-management improves management outcomes, promotes collective ownership, increases compliance; ensures better monitoring, control and surveillance and encourages diverse knowledge sharing (Nursey-Bray et al. 2018)

Trust building (Cvitanovic et al. 2016)

Climate justice advanced

Maintenance of common property rights over resources (Faraco et al. 2016)

Reduced conflict

Minimise conflicts between fishing nations (Asch et al. 2018) including with new fish stocks (Pinsky et al. 2018)

Improved security

Maintain security (Finkbeiner et al. 2018)

Improved adaptive management

Aid disaster preparedness (Asch et al. 2018)

Improved climate adaption decision making (Finkbeiner et al. 2018)

Enable adaptive capacity in fisheries management (Nursey-Bray et al. 2018)

Allows for better informed adaptive responses (Payne et al. 2017)

MPAs provide steppingstones for dispersal and safe landing zones for climate migrants (Roberts et al. 2017) maintaining high levels of ecological and evolutionary connectivity (Jones et al. 2018)

Require adaptive management and consideration of the cumulative effects (Gourlie et al. 2018)

Enhances the analytical capabilities within fisheries, enhancing informed ecosystem-based fisheries management and policy decisions (Colburn et al. 2016)

C.2.4 Economic

Increased revenue/income

Export creation opportunities, commercial development and the creation of jobs (Valmonte-Santos et al. 2016)

Better bargaining power producers and higher production lead to higher profits (Harkes et al. 2015)

Increased financial resources available

Subsidies required to support adaptions (Bell et al. 2018)

Promote economic growth (Asch et al. 2018)

Possibility of funding mechanisms (Gourlie et al. 2018)

C.2.5 Knowledge

Informed decision making tools

Collection of key information (Gourlie et al. 2018)

Reduce risks and uncertainties associated with seafood supply (Ho et al. 2016)

Create a more integrated picture of climate change (Colburn et al. 2016)

Enhances the analytical capabilities within fisheries, enhancing informed ecosystem based fisheries management and policy decisions (Colburn et al. 2016)

Provides a blueprint for strengthening the production and use of climate-related information needed promote effective fisheries management in a changing climate (Busch et al. 2016)

Better knowledge inputs on markets behaviour may help avoiding or limiting i) too much anticipated and highly uncertain responses, rushing for mitigation without clear evidence, and ii) short-term reactions, tending to overexploitation of natural resources as a way to maintain producers income (Rodríguez-Rodríguez and Bande Ramudo, 2017)

Improved co-production of knowledge

Improved understanding of strategies outcomes for at risk groups and gender (Novak Colwell et al. 2017)

Stimulates exchange of information and knowledge (Harkes et al. 2015)

Improved relevance of products

Understanding both high-level processes and individual-level relationships, provides valuable insight into people's livelihood choices that traditional models of gender and the environment do not (Novak Colwell et al. 2017)

C.3 Constraints and limitations

C.3.1 Physical

Geographic remoteness from markets of reasonable size (Valmonte-Santos et al. 2016)

C.3.2 Ecological

Complex interactions between species and habitats (Bell et al. 2018)

Certain responses may demand higher energy use and thus increase CO_2 emissions, The construction of shrimp farms leads to the removal of above and below ground carbon, along with the potential for future carbon sequestration, increased shrimp farms require mangroves to be removed for space and pollute surface water (Harkes et al. 2015)

C.3.3 Social

Less developed coastal countries have a high dependence on the oceans for food and livelihood, while having limited adaptive capacity (Cheung et al. 2018)

Lack of trust among local communities and external scientists (Cvitanovic et al. 2016)

Engagement of end users in climate change science (Cvitanovic et al. 2016)

Limiting adaption and diversification options (Faraco et al. 2016)

Uneven socioeconomic impacts of climate change (Finkbeiner et al. 2018)

Difficulty in balancing social and ecological objectives (Finkbeiner et al. 2018)

Involves reforms for many stock (Gaines et al. 2018)

Limited assets (Cahaya, 2015)

Lack of bargaining power (Cahaya, 2015)

Reduction of aquaculture and degradation of aquaculture areas ((Ho et al. 2016)

Lack of effective adaptation strategies ((Ho et al. 2016)

Dependency on marine fisheries for livelihoods, lack of alternative livelihood (Islam et al. 2013)

Lack of physical, natural and financial capital (Islam et al. 2013)

Small scale fisheries are extremely intricate social-ecological systems (Le Cornu et al. 2018)

Inshore resources are heavily exploited and offshore resources are difficult to access for subsistence fishers (Valmonte-Santos et al. 2016), slow development in aquaculture (Valmonte-Santos et al. 2016)

High fuel costs, lack of appropriate fishing gear and limited infrastructure (Valmonte-Santos et al. 2016) in a highly competitive industry

Lack of awareness of coastal communities of the consequences of over-exploitation (Valmonte-Santos et al. 2016)

Limited interaction between stakeholders (Valmonte-Santos et al. 2016)

High likelihood of individuals employing reactive strategies that may threaten their longer-term livelihood sustainability (Novak Colwell et al. 2017)

Lack of intersectionality in resource management research (Novak Colwell et al. 2017)

C.3.4 Governance

Conflicts between fishing nations as stocks migrate (Asch et al. 2018; Gaines et al. 2018)

Emerging conflict between maximising yield of target species and maintaining ecosystem structure/function. Solutions to one of the conflicts may work against a solution for another (Hobday et al. 2015)

Lack of fisheries management and conservation plans (Cheung et al. 2018)

Lack of consideration of climate risk in species conservation planning (Cheung et al. 2018)

Lack of cohesive and connected co-management frameworks within fisheries management arrangements (Nursey-Bray et al. 2018)

Co-management lacks resources and legislation conducive to building fishery support (Nursey-Bray et al. 2018)

Lack of effective international coordination (Cheung et al. 2018; Gaines et al. 2018)

Effective management in Pacific Island communities (Cvitanovic et al. 2016)

Inappropriate governance structures (Heenan et al. 2015; Cvitanovic et al. 2016)

Lack of political and technical support (Cvitanovic et al. 2016)

Lack of consistent frameworks and agreements between Pacific Island nations and local government levels(Cvitanovic et al. 2016)

Problems with access to and management of natural resources (Faraco et al. 2016)

Poor biodiversity and conservation policies (Faraco et al. 2016)

Limited financial and political support (Faraco et al. 2016)

Coastal fisheries receive less attention from government managers (Gourlie et al. 2018)

Legislation gaps (Gourlie et al. 2018)

Legally challenging (Jones et al. 2018), difficulties with enforcing compliance beyond national jurisdiction (Jones et al. 2018)

The current legal framework does not directly account for changing distributions (Pinsky et al. 2018)

Prevailing weak management of fish stocks globally (Pinsky et al. 2018)

Minimal cooperation between regional fishing management organisations on the potential for future shared stocks (Pinsky et al. 2018)

Judicial decisions do not always resolve conflicts and require adherence by the parties (Pinsky et al. 2018)

Limited institutional capacities (Valmonte-Santos et al. 2016)

Concerns about managing displaced fishing efforts with MPAs (Roberts et al. 2017)

Lack of institutional and financial support to establish buffer zones; although there are shrimp farmers associations, the activities of individual farms, are not coordinated; access to loans and insurance is difficult as interest rates are high and government support is lacking; absence of a specific law for aquaculture (Harkes et al. 2015)

C.3.5 Economic

Lack of resources (Cvitanovic et al. 2016; Bell et al. 2018)

Weak capital structures (Cahaya, 2015)

Limited financial and technical resources (Valmonte-Santos et al. 2016)

MPAs under-resourced. Lack of staff, equipment and funding (Roberts et al. 2017)

Global market and demographic shifts (Le Cornu et al. 2018)

C.3.6 Knowledge

Lack of frequent data collection (Heenan et al. 2015) and management updates (Gaines et al. 2018)

Lack of access to data and science (Cahaya, 2015)

Lack of scientific knowledge and studies (Rodríguez-Rodríguez and Bande Ramudo, 2017). Risks of mismanagement resulting from lack of scientific knowledge, focus on market intelligence may distract from the root causes of system degradation (Rodríguez-Rodríguez and Bande Ramudo, 2017)

Lack of studies relating to fish migration and live-release by-catch survival rates, great deal of coordination required to collect some indicators, difficult to collect indicators as the open sea is so vast (Hobday et al. 2015)

Future projections of ocean conditions are uncertain (Cheung et al. 2018) and it is difficult to predict where fish distribution will shift to (Gaines et al. 2018)

Limited knowledge on the sensitivity and adaptive capacity of marine species to climate change and fishing (Cheung et al. 2018)

Cultural differences between western science and cultural knowledge (Cvitanovic et al. 2016)

Challenges related to defining the human component of ecological systems (Payne et al. 2017)

Gap between climate modelling and marine science communities (Payne et al. 2017)

Access to forecast data, focus of marine science has been on describing rather than predicting systems, complexity of biological systems, difficulty observing life in the ocean (Payne et al. 2017)

Lack of awareness and engagement by fishers surrounding climate issues (Salim et al. 2014)

Uncertainty surrounding the environmental tolerances and adaptability for most species when planning MPAs (Bruno et al. 2018)

Inadequate communication and support with local communities in relation to MPA management (Roberts et al. 2017)

Knowledge of climate-induced impacts and vulnerability on the local-scale of fishery-based livelihoods is limited (Islam et al. 2013)

Research that is too focussed on gender can further marginalise other women and also large segments of the male population, great potential to exacerbate existing inequitable power structures (Novak Colwell et al. 2017)

C.4 Costs

C.4.1 Physical

Inundation of infrastructure to allow for mangroves to migrate inland (Bell et al. 2018)

Vandalism and natural disasters (Valmonte-Santos et al. 2016)

C.4.2 Economic

Expensive to raise and plant seedlings (Bell et al. 2018)

Resources required for monitoring (Bell et al. 2018)

Unequal distribution of costs and benefits (Faraco et al. 2016)

MPAs are a viable low-tech and cost effective adaption strategy (Roberts et al. 2017)

C.4.3 Knowledge

Forecast may be used and interpreted incorrectly (Payne et al. 2017)

Forecasts may fail in a technical sense (Payne et al. 2017)

Participatory research approaches need to be sustained (Cvitanovic et al. 2016)

D. Human System: Coastal Tourism

D.1 Adaptation responses

D.1.1 Physical

Hard engineering responses

High financial investments for construction of hard protection structures (Rangel-Buitrago et al. 2015)

Regulated tidal exchange infrastructure (MacDonald et al. 2017)

Managed retreat and coastal realignment

Large coastal managed realignment projects (MacDonald et al. 2017)

D.1.2 Ecological

Nature based solutions

Natural resource management (Papageorgiou, 2016) and economic evaluations of ecosystem value (Hernández-Delgado, 2015)

D.1.3 Social

Sustainable resource use

Sustainable water use management (Papageorgiou, 2016; Klinsky et al. 2017)

Promote wise allocation of coastal and marine tourism activities so as to mitigate environmental degradation (Papageorgiou, 2016)

Empowering communities and addressing inequality

Improving stakeholders in the tourism industry's understanding of their vulnerability to climate change to empower them to take appropriate actions to adapt (Tapsuwan and Rongrongmuang, 2015)

D.1.4 Governance

Developing partnerships and building capacity

Developing public-private partnerships (Klinsky et al. 2017)

D.1.5 Economic

Improving financial resources availability

Involving the tourism industry in adaption finance (Klinsky et al. 2017)

Adaptation taxes and levies (Klinsky et al. 2017)

Adaptation strategies to counteract market share losses induced by climate change (Bujosa et al. 2015)

Improving access to insurance products

Risk transfer mechanisms (Klinsky et al. 2017)

Improving access to international funding programmes

Adaptation funds (Klinsky et al. 2017)

D.1.6 Knowledge

Better monitoring and modelling

Hadley Centre Coupled Model (HadCM3)and Canadian Global Climate Model (CGCM2) (Bujosa et al. 2015)

Improving decision support frameworks

Matrix of exposition degree versus adaptive capacity. Diagram for Integrated Coastal Vulnerability Assessment (Lins-de-Barros, 2017)

Generic management framework (Michailidou et al. 2016)

Protection Motivation Theory framework (Tapsuwan and Rongrongmuang, 2015)

Social representation of managed realignment (Schliephack and Dickinson, 2017)

Using marine spatial planning to organise and plan coastal and marine tourism activities (Papageorgiou, 2016)

Stakeholder identification, outreach and education

Changing perceptions of key stakeholders (Klinsky et al. 2017)

Multiple adaptation responses used

Natural resource management, governance, economic efficiency and welfare maximisation (Hernández-Delgado, 2015)

D.2 Benefits

D.2.1 Physical

Physical processes supported

Restores intertidal habitat by removing or breaching built infrastructure so the land behind them floods, allowing the intertidal habitat to migrate inland (MacDonald et al. 2017)

Hard engineering responses

Many protection structures have been built and installed in response to local stakeholder pressure (Rangel-Buitrago et al. 2015)

D.2.2 Ecological

Ecosystem/ecological resilience supported

Coastal protection services offered by ecosystems (Hernández-Delgado, 2015)

Promotes resilience against climate change effects (Papageorgiou, 2016)

Increased biodiversity

Biodiversity benefits provided by ecosystems supports coastal tourism (Hernández-Delgado, 2015)

D.2.3 Social

Improving access to/storage of natural resources

Healthy ecosystems improve access to services like fisheries, construction materials, medicines, cosmetics and the aquarium trade (Hernández-Delgado, 2015)

Intertidal habitats provide significant ecosystem services, such as carbon sequestration in accreting sediments, flood defences for coastal communities, hunting of wintering wildfowl and nursery areas for commercially-caught fish (MacDonald et al. 2017)

Human systems supported

A more resilient tourism industry (Bujosa et al. 2015; Hernández-Delgado, 2015; Klinsky et al. 2017)

Ensures that that coastal and marine space is not overwhelmed by tourism facilities and activities (Papageorgiou, 2016)

Increased adaptive capacity

Enhanced adaptation to climate change effects (Papageorgiou, 2016)

D.2.4 Governance

Development supported

Fostering development (Klinsky et al. 2017)

D.2.5 Economic

Increased revenue/income

Generate employment (Klinsky et al. 2017)

Increased tax revenues (Klinsky et al. 2017)

Justifying the value of protecting natural resources (Klinsky et al. 2017)

Ensures good environmental conditions for the tourism industry to prosper (Papageorgiou, 2016)

Reduced conflict

Minimises conflicts and create synergies among sectors (Papageorgiou, 2016)

D.2.6 Knowledge

Improving decision support frameworks

Multi-criteria decision making assessments improved (Lins-de-Barros, 2017)

Allows for benchmarking when choosing interventions/measures/alternatives by taking into consideration local specific characteristics (Michailidou et al. 2016)

Social representation of managed realignment shapes wider understandings of climate change adaptation (Schliephack and Dickinson, 2017)

D.3 Constraints and limitations

D.3.1 Governance

Public policy changes and reliability (Klinsky et al. 2017)

Non-transparent and unreliable political systems (Klinsky et al. 2017)

Need to update current legislation with strong coastal management laws (Rangel-Buitrago et al. 2015)

The performance of managed realignment specifically in delivering ecosystem services and biodiversity benefits in England has been questioned (MacDonald et al. 2017)

D.3.2 Social

Cumulative effects of coastal tourism may affect multiple ecosystem functions, compromise food security and sovereignty, public health, local economies and people's livelihood sustainability in still largely unknown ways (Hernández-Delgado, 2015)

D.3.3 Economic

Development of international tourism flows (Klinsky et al. 2017)

Knowledge; Unclear magnitudes and time scales of regional and local climate change impacts (Klinsky et al. 2017)

Reluctance to finance adaptation in the tourism sector (Klinsky et al. 2017)

Finding sustainable arrangements for funding and financing coastal management legislation (Rangel-Buitrago et al. 2015)

D.3.4 Knowledge

Unclear magnitudes and time scales of regional and local climate change impacts (Klinsky et al. 2017)

This paper focused on a specific destination with unique features and a tailored managed realignment strategy. Strategies, features of tourism interest and use values will vary in other destinations (Schliephack and Dickinson, 2017)

Fuzzy and multidisciplinary nature of tourism creates difficulty in identifying synergies and conflicts; coastal and marine tourism are generally perceived as non-threatening activities to other human uses. Requires much more time and effort than less effective responses (Papageorgiou, 2016)

D.4 Costs

D.4.1 Governance

Need for government incentive and frameworks (Klinsky et al. 2017)

D.4.2 Economic

The overall costs of climate change may be equivalent to losing at least 5% of the global GDP each year (Bujosa et al. 2015)

The greater the uncertainty associated with biophysical estimates, the less easy it is to determine how economically valuable a strategy like managed realignment may be. Intertidal sediment accretion is dynamic and site-dependent, such that applying values from other sites could be inaccurate (MacDonald et al. 2017)

E. Human System: Government Systems

E.1 Adaptation responses

E.1.1 Ecological

Ecosystem restoration and protection

Enhancing coral reefs and mangroves for ecosystem services (Gallo et al. 2017)

E.1.2 Social

Developing adaptive networks

Network building (Aylett, 2015)

E.1.3 Governance

Adopting/mainstreaming sustainability policies

Investment and policies for adaptation to climate change (Buurman and Babovic, 2016)

Mainstreaming and integration of adaptation policies (Aylett, 2015)

Apply a precautionary approach until accurate science is available (Johnson et al. 2018)

Improving disaster response programmes

Integrative risk management (Gerkensmeier and Ratter, 2018)

Improving implementation and coordination of policies

Improving synergies (Aylett, 2015; Rosendo et al. 2018)

Supporting marine and coastal Nationally Determined Contributions (Gallo et al. 2017)

Aligning the policies of local authorities (Porter et al. 2015)

Development of targets and statutory duties for local authorities (Porter et al. 2015)

Cross-sectorial approaches (Serrao-Neumann et al. 2013)

Modern legislation and administrative solutions (Vikolainen et al. 2017)

Formal institutional reforms (Aylett, 2015)

Crosscutting action across multiple sectors of urban life carried out by a variety of actors, coordinated policy responses across multiple sectors (Aylett, 2015)

Multi-functionality: a solution that meets societal demands and generates socioeconomic and environmental opportunities (Vikolainen et al. 2017)

Adequate governance and management systems (Johnson et al. 2018)

Increase co-operation between contracting parties and marine sub-regions (Gormley et al. 2015)

Improving ICM/MPAs

MPAs (Gallo et al. 2017; Johnson et al. 2018)

Improving ICM/MPAs (Rosendo et al. 2018)

Incorporating climate science into MPAs network processes. Consider how marine biodiversity will change in the future. Design criteria for climate change resilience (Hopkins et al. 2016)

Area-Based Management Tools. Evaluate levels of connectivity to see where new alternative areas are best located (Johnson et al. 2018)

Develop adaptive management strategies for Priority Marine Habitats and increase MPAs in some sub-regions (Gormley et al. 2015)

Bi-directional knowledge sharing and stakeholder participation in ICZM (Abelshausen et al. 2015)

Horizontal/vertical integration of governance

Multi-level governance systems (Serrao-Neumann et al. 2013)

Increase co-operation between contracting parties and marine sub-regions (Gormley et al. 2015)

Developing partnerships and building capacity

Strengthen capacity of local marine institutions (Gallo et al. 2017)

Community governance responses (Nunn et al. 2014) including empowering community leaders to make appropriate decisions, bolstering stakeholder awareness of the science surrounding climate change (Nunn et al. 2014)

Strengthening local governance (Paterson et al. 2017)

Building capacity at a local level (Paterson et al. 2017)

Building collaborative networks between municipal agencies (Aylett, 2015)

Improve collaborative efforts (Johnson et al. 2018)

Pursuing climate justice

Climate change research must include equity issues (Klinsky et al. 2017)

E.1.4 Knowledge

Better monitoring and modelling

Improve scientific climate models and marine observations (Gallo et al. 2017; Johnson et al. 2018)

Monitoring processes at the coast (Gerkensmeier and Ratter, 2018)

Strong monitoring frameworks; employing an adaptive approach to the overall management of an MPA network (Hopkins et al. 2016)

Draw up an Atlantic-wide assessment and monitoring programme (Johnson et al. 2018)

The use of predictive Species Distribution Modelling methods (Gormley et al. 2015)

Improving decision support frameworks

Development of more policy-focused adaptation science (Porter et al. 2015)

Scenario planning, mathematical modelling, multi-criteria analysis, adaptation pathways approach to decision making (Buurman and Babovic, 2016)

Incorporating climate science into MPAs network processes (Hopkins et al. 2016)

Improving participatory processes

Risk analysis and assessment, using stakeholder perceptions to define risk, improving multi-stakeholder partnerships, participative and flexible risk management processes (Gerkensmeier and Ratter, 2018; Rosendo et al. 2018)

Bi-directional knowledge sharing and stakeholder participation in ICZM includes stakeholders as co-designers and co-decision makers (Abelshausen et al. 2015)

Integrating knowledge systems

Takes traditional values into account and ensures that responses meet the needs of the stakeholders (Abelshausen et al. 2015)

Improving location and context specific knowledge

Assessing and addressing knowledge gaps (Cooley et al. 2016)

Stakeholder identification, outreach and education

Educational programmes (Aylett, 2015)

Increased education and outreach programmes (Cooley et al. 2016)

Creates a platform that allows for bi-directional knowledge sharing and improves social learning (Abelshausen et al. 2015)

E.2 Benefits

E.2.1 Physical

Supporting physical processes

Major sink for CO_2 and for the heat resulting from the associated greenhouse effect (Johnson et al. 2018)

E.2.2 Ecological

Ecosystem restoration and protection

Promotes the sustainable use, development and protection of coastal environments (Rosendo et al. 2018)

Enhance the resilience of species and habitats to climate change impacts (Hopkins et al. 2016)

Provide important habitat for resident and migratory species of fish, sea birds and marine mammals (Johnson et al. 2018)

Protecting biodiversity and setting appropriate conservation priorities (Gormley et al. 2015)

Raises the potential for habitat restoration as well as the risks posed by non-indigenous species as niches become available (Gormley et al. 2015)

E.2.3 Social

Sustainable resource use

Promotes the sustainable use, development and protection of coastal environments (Rosendo et al. 2018)

Improved employment and livelihoods

Improved human well-being (Klinsky et al. 2017)

Improved community participation

Anchors coastal risk management within society; strengthens multi-risk, multi-scale and multi-stakeholder perspectives; enhance participation and communication between stakeholders (Gerkensmeier and Ratter, 2018; Rosendo et al. 2018)

Increased adaptive capacity

Help marine resource-dependent communities adapt to existing acidification (Cooley et al. 2016; Rosendo et al. 2018)

Improving access to community services

Provide cultural services that are important to (coastal) nations and their citizens (Johnson et al. 2018)

Reduced inequality

A focus on equity establishes long-term legitimacy for strategies (Klinsky et al. 2017), informing implications of trade-offs for diverse individuals and groups (Klinsky et al. 2017)

E.2.4 Governance

Better planning processes supported

Enhanced consideration of social processes in risk management (Gerkensmeier and Ratter, 2018; Rosendo et al. 2018)

Improve future systematic conservation planning (Johnson et al. 2018)

Improved implementation and policies

Improved service delivery (Aylett, 2015)

Improved rationality and effectiveness of policy making (Serrao-Neumann et al. 2013; Rosendo et al. 2018)

Reduced policy contradictions (Serrao-Neumann et al. 2013)

Reduced trade-offs (Serrao-Neumann et al. 2013)

Improved transparency and trust

Improved transparency (Serrao-Neumann et al. 2013)

Horizontal/vertical integration of governance

Support the local implementation of national climate change policy, bridges different administrative scales (national, regional, local) (Rosendo et al. 2018)

Improved adaptive management

Improved governance for climate adaptation (Serrao-Neumann et al. 2013)

Enables management for a changing climate (Gormley et al. 2015)

Addresses disruption to habitat connectivity and the coherence of MPA networks if these habitats become fragmented, highlights certain theoretical problems (Gormley et al. 2015)

E.2.5 Economic

Increased revenue/income

Economic growth and innovation (Vikolainen et al. 2017)

Increased financial resources available

Financial incentives for countries reliant on marine fisheries (Gallo et al. 2017)

Knowledge

Informed decision making tools

Real Options Analysis and Adaption Pathways allows for increased flexibility, takes into account uncertainties associate with climate change, better policies and investments, prepares for various future outcomes (Buurman and Babovic, 2016)

Improved co-production of knowledge

Multi-functional natural infrastructure helps develop knowledge and innovation (Vikolainen et al. 2017)

E.3 Constraints and limitations

E.3.1 Physical

Impacts of climate change are not confined to spatial or sectorial boundaries (Serrao-Neumann et al. 2013)

Preference for hard measures by local authorities (Vikolainen et al. 2017)

E.3.2 Social

Measures can stall when larger coalitions of individuals are needed for approval (Cooley et al. 2016)

E.3.3 Governance

Competing local priorities (Aylett, 2015)

Silo culture in local governance agencies (Aylett, 2015)

Lack of capacity (Serrao-Neumann et al. 2013; Aylett, 2015; Porter et al. 2015)

Lack of a champion to push adaption policy at the local level (Porter et al. 2015)

Lack of effective coordination across sectors (Serrao-Neumann et al. 2013)

Institutional weakness of environmental agencies (Aylett, 2015) and institutional fragmentation (Porter et al. 2015)

No single model for the institutionalisation of local climate adaptation planning (Aylett, 2015)

Organisational complexity, nascent and varied efforts to effectively institutionalise adaption planning (Aylett, 2015)

Complex, interlinked systems with manifold uncertainties (Buurman and Babovic, 2016)

Leadership challenges (Aylett, 2015; Cooley et al. 2016)

Lack of local government jurisdiction over key policy areas (Aylett, 2015)

No national approach to coastal management (Vikolainen et al. 2017)

Difficulty mainstreaming climate change into existing departmental functions (Aylett, 2015)

Unwillingness of senior management to depart from established job descriptions and departmental mandates (Aylett, 2015)

Inconsistency between local measures (Cooley et al. 2016)

Political will drives the consideration of marine issues within national climate action plans (Gallo et al. 2017)

Lack of political support (Serrao-Neumann et al. 2013; Porter et al. 2015)

Practical implementation of Integrated Risk Management Approach is a major challenge (Gerkensmeier and Ratter, 2018)

Coastal management is not viewed as a priority by national government (Vikolainen et al. 2017)

Lack of awareness among key community decision makers about climate change and associated environmental sustainability (Nunn et al. 2014)

Inappropriateness of traditional decision making structures for dealing with climate change (Nunn et al. 2014)

Short-term views of resource management and sustainability held by many community decision makers (Nunn et al. 2014)

Shifting of responsibility from central government towards local actors has not been accompanied by adequate human or financial resources (Paterson et al. 2017)

Structural barriers faced by local authorities (Paterson et al. 2017)

Personalities are often the basis of interaction and not organisational structures (Paterson et al. 2017)

Poor coordination between levels of government (Porter et al. 2015) and within organisations (Vikolainen et al. 2017)

Climate adaptation is not viewed as important as meeting immediate obligation by local authorities (Porter et al. 2015)

Time lag between policy development, implementation and on-ground outcomes (Serrao-Neumann et al. 2013)

Legislative barriers (Serrao-Neumann et al. 2013)

Different stages of development of coastal management policy and legislation in countries, difficulties relating to defining the roles and responsibilities of different levels of government, lack of funding to undertake climate change impact assessments, and financial and human capacity constraints (Rosendo et al. 2018)

Personnel, relevant skills, and sustainable mechanisms for collaboration and coordination of coastal issues across different sectors and stakeholders

E.3.4 Economic

Resource related challenges (Serrao-Neumann et al. 2013; Aylett, 2015; Porter et al. 2015; Cooley et al. 2016)

Large cities are prioritised in terms of human and economic assets and political visibility (Paterson et al. 2017)

Mismatch between the aspirations of the community and the finite funds available at national level (Vikolainen et al. 2017)

Few MPA programmes have directly considered climate change in the design, management or monitoring of an MPA network, adaptive management of MPA networks is important but hard to implement, Conflict exists between local and national initiatives with differing priorities and differing capacities to implement MPAs or MPA networks; The slow process of implementation; jurisdictional complexity of the MPA process; legal or political barriers and realities (Hopkins et al. 2016)

A large portion of the sea lies beyond national jurisdiction; more research is needed on the impacts of pH and reduction in the Atlantic Meridional Overturning Circulation to complete impact assessments; lack of climate models with high precision for a 20–50 year time horizon, lack of research related to ecosystem responses (Johnson et al. 2018)

Focus on ICM at the local level will divert resources from other competing issues (Rosendo et al. 2018)

E.3.5 Knowledge

Challenges related to information and awareness (Aylett, 2015)

Problem framing arises from the aims of dominant policy actors (Paterson et al. 2017)

Information needed for effective decision making is centralised at a national level (Paterson et al. 2017)

Technical-cognitive barriers to adaption (Porter et al. 2015)

Lack of usable scientific information (Porter et al. 2015)

Focus on immediate risks (Porter et al. 2015)

Lack of examples of environmental policy integration emerging from practice (Serrao-Neumann et al. 2013)

Limited understanding of the concept of integration for climate adaptation (Serrao-Neumann et al. 2013)

Structural inequality and different worldviews constrain planning with a focus on equity (Klinsky et al. 2017)

Assumptions that concerns for equity create barrier for climate action (Klinsky et al. 2017)

Model uncertainties at high resolution; current marine management strategies are concerned with managing the status quo; regional differences in the predicted changes and some countries will experience greater/different changes than others (Gormley et al. 2015)

Great reluctance for change affects the implementation of ICZM; level of power of stakeholders and the level to which stakeholders are embedded in the top-down tradition; difference in interpretation of ICZM; corruption and lack of political will. Social learning takes a long time and is not an immediate response, often making it inappropriate to deal with immediate issues (Abelshausen et al. 2015)

E.4 Costs

E.4.1 Social

Focus on climate adaptation at the local scale results in trade-offs which may result in serious justice implications (Paterson et al. 2017)

Governance

Possibility of piecemeal and localised resilience that accentuates rather than helps overcome social inequalities (Paterson et al. 2017)

E.4.2 Economic

Financial support needed for least developed countries (Gallo et al. 2017)

Incentives and compensation provided by government in the case of planned retreat (Serrao-Neumann et al. 2013)

F. Human System: Human Health

F.1 Adaptation responses

F.1.1 Governance

Improving implementation and coordination of policies

Changes in industry practices (Jacobs et al. 2015)

F.1.2 Economic

Improving financial resources availability

Effective allocation of technologies and resources (Wu et al. 2016)

F.1.3 Knowledge

Better monitoring and modelling

Modelling approaches to inform adaption strategies (Jacobs et al. 2015)

Improving understanding of climate change patterns (Wu et al. 2016)

Improving forecasting and early warning systems

Improve prediction of spatial-temporal process of climate change and infectious diseases (Wu et al. 2016)

Establish early warning systems (Wu et al. 2016)

Improving decision support frameworks

Improving understanding of compound disease-specific health effects (Wu et al. 2016)

Stakeholder identification, outreach and education

Education (Jacobs et al. 2015)

Raising public awareness (Wu et al. 2016)

F.2 Benefits

F.2.1 Social

Improved health

Alleviate the negative health impacts of climate change (Wu et al. 2016)

F.2.2 Knowledge

Informed decision making tools

Enhanced prediction over time and spatial scales relevant to public health intervention (Jacobs et al. 2015)

Inform adaption and mitigation efforts to minimise risk of disease (Jacobs et al. 2015)

F.3 Constraints and limitations

F.3.1 Social

Social and economic factors play a significant role in adaptation to infectious diseases, including differing vulnerabilities (Wu et al. 2016)

Lack of effective communication and public health systems in developing countries (Wu et al. 2016)

F.3.2 Economic

Inadequate financial and medical resources in developing nations (Wu et al. 2016)

F.3.3 Knowledge

Limited studies on the effects of climate change on coastal water-borne pathogens (Jacobs et al. 2015)

Models do not account for changing demographics, intervention strategies and sanitation practices (Jacobs et al. 2015)

Challenges with predicting extreme weather events and their health impacts (Wu et al. 2016)

Peer review literature does not agree on the health effects of changes in climate variables (Wu et al. 2016)

F.3.4 Governance

Developing countries will need assistance from developed countries (Wu et al. 2016)

SM5.7 Observed Changes in the Ocean and Related Impacts in Support of Figure 5.24

Figure 5.24 shows the synthesis of regional consequences and impacts in ocean assessed in Chapter 5. Tables SM5.10a, SM5.10b and SM5.10c give respectively the links to the specific section in this chapter or in AR5 WG1 or WG2 reports where appropriate. Table SM5.10a refers to the ocean Physical Changes, Table SM5.10b refers to the ocean Ecosystems and Table SM10.c refers to the Human systems and Ecosystems services columns of the assessments.

Table SM5.10a | The observed physical changes in the ocean covered by Chapter 5. The regions are shown in Figure 5.24, hazards column is the observed change for the period defined by the start and ends dates, and direction is either increase, decrease or neutral. Detection column is the observed changes for the period, and attribution column is whether there is a detectable human influence in the change and the reference column points to the traceable evidence from Chapter 5 or from the IPCC 5th Assessment Report (AR5) Working Group I (WGI) or Working Group II (WGII) report. Some trends analyse and attributed based on zonal averages depending on the particular variable and quality of attribution. Temperature: means averages of temperature 0–-700 m depth layer, Oxygen: means change in oxygen levels in the oxygen minimum zone or from the surface to 1200 m, Ocean pH is changes in pH at the surface of the ocean, Sea Level is changes in mean sea level, EBUS is Eastern Boundary Upwelling System, SLR is sea level rise. The standard likelihood and confidence language is used to indicate the level of confidence in the assessment.

Region	Hazards	Notes	Data types	Start year	End year	Direction of changes	Detection	Attribution	Reference
EBUS	Temperature	Ocean temperature	*In situ*	1960	2017	Increase and decrease	Low	Low	Section 5.2, Box 5.3
EBUS	Oxygen	Oxygen	*In situ*	1990	2010	Increase and decrease	Low	Low	Section 5.2, Box 5.3
EBUS	Ocean pH	pH	*In situ*	1993	2016	Decrease	Very likely	Likely	Section 5.2, Box 5.3
EBUS	SLR	m	*In situ*/Sat.	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
Tropical Pacific	Temperature	Ocean temperature	*In situ*	1970	2017	Increase and decrease	Low	Low	Section 5.2.2.2, AR5 WG1, Section 10.9
Tropical Pacific	Oxygen	Oxygen	*In situ*	1970	2015	Decrease	Medium	Low	Section 5.2.2.4
Tropical Pacific	Ocean pH	pH	*In situ*	1970	2016	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
Tropical Pacific	SLR	m	In situ/Sat.	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
North Pacific	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
North Pacific	Oxygen	Oxygen	*In situ*	1970	2010	Decrease	Medium	Low	Section 5.2.2.4
North Pacific	Ocean pH	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
North Pacific	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
Tropical Atlantic	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
Tropical Atlantic	Oxygen	Oxygen	*In situ*	1970	2010	Decrease	Low	Low	Section 5.2.2.4
Tropical Atlantic	Ocean pH	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
Tropical Atlantic	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
North Atlantic	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
North Atlantic	Oxygen	Oxygen	*In situ*	1990	2010	Decrease	Low	Low	Section 5.2.2.4
North Atlantic	Ocean pH	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
North Atlantic	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually Certain	Medium	Section 4.2.2.4
Tropical Indian Ocean	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
Tropical Indian Ocean	Oxygen	Oxygen	*In situ*	1970	2010	Decrease	Low	Low	Section 5.2.2.3
Tropical Indian Ocean	Ocean pH	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.2 Table 1
Tropical Indian Ocean	SLR	M	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.6
Temperate Indian Ocean	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
Temperate Indian Ocean	Oxygen	Oxygen	*In situ*	1970	2010	Increase and decrease	Low	Low	Section 5.2.2.4
Temperate Indian Ocean	Ocean acidification	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM 5.1 Table SM5.3
Temperate Indian Ocean	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
South Pacific	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9

Region	Hazards	Notes	Data types	Start year	End year	Direction of changes	Detection	Attribution	Reference
South Pacific	Oxygen	Oxygen	*In situ*	1970	2010	Increase and decrease	Low	Low	Section 5.2.2.4
South Pacific	Ocean acidification	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
South Pacific	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4
South Atlantic	Temperature	Ocean temperature	*In situ*	1970	2017	Increase	High	Medium	Section 5.2.2.2, AR5 WG1, Section 10.9
South Atlantic	Oxygen	Oxygen	*In situ*	1990	2010	Decrease	Low	Low	Section 5.2.2.4
South Atlantic	Ocean acidification	pH	*In situ*	2000	2010	Decrease	Very likely	Likely	Section 5.2.2.3, SM5.1 Table SM5.3
South Atlantic	SLR	m	*In situ/Sat.*	1996	2015	Increase	Virtually certain	Medium	Section 4.2.2.4

Table SM5.10b | The observed impacts in selected coastal and ocean ecosystems from 1940 to the present day covered by Chapter 5. The regions are shown in Figure 5.24, ecosystem column is the assessed ecosystem types in Chapter 5. The observed direction of impacts are either positive, negative, or both position and negative. Detection column is the confidence level assessed for the observed impacts, and attribution column is whether there is the level of confidence on whether the detected impacts are contributed by climate change. EBUS is Easter Boundary Upwelling Systems.

Region	Ecosystems	Direction of impacts	Impact types	Detection	Attribution	Reference
EBUS	Epipelagic	Negative	Shift in biogeography, mass mortality of organisms, decrease in abundance	Medium	Low	Box 5.3
EBUS	Coral	N/A	N/A	N/A	N/A	N/A
EBUS	Coastal wetlands	N/A	N/A	N/A	N/A	N/A
EBUS	Kelp forest	Negative	Shift to turfs, reduction in recruitment	High	Medium	Section 5.3.6
EBUS	Rocky shores	N/A	N/A	N/A	N/A	N/A
EBUS	Deep sea	N/A	N/A	N/A	N/A	N/A
North Atlantic	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	High	High	Section 5.2.3
North Atlantic	Coral	Negative	Shift in depth distribution	Low	Low	Box 5.2
North Atlantic	Coastal wetlands	Positive and negative	Increase in area in some sub-tropical area but expansion of one vegetation, invasion by grazers impacting vegetated habitats	High	Medium	Section 5.3.2
North Atlantic	Kelp forest	Negative	Shift to turfs and algae	High	Medium	Section 5.3.6
North Atlantic	Rocky shores	Negative	Changes in species composition	High	High	Section 5.3.5
North Atlantic	Deep sea	N/A	N/A	N/A	N/A	N/A
North Pacific	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	High	Medium	Section 5.2.3
North Pacific	Coral	N/A	N/A	N/A	N/A	N/A
North Pacific	Coastal wetlands	Positive and negative	Increase in area in some sub-tropical area but expansion of one vegetation, invasion by grazers impacting vegetated habitats	High	Medium	Section 5.3.2
North Pacific	Kelp forest	Negative	Shift to turfs and algae, increase tropical sargassum species, reduction in recruitment and recovery	High	Medium	Section 5.3.6
North Pacific	Rocky shores	Negative	Changes in species composition	Medium	Medium	Section 5.3.5
North Pacific	Deep sea	Positive or negative	Benthic communities	Low	Low	Section 5.4.2.4
South Atlantic	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	Medium	Medium	Section 5.2.3
South Atlantic	Kelp forest	Negative	Replacement by turfs	High	Low	Section 5.3.6
South Atlantic	Coral	N/A	N/A	N/A	N/A	N/A
South Atlantic	Coastal wetlands	Negative	Increased mortality of vegetation, loss of habitats, changes in community and ecosystem structure	High	Medium	Section 5.3.2
South Atlantic	Rocky shores	N/A	N/A	N/A	N/A	N/A

Region	Ecosystems	Direction of impacts	Impact types	Detection	Attribution	Reference
South Pacific	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	Medium	Medium	Section 5.2.3
South Pacific	Kelp forest	Negative	Loss of canopy forming species, shift to turfs	High	Low	Section 5.3.6
South Pacific	Coral	Negative	Coral bleaching	Very high	High	Section 5.3.4
South Pacific	Coastal wetlands	Negative	Increased mortality of vegetation, loss of habitats, changes in community and ecosystem structure	High	Medium	Section 5.3.2
Temperate Indian Ocean	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	Medium	Low	Section 5.2.3
Temperate Indian Ocean	Coral	N/A	N/A	N/A	N/A	N/A
Temperate Indian Ocean	Coastal wetlands	Positive and negative	Increase in area in some sub-tropical area but expansion of one vegetation, invasion by grazers impacting vegetated habitats.	High	Medium	Section 5.3.2
Temperate Indian Ocean	Kelp forest	Negative	Shift to turfs, reduction in recovery	Medium	Low	Section 5.3.6
Temperate Indian Ocean	Rocky shores	Negative	Changes in species composition	Low	Low	Section 5.3.5
Temperate Indian Ocean	Deep sea	N/A	N/A	N/A	N/A	N/A
Tropical Atlantic	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	High	Medium	Section 5.2.3
Tropical Atlantic	Coral	Negative	Coral bleaching	Very high	High	Section 5.3.2
Tropical Atlantic	Coastal wetlands	Negative	Increased mortality of vegetation, loss of habitats, changes in community and ecosystem structure	High	Medium	Section 5.3.2
Tropical Atlantic	Kelp forest	N/A	N/A	N/A	N/A	N/A
Tropical Atlantic	Rocky shores	N/A	N/A	N/A	N/A	N/A
Tropical Atlantic	Deep sea	N/A	N/A	N/A	N/A	N/A
Tropical Indian Ocean	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	Medium	Low	Section 5.2.3
Tropical Indian Ocean	Coral	Negative	Coral bleaching	Very high	High	Section 5.3.2
Tropical Indian Ocean	Coastal wetlands	Negative	Increased mortality of vegetation, loss of habitats, changes in community and ecosystem structure	High	Medium	Section 5.3.2
Tropical Indian Ocean	Kelp forest	N/A	N/A	N/A	N/A	N/A
Tropical Indian Ocean	Rocky shores	N/A	N/A	N/A	N/A	N/A
Tropical Pacific	Coastal wetland	Negative	Increased mortality of vegetation, loss of habitats, changes in community and ecosystem structure	High confidence	Medium	Section 5.3.2
Tropical Pacific	Kelp forest	Negative	Loss of canopy forming species, shift to turfs	High	Low	Section 5.3.6
Tropical Pacific	Rocky shores	N/A	N/A	N/A	N/A	N/A
Tropical Pacific	Deep sea	N/A	N/A	N/A	N/A	N/A
Tropical Pacific	Epipelagic	Negative	Alteration of biogeography/phenology/ community structure	Medium	Medium	Section 5.2.3
Tropical Pacific	Coral	Negative	Coral bleaching	Very high	High	Section 5.3.4

Table SM5.10c | The observed impacts of selected human systems and ecosystem services from 1940 to the present day covered by Chapter 5. The regions are shown in Figure 5.24, ecosystem services column is the assessed ecosystem types in Chapter 5. The observed direction of impacts are either positive, negative, or both position and negative. Detection column is the confidence level assessed for the observed impacts, and attribution column is whether there is the level of confidence on whether the detected impacts are contributed by climate change. EBUS is Eastern Boundary Upwelling System.

Region	Human systems and ecosystem services	Direction of changes	Impact types	Detection	Attribution	Reference
EBUS	Fisheries	Negative	Species composition and catch potential	Medium	Low	Box 5.3
EBUS	Tourism	Negative	Tourism opportunities	Low	Low	Box 5.3
EBUS	Carbon sequestration	N/A	N/A	N/A	N/A	Box 5.3
EBUS	Habitat service	Negative	Modification of habitat conditions	Low	Low	Box 5.3
EBUS	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
EBUS	Culture	N/A	N/A	N/A	N/A	N/A

Region	Human systems and ecosystem services	Direction of changes	Impact types	Detection	Attribution	Reference
Tropical Pacific	Fisheries	Negative	Species composition and catch potential	High	Low	Section 5.4.1.1
Tropical Pacific	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
Tropical Pacific	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Low	Section 5.3, 5.4.2, 5.5.1.2
Tropical Pacific	Habitat service	Negative	Loss/degradation of habitat and their functions	High	Medium	Section 5.4.3
Tropical Pacific	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
Tropical Pacific	Culture	N/A	N/A	N/A	N/A	N/A
North Pacific	Fisheries	Negative	Species composition and catch potential	High	Low	Section 5.4.1.1
North Pacific	Tourism	Negative	Tourism opportunities	High	Low	Section 5.4.2.3.2
North Pacific	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Medium	Section 5.3, 5.4.2, 5.5.1.2
North Pacific	Habitat service	Negative	Loss/degradation of habitat and their functions	High	Medium	Section 5.4.3
North Pacific	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
North Pacific	Culture	Negative	Food and ceremonial use of marine resources	High	Low	Section 5.4.2.1.3, 5.4.2.2.1
Tropical Atlantic	Fisheries	Negative	Change in species composition and catch potential	High	Medium	Section 5.4.1.1
Tropical Atlantic	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
Tropical Atlantic	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Low	Section 5.3, 5.4.2, 5.5.1.2
Tropical Atlantic	Habitat service	Negative	Loss/degradation of habitat and their functions	High	Medium	Section 5.4.3
Tropical Atlantic	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
Tropical Atlantic	Culture	N/A	N/A	N/A	N/A	N/A
North Atlantic	Fisheries	Negative	Species composition and catch potential	High	High	Section 5.4.1.1
North Atlantic	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
North Atlantic	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Medium	Section 5.3, 5.4.2, 5.5.1.2
North Atlantic	Habitat service	Negative	Loss/degradation of habitat and their functions	High	Medium	Section 5.4.3
North Atlantic	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
North Atlantic	Culture	Negative	Changes in coastal livelihood	Medium	Low	Section 5.4.2.3.1, 5.4.2.2.1
Tropical Indian Ocean	Fisheries	Negative	Species composition and catch potential	Low	Low	Section 5.4.1.1
Tropical Indian Ocean	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
Tropical Indian Ocean	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Medium	Section 5.3, 5.4.2, 5.5.1.2
Tropical Indian Ocean	Habitat service	Negative	Loss/degradation of habitat and their functions	Medium	Medium	Section 5.4.3
Tropical Indian Ocean	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
Tropical Indian Ocean	Culture	N/A	N/A	N/A	N/A	N/A
Temperate Indian Ocean	Fisheries	Negative	Species composition and catch potential	Low	Low	Section 5.4.1.1
Temperate Indian Ocean	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
Temperate Indian Ocean	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Low	Section 5.3, 5.4.2, 5.5.1.2
Temperate Indian Ocean	Habitat service	Negative	Loss/degradation of habitat and their functions	Medium	Low	Section 5.4.3
Temperate Indian Ocean	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
Temperate Indian Ocean	Culture	N/A	N/A	N/A	N/A	N/A
South Pacific	Fisheries	Negative	Species composition and catch potential	High	Low	Section 5.4.1.1
South Pacific	Tourism	Negative	Perception of local and international tourisms	Low	Low	Section 5.4.2.3.2
South Pacific	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Low	Section 5.3, 5.4.2, 5.5.1.2

Region	Human systems and ecosystem services	Direction of changes	Impact types	Detection	Attribution	Reference
South Pacific	Habitat service	Negative	Loss/degradation of habitat and their functions	High	Medium	Section 5.4.3
South Pacific	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
South Pacific	Culture	Negative	Influences on perceptions, values, traditions	High	Low	Section 5.4.2.2.1
South Atlantic	Fisheries	Negative	Species composition and catch potential	Medium	Low	Section 5.4.1.1
South Atlantic	Tourism	N/A	N/A	N/A	N/A	Section 5.4.2.3.2
South Atlantic	Carbon sequestration	Negative	Loss of coastal blue carbon habitat	High	Low	Section 5.3, 5.4.2, 5.5.1.2
South Atlantic	Habitat service	Negative	Loss/degradation of habitat and their functions	Medium	Low	Section 5.4.3
South Atlantic	Transportation and shipping	N/A	N/A	N/A	N/A	N/A
South Atlantic	Culture	N/A	N/A	N/A	N/A	N/A

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