

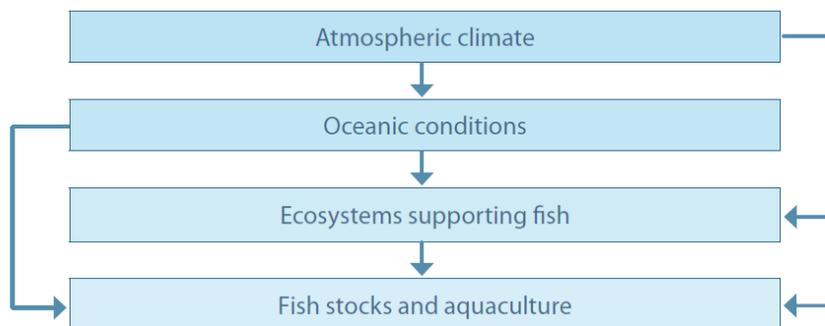
## 6. Technical summaries

### 6.1 General approach and use of climate models

#### General approach

The assessments of the vulnerability of fisheries and aquaculture in Pacific Island countries and territories summarised in this volume were based on the best science available at the time. Published scientific results were integrated with the outputs of climate and ecosystem models, and the expert opinion of authors, to determine the degree to which access to oceanic, coastal and freshwater fisheries resources, and the productivity of aquaculture, is likely to be affected by the changing climate (Chapter 1). The approach used to assemble the technical information required for the vulnerability assessments involved four steps (Figure 6.1).

1. Describing the observed and projected changes to atmospheric (surface) climate in the region (Chapter 2)<sup>11</sup>.
2. Describing the observed and projected changes to the main features of the tropical Pacific Ocean (Chapter 3)<sup>12</sup>.
3. Assessing the way in which projected changes to the climate and ocean are likely to affect the ecosystems that support fisheries resources, i.e. the food webs in the open ocean (Chapter 4)<sup>13</sup>, coral reefs (Chapter 5)<sup>14</sup>, mangroves, seagrasses and intertidal flats (Chapter 6)<sup>15</sup>, and freshwater and estuarine habitats (Chapter 7)<sup>16</sup>.
4. Assessing the likely direct effects of projected changes to surface climate and the ocean, and the indirect effects of projected changes to ecosystems, on the abundance and distribution of species supporting oceanic fisheries (Chapter 8)<sup>17</sup>, coastal fisheries (Chapter 9)<sup>18</sup>, and freshwater and estuarine fisheries (Chapter 10)<sup>19</sup>, and aquaculture production (Chapter 11)<sup>20</sup>.



**Figure 6.1** Summary of the approach used to assess the vulnerability of fish stocks and aquaculture in the tropical Pacific to climate change.

## Use of climate models

Global climate models were used to provide the projections involved in Steps 1 and 2 of the approach outlined above. A climate model is a numerical description of our understanding of the physics, and in some cases chemistry and biology of the ocean, atmosphere, land surface and ice regions (Chapter 1). Climate models with reasonable 'skill' in capturing present and past states of the climate system are the best tools we have to make projections of what the future might hold.

At its most basic level, a climate model describes (1) Newton's law that the motion of a fluid (water or air) can be determined if the forces acting on it are known (e.g. the winds pushing the surface of the ocean, or the friction trying to oppose any motion), and (2) the laws of conservation of mass and energy (e.g. if water flows into an obstacle it will be deflected, or if solar energy penetrates the ocean surface, the water will warm). In principle, we should be able to use these mathematical formulas to give a near perfect description of the real world, but in practice compromises must be made due to computational limitations.

To implement these physical laws within the architecture of even the most powerful computers, our simulation of the climate system must be greatly simplified and broken down into a collection of grid 'boxes'. For the current generation of global climate models, these boxes have a resolution in the ocean that is typically 100–200 km on each side (atmospheric resolutions are generally even coarser). This means that all ocean currents (or variations in temperature or salinity, etc.) within the area of a particular box will be represented by a single average current (temperature or salinity, etc.). Consequently, many smaller-scale processes (e.g. finer-scale circulation in coastal zones) with widths of a few kilometres are not resolved by the models. Unfortunately, these smaller scales are often the ones we are most interested in and care must be taken in 'downscaling' the projections from models to ensure they are useful in assessing regional impacts. To help address this limitation, many of the unresolved processes are 'parameterised'. These parameterisations essentially translate the effect of small-scale processes to the larger scales on which the models operate.

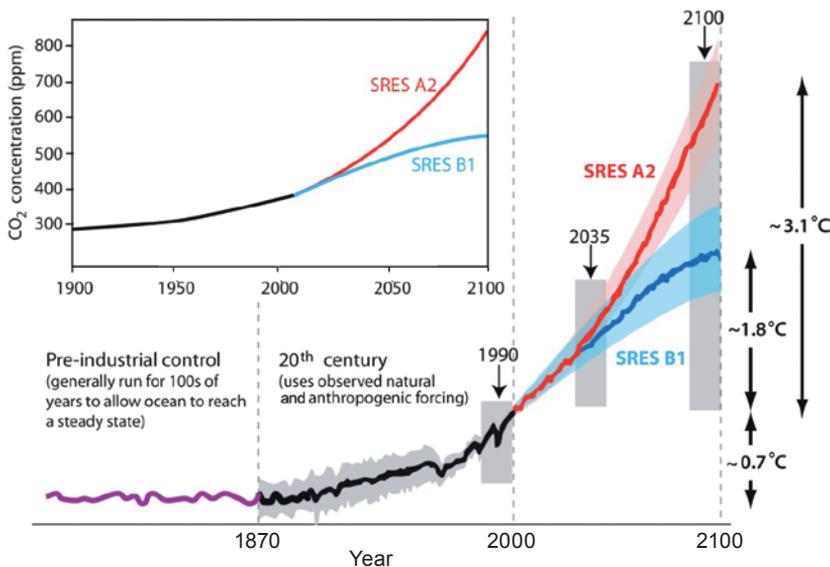
Model results used for the vulnerability assessments reported here are primarily from the Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set, which was used by the Fourth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR4). All models are state-of-the-art 'coupled' models, meaning that ocean, atmosphere, land and ice models are coupled together, with information continuously being exchanged between these components to produce an estimate of global climate that evolves with time.

These global climate models are generally run for hundreds of simulation-years subject to constant, pre-industrial (1870) forcing, i.e. constant solar energy and appropriate greenhouse gas levels (Figure 6.2). This gives the ocean time to 'settle

down' into a near equilibrium. Using the 'pre-industrial run' as a baseline, the 20<sup>th</sup> century simulations incorporate increasing greenhouse gases<sup>i</sup> in the atmosphere in line with historical emissions and take observed natural forcing (e.g. changes in solar radiation, volcanic eruptions) into account.

At the end of the 20<sup>th</sup> century, projection simulations are carried out based on predefined 'plausible' future emission trajectories. In our case, we focus on two of these trajectories, corresponding to low (B1) and high (A2) emissions scenarios.

Assessments are made of the ability of the models to simulate the atmosphere and ocean (for the end of the 20<sup>th</sup> century) and both near-term (2035) and long-term (2100) projections (Figure 6.2). These models are far from perfect, however, and represent only an approximation of the real world. Two different models will simulate two different climate trajectories, even when subject to the same carbon dioxide equivalent emissions, due to the use of different parameterisations and levels of approximation.



**Figure 6.2** Globally averaged surface air temperature simulated by a multi-model average of the CMIP3 coupled climate models the pre-industrial period (purple), the 20<sup>th</sup> century (black), B1 emissions scenario during the 21<sup>st</sup> century (blue) and the A2 scenario in the 21<sup>st</sup> century (red). The spread associated with output from different models is highlighted by the translucent shading. Also shown are observed and multi-model average changes in surface air temperature relative to 1980–2000. Information after 1900 is based on IPCC-AR4. Inset shows the historical and future CO<sub>2</sub> concentrations used by the models.

The difference between models is highlighted by the spread in the projections around each of the scenarios in Figure 6.2. In general, the projected changes tend to be more certain at large spatial scales (e.g. global average temperature) but become

i Some simulations also include sulphate aerosols and ozone.

increasingly uncertain at more local scales (e.g. the strength of a particular ocean current). To overcome some of these uncertainties, the average output from suites of independent climate models with a good ability to simulate present climate was used. By averaging across multiple models many of the biases inherent in individual models were reduced. However, systematic biases still persist in some cases, so it is important to interpret model results with an awareness of their shortcomings.

### **Biogeochemical models**

The CMIP3 models only provide projections of the physical climate and do not explicitly simulate responses of habitats and fish stocks to climate change. Such responses must be inferred from our best understanding of how productivity and higher levels of the food web react to observed climate variability. For some of the analyses, a number of biological components were coupled to one of the CMIP3 models (IPSL-CM4) to make projections of (1) primary production and the extent of the different ecological provinces in the tropical Pacific Ocean (Chapter 4), and (2) catches of skipjack and bigeye tuna (Chapter 8). Thus, any uncertainties associated with the IPSL-CM4 model are transferred to the simulated biological responses.

### **How to use the technical summaries**

Sections 6.2 to 6.11 provide brief descriptions of the main technical results of the approach described in Figure 6.1. Links are provided (in curly brackets) within each technical summary to the comprehensive vulnerability assessment (published as a peer-reviewed book) for readers interested in the full details of the analyses.

## 6.2 Observed and projected changes in surface climate of the tropical Pacific {Chapter 2}<sup>11</sup>

Weather is defined as the state of the atmosphere as described from day-to-day by measurable variables, such as air temperature, rainfall, wind speed and direction, cloud cover and humidity. Climate is the long-term average weather – what is expected at a particular time and place – and is based on observations over many years. Descriptions of climate can include both the average values and measures of variability from year-to-year. Climate change is defined as a significant alteration in what we expect the weather to be like at a particular location and season. Changes occur in average values and/or in the variability around the average, i.e. the range of extremes. Projecting the nature and significance of changes in climate globally or regionally requires on long-term, uniform weather observations from as many locations as possible.

The ecosystems that Pacific Island countries and territories (PICTs) rely on for economic development, and the food security and livelihood opportunities for their people, are adapted to the prevailing climate conditions and their normal seasonal variations. Global and regional climates have varied on spatial and temporal scales in the past due to a range of forcing factors, such as ice age cycles caused by changes in the earth's orbit. Increasing concentrations of atmospheric greenhouse gases, and the associated changes in climate, have now has been linked unequivocally to human activities since the late 18<sup>th</sup> century<sup>9</sup>. The concentration of the main greenhouse gas, carbon dioxide (CO<sub>2</sub>), increased from 280 parts per million (ppm) in 1750 to 385 ppm in 2008, and has continued to rise at approximately 2 ppm since then {Chapter 1}. The 38% increase in atmospheric CO<sub>2</sub> between 1750 and 2008 represents the highest concentration of this greenhouse gas in the last 800,000 years. The associated warming of the global climate observed during the 20<sup>th</sup> century is estimated to have occurred at a rate 10 times faster than the 4–7°C warming since the last glacial period ~ 21,000 years ago. Climate change due to human activities is not a future event, significant changes in climate have already been observed.

Observed trends in the last 50 years show increases in air temperatures, changes to atmospheric circulation and rainfall, and possible increases in cyclone intensity. Under the B1 and A2 emissions scenarios in 2035 and 2100, surface climate in the tropical Pacific region is projected to continue to warm rapidly. This warming will cause changes to atmospheric conditions and rainfall.

The present-day surface climate in the region, observed trends, and projections of how the climate of the tropical Pacific will change with continued increased emissions of greenhouse gases, are summarised below.

## **Present-day surface climate**

### *Atmospheric circulation {Chapter 2, Section 2.3.1}*

The surface climate of PICTs is dominated by the vast surrounding Pacific Ocean, the large-scale atmospheric circulations (Hadley and Walker Circulations) and the ocean currents associated with the northeast and southeast trade wind regimes. The atmospheric circulations from the two hemispheres meet in the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). The SPCZ is one of the most significant features of tropical and subtropical climate in the Southern Hemisphere. It is characterised by a convergence of air flow leading to uplift and a band of clouds and rainfall stretching from the Western Pacific Warm Pool (Warm Pool) (Section 6.3) in the western Pacific southeast towards French Polynesia. The atmospheric and oceanic conditions are also at the heart of the major source of interannual climate variability in the tropical Pacific – El Niño-Southern Oscillation (ENSO) events.

### *Air temperature {Chapter 2, Section 2.3.2}*

The tropical Pacific consists primarily of ocean, with extremely small land areas {Chapter 1, Table 1.1}, and therefore the mean air temperatures are dominated by average sea surface temperatures (SSTs). SSTs are similar to air temperatures for low-lying land areas and are a good proxy for surface air temperatures. In general, average SSTs are warmer in the western Pacific compared to the eastern Pacific. The annual maximum SST of the Warm Pool is ~ 30°C {Chapter 3} (Section 6.3).

### *Seasonal variation in temperatures and rainfall {Chapter 2, Section 2.3.3}*

The equatorial areas of the Pacific experience very small annual variations in air temperature and SST. For example, the annual range of SSTs is < 2°C throughout much of the western tropical Pacific. The annual ranges of air temperature and SST increase with latitude in the Southern Hemisphere. The greatest annual variability in air temperature and SST in the region occurs in subtropical areas. Maximum rainfall occurs in the austral summer, a pattern that is strongest between 10°S and 20°S. However, at higher (subtropical) latitudes, there is little seasonality in monthly rainfall.

### *Tropical cyclones {Chapter 2, Section 2.3.4}*

Tropical cyclones occur mainly in subtropical areas during the respective summer seasons and are rarely observed within about 5–10° of the equator. Tropical cyclones bring strong winds, high rainfall, and destructive storm surges to the southwest, northeast and northwest tropical Pacific. In the southwest Pacific, tropical cyclones usually develop during the austral summer season, from November to April, but

occasionally occur in May. Peak cyclone occurrence is usually from January to March. About half of the storms that develop in the tropical Pacific reach cyclone force with mean wind speeds of > 118 km/h. Regionally, the highest frequencies of tropical cyclones occur between New Caledonia and Vanuatu in the Coral Sea, and towards Fiji.

### *Climate variability in the tropical Pacific {Chapter 2, Section 2.3.5}*

Various sources of natural variability are superimposed on the seasonal cycles and observed trends in surface climate. This variability modulates atmospheric and ocean climate on time scales of weeks to decades. ENSO is the main source of interannual global climate variability and is centred in the tropical Pacific. ENSO fluctuates between two phases, El Niño and La Niña, with large parts of the tropical Pacific experiencing significantly warmer-than-normal SSTs during El Niño events. Conversely, significantly cooler SSTs occur during La Niña events. Different patterns of rainfall are also associated with the two phases of ENSO. The interannual variability of ENSO is modulated by the Pacific Decadal Oscillation (PDO) on decadal time scales. The PDO causes distinct anomalies in the warm or cool phases of Pacific SST which can persist for several decades. The Southern Annular Mode (SAM) is the most important source of variability in the atmospheric circulation of mid to high (temperate) latitudes. SAM fluctuates between two phases that influence the strength of the westerly winds of the Southern Ocean as well as sea-level and ocean circulation patterns in the southern Pacific Ocean, including subtropical areas {Chapter 3}, on time scales longer than ~ 50 days.

## **Observed trends in surface climate**

### *Air temperature {Chapter 2, Section 2.4.1}*

Observational records show that tropical Pacific air temperatures over the islands have already warmed significantly and that the rate of warming has accelerated in recent decades. Observed average global land temperatures have warmed ~ 0.7–0.8°C over the past 100 years and the rate of warming has accelerated over the past 50 years. Although warming of air temperatures in PICTs has not been as great as over land at higher latitudes, the tropical Pacific is still warming at ~ 70% of the global average rate.

### *Rainfall {Chapter 2, Section 2.4.2}*

There have been some significant changes in the observed annual and daily rainfall climate of the southwest tropical Pacific, primarily on islands east of 160°W. Changes in rainfall to the west have tended to be small and incoherent. Generally, over the period 1961–2000, there has been more rainfall and more intense rainfall northeast of the SPCZ and less rainfall to the southwest of the SPCZ.

### *South Pacific Convergence Zone {Chapter 2, Section 2.4.3}*

Long-term variations in the position of the SPCZ do not show any significant change over the period 1890–2005. There are, however, decadal variations in the position of the SPCZ that closely align with the warm and cool phases of the PDO and ENSO. These variations significantly affect rainfall patterns throughout the southern tropical Pacific.

### *Tropical cyclones {Chapter 2, Section 2.4.4}*

On average, there are nine tropical cyclones in the southwest Pacific per year. There has been no discernible trend in the frequency of tropical cyclones in the southwest Pacific over the past 30 years, and no evidence yet for any significant change in the intensity of cyclones in the region.

## **Projected changes in surface climate**

Near-term (2035) and long-term (2100) projections of tropical Pacific surface climate for low (B1) and high (A2) emissions scenarios are based on averaging projections from several global climate models {Chapter 1, Section 1.8.2; Chapter 2, Section 2.5}. Given that none of these complex models are perfect, this averaging procedure emphasises changes that are common among different models and identifies areas/variables where projected changes cannot be made with confidence due to model disagreement. Projections resulting from the multi-model averages for the main features of surface climate are summarised below (Table 6.1).

### *Air temperature {Chapter 2, Section 2.5.1}*

Surface air temperatures in the tropical Pacific are projected to continue their observed warming trend. By 2035, air temperatures are likely to be 0.5–1.0°C higher than the 1980–1999 average. By 2100, the increase is expected to be 1.0–1.5°C under the B1 emissions scenario and 2.5–3.0°C under the A2 scenario.

### *Rainfall {Chapter 2, Section 2.5.2}*

There is more uncertainty between the different climate models as to how rainfall patterns will change across the tropical Pacific. However, it seems likely that rainfall will increase in the convergence zones near the equator and decrease in the subtropics. Warming oceans are expected to intensify the hydrological cycle, which is likely lead to more extreme rainfall events and, given warmer air temperatures, more intense droughts.

*El Niño-Southern Oscillation {Chapter 2, Section 2.5.3}*

It is still uncertain how the frequency and/or intensity of ENSO events may change in a warming world. Nevertheless, ENSO events are likely to continue to be a major source of interannual climate variability in the tropical Pacific.

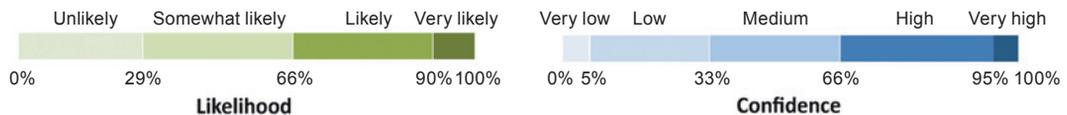
*Tropical cyclones {Chapter 2, Section 2.5.4}*

There may be fewer tropical cyclones in the region in the future but those that do occur are likely to be more intense. The location of tropical cyclone activity is not projected to change significantly.

**Table 6.1** Summary of projected changes to tropical Pacific surface climate relative to average values for 1980–1999. Recent and projected concentrations of atmospheric carbon dioxide (CO<sub>2</sub>) are also shown.

Variable	1980–1999 average	Projected change			
		B1 2035	A2 2035	B1 2100*	A2 2100
Air temperature (°C)	27.4	+0.5 to +1.0 	+0.5 to +1.0 	+1.0 to +1.5 	+2.5 to +3.0 
Rainfall	n/a	Equatorial +5 to +15% 	+5 to +20% 	+10 to +20% 	+10 to +20% 
		Subtropics -5 to -10% 	-5 to -20% 	-5 to -20% 	-5 to -20% 
ENSO events	Interannual variable	Continued source of interannual climate variability			
PDO-decadal variability	Decadal variable	Continued source of decadal modulation in Pacific basin climate and ENSO events			
Tropical cyclones	9	<ul style="list-style-type: none"> <li>➤ Total number of tropical cyclones may decrease</li> <li>➤ Cyclones are likely to be more intense</li> </ul>			
Atmospheric CO <sub>2</sub> (ppm)	339–368	400–450	400–450	500–600	750–800

\* Approximates A2 in 2050; ENSO = El Niño-Southern Oscillation; PDO = Pacific Decadal Oscillation; n/a = data not available.



## 6.3 Observed and projected changes to the tropical Pacific Ocean {Chapter 3}<sup>12</sup>

The fish and invertebrates harvested in the tropical Pacific depend intimately on the oceanic environment. Large- and small-scale circulation patterns influence larval dispersal and the migration of species; and water temperature, salinity, nutrient availability, dissolved oxygen concentration and pH affect biological activity. Oceanic currents, waves and sea level also shape the coastal habitats on which many fish species depend.

The main features of the tropical Pacific Ocean, recent observed changes in these features, and projections of how the ocean will change with continued forcing due to increasing greenhouse gases, are summarised below.

### Features of the tropical Pacific Ocean

#### *Large-scale ocean currents {Chapter 3, Section 3.2.1}*

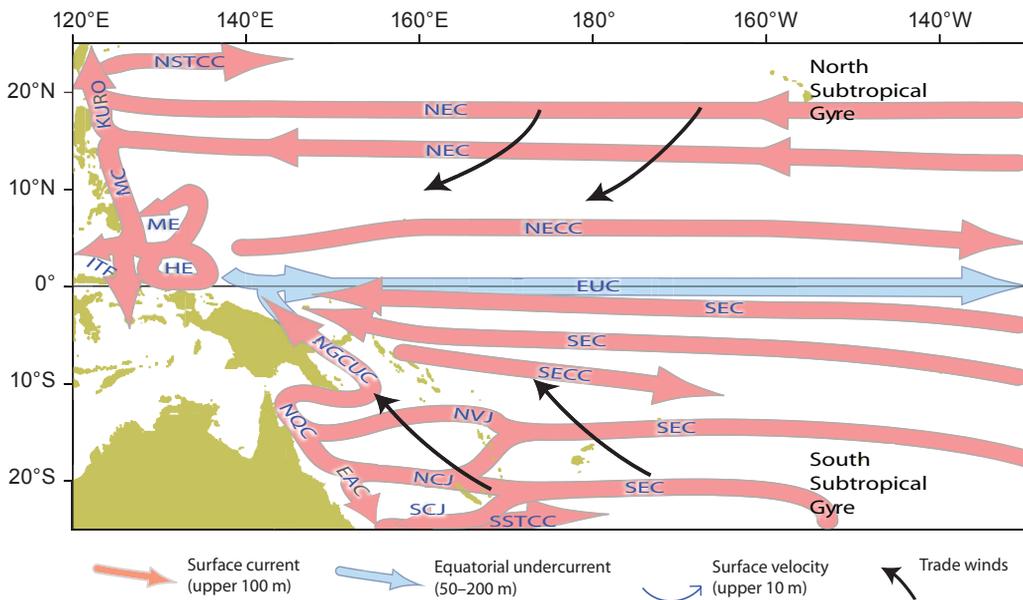
The main currents in the tropical Pacific Ocean (Figure 6.3) are driven by the southeast trade winds. Due to the interaction between the trade winds and the Coriolis force, surface waters near the equator are driven poleward by 'Ekman transport' to subtropical latitudes. Waters at latitudes higher than 25°S and 25°N are forced towards the equator by westerly winds. The convergence of the water bodies moving in different directions produces two west-flowing currents: the North Equatorial Current (NEC) and the South Equatorial Current (SEC). These currents are diverted when they encounter islands and land, feeding a number of smaller currents and undercurrents, and the Warm Pool. The NEC and SEC are also altered by the presence of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). These convergence zones alter local wind conditions, resulting in two east-flowing counter currents; the North Equatorial Counter Current (NECC) under the ITCZ, and the South Equatorial Counter Current (SECC) under the SPCZ. The boundaries where the westward currents and eastward counter currents meet create eddies that can cause upwelling of nutrient-rich water. Currents in the southeast Pacific remain fairly constant throughout the year, whereas currents in the western Pacific vary in intensity and direction due to season and ENSO.

#### *Ocean temperature {Chapter 3, Section 3.2.2}*

Sea surface temperature (SST) in the tropical Pacific Ocean varies spatially and temporally. Spatial deviations occur where winds move surface waters or cause upwelling. For example, the southeast trade winds push warm water to the western Pacific, forming the Warm Pool. The world's warmest oceanic temperatures occur in the Warm Pool, which is defined by SSTs greater than 28°C. The prevailing southeast trade winds along the equator also cause upwelling that brings deep, cool, nutrient-

rich waters to the surface, reducing SSTs. Seasonal changes in SST near the equator are weak and interannual variations are limited to 2 to 3°C. Seasonal variation in SST is greatest away from the equator, where it can vary by up to 7°C throughout the year.

The temperature of the tropical Pacific Ocean also varies with depth, declining as depth increases. The warmer surface water also has a lower density than the deeper cooler waters. Where the two layers meet at the ‘thermocline’, the water temperature changes rapidly. In the tropical Pacific Ocean, the thermocline usually lies in the upper 500 m and the temperature across the thermocline drops by 20°C.



**Figure 6.3** The main ocean currents in the upper 100 to 200 m of the water column. Currents shown are: North Subtropical Counter Current (NSTCC); Kuroshio Current (KURO); Mindanao Current (MC); Mindanao Eddy (ME); Halmahera Eddy (HE); North Equatorial Current (NEC); North Equatorial Counter Current (NECC); Equatorial Undercurrent (EUC); Indonesian Throughflow (ITF); New Guinea Coastal Undercurrent (NGCUC); North Queensland Current (NQC); East Australian Current (EAC); North Vanuatu Jet (NVJ); North Caledonian Jet (NCJ); South Caledonian Jet (SCJ); South Equatorial Counter Current (SECC); South Equatorial Current (SEC) and South Subtropical Counter Current (SSTCC).

### *Ocean eddies {Chapter 3, Section 3.2.3}*

Eddies in ocean, and in coastal areas, can draw nutrient-rich water from the deeper layers of the ocean towards the surface, stimulating primary production {Chapter 4, Box 4.1}. Eddies also transport heat, nutrients, particles and larval fish and invertebrates at local scales. The size of eddies depends strongly on latitude – in the tropical Pacific they range from ~ 150 to 300 km in diameter. The passage of eddies is associated with important variations in local currents, sea surface height and the vertical structure of the water column.

### *Nutrient supply {Chapter 3, Section 3.2.4}*

Biological processes (e.g. photosynthesis by phytoplankton) at the ocean surface deplete the supply of nutrients. Consequently, concentrations of nutrients are much greater at depths of > 100 m than at the surface. Ocean circulation, or deep mixing of the water column, is needed to transfer nutrients back to the surface. However, the strong density stratification in the Pacific Ocean inhibits the vertical exchange of water (and therefore nutrients) between the deep and shallow layers of the ocean. The main processes that can overcome the stratification barrier and deliver nutrient-rich water to the upper layers are turbulence in the surface mixed layer, wind-driven upwelling, and eddies.

### *Dissolved oxygen {Chapter 3, Section 3.2.5}*

Dissolved oxygen ( $O_2$ ) levels in surface waters of the tropical Pacific Ocean are determined by (1) the rate of oxygen transfer from the atmosphere (which is dependent on SST); (2) the rate oxygen is produced from photosynthesis; and (3) the rate at which the oxygen-rich surface waters are submerged via ocean currents and mixing. At high latitudes, cold surface waters rich in oxygen are pushed to lower latitudes, below lighter subtropical waters. These waters gradually lose  $O_2$  as organic matter is remineralised by bacteria. The concentration of  $O_2$  at any point in the water column is a balance between the original  $O_2$  content, the effect of remineralisation of organic matter by bacteria, and the rate at which water is replaced through ocean circulation. In regions of high bacterial activity, consumption of  $O_2$  can exceed replenishment from ocean circulation, causing oxygen depletion and anoxic conditions.

### *Ocean acidification {Chapter 3, Section 3.2.6}*

The acidity of the ocean has been relatively stable for millions of years. Due to this stability, carbonate ions are naturally abundant and the common pure minerals of calcium carbonate (aragonite and calcite) are formed in surface waters and do not dissolve. The pH of the ocean is related to the amount of carbon dioxide in the atmosphere {Chapter 3, Box 3.3}. Average ocean pH is now ~ 8.1. Ocean pH varies seasonally and spatially by ~ 0.3 units due to changes in SST and upwelling of deep waters rich in carbon dioxide.

### *Wave height {Chapter 3, Section 3.2.7}*

The size of surface waves on the ocean depends on the strength of the wind, the distance over which the wind blows, the length of time the wind has been blowing and the water depth. Waves have a major influence on ocean surface mixing, sediment suspension and transport. In the tropical Pacific Ocean, model simulations show that

average significant wave height ranges from 1.5 to 2.5 m, and generally decreases to the west. There are large natural variations in the wave conditions of the tropical Pacific Ocean due to storm activity and large-scale climate patterns, such as ENSO.

#### *Sea level {Chapter 3, Section 3.2.8}*

Sea level at a given location is determined by a number of factors that vary in time and space. Tides affect sea level on a predictable periodic basis, the effects of storms and eddies are episodic and can last from hours to days, and circulation changes (like those associated with ENSO) can cause large interannual variation. The interaction of these factors causes substantial variation in sea level. For example, regional changes in sea level due to ENSO events can be as great as 20 to 30 cm.

#### *Coastal circulation and island effects {Chapter 3, Section 3.2.9}*

Regional oceanic processes that occur along coastlines and around islands also influence the features of the coastal environment at local scales. There is considerable variation in circulation (e.g. currents and eddies), SST, nutrient supply and ultimately productivity, among coastal areas across the region.

### **Recent observed changes in the tropical Pacific Ocean**

#### *Large-scale currents and eddies {Chapter 3, Sections 3.3.1 and 3.3.3}*

The intensity of ocean circulation caused by the South Pacific Subtropical Gyre and the SEC increased between 1993 and 2003, presumably due to the combined effects of natural variability and global warming. As a result, sea level at the centre of this gyre has increased by 12 cm. The North Pacific Subtropical Gyre also intensified over this period but with weaker amplitude. Eddy activity in the tropical Pacific Ocean between 1993 and 2001 varied by 15–30%. In general, there were stronger interannual changes in the occurrence and distribution of eddies.

#### *Ocean temperature {Chapter 3, Section 3.3.2}*

In the past 50 years, average annual SST has increased by  $> 1^{\circ}\text{C}$  in the southwest and northeast of the tropical Pacific. The warming reached a depth of 200 m at several latitudes and has been as great as  $2^{\circ}\text{C}$  in some locations.

#### *Nutrient supply {Chapter 3, Section 3.3.4}*

The two longest time-series of oceanographic data in the tropical northern Pacific, spanning 30 years, indicate that there has been a slight decrease in nutrient supply over this period. This trend is consistent with increased stratification caused by a

warming ocean. However, the data are insufficient to establish whether a basin-scale trend is occurring. Trends in nutrient supply to the surface layer of the ocean due to climate change are still difficult to gauge because of the strong influence of ENSO and PDO.

#### *Dissolved oxygen {Chapter 3, Section 3.3.5}*

A major westward expansion of the oxygen-minimum waters in the eastern Pacific basin has been detected over the past 50 years. The thickness of the oxygen-poor layer has also increased over this time in the Pacific Equatorial Divergence Province. These observations are consistent with climate projections. Lower oxygen concentrations can have consequences for ecosystems {Chapter 4} and the distribution of tuna {Chapter 8}.

#### *Ocean acidification {Chapter 3, Section 3.3.6}*

Increased emissions of carbon dioxide have decreased the pH of the tropical Pacific Ocean by 0.06 pH units since the beginning of the industrial era. The current rate of decrease is ~ 0.02 units per decade and is unprecedented in the past 300 million years. The aragonite saturation level (related to acidification of the ocean) is close to the point where calcareous organisms, such as corals and a number of planktonic species, may already be experiencing a weakening in their skeletons and shells. These changes are likely to reduce the fitness of calcareous organisms and their resistance to predation.

#### *Wave height {Chapter 3, Section 3.3.7}*

Around the world, visual reports from shipping show an increase in significant wave heights (SWH) at mid- and high-northern latitudes since 1950. However, in the far western part of the Warm Pool, SWH has decreased at a rate of 8 cm per decade. There are insufficient data from other parts of the tropical Pacific Ocean to determine whether SWH has changed over recent decades.

#### *Sea level {Chapter 3, Section 3.3.8}*

Sea level has risen by ~ 17 cm globally since pre-industrial times and 6 cm since 1960. The rate of increase appears to be accelerating due to more rapid ice melt and thermal expansion of the upper ocean. Based on long-term tide gauge data in the tropical Pacific Ocean sea level is currently rising by ~ 2.5 cm per decade.

#### *Coastal circulation and island effects {Chapter 3, Section 3.3.9}*

Changes in the strength and location of mesoscale upwellings close to coasts are likely to have occurred due to changes in the wind field and/or thermal structure of the ocean. However, such changes have not been quantified.

## Projected changes in the tropical Pacific Ocean

The projected changes to the main features of the tropical Pacific Ocean are outlined below and summarised in Table 6.2.

### *Large-scale currents and eddies {Chapter 3, Sections 3.3.1 and 3.3.3}*

The currents in the tropical Pacific Ocean are expected to change due to global warming, particularly near the equator. The flow of the SECC is projected to decrease by 8% under the B1 scenario, and 18% under A2, in 2035. By 2100, flow of the SECC is expected to reduce by 28% under B1 and 60% under A2. The SEC is projected to decrease in strength by 3–5% under B1 and A2 in 2035 and by 8–18% in 2100, with corresponding reductions in SEC transport (volume of water dispersed). The Equatorial Undercurrent (EUC) is expected to increase in strength and transport by 2100, reducing the depth penetration of the SEC. In the Northern Hemisphere, a decrease is projected in the eastern half of the NECC, with a slight decrease in the NEC. Eddy activity can be expected to increase or decrease in association with projected changes in current strength.

### *Ocean temperature {Chapter 3, Section 3.3.2}*

Ocean temperature is expected to continue rising substantially, with higher warming rates near the surface, especially in the first 100 m. SST is expected to increase by 0.7°C in 2035, 1.4°C in 2100 under the B1 emissions scenarios, and 2.5°C under A2. The salinity of the tropical western Pacific Ocean is projected to decrease due to the intensified hydrological cycle {Chapter 2}. The salinity front associated with the Warm Pool is likely to extend further east by ~ 2000 km, while the 29°C isotherm is expected to move further east at the equator. The area of the Warm Pool with SST > 29°C is projected to expand by 250% by 2035 and > 700% by 2100 under the A2 emissions scenario.

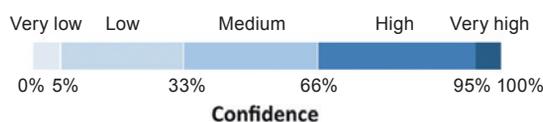
### *Nutrient supply {Chapter 3, Section 3.3.4}*

Projected changes to physical features of the ocean that control the supply of nutrients, include stratification; maximum depth of the mixed layer during winter; upwelling or downwelling at a depth of 50 m; and the areas where currents converge. For the region as a whole, stratification is expected to increase by ~ 10% for both scenarios in 2035, compared with the 1980–1999 average. In 2100, the increase in stratification is projected to be 10% to 20% for the B1 scenario, and 20% to 30% for A2, with the greatest changes in the Warm Pool. The mixed layer depth is projected to be shallower. Minor decreases in upwelling at the equator, and downwelling in adjacent waters, are expected to occur but should not affect the supply of nutrients substantially in the Pacific Equatorial Divergence Province. The major projected change to convergence of currents occurs in the region of the SECC (around 8°S), where the area of eastward flow near the surface is expected to retract west by about 1500 km in 2100 under the A2 scenario.

**Table 6.2** General summary of observed and projected changes to the main features of the tropical Pacific Ocean. Observed changes are relative to the period 1950–1960. Projected changes are relative to 1980–1999. Estimates of confidence are provided for each projection (see key below).

Ocean feature	Observed changes	2035		2100		
		B1	A2	B1	A2	
Currents	South Pacific gyre has strengthened	SEC decreases at the equator; EUC becomes shallower; SECC decreases and retracts westward in the upper 50 m				
Sea surface temperature		Projected to increase significantly over the entire region				
		+0.6 to +0.8°C	+0.7 to +0.8°C	+1.2 to +1.6°C	+2.2 to +2.7°C	
Ocean temperature at 80 m	+0.6 to 1°C since 1950	+0.4 to +0.6°C		+1.0 to +1.3°C	+1.6 to +2.8°C	
Warm Pool	Warmer and fresher	Extends eastward; water warms and becomes fresher, and area of warmest waters increases				
Equatorial upwelling	Decreased	Integral transport 9°S–9°N remains unchanged				
Eddy activity	No measurable changes	Probable variations in regions where major oceanic currents change				
Nutrient supply	Decreased slightly in two locations	Decrease due to increased stratification and shallower mixed layer, with a possible decrease of up to 20% under A2 by 2100				
Dissolved oxygen	Expansion of low-oxygen waters	Possible decrease due to lower oxygen intake at high latitudes				
		Possible increase near the equator due to decreased remineralisation				
		Aragonite saturation ( $\Omega$ ) projected to continue to decrease significantly				
Ocean acidification	➤ $\Omega$ decreased from 4.3 to 3.9	n/a	$\Omega \sim 3.3$	$\Omega \sim 3.0$	$\Omega \sim 2.4$	
	➤ $\Omega$ horizon rises from 600 to 560 m	n/a	~ 456 m	n/a	~ 262 m	
	➤ pH decreased from 8.14 to 8.08	n/a	~ 7.98	n/a	~ 7.81	
Waves	Decreased in far west Pacific; no data elsewhere	Slight increase (up to 10 cm) in swell wave height; patterns depend on ENSO and tropical cyclones				
		Projected to rise significantly				
Sea level	+6 cm since 1960	*	+8 cm	+18 to +38 cm	+23 to +51 cm	
		**	+20 to +30 cm	+70 to +110 cm	+90 to +140 cm	
Island effects	Not observed	Probable; undocumented				

\* Projections from the IPCC-AR4, not including any contribution due to dynamical changes of ice sheets; \*\* projections from recent empirical models (Section 3.3.8.2); SEC = South Equatorial Current; EUC = Equatorial Undercurrent; SECC = South Equatorial Counter Current; ENSO = El Niño-Southern Oscillation; n/a = estimate not available.



### *Dissolved oxygen {Chapter 3, Section 3.3.5}*

Dissolved oxygen is expected to decline in many parts of the region due to larger-scale processes occurring at higher latitudes. In particular, the increasing temperature and stratification of the ocean at higher latitudes are projected to lead to decreased transfer of O<sub>2</sub> from the atmosphere to the ocean, resulting in lower concentrations of O<sub>2</sub> in the tropical thermocline. The existing low levels of O<sub>2</sub> and suboxic areas in the eastern Pacific are also expected to intensify. In contrast, increased concentrations of O<sub>2</sub> are projected to occur in the equatorial thermocline due to reduced biological production (and therefore remineralisation/oxidation) within the water masses flowing to the equator.

### *Ocean acidification {Chapter 3, Section 3.3.6}*

Increases in atmospheric carbon dioxide are projected to lead to substantial additional acidification of the ocean, reducing the average pH of the ocean by 0.2–0.3 units under the B1 and A2 scenarios by 2100. At such rates of change, aragonite saturation levels in the tropical Pacific Ocean are expected to fall below 3.25 under A2 by 2035. The aragonite saturation level is expected to decrease to 2.4 under A2 in 2100. The average depth of the aragonite saturation horizon {Chapter 3, Box 3.3} in the region has been 300 m at 8°N, and deeper to the south and to the north. The horizon is projected to become shallower over time, reaching 150 m in 2100 under the A2 scenario.

### *Wave height {Chapter 3, Section 3.3.7}*

An increase in SWH of 8 to 10 cm in the southern tropical Pacific is projected for 2100 under the A2 emissions scenario. This increase is expected to be most pronounced in the east. No change or a decrease of about 4 cm is expected by 2100 in the northern tropical Pacific. The 20-year return SWH (the value that significant wave height exceeds at least once over a 20-year period) is projected to increase by about 30 cm in the eastern half of the southern tropical Pacific under A2 in 2100. The nature of future ENSO events is also expected to affect wave height.

### *Sea level {Chapter 3, Section 3.3.8}*

The rate of sea-level rise is expected to accelerate. Projections from IPCC-AR4 that sea level will rise by up to 18 cm under B1, and up to 51 cm under A2, by 2100 are now considered to be conservative because they do not include the effects of increased flow from the melting of land ice. Some projections based on historical reconstructions for global sea-level rise, which include the effects of ice melt and thermal expansion, indicate that sea-level rise could be 20 to 30 cm under the B1 and A2 scenarios in 2035, 70 to 110 cm under B1 in 2100 and 90 to 140 cm under A2 in 2100. However, this estimate should be used with caution until the limitations of the methods involved are better understood<sup>ii</sup>.

*Coastal circulation and island effects {Chapter 3, Section 3.3.9}*

Climate change is expected to have localised effects on the waters surrounding different islands through interactions between large-scale oceanic and atmospheric processes and island topography. However, the necessary local projections are scarce and there is a need for specific studies to downscale future climate simulations {Chapter 3, Section 3.5}.

ii See 'Climate Change in the Pacific: Scientific Assessment and New Research' ([www.cawcr.gov.au/projects/PCCSP](http://www.cawcr.gov.au/projects/PCCSP)) for other estimates of sea-level rise.

## 6.4 Vulnerability of open ocean food webs in the tropical Pacific to climate change {Chapter 4}<sup>13</sup>

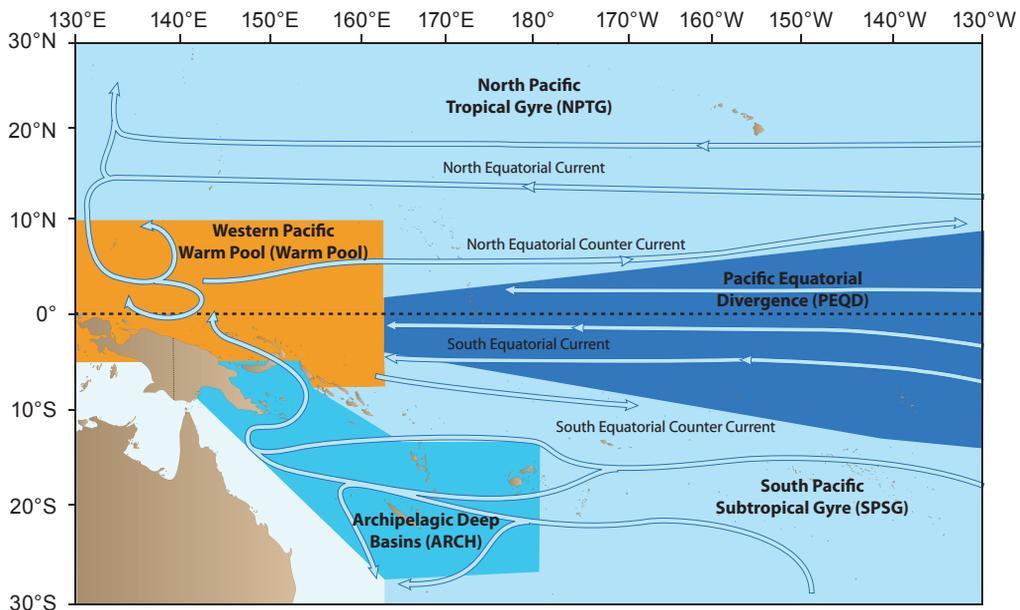
The tropical Pacific Ocean represents a vast area of fish habitat, dwarfing the total area of land {Chapter 1} and associated coastal fish habitats {Chapters 5 and 6} under the jurisdiction of Pacific Island countries and territories (PICTs).

Although much of this open ocean domain is relatively unproductive, it supports some of the largest tuna fisheries in the world. Recent catches of skipjack tuna, yellowfin tuna, bigeye tuna and South Pacific albacore from the Western and Central Pacific Ocean (WCPO) have been ~ 2.5 million tonnes per year, representing > 25% of the total global tuna catch {Chapters 1, 8 and 12}.

The production of the four species of tuna, and other large pelagic fish, is underpinned by food webs based not only on the direct photosynthetic productivity of phytoplankton (primary production) in the sunlit surface layer (photic zone) of the ocean, but also by detritus and bacteria, derived from phytoplankton. Most of this primary production occurs where nutrients, such as nitrogen, phosphorus and silicon, are transported to surface waters from the deeper layers of the ocean by physical processes {Chapter 3}.

The energy produced through primary production moves through a ‘trophic pyramid’ via a range of zooplankton (such as copepods and larval fish), macrozooplankton (including jellyfish and salps) and micronekton (such as squid, shrimp and small fish), to sustain tuna and other large pelagic fish. Changes in ocean processes that deliver nutrients to the photic zone, and to the physical and chemical properties of the ocean, are expected to affect phytoplankton, zooplankton and micronekton.

Not surprisingly, the vast area of the tropical Pacific Ocean does not provide a uniform habitat for the organisms comprising the food webs for tuna. Instead, the region is divided into five ecological provinces, called the Pacific Equatorial Divergence (PEQD), Western Pacific Warm Pool (Warm Pool), North Pacific Tropical Gyre (NPTG), South Pacific Subtropical Gyre (SPSG) and Archipelagic Deep Basins (ARCH) (Figure 6.4). The borders of these provinces are generally defined by convergence zones of surface currents, and each province has a specific wind regime and vertical hydrological structure. The locations of PEQD and the Warm Pool change from year to year, depending on prevailing El Niño-Southern Oscillation (ENSO) conditions.



**Figure 6.4** The five ecological provinces of the tropical Pacific Ocean together with the major ocean currents of the region.

### Physical nature of the provinces in the region {Chapter 4, Section 4.3}

#### *Pacific Equatorial Divergence*

PEQD is generated by the effects of the earth's rotation (Coriolis force) on the South Equatorial Current (SEC) in the two hemispheres (Chapter 3). There is significant upwelling of nutrients, creating the richest surface waters in the region. The waters of PEQD are characterised by higher salinity, partial pressure of carbon dioxide ( $p\text{CO}_2$ ), nutrient concentrations and phytoplankton abundance (chlorophyll  $a$ ). These nutrient-rich waters span much of the equatorial Pacific and drift polewards before submerging at the convergence with the North Equatorial Counter Current (NECC) and the South Equatorial Counter Current (SECC). Although the nutrients available in PEQD exceed those needed for prolific growth of phytoplankton, primary production is limited by low concentrations of iron. Therefore, regardless of the level of macronutrients, phytoplankton biomass remains relatively constant.

#### *Western Pacific Warm Pool*

The surface waters of the Warm Pool have a significantly lower salinity than PEQD, due to high rainfall (Chapter 2). The Warm Pool is also nutrient poor because there is no upwelling. The thermocline in the Warm Pool is relatively deep (~ 80 m) under average conditions, but becomes shallower (~ 40 m) during El Niño episodes. When this occurs, there is an increase in primary production, stimulated by the supply of more nutrients to the photic zone below the thermocline.

### *North Pacific Tropical Gyre and South Pacific Subtropical Gyre*

NPTG and SPSG are created by the large atmospheric anticyclones in the northern and southern subtropical Pacific, which generate oceanic gyres. These two provinces are characterised by a very deep but weak thermocline, which allows some nutrient inputs to the photic zone from deep water through mixing and diffusion. However, during summer, a strong and shallower (40–60 m) thermocline is superimposed on the main thermocline, creating an effective barrier to nutrient inputs. This leads to lower primary production in the upper part of the photic zone in summer.

### *Archipelagic Deep Basins*

As the name implies, ARCH is characterised by the occurrence of many archipelagos and seamounts. It is a patchwork of processes, on a variety of spatial scales, with varied vertical structures, driven by the way the landmasses divert surface currents and create eddies (Chapter 3). ARCH also receives nutrients via runoff from high islands.

## **Projected changes to key physical and chemical features of provinces {Chapter 4, Section 4.7}**

Climate change is likely to have three main effects on the surface areas of provinces under the B1 and A2 scenarios (1) the area of PEQD is expected to be reduced by 20–27% in 2035, 30% under B1 in 2100 and 50% under A2 in 2100; (2) the area of the Warm Pool is projected to increase correspondingly by 18–21% in 2035, and 26% and 48% under B1 and A2, respectively, in 2100; and (3) the gyres are expected to expand towards the poles and to the west.

For all provinces, the average mixed layer depth (MLD) is projected to decrease under both scenarios in 2035 and 2100, except for PEQD (which is dominated by upwelling). A decreasing MLD is expected to reduce nutrient inputs into the photic zone in the gyres and ARCH.

Ubiquitous warming of the region is projected to increase stratification (Chapter 3) in all provinces except PEQD, inhibiting the supply of nutrients. Enhanced warming of the equatorial region is expected to reduce the upwelling of deep, nutrient-rich water, and result in a contraction of PEQD. This contraction is expected to be most pronounced in the A2 scenario and likely to cause a decrease in net primary production across the entire equatorial Pacific by 2100 under high emissions of CO<sub>2</sub>.

Dissolved oxygen (O<sub>2</sub>) is projected to decrease by up to 26% in PEQD to a depth of 300 m by 2100 under the A2 scenario, and increase by 7–8% in NPTG by 2100 under the B1 and A2 scenarios. Elsewhere, changes to O<sub>2</sub> at 300 m are minor and, in all provinces except PEQD, percentage saturation of O<sub>2</sub> is expected to be 50–75%. In PEQD, however, it is projected to drop to 22–28%.

Ocean acidification is expected to affect all provinces, resulting in decreases in aragonite saturation ( $\Omega$ ) levels {Chapter 3}. Depending on the emissions scenario, the projected decrease of  $\Omega$  ranges between 8% and 35%.

### **Projected vulnerability of food webs in provinces to key features of the ocean {Chapter 4, Section 4.8}**

The vulnerability of food webs for tuna in different provinces to projected changes in the tropical Pacific Ocean in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt is summarised below.

#### *Sea temperature {Chapter 4, Section 4.8.1}*

The organisms that comprise the food webs for tuna in all provinces are expected to be highly exposed to projected increases in sea surface temperature and the temperature deeper in the water column (Section 6.3). Food web organisms are sensitive to increasing water temperatures in two ways (1) their metabolism and respiration increases then plateaus and declines when temperatures exceed threshold levels; and (2) increasing stratification at higher temperatures reduces the supply of nutrients required for primary production. Food web organisms that undergo daily vertical migrations {Chapter 4, Box 4.2} have considerable capacity to adapt to these changes because they are already exposed to high variation in temperature. Other organisms are expected to occur in greater abundance where temperature ranges are more favourable. However, adapting to reductions in nutrient supply will be difficult for many organisms (see below). Overall, changes in community composition can be expected.

#### *Mixed layer depth (MLD) {Chapter 4, Section 4.8.2}*

The projected shoaling (shallowing) of the MLD, and resulting declines in nutrient supply from deeper water, are expected to affect the food webs supporting tuna, particularly in the NPTG and SPST Provinces {Chapter 4, Section 4.7}. The potential impacts are a reduction in the average size and total biomass of phytoplankton, leading to a greater number of trophic links and less efficient food webs. Phytoplankton are unlikely to be able to adapt to reduced nutrients and shifts in community composition are expected.

#### *Upwelling {Chapter 4, Section 4.8.3}*

The food web in the PEQD Province is not projected to be exposed to major changes in upwelling. However, the food web in PEQD may benefit from increases in iron concentrations due to the projected strengthening of the Equatorial Undercurrent

{Chapter 3}. Increases in iron concentrations would help overcome the present limitation to primary production and increase the size of phytoplankton, resulting in a more efficient food web with fewer trophic links.

#### *Solar radiation {Chapter 4, Section 4.8.4}*

The Warm Pool, ARCH and PEQD provinces are expected to be exposed to projected lower levels of light due to increasing cloud cover associated with the altered hydrological cycle (Section 6.2). In contrast, SPSG and NPTG are expected to be exposed to higher light levels. Primary production in all ocean provinces is sensitive to changes in light because photoinhibition influences photosynthesis and usually occurs in the upper 30 m of the ocean. However, the potential impacts are expected to be minimal because net primary production is also determined by nutrient concentrations. Nevertheless, changes in the structure of phytoplankton and zooplankton communities can be expected as phytoplankton redistribute to depths with optimal light levels for photosynthesis.

#### *Dissolved oxygen {Chapter 4, Section 4.8.5}*

Although many organisms in the food web of each province are highly sensitive to dissolved oxygen levels, the potential impacts are projected to be minimal (except in PEQD) because oxygen concentrations are high enough to allow for some decrease without affecting productivity. The larger organisms (macrozooplankton and micronekton) living in the deeper layers are expected to be able to escape anoxic conditions by vertical migration {Chapter 4, Box 4.2}.

#### *Ocean chemistry {Chapter 4, Section 4.8.6}*

All provinces are expected to be highly exposed to projected decreases in ocean pH and aragonite saturation (Section 6.3). Decreases in the thickness of the skeletons and shells of some calcareous phytoplankton and zooplankton can be expected to occur, making them more susceptible to predation. However, effects in all provinces are likely to be limited because calcareous organisms comprise only a minor part of the food web (~ 5% of phytoplankton and zooplankton). Calcareous species adversely affected by ocean acidification are expected to be replaced by other species.

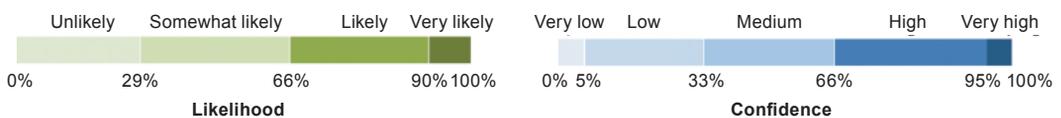
### **Overall vulnerability**

The integrated vulnerability of food webs in each province under the B1 and A2 emissions scenarios in 2035 and 2100 is summarised in Table 6.3.

**Table 6.3** Integrated vulnerability assessments for each of the five ecological provinces in the tropical Pacific Ocean for 2035 and 2100 for the B1 and A2 scenarios combined. Where ranges of values are provided for the projected changes, the lower and higher values represent the projections for B1 and A2, respectively. The likelihood and confidence values associated with these assessments are also shown.

Province	Year	Vulnerability	Projected changes
PEQD	2035	Moderate 	Decrease in surface area of 20–27% as western boundary of PEQD moves eastwards from 180° to 170°W. Minor (2%) reduction in zooplankton biomass. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or composition of plankton.
	2100	High 	Decreases in surface area of 30–50% and movement of boundary to 160–150°W. A 2–4% increase in NPP and 3–6% decrease in biomass of zooplankton. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
Warm Pool	2035	Moderate 	Increase in surface area eastwards by 18–21%, with a 5–7% reduction in NPP and 3–6% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
	2100	High 	Increase in surface area eastwards by 26–48%, with a 9% reduction in NPP and 9–10% decrease in biomass of zooplankton throughout the water column. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
NPTG	2035	Low 	Surface area increases limited to 1% as the province extends to the north. NPP decreases by 3–5% and zooplankton biomass declines by 3 to 4%. No direct effect of higher SST and O <sub>2</sub> , or lower pH, on biomass or species composition of plankton.
	2100	Moderate 	Increase in surface area stabilises at an increase of 1% but NPP decreases greatly (11–22%) and biomass of zooplankton declines by 10–18%. No direct effect of higher SST and O <sub>2</sub> , or lower pH, on biomass or species composition of plankton.
SPSG	2035	Low 	Surface area increases by 3–7%. NPP decreases by 4–5% and biomass of zooplankton declines by 3–4%. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
	2100	Low-Moderate 	Surface area increases by 7–14% and extends poleward, with a 3–6% reduction in NPP and 5–10% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
ARCH	2035	Low 	No change in surface area. A reduction in NPP of 5–8% and a 5–6% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.
	2100	Moderate 	No change in surface area. Greater (20–33%) reduction in NPP and a 17–26% decrease in biomass of zooplankton due to deepening of the thermocline. No direct effect of higher SST, and lower O <sub>2</sub> and pH, on biomass or species composition of plankton.

SST = sea surface temperature; O<sub>2</sub> = dissolved oxygen percentage saturation at 300 m; PEQD = Pacific Equatorial Divergence; Warm Pool = Western Pacific Warm Pool; NPTG = North Pacific Tropical Gyre; SPSG = South Pacific Subtropical Gyre; ARCH = Archipelagic Deep Basins.



## 6.5 Vulnerability of coral reefs in the tropical Pacific to climate change {Chapter 5}<sup>14</sup>

Coral reefs are one of the most important coastal habitats in the tropical Pacific. Thousands of fish and invertebrate species are associated with the structures created by corals, many of which are important for the food security and livelihoods of Pacific Island people. Coral reefs support important fisheries for demersal fish, some nearshore pelagic fish, invertebrates targeted for export commodities, and invertebrates gleaned from shallow subtidal and intertidal areas for food {Chapter 9}. Maintaining the structural complexity of reef frameworks is vitally important to the continuation of these fisheries.

Under the B1 and A2 emissions scenarios in 2035 and 2100, coral reefs are projected to be vulnerable to increasing sea surface temperature (SST), ocean acidification, sea level, nutrient supply and cyclone intensity, as well as to changes to solar radiation, ocean circulation and upwelling. The vulnerability of coral reefs to the projected changes in these variables {Chapters 2 and 3}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### Vulnerability of coral reefs to climate change

#### *Sea surface temperature {Chapter 5, Section 5.6.1}*

Coral reefs will be highly exposed and sensitive to the projected increases in SST {Chapter 3, Section 3.3.2}, with the symbiotic relationship between coral hosts and symbiotic dinoflagellates (*Symbiodinium*) breaking down under extended periods of thermal stress. The impact of thermal stress – known as coral bleaching – has been positively correlated with periods when SST exceeds the summer maxima by 1–2°C for 3–4 weeks or more, especially during strong El Niño events {Chapter 5, Section 5.5.1}. Varying thermal sensitivity of some coral genera is expected to lead to shifts in the species composition of corals on reefs as SST continues to increase. In particular, there is expected to be progressive dominance by heat-tolerant species. Certain corals appear to have the capacity to adapt to warmer waters by increasing the proportion of more temperature-tolerant *Symbiodinium* in their tissues. However, this strategy seems to provide added tolerance only up to increases of 1.5°C, and not extreme heat stress. This potential adaptive mechanism (called symbiont shuffling) also results in slower growth rates and potentially negative ecological implications. Therefore, it is unlikely to protect reefs from the severe and repeated damage projected to occur due to rapid warming of the tropical Pacific Ocean.

#### *Solar radiation {Chapter 5, Section 5.6.2}*

Coral reefs will be moderately exposed to changes in cloud cover associated with projected changes to the hydrological cycle {Chapter 2} and are sensitive to increases

in photosynthetically active radiation (PAR) and ultraviolet radiation (UVR). Higher levels of PAR may exacerbate coral bleaching, whereas higher levels of UVR have the potential to increase damage to cellular components such as DNA. Corals have some ability to adapt to high and variable solar radiation through photoacclimation over a period of 5–10 days, although they remain physiologically stressed.

#### *Ocean acidification {Chapter 5, Section 5.6.3}*

Coral reefs will be highly exposed to the projected decreases in ocean pH {Chapter 3, Section 3.3.6}. Corals are expected to be highly sensitive to the reduced aragonite saturation levels that will result as more carbon dioxide (CO<sub>2</sub>) dissolves in the sea {Chapter 3, Box 3.3} because they will be unable to build their skeletons at the same rate. The ability of corals and other marine calcifying organisms to maintain a positive reef carbonate balance is expected to fall into deficit when atmospheric concentrations of CO<sub>2</sub> exceed 450 ppm. Substantial decreases in calcification can be expected to result in more fragile and degraded reef frameworks. There is little evidence of calcifying organisms adapting to the lower concentrations of carbonate ions projected to occur under ocean acidification during the 21<sup>st</sup> century.

#### *Cyclones and storms {Chapter 5, Section 5.6.4}*

Coral reefs will be exposed to any increases in cyclone and storm intensity, and are highly sensitive to the local physical damage they cause, particularly in shallow reef environments. There are numerous examples of the physical impact of cyclones on coral reefs in the tropical Pacific, with full recovery taking 10–50 years. Coral communities regularly exposed to cyclones and storms are usually dominated by species with stout growth forms, and by fast-growing species, such as *Acropora* spp. However, these reefs have had thousands of years to adapt and no level of adaptation protects coral reefs from the severe damage caused by more intense (category 4 or 5) cyclones.

#### *Rainfall patterns {Chapter 5, Section 5.6.4}*

Coral reefs fringing high islands in the tropics will be highly exposed to the projected increases in rainfall {Chapter 2}. Corals are sensitive to the higher turbidity and nutrient enrichment, and lower salinity, associated with higher rainfall and floods. More intense rainfall is expected to deliver sediment and nutrient loads to coastal coral reefs, impeding photosynthesis of symbiotic dinoflagellates and creating more favourable conditions for the epiphytic algae that compete with corals. As a result, chronic impacts are expected on coral growth, recruitment and recovery after disturbances. Some corals can photoacclimate to lower light levels in turbid waters (with turbidity potentially protecting them from bleaching) and some species are more tolerant of higher sedimentation. However, these adaptations come at an energy cost and such corals may no longer form reefs of high complexity.

### *Sea level {Chapter 5, Section 5.6.5}*

Coral reefs are expected to be exposed to the projected increases in sea level. Their sensitivity is expected to depend on the rate and magnitude of sea-level rise, as well as the influence of other factors on coral growth rate. In particular, reefs that are heavily stressed by increasing SST and ocean acidification are likely to be more sensitive to sea-level rise. It is difficult to be more specific about the response of coral reefs to rising sea level due to the uncertainty about the rate at which glaciers and ice caps will melt. Flows from melting land ice are an important determinant of sea-level rise (Chapter 3), and the growth rate required by corals to keep pace with this rise.

### *Ocean circulation {Chapter 5, Section 5.6.6}*

Coral reef ecosystems are expected to be exposed to changes in ocean circulation, upwelling and nutrient supply, and are highly sensitive to reductions in connectivity and net primary productivity. Changes in currents will have potential impacts on the replenishment rate of coral reef communities. Reductions in net primary production due to increased stratification (Chapters 3 and 4) are expected to cause disruptions to the ecology of both phototrophic species (e.g. corals and seaweed) and heterotrophic species (e.g. fish and invertebrates) associated with reefs. The relatively rapid projected rate of change in the availability of nutrients and the strength of currents means that many reef-associated species are unlikely to adapt.

## **Overall vulnerability**

Ultimately, coral reefs are most vulnerable to increasing SST and ocean acidification (Table 6.4).

- Coral reefs have very high vulnerability to further increases in SST, and the projected increase in SST in the tropical Pacific region of 1–3°C by 2100 will influence the structure and function of coral reefs. Effects are expected to be clearly evident by 2035, with increasing frequency of mass coral bleaching events.
- The reduction in calcification rates at lower ocean pH suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification. Increases in atmospheric CO<sub>2</sub> above 450 ppm are likely to result in net erosion of coral reefs throughout the tropical Pacific.
- On the basis of their capacity to photoacclimate within days, coral reefs appear to have a relatively low vulnerability to the projected changes in solar radiation.
- Coral reefs are expected to be moderately vulnerable to any increases in cyclone and storm intensity, and highly vulnerable to increases in rainfall and terrestrial inputs of sediments and nutrients due to more intense floods.
- The location of coral reefs will have a strong effect on the extent of their vulnerability to changes in ocean circulation – some reefs will receive fewer essential nutrients and recruits, whereas others will receive more.

- Coral reefs are likely to have low vulnerability to sea-level rise if the conservative projections from IPCC-AR4 (Chapter 3) are realised but will have moderate vulnerability if glaciers and ice caps melt rapidly as expected in more recent projections.

**Table 6.4** Vulnerability of coral reefs to projected changes in surface climate and the ocean.

Sea surface temperature	Solar radiation	Ocean chemistry	Cyclones and storms	Rainfall patterns	Sea level*	Ocean circulation
Very high	Low	Very high	Moderate	High	Low-moderate	Moderate

\* Range of vulnerability reflects the significant uncertainty regarding the rate of sea-level rise.

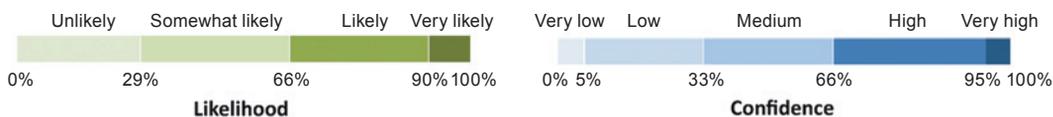
### Projected changes in habitat area

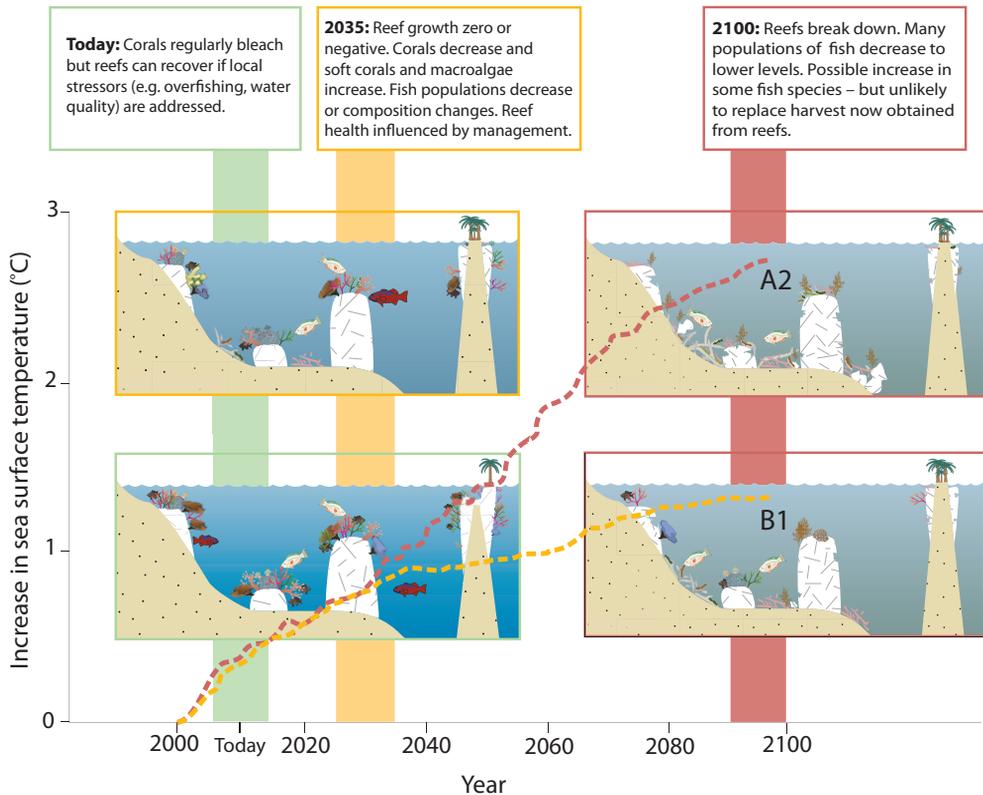
Coral reef habitats are projected to change as emissions of greenhouse gases increase. Coral cover is expected to decline under both the B1 and A2 scenarios in the medium (2035) and long term (2100). Macroalgae (fleshy and turf algae) are projected to become more dominant (Figure 6.5).

Management of other human pressures on reefs, such as reduction of sediment and nutrient delivery from catchments, will assist reefs to tolerate increasing SST and ocean acidification and recover from disturbances. Strong management is expected to limit the loss of coral and proliferation of macroalgae under both scenarios in 2035, and B1 in 2100 but could have little effect under A2 in 2100 (Table 6.5).

**Table 6.5** Estimated projected changes in the percentage cover of live coral and macroalgae on reefs in 2035 and 2100 for the B1 and A2 scenarios under poor and strong management, relative to 2010. The expected remaining cover (%) of coral and macroalgae (including fleshy algae and algal turfs) is also shown. Likelihood and confidence associated with the projections are based mainly on the combined understanding of the expected responses of coral and macroalgae.

Year	Scenario	Management	Coral cover		Macroalgal cover	
			%	% decrease	%	% increase
2035	B1/A2	Strong	15–30	25–65	40	130
		Poor	15	65	40–60	130–200
2100	B1	Strong	10–20	50–75	50	> 150
		Poor	< 5	> 85	80	> 250
	A2	Strong	< 2	> 90	> 95	> 300
		Poor	< 2	> 90	> 95	> 300





**Figure 6.5** The future of coral reefs under B1 and A2 emissions scenarios. Note that the B1 and A2 trajectories are largely indistinguishable by 2035 but diverge after 2050. Under the B1 scenario in 2100, coral populations are projected to decrease and reefs are expected to be dominated by non reef-building species. Under the A2 scenario in 2100, sea surface temperatures and ocean acidity, as well as other factors such as turbidity and possibly cyclone intensity, are expected to increase. This is likely to lead to the complete loss of reef-building corals from reefs. Yellow and red vertical columns correspond to the range of years used to model the B1 and A2 emissions scenarios.

## 6.6 Vulnerability of mangroves, seagrasses and intertidal flats in the tropical Pacific to climate change {Chapter 6}<sup>15</sup>

The mosaic of mangroves, seagrasses, intertidal flats<sup>i</sup> and coral reefs along the coasts of Pacific Island countries and territories (PICTs) creates important fish habitats. Mangroves and seagrasses provide nursery areas for commonly harvested fish and invertebrates, and feeding grounds for many species of adult demersal fish targeted by coastal fisheries. Seagrasses and intertidal flats are permanent habitats for sea cucumbers – one of the main invertebrate export commodities from the region – and for a wide range of molluscs gleaned for subsistence {Chapter 9}. Maintaining these habitats is vitally important to the continuation of these fisheries.

Under the B1 and A2 emissions scenarios in 2035 and 2100, mangroves are projected to be vulnerable to sea-level rise, and possibly more intense cyclones. Seagrasses are expected to be vulnerable to increasing sea surface temperature (SST), variable solar radiation, changes to rainfall and possible increases in cyclone intensity. Intertidal flats are vulnerable to sea-level rise. The vulnerability of the plant species that create these habitats (including the algal mats of intertidal flats) to the projected changes in these variables {Chapters 2 and 3}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### Vulnerability of coastal habitats to climate change

#### *Temperature {Chapter 6, Sections 6.6.1.2 and 6.6.2.2}*

*Mangroves* are expected to be highly exposed to increases in air and sea surface temperatures (SST). The trees are likely to be moderately sensitive to increases in SST because their respiratory demands will increase. Potential impacts for some mangrove species include development of more silt roots and smaller leaves, and greater mortality of young seedlings. Mangroves are able to adapt to higher air temperatures by reducing the apertures of their leaf stomata to cope with water loss induced by increased evaporation under heat stress. But mangroves have limited capacity to adapt to increasing SST.

*Intertidal and subtidal seagrasses* are also expected to be highly exposed to increases in air temperature and SST. These seagrasses are expected to be highly sensitive because chronic elevated SST increases respiratory demand that can exceed photosynthesis and affect their growth and survival. The potential impacts of increased SST include changes in species composition, relative abundance and distribution of seagrasses, as well as acute ‘burn off’ during short-term temperature spikes. The high light requirements of many tropical seagrass species and overall respiration demand will limit their ability to adapt to increasing SST by colonising deeper areas.

i Includes intertidal areas of sand and mud above mean low tide, but not intertidal coral reef or seagrass habitats.

*Solar radiation {Chapter 6, Sections 6.6.1.1 and 6.6.2.1}*

*Mangroves* are expected to be highly exposed to projected increases in solar radiation in subtropical areas. Mangroves are sensitive to increases in light but not to decreases. High levels of light, when coupled with lower rainfall, have the potential to overheat mangroves and damage cellular components such as DNA. Mangroves have limited ability to adapt to higher solar radiation.

*Seagrasses* are expected to be highly exposed to the projected reductions in solar radiation in the tropics. Seagrasses are sensitive to decreases in light, because the related declines in photosynthesis affect growth rates and eventually the species composition of seagrass communities. Where reduced light persists for long periods, the area of seagrass habitat decreases. High levels of UV light reduce production of chlorophyll in seagrass tissues and enhance production of pigments, causing ‘reddening’ of plant leaves. Seagrasses are able to respond to short-term reductions in light through a range of morphological and physiological adjustments.

*Atmospheric carbon dioxide and ocean chemistry {Chapter 6, Sections 6.6.1.6 and 6.6.2.6}*

*Mangroves* are expected to be exposed to projected increases in concentrations of atmospheric carbon dioxide (CO<sub>2</sub>). Respiration and productivity of mangroves are likely to improve as atmospheric concentrations of CO<sub>2</sub> increase. A potential impact of higher atmospheric CO<sub>2</sub> concentrations is greater productivity of mangroves. Changes to the species composition of mangrove communities and encroachment into adjacent inland environments are likely to occur. Mangroves are also projected to be exposed to ocean acidification but are not expected to be sensitive.

*Seagrasses* are expected to be exposed to decreases in ocean pH but are unlikely to be sensitive because they currently experience greater variations in pH on a daily basis. Seagrass may in fact benefit from increasing CO<sub>2</sub> concentration through increased productivity, biomass and reproductive output as a result of faster photosynthetic rates. This could allow some species of seagrass to colonise areas with lower light, such as deeper water.

*Cyclones and storms {Chapter 6, Sections 6.6.1.5 and 6.6.2.5}*

*Mangroves* are likely to be exposed to any increases in cyclone and storm intensity, and are highly sensitive because cyclones damage foliage, desiccate plant tissues, and increase evaporation rates and salinity stress. More powerful wave surge during cyclones erodes sediments on the seaward edge of mangroves and reduces the stability of plants. Mangrove species have different tolerances to cyclone damage – some species can resprout from dormant buds. Over time, recruitment of mangrove seedlings occurs from adjacent undamaged areas.

*Seagrasses* in intertidal and shallow subtidal areas will also be exposed to any increases in cyclone and storm intensity, and are particularly sensitive to the physical effects of storm surge and increased turbidity associated with cyclones. Severe storms can impact seagrass habitats through the combined effects of physical disturbance (stripping leaves and uprooting plants), reductions in light (reducing photosynthesis) and salinity, and movement of sediments (smothering plants). Small species of seagrass suffer more damage from cyclones than larger species which have rhizomes buried deeper in the sediment. However, smaller species have the capacity to recover rapidly provided propagules are available from nearby meadows.

#### *Rainfall patterns {Chapter 6, Sections 6.6.1.3 and 6.6.2.3}*

*Mangroves* are expected to be highly exposed to projected changes in rainfall and are moderately sensitive to the resultant changes in soil salinity, freshwater saturation and sediment delivery. Increased rainfall will lower salinity, which may benefit mangroves but will also increase soil inundation by freshwater, potentially affecting root growth, especially in seedlings. Decreased rainfall has the potential to cause more significant impacts, by increasing soil salinity to the point where it affects plant growth, reducing sediment delivery for vertical accretion, and reducing flowering and fruiting. Mangroves can adapt to decreasing rainfall by using water more efficiently and reducing transpiration rates to avoid water loss.

*Seagrasses* are expected to be highly exposed to increases in rainfall in the tropics. Seagrasses are moderately sensitive to the associated changes in turbidity, sedimentation, delivery of nutrients and pollutants, salinity and physical scouring. Seagrasses have low adaptive capacity to high levels of turbidity, sediment deposition, pollution and scouring. However, some species are more tolerant of low salinity and such species would be expected to become more prevalent.

#### *Sea level {Chapter 6, Sections 6.6.1.7 and 6.6.2.7}*

*Mangroves* are expected to be highly exposed to projected rises in sea level. In particular, mangroves are expected to be inundated by sea water more frequently, and to be inundated permanently in low-lying areas. The sensitivity of mangroves is expected to be high to very high depending on the rate and magnitude of sea-level rise. More frequent inundation by sea water has critical implications for plant growth, respiration and survival. The ability of mangroves to migrate landward as sea level rises is an important adaptation, but will depend on (1) topography, (2) the rate of sea-level rise, (3) hydrology, (4) sediment composition, and (5) competition with non-mangrove species in landward areas. There is concern that the capacity of mangroves to migrate landward may not be able to keep pace with the projected accelerated rate of sea-level rise. In many places, steep terrain and existing infrastructure (e.g. roads) will prevent any migration.

*Seagrasses* are also expected to be exposed to projected sea-level rise and are likely to be sensitive because increasing depth reduces the light available to deeper plants, limiting photosynthesis and growth. The potential impacts are expected to be losses in seagrass area or changes in species composition in deeper meadows. Seagrasses growing along the deeper margins of meadows are at the limit of their light tolerance and are unlikely to be able to adapt to further light reductions. However, seagrasses in some intertidal and shallow subtidal areas can adapt to rising sea levels by growing landward, provided the newly inundated sediments are suitable.

*Intertidal flats* and the productive benthic microalgae communities that they support are expected to be highly exposed to sea-level rise. Intertidal flats are likely to be highly sensitive to rising sea levels where there is little scope for expansion landward due to barriers. The potential impacts of sea-level rise include considerable losses of intertidal habitat, and the associated species that are not adapted to live subtidally.

#### *Nutrient delivery {Chapter 6, Sections 6.6.1.4 and 6.6.2.4}*

*Mangroves* are expected to be exposed and sensitive to projected changes in nutrient levels associated with more variable rainfall patterns. In general, increased nutrients may fertilise mangroves and increase their growth. The additional sediments usually associated with higher levels of runoff can also assist mangroves to adapt to rising sea levels through enhancement of vertical accretion. But reductions in nutrient delivery due to low rainfall also have the potential to affect plant growth and the species composition of mangrove communities. The potential beneficial impacts of increases to nutrients will be most evident when coupled with increases in air temperature and CO<sub>2</sub>. Adaptations of mangroves to changes in nutrient levels are expected to be most evident at the community level, with different species dominating under particular nutrient conditions.

*Seagrasses* are expected to be exposed to projected changes in nutrient delivery and will be moderately sensitive. Increases in nutrients up to a certain level in the water column are expected to enhance seagrass growth. However, excessive nutrient concentrations promote the growth of epiphytes on seagrass leaves, blocking light and retarding seagrass growth. On balance, the potential impacts are likely to be generally beneficial but seagrasses have little capacity to adapt to heavy growth of epiphytes.

#### **Overall vulnerability**

*Mangroves* are projected to be most vulnerable to sea-level rise, changes to rainfall and any increase in cyclone and storm intensity. Mangroves are expected to have an overall moderate vulnerability to climate change in 2035 under both scenarios, increasing to high under B1 in 2100, and very high under A2 in 2100 (Table 6.6).

*Seagrasses* are projected to be most vulnerable to increasing SST, decreasing light, changing rainfall patterns and any increases in cyclone and storm intensity. Seagrasses are expected to have an overall moderate vulnerability under both scenarios in 2035 and B1 in 2100, increasing to high under A2 in 2100 (Table 6.6).

*Intertidal flats* are projected to be most vulnerable to sea-level rise, and are expected to have low vulnerability under the B1 and A2 emissions scenarios in 2035, increasing to high in 2100.

**Table 6.6** Summary of vulnerability of mangroves and seagrasses to projected changes in surface climate and the ocean.

	SST	Solar radiation	Ocean chemistry	Cyclones and storms	Rainfall patterns	Sea level	Nutrients
<b>Mangroves</b>							
B1/A2 2035	Very low	Low	Very low	Moderate	Low	High	Low
B1 2100*	Very low	Low	Very low	Moderate	Moderate	Very high	Low
A2 2100	Very low	Low	Very low	Moderate	Moderate	Very high	Low
<b>Seagrasses</b>							
B1/A2 2035	Moderate	Moderate	Very low	Moderate	Moderate	Low	Low
B1 2100*	Moderate	Moderate	Very low	Moderate	Moderate	Moderate	Low
A2 2100	High	High	Very low	High	High	Moderate	Moderate

\* Approximates A2 in 2050; SST = sea surface temperature.

### Projected changes in habitat area

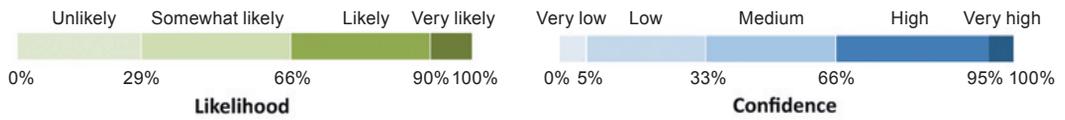
Ultimately, the vulnerability of mangroves to sea-level rise, changes in rainfall and possible increases in cyclone intensity, is projected to reduce the areas of mangrove habitat in Pacific Island countries and territories, with the declines becoming greater over time.

The vulnerability of seagrasses to increasing SST, decreasing solar radiation, changing rainfall patterns and possible increases in cyclone intensity is projected to reduce seagrass area, with declines expected under both the B1 and A2 scenarios in the short term (2035) and long term (2100) (Table 6.7).

The area of intertidal flats is also expected to decrease. However, it is not possible to estimate the area likely to be lost due to poor baseline data for this habitat in the region.

**Table 6.7** Projected loss of mangrove and seagrass habitat under B1 and A2 emissions scenarios in 2035 and 2100, relative to 2010.

Year	Scenario	Mangrove area (%)	Seagrass area (%)
2035	B1/A2	-10 to -30	< -5 to -20
2100	B1	-50 to -70	-5 to -35
2100	A2	-60 to -80	-10 to -50



## **6.7 Vulnerability of freshwater and estuarine habitats in the tropical Pacific to climate change {Chapter 7}<sup>16</sup>**

Freshwater and estuarine habitats occur mainly in the western Pacific, where rivers and lakes support a diversity of fish and invertebrates {Chapter 10}. The extent of some of these habitats is significant - the Sepik-Ramu, Fly and Purari rivers in Papua New Guinea (PNG) have annual discharges among the highest in the world. On the other hand, many rivers in other Pacific Island countries and territories are too small to maintain permanent freshwater flows. Nevertheless, throughout much of the region, freshwater and estuarine fish and invertebrates contribute to food security {Chapter 10}.

Under the B1 and A2 emissions scenarios in 2035 and 2100, freshwater and estuarine habitats in the subtropical Pacific are projected to be vulnerable to decreases in rainfall, sea-level rise, increasing temperature and possibly increasing cyclone intensity. However, freshwater habitats in equatorial regions may benefit from increasing rainfall and air temperatures. The vulnerability of these habitats to the projected changes in surface climate and the ocean {Chapters 2 and 3}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### **Vulnerability of freshwater and estuarine habitats**

#### *Temperature {Chapter 7, Sections 7.5.4 and 7.6.2}*

Freshwater and estuarine habitats are expected to be exposed to projected increases in temperature. Shallow, low-flow environments, such as high-elevation lakes, river edges and floodplain wetlands, are expected to be sensitive to these changes because warmer air temperatures will increase evaporation and water temperatures. The limited mixing in shallow freshwater floodplain and edge environments is likely to result in water temperatures that exceed the tolerance of many fish and invertebrates, particularly those living in coldwater lakes. The macrophyte species that create fish habitats in environments such as intertidal estuaries, that already experience daily temperature fluctuations of up to 10°C, are likely to be able to adapt. However, some macrophytes in other habitats may have limited capacity to adapt to increasing water temperatures.

#### *Cyclones and storms {Chapter 7, Sections 7.5.2 and 7.6.2}*

Freshwater habitats in coastal areas and estuaries may be exposed to more severe cyclones and storms. The vegetation that creates many freshwater and estuarine fish habitats is sensitive to damage by floods associated with cyclones. Floods can also change riverine landscapes. Potential impacts include creation of new channels, transport of coarse sediments, floodplain sedimentation, the collapse of river banks

and scouring of river beds. However, freshwater river habitats are dynamic systems that change and reform in response to floods, provided the capacity for river beds to expand and contract is not constrained. Storm surge is also expected to cause saline intrusion in floodplain and freshwater environments, and higher saltwater penetration in coastal plain estuaries and tidal rivers. The vegetated components of freshwater fish habitats have limited capacity to adapt to increasing salinity or extended inundation by salt water.

#### *Rainfall patterns {Chapter 7, Sections 7.5.1 and 7.6.2}*

Freshwater and estuarine habitats are expected to be highly exposed to projected changes in rainfall and to be sensitive to both increases and decreases in rainfall. Higher rainfall will lead to greater flows and flooding, which will improve connectivity between the mosaic of habitats but also increase erosion and sedimentation. On balance, freshwater habitats in the tropics are expected to benefit from the projected increases in rainfall. However, in the subtropics, the decreases in rainfall are expected to reduce flows and connectivity. In floodplain habitats, the vegetation that helps create many fish habitats is likely to have much potential to adapt to increases in the frequency and duration of inundation.

#### *Sea level {Chapter 7, Sections 7.5.5 and 7.6.2}*

Freshwater habitats in low-lying areas and estuaries are expected to be highly exposed to inundation by sea water due to projected sea-level rise. The plants in these habitats will be sensitive to the changes in salinity. In particular, mangroves and salt marsh vegetation are expected to move landward and freshwater vegetation with little tolerance to increases in salinity is expected to disappear. However, if the rate of sea-level rise is rapid, the ability of mangroves to colonise new areas will be compromised {Chapter 6}. Where the upstream extent of estuaries is not constrained, estuarine habitats are expected to migrate landward. However, estuaries that are unable to retreat because of steep topography or other barriers are likely to be reduced in area.

### **Overall vulnerability**

Freshwater habitats in equatorial areas are expected to benefit from increasing rainfall that will enhance river flows and result in better growth of aquatic vegetation at higher temperatures. In the subtropics, freshwater habitats are expected to be vulnerable to the projected decreases in rainfall, particularly in shallow low-flow environments. Estuaries and low-lying freshwater habitats close to the coast are likely to have high vulnerability to sea-level rise, and any increase in cyclone intensity, under both scenarios in 2035 and 2100 (Table 6.8).

**Table 6.8** Vulnerability of freshwater and estuarine habitats to projected changes in surface climate in 2035 and 2100, relative to 2010.

	Temperature	Cyclones and storms <sup>a</sup>	Rainfall	Sea level <sup>a</sup>
<b>Equatorial</b>				
B1/A2 2035	Low	Low/High	Low	Low/High
B1 2100*	Low	Low/High	Low	Low/High
A2 2100	Low	Low/High	Low	Low/High
<b>Subtropical</b>				
B1/A2 2035	Low	Low/High	Moderate	Low/High
B1 2100*	Moderate	Low/High	High	Low/High
A2 2100	High	Low/High	High	Low/High

\* Approximates A2 in 2050; a = vulnerability reflects the different locations of habitats with coastal and low-lying freshwater and estuarine habitats having high vulnerability to more intense cyclones and sea-level rise, whereas inland areas are expected to have a low vulnerability.

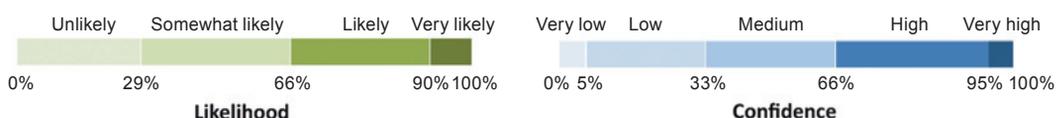
### Projected changes in habitat area

Ultimately, the projected effects of climate change are expected to increase the area of freshwater habitats in equatorial regions and reduce the area of these habitats in the subtropics (Table 6.9).

Maintaining riparian vegetation to shade rivers and control water temperature, and minimising the loss of catchment vegetation to reduce delivery of sediments and nutrients to rivers, will assist freshwater and estuarine habitats to cope with projected changes to the climate. These management measures should also facilitate increases in habitat area where conditions are suitable.

**Table 6.9** Projected change in freshwater habitat (%) under B1 and A2 emissions scenarios in 2035 and 2100, relative to 2010.

Year	Scenario	Freshwater area (%)
2035	B1/A2	-5 to +10
2100	B1	-10 to +20
2100	A2	-20 to + > 20



## 6.8 Vulnerability of oceanic fisheries in the tropical Pacific to climate change {Chapter 8}<sup>17</sup>

Oceanic fisheries are of vital importance to the economies and people of Pacific Island countries and territories. These fisheries are dominated by skipjack, yellowfin, bigeye and albacore tuna, with recent total catches from the Western and Central Pacific Ocean (WCPO) for all species combined approximating 2.5 million tonnes per year. The catch from the WCPO provided 58% of the estimated global tuna catch in 2009 and the catch from the EEZs of Pacific Island countries and territories made up 48% of the catch from the WCPO. The distributions and abundances of the four tuna species, and other pelagic fish, are influenced greatly by oceanic conditions. Changes in currents, ocean temperature, dissolved oxygen and the nature of the five ecological provinces in the WCPO {Chapter 4} are expected to affect the catches of tuna.

Under the B1 and A2 emissions scenarios in 2035 and 2100, tuna are expected to be exposed directly to changes in ocean temperature, currents and ocean chemistry, and dissolved oxygen. Tuna are also likely to be exposed to changes in the food webs on which they depend. However, due to the high mobility of adult tuna, these changes are not expected to result in significant vulnerability of oceanic fisheries. Rather, they are expected to cause shifts in distribution of tuna to the east and changes in the ‘catchability’ of tuna. The vulnerability of tuna species to the projected changes in the main physical, chemical and biological features of the tropical Pacific Ocean {Chapters 3 and 4}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### Vulnerability of tuna to the direct effects of climate change

#### *Ocean temperature {Chapter 8, Section 8.4.1}*

The four main species of tuna in the tropical Pacific are expected to be highly exposed to projected increases in surface and sub-surface temperature. These species are also expected to be sensitive to changes in temperature because it regulates metabolism and development, and limits activity and distribution. Tuna are most sensitive to changes in temperature during their larval and juvenile life stages but have wider temperature tolerances as they mature. Projected ocean warming may affect the distribution of tuna by changing spawning locations and success, and accessibility to feeding areas due to increased stratification of the water column. However, the four tuna species are expected to adapt fairly easily to the changing conditions in the ocean. Both juvenile and adult tuna are highly mobile and can follow their preferred temperature range and prey, as presently observed during the different phases of the El Niño-Southern Oscillation.

### *Ocean chemistry {Chapter 8, Section 8.4.4}*

Tuna species will be exposed to projected ocean acidification and are expected to be sensitive because ocean chemistry affects blood pH, otolith formation and ocean acoustics. Most fish tolerate a wide range of dissolved CO<sub>2</sub> concentrations and pH, but there are likely to be potential physiological impacts associated with compensating for acidosis (lower blood pH), such as lower growth rates and egg production. Other potential impacts include reduced otolith formation (because otoliths are made of aragonite), and impaired acoustic ability of tuna to assess their physical and biological environment, and detect prey and predator species. Acidosis could also lead to a narrowing of the optimal thermal performance range and, consequently, altered resistance, metabolic rate and behaviour of tuna. Ocean acidification could also affect the behaviour of tuna larvae, reducing survival. The capacity of tuna to adapt to ocean acidification is unknown.

### *Ocean circulation {Chapter 8, Section 8.4.3}*

Tuna are expected to be exposed to changes in ocean circulation and are likely to be sensitive to such changes because currents (and SST) determine the location of spawning grounds, the dispersal of larvae and juveniles, and the distribution of prey. Potential impacts include changes in the location of spawning grounds eastward or to higher latitudes, altered retention of larvae in areas favourable for growth and survival, and shifts in the distribution of prey for juveniles and adults to the east {Chapter 4}. Tuna are expected to have considerable capacity to adapt their behaviour to seek out suitable conditions for spawning and productive feeding areas. Such alterations in behaviour are likely to result in changes in distribution to the east and to higher latitudes.

### *Dissolved oxygen {Chapter 8, Section 8.4.2}*

Tuna will be highly exposed to possible reductions in dissolved oxygen (O<sub>2</sub>), and are expected to be sensitive to these changes because O<sub>2</sub> is critical for maintaining metabolic rate and mobility. Sensitivity to the availability of dissolved oxygen and to lethally low levels of O<sub>2</sub> vary among tuna species. Skipjack tuna and albacore tuna are less tolerant to low oxygen concentrations than yellowfin tuna. Bigeye tuna are the most tolerant species. Changes in O<sub>2</sub> in subsurface waters are expected to have limited impact on skipjack tuna, which inhabit the surface layer. However, greater impacts are possible for tuna species that swim regularly between the surface and subsurface (yellowfin tuna and albacore) and to deeper layers (bigeye tuna). Any decrease in O<sub>2</sub> concentrations at mid to high latitudes may limit the extension of tuna habitat into more temperate areas. Tuna can adapt to reductions in dissolved oxygen by changing the ocean layers they use, with subsurface areas expected to be used more in the northern than in the southern Pacific, due to marked differences in projected O<sub>2</sub> levels. Changes in the concentration of dissolved oxygen are expected to have effects on the distribution and catchability of tuna.

## Vulnerability of oceanic fisheries to the indirect effects of climate change

### *Changes to food webs {Chapter 8, Sections 8.5.1 and 8.5.2}*

Tuna are eventually expected to be exposed to declines in primary productivity in much of the tropical Pacific Ocean due to increased stratification of the water column {Chapter 3}. The reduced supply of nutrients is likely to change the composition of food webs for tuna {Chapter 4}. Tuna are expected to be particularly sensitive to any decrease in the productivity of the micronekton they feed on because of their high energy requirements for rapid growth, great rates of egg production, and constant and fast swimming activity. Any mismatches between periods of high primary productivity and spawning events, and between the distribution of larvae and their zooplanktonic food, are expected to affect the survival of larvae and subsequent recruitment success of tuna. A projected shift of the convergence between the Warm Pool and Pacific Equatorial Divergence Province {Chapter 4} to the east would change the location of the best feeding grounds for skipjack tuna. The projected reductions in the productivity of food webs in the Warm Pool and the subtropical gyres (Section 6.4) are likely to result in lower catches of tuna in these provinces. The highly mobile nature of tuna is expected to assist them to adapt to changes in the availability of micronekton prey by moving to more favourable feeding grounds.

### Overall vulnerability

The skipjack tuna that underpin much of the catch by oceanic fisheries in the tropical Pacific are projected to be most vulnerable to increasing ocean temperatures, lower primary productivity and to a lesser extent reduced dissolved oxygen (Table 6.10). The greatest effects on skipjack tuna are projected to be distributional shifts eastward and to higher latitudes, primarily as a result of (1) increasing ocean temperature making the western equatorial Pacific unsuitable for spawning; and (2) the contraction of the productive convergence zone between the Warm Pool and the Pacific Equatorial Divergence Province to the east.

**Table 6.10** Vulnerability of adult skipjack and bigeye tuna to projected changes in the tropical Pacific Ocean

	Ocean temperature	Ocean chemistry	Ocean circulation*	Dissolved oxygen	Primary productivity (mid trophic)**
<b>Skipjack</b>					
B1/A2 2035	Low	Low	Low	Low	Medium
B1 2100*	Medium	Low	Low	Low	High
A2 2100	High	Medium	Medium	Medium	High
<b>Bigeye</b>					
B1/A2 2035	Low	Low	Low	Low	Low
B1 2100*	Medium	Low	Low	Medium	Medium
A2 2100	High	Medium	Medium	High	High

\* Approximates A2 in 2050; \*\* larvae will be more vulnerable than the more mobile adults.

## Projected changes in oceanic fisheries

Preliminary modelling indicates that catches of skipjack tuna are likely to increase across the region in 2035, although the increases are expected to be greater for PICTs in the eastern Pacific than in the western Pacific. By 2100 under the B1 scenario (A2 in 2050), catches for the western Pacific are projected to decrease and return to the average levels for the region in 1980–2000. In contrast, average catches in the eastern Pacific are expected to increase by > 40% (Table 6.11).

Under the A2 scenario in 2100, average catches of skipjack tuna for the western Pacific are estimated to decline by > 20%. Although catches in the eastern Pacific are still projected to be substantially greater compared to 1980–2000 levels, they are expected to decrease relative to the projections for the B1 scenario. Across the entire region, total catch is projected to decrease by 7.5% under the A2 scenario by 2100 (Table 6.11).

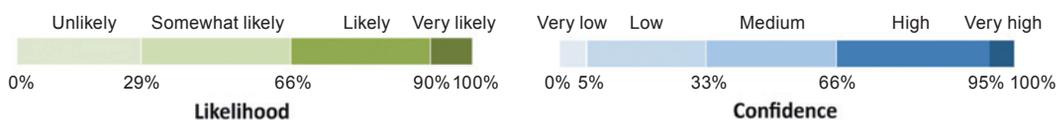
For bigeye tuna, small decreases in catch (usually < 5%) are projected to occur across much of the region by 2035. The magnitude of the reduced catches is projected to increase to 5–10% under the B1 scenario by 2100, and 10–30% for many PICTs under the A2 scenario in 2100 (Table 6.11).

Modelling for yellowfin tuna and albacore is now in progress.

**Table 6.11** Projected percentage changes in average catches of skipjack and bigeye tuna for the eastern and western Pacific, in 2035 and 2100 under the B1 and A2 emissions scenarios relative to 1980–2000 levels (note that results are based on preliminary modelling only).

	West <sup>a</sup>			East <sup>b</sup>		
	B1/A2 2035	B1 2100*	A2 2100	B1/A2 2035	B1 2100*	A2 2100
Skipjack tuna	+10	0	-20	+30 to 35	+40 to 45	+25 to 30
Bigeye tuna	0 to -5	-10 to -15	-30 to -35	0 to +5	0 to -5	-15 to -20

\* Approximates A2 in 2050; a = 15°N–20°S and 130°–170°E; b = 15°N–15°S and 170°E–150°W.



## 6.9 Vulnerability of coastal fisheries in the tropical Pacific to climate change {Chapter 9}<sup>18</sup>

Coastal fisheries contribute significantly to the food security, livelihoods, and culture of Pacific Island people – fish consumption per person across much of the region is at least 2–4 times higher than the global average. The wide variety of species caught by coastal fisheries can be separated into demersal fish (bottom-dwelling fish associated with coral reef, mangrove and seagrass habitats), nearshore pelagic fish, invertebrates targeted for export and invertebrates gleaned from subtidal and intertidal habitats. The total contribution of subsistence and commercial coastal fisheries to national gross domestic product (GDP) across the region is estimated to be USD 272 million, with > 70% of the total catch being taken by subsistence fishing.

Under the B1 and A2 emissions scenarios in 2035 and 2100, the fish and invertebrate species that comprise coastal fisheries are projected to be directly exposed to increasing sea surface temperature (SST), ocean acidification, and changes to ocean circulation. These species are also expected to be indirectly exposed to climate change through alterations to their supporting habitats. The vulnerability of coastal fisheries species to the projected changes in these variables {Chapters 3, 5 and 6}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### Vulnerability of coastal fish and invertebrates to the direct effects of climate change

#### *Sea surface temperature {Chapter 9, Section 9.3.1.1}*

Coastal fisheries species are expected to be highly exposed to projected increases in SST, and are likely to be sensitive to these changes because temperature regulates metabolism and development, and influences activity and distribution. Many coastal fish and invertebrate species experience a range of temperatures each day, and during different seasons. As a result, such species are relatively tolerant of short-term changes in temperature. However, all species have a thermal optimum and when this threshold is exceeded, increased metabolic rate and oxygen demand may interfere with reproduction, recruitment and growth of juvenile and adult fish. Many species may be able to adapt through settlement of larvae in places outside the normal distributional range of the species where temperatures remain below the thermal optimum threshold. Such adaptation will be difficult for species that depend on coral reefs, if there are no reefs available within the relocated optimal temperature range.

#### *Ocean acidification {Chapter 9, Section 9.3.1.2}*

Coastal fisheries species are expected to be exposed to ocean acidification which is projected to result in decreases in aragonite saturation state {Chapter 3}. Invertebrates

are sensitive to decreases in aragonite saturation states below the threshold levels needed for them to build shells of normal thickness – predation is expected to be greater on molluscs with thinner shells. The sensory ability of larval and postlarval demersal fish can also be impaired by acidification of the ocean, leading to a loss of their ability to navigate to reefs, distinguish beneficial settlement sites and detect and avoid predators. The adaptive capacity of coastal fisheries species to ocean acidification is expected to be low because ocean pH has changed very little over the past 800,000 years. Consequently, marine organisms are likely to lack the genetic variation necessary for rapid adaptation to changes in seawater chemistry.

### *Ocean circulation {Chapter 9, Section 9.3.1.3}*

The pelagic larval stages of coastal fish and invertebrates are expected to be exposed to changes in ocean circulation particularly in areas under the influence of the South Equatorial Current and South Equatorial Counter Current {Chapter 3}. Resident adults on coral reefs and in other coastal habitats are also likely to be exposed to changes in the strength and persistence of upwellings and associated delivery of nutrients from deepwater. Fisheries species can be expected to be sensitive to the reduced opportunities for larval dispersal and nutrition resulting from this exposure. Potential impacts include changes in the supply of postlarvae to replenish resident populations, resulting in a general decline in productivity of coastal fisheries. The composition of demersal fish communities can be expected to change in favour of species with good potential for local self-replenishment.

### *Other variables*

Coastal fisheries species are projected to have low vulnerability to sea-level rise, changes to rainfall and solar radiation, and possible increases in cyclone and storm intensity. These variables are expected to have the most influence on fish and invertebrate species, indirectly, through their effect on coastal habitats (see below).

## **Vulnerability of coastal fish and invertebrates to the indirect effects of climate change**

### *Habitat degradation {Chapter 9, Section 9.3.2}*

Coastal fish and invertebrate species are expected to be indirectly exposed to climate change through the projected changes to the coral reef, mangrove, seagrass and intertidal flat habitats {Chapters 5 and 6} on which they depend. Coastal fisheries species are likely to be highly sensitive to changes to the habitats that provide them with food and shelter. The potential impacts include reduced diversity and abundance of fish and invertebrates as food resources decline, and increased rates of mortality (predation) as structurally complex habitat (shelter) is lost. Specialist species that depend directly on live coral for food and shelter are likely to experience

greater impacts than generalists, which can switch to using alternative resources. Generalist species such as the carnivorous snappers and emperors are expected to adapt because they already use a range of habitats. Significant changes in species composition of demersal fish associated with coral are expected. In particular, the proportions of herbivores (parrotfish, surgeonfish, rabbitfish) are likely to increase as the percentage cover of live corals declines and the cover of macroalgae (seaweed) increases.

### **Overall vulnerability**

Coastal fisheries species are projected to be most vulnerable to increasing SST, ocean acidification, changes to ocean circulation and habitat degradation. The demersal fish which are estimated to make up 50–60% of coastal fisheries production across the region are expected to have a low vulnerability to the combined effects of the projected increases in SST, ocean acidification, changes in currents and alterations to habitats in 2035. However, their vulnerability is expected to increase to moderate in 2100 under the B1 emissions scenario, and to high under the A2 scenario.

The vulnerability of the nearshore pelagic fish, which comprise ~ 30% of the coastal fisheries catch, is likely to differ across the region due to the different contributions of tuna to this catch in the east and the west, and the projected shift in distribution of skipjack and yellowfin tuna to the east {Chapter 8}. In the west, nearshore pelagic fish are expected to have little or no vulnerability to climate change in 2035, increasing to low to moderate in 2100 under the B1 scenario and to moderate under A2. In the east, the net effect of climate change on nearshore pelagic fish is expected to be positive under all scenarios.

Targeted invertebrates are estimated to have a low vulnerability to climate change in 2035, increasing to moderate under the B1 scenario, and to high under the A2 scenario, in 2100. The suite of invertebrates gleaned from intertidal and subtidal habitats are estimated to have little or no vulnerability to climate change in 2035, increasing to low to moderate under the B1, and to moderate under A2, in 2100.

### **Projected changes in fisheries productivity**

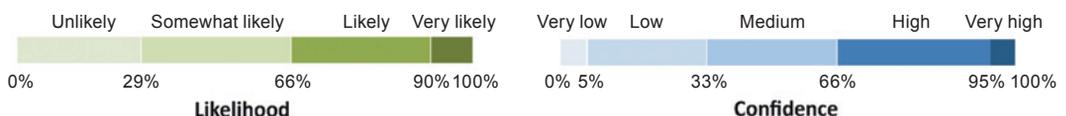
Overall, the production of demersal fish is estimated to decrease by < 5% in 2035 due to the effects of climate change. However, production of demersal fish is expected to be reduced by 20% under the B1 scenario in 2100 (A2 in 2050), and by 20–50% under A2 in 2100. Although demersal fish dominate the production of coastal fisheries, the overall decreases in total coastal fisheries production are tempered by the projected changes to catches of nearshore pelagic fish, which consist of a high proportion of tuna in many PICTs. Decreases in productivity of the two invertebrate groups are also expected to be lower than for demersal fish.

When the different projected changes in production of the four components of coastal fisheries due to climate change are combined, negligible reductions in total coastal fisheries catch are expected by 2035 in both the western and eastern parts of the region (Table 6.12). By 2100 in the west, a decrease in total production of 10–20% is expected under the B1 scenario (A2 in 2050), and a decrease of 20–35% is projected under A2. Due the expected shift in distribution of tuna, the decreases in total coastal fisheries production in the east are expected to be limited to 5–10% under B1 in 2100 (A2 in 2050) and 10–30% under A2 in 2100.

**Table 6.12** Vulnerability (V) and projected changes in production (P) of the four categories of coastal fisheries and total coastal fisheries production in 2035 and 2100 for the B1 and A2 emissions scenarios. Note that the availability of nearshore pelagic fish is expected to increase in the eastern part of the region (Chapter 8). The main potential impacts of climate change projected to cause future variations in production of coastal fisheries are also summarised here.

Variable	Coastal fisheries category								
	Demersal fish		Nearshore pelagic fish		Targeted invertebrates	Shallow subtidal and intertidal invertebrates	Total coastal fisheries***		
Present contribution to coastal fisheries production	56%		28%		2%	14%			
			West*	East**			West*	East**	
Vulnerability and projected change in production	B1/A2 2035	V	L	nil	L	L	nil <sup>a</sup>	nil <sup>a</sup>	nil <sup>a</sup>
		P	-2 to -5%	nil	+15 to +20%	-2 to -5%	nil	Negligible	Negligible
	B1 2100	V	M	L-M	L	L-M	L	M	L
		P	-20%	-10%	+20%	-10%	-5%	-10 to -20%	-5 to -10%
	A2 2100	V	H	M	L	M	L-M	M-H	M
		P	-20 to -50%	-15 to -20%	+10%	-20%	-10%	-20 to -35%	-10 to -30%
Major impacts	Habitat loss, and reduced recruitment due to ↑SST and ↓ currents		Reduced production of zooplankton in food webs for non-tuna species and changes in distribution of tuna		Habitat degradation, and declines in aragonite saturation due to ocean acidification	Declines in aragonite saturation due to ocean acidification			

\* 15°N–20°S and 130°–170°E; \*\* 15°N–15°S and 170°E–150°W; \*\*\* assumes that the proportions of the four coastal fisheries categories remain constant; a = nil or very low vulnerability; ↑ = increasing sea surface temperature; ↓ = reduced currents; L = low; M = moderate; H = high.



## **6.10 Vulnerability of freshwater and estuarine fisheries in the tropical Pacific to climate change {Chapter 10}<sup>19</sup>**

Freshwater and estuarine fisheries in the tropical Pacific provide ~ 24,000 tonnes of fish and invertebrates per year and contribute 4% of the regional contributions to GDP derived from fisheries. Most of this production comes from Papua New Guinea (PNG), although significant harvests are also made in Fiji and Solomon Islands. Freshwater and estuarine fish form an important part of the diet for people in some inland areas in PNG. For example, communities living along parts of the Fly River in PNG consume up to 2 kg of fish per person per week. Alterations in freshwater and estuarine fish production as a result of climate change have the potential to affect the food security and livelihoods of people in inland areas of the region.

Under the B1 and A2 emissions scenarios in 2035 and 2100, freshwater and estuarine fish and invertebrate species are projected to be directly exposed to increasing water temperature and changes in river flows, salinity, dissolved oxygen and turbidity. These species are also expected to be indirectly vulnerable to climate change through alteration to the habitats that support them {Chapter 7}. The vulnerability of these species to the projected changes in surface climate {Chapter 2}, river flow and fish habitats {Chapter 7}, in terms of their exposure and sensitivity, the potential impact of these changes, and their capacity to adapt, is summarised below.

### **Vulnerability of freshwater and estuarine fisheries to the direct effects of climate change**

#### *Water temperature {Chapter 10, Section 10.3.1}*

Freshwater and estuarine fish and invertebrates are expected to be exposed to projected increases in water temperature of 0.5–1.0°C in 2035, up to 1.5°C under the B1 emissions scenario in 2100 (A2 in 2050) and up to 3.0°C under A2 in 2100. Clearing of catchment vegetation may also increase the warming of aquatic habitats. Depending on their distribution within river systems, some fish and invertebrate species are expected to be sensitive to these changes. Species inhabiting shallow low-flow environments, such as high-elevation lakes, river edges and floodplain wetlands, are expected to have the greatest sensitivity to warmer temperatures. Increasing water temperatures are likely to have potential impacts on larval fish growth, muscle fibre development, swimming ability, metabolic rate and sex ratios. However, not all the expected effects are negative – some freshwater fish and invertebrate species are likely to benefit. In particular, the distributions of species currently limited by their lower temperature tolerances are expected to expand as waters warm. Growth rates are also estimated to increase where temperatures remain within the ranges tolerated by species. However, where increases in temperature are coupled with contaminants from mining, forestry and intensive agriculture operations, the temperature tolerances of species could decrease by more than 4°C.

### *Rainfall and river flow {Chapter 10, Section 10.3.2}*

Freshwater and estuarine fish species are expected to be exposed to projected increases in rainfall and river flow in the tropics, and decreases in the subtropics {Chapters 2 and 7}. These species are likely to respond positively to the increases in water quality and habitat area resulting from higher rainfall and greater flows. On the other hand, negative responses are expected where rainfall and flow are reduced. River flows, in particular, have a strong effect on the production of freshwater and estuarine species through effects on habitat availability, nutrient transport, food web processes and cues for migration. Pacific Island countries and territories with increased river flows are therefore expected to yield greater catches, whereas those with more variable rainfall, such as New Caledonia, are expected to have more uncertain catches.

### *Sea level and salinity {Chapter 10, Section 10.3.3}*

The fish and invertebrate species inhabiting lowland rivers and estuaries are expected to be highly exposed to projected sea-level rise {Chapter 3} and associated increases in salinity. Changes in salinity will be greatest in drought years when salt water penetrates further inland. Estuarine species are unlikely to be sensitive to these changes, whereas freshwater species in lowland areas are expected to have high sensitivity. The capacity of fish and invertebrates in lowland river habitats to adapt to the effects of sea-level rise will depend on their salinity tolerances. Changes in species composition can be expected to occur, with estuarine species expected to replace freshwater fish and invertebrates in existing lowland reaches.

### *Dissolved oxygen {Chapter 10, Section 10.3.4}*

Freshwater and estuarine fish and invertebrates are expected to be exposed to projected decreases in dissolved oxygen ( $O_2$ ) because oxygen solubility decreases with higher temperatures and salinities, although the projected decline in oxygen availability is expected to be small in most habitats. However, oxygen demand by fish and invertebrates increases with increasing water temperature and sensitivity of freshwater fish and invertebrate species to changes in  $O_2$  will depend on their preferred habitats and their tolerance to oxygen depletion. Potential impacts include limits to recruitment and increases in invasive fish species that tolerate low oxygen levels. Some fish species have physiological adaptations to low oxygen, such as increased blood-oxygen affinity or accessory air-breathing organs. Other species have behavioural adaptations such as avoidance of hypoxic habitats or the ability to respire from the air-water interface. In locations with low flow where the combination of increased temperature and salinity combine to reduce  $O_2$  significantly, fish assemblages are likely to be dominated by hypoxia-tolerant species.

*Turbidity {Chapter 10, Section 10.3.5}*

Exposure of freshwater and estuarine fish and invertebrates to increased turbidity under future climatic conditions will depend on the state of catchment vegetation. Rivers draining catchments where vegetation is intact are likely to experience only minor increases in turbidity due to limited transport of sediments in runoff. However, in catchments that have been extensively cleared, the projected increases in rainfall are expected to cause some naturally clear streams to become permanently turbid. Heavy suspended sediment loads can damage the gill epithelium of fish and affect respiration. Increased deposition of sediments reduces the reproductive success of species with adhesive demersal eggs. Fish in naturally turbid rivers will be less sensitive to changes in turbidity than those in naturally clear habitats. Potential impacts include reduced recruitment success by some fish species and reduced growth and survival of fish with a high dependence on visual feeding. The capacity of freshwater fish to adapt to increased turbidity will depend on the species and the prevailing environmental conditions.

### **Vulnerability of freshwater and estuarine fisheries to the indirect effects of climate change**

*Habitat changes {Chapter 10, Section 10.4.1}*

Freshwater and estuarine fish and invertebrates are also expected to be exposed to climate change through projected alterations to their habitats as a consequence of new patterns of rainfall and river flow, and higher temperatures (Chapter 7). Fisheries species are likely to be highly sensitive to these changes because they depend on a range of habitats within rivers, lakes, floodplains and estuaries for shelter and food. The potential effects include (1) increased yields of fish from lowland river areas as the extent of floodplain habitat expands due to higher rainfall; (2) greater fish production from the increased estuarine areas expected to be created by rising sea levels; and (3) lower catches of coldwater species such as rainbow trout and snow trout in the highlands of PNG as the extent of their habitat is reduced due to higher air temperatures. The capacity of fish and invertebrates to take advantage of increased floodplain habitat will depend on removing any barriers to movement of animals into the additional habitat. It will also depend on maintaining catchment vegetation in good condition to prevent erosion and pollution.

### **Overall vulnerability**

Freshwater and estuarine fish and invertebrates are expected to have a low overall vulnerability to the direct and indirect effects of climate change, except in disturbed catchments (Table 6.13). Indeed, the effects of climate change on these species are expected to be positive.

The greatest benefits of climate change for freshwater and estuarine fisheries are expected to result from increases in rainfall and river flow, which increase habitat availability and quality, provide cues for fish migration, and enhance reproduction and recruitment. Production of freshwater fish and invertebrates in the tropical Pacific is projected to increase under both scenarios in 2035 and 2100. Changes are expected to be negligible or negative in locations where rainfall is projected to decrease.

**Table 6.13** Vulnerability of freshwater and estuarine fisheries to projected changes in climate in well-managed and disturbed catchments.

	Temperature	River flow	Salinity	Dissolved oxygen	Turbidity
Well-managed catchments	Moderate	Very low	Low	Low	Low
Disturbed catchments	High	Low/High <sup>a</sup>	Moderate	Moderate	Moderate

a = High vulnerability applies only to substrate-spawning species.

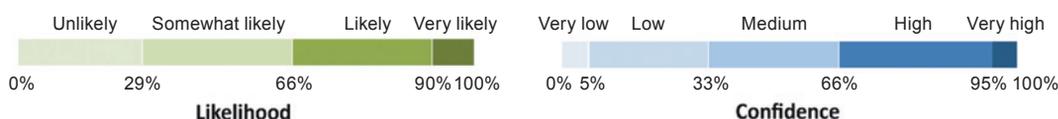
### Projected changes in fisheries productivity

Ultimately, the projected changes in freshwater production are expected to translate into additional fisheries catches (Table 6.14). However, catches are likely to be reduced in disturbed catchments where human activities have increased the vulnerability of fisheries species to climate change.

**Table 6.14** Projected change in production of freshwater and estuarine fisheries from well-managed catchments under B1 and A2 emissions scenarios in 2035 and 2100, relative to 2010.

Scenario	Freshwater and estuarine fisheries production (%)	
B1/A2 2035	0 to +2.5	
B1 2100*	-2.5 to +7.5 <sup>a</sup>	
A2 2100	0 to +12.5 <sup>a</sup>	

\* Approximates A2 in 2050; a = fisheries production lower values are only for New Caledonia and all other PICTs are projected to show a productivity increase by 2100.



## 6.11 Vulnerability of aquaculture in the tropical Pacific to climate change {Chapter 11}<sup>20</sup>

Aquaculture has considerable potential to contribute to food security and sustainable livelihoods in the tropical Pacific. A wide range of aquaculture activities are currently underway in 16 Pacific Island countries and territories (PICTs). In general, freshwater aquaculture activities focus on producing commodities for food security, whereas those in coastal waters are usually aimed at creating livelihoods.

The species used to produce aquaculture commodities are potentially vulnerable to changes in surface climate {Chapter 2}, the ocean {Chapter 3} and coastal habitats {Chapters 5 and 6}. The vulnerability of aquaculture operations to climate change, in terms of the exposure and sensitivity of the species involved, the potential impact of these changes, the capacity of the species to adapt, and the exposure of infrastructure, is summarised below.

### Vulnerability of aquaculture commodities for food security

#### *Tilapia and carp {Chapter 11, Section 11.3.1.1}*

Aquaculture operations for tilapia and carp are expected to be exposed to projected increases in water temperature and rainfall. Low-lying tilapia ponds near the coast are also expected to be exposed to sea-level rise and possibly more intense cyclones. These farming activities are expected to be sensitive to these changes because temperature regulates growth and reproduction of tilapia and carp, and rainfall modulates water temperature and water exchange (and its effect on dissolved oxygen levels) in ponds. Aquaculture operations for tilapia and carp are expected to benefit from the projected increases in temperature and rainfall as growth rates increase and the more locations become suitable for pond aquaculture. However, care will be needed to construct ponds where they are not prone to flooding under higher rainfall conditions, or to inundation or damage from sea-level rise or storm surge. Potential negative impacts could occur if climate change limits the supply of fishmeal from overseas, or increases the risk of fish diseases. Tilapia and carp farming operations have a high capacity to be adapted to a changing climate because stocking densities can be altered to suit the prevailing conditions and availability of fish feeds. However, intensive culture systems that rely on high stocking densities have a lower adaptive capacity than extensive farming operations.

#### *Milkfish {Chapter 11, Section 11.3.1.2}*

Aquaculture activities based on farming milkfish in ponds are likely to have a similar vulnerability to that of tilapia culture. Milkfish are expected to be exposed to projected increases in water temperature and rainfall. Low-lying ponds near the coast could also be exposed to sea-level rise and possibly more intense cyclones.

Ocean acidification and changes in coastal habitats {Chapters 3 and 6} could also affect the supply of the wild-caught fry used to stock ponds. Milkfish are expected to be sensitive to increases in temperature because it regulates growth and reproduction of fish in shallow ponds. They are also expected to be sensitive to changes in rainfall because rain can modulate water temperature and water exchange in ponds. The projected increases in temperature are expected to increase the production of milkfish due to faster rates of growth, and extend the geographical range and season for capturing wild juveniles. Greater rainfall should increase the number of areas where ponds can be constructed. However, some potential impacts are possible if climate change limits the supply of fishmeal to formulate diets, or increases the risk of fish diseases. Milkfish farming based on the collection of wild fry may be able to adapt to the greater projected variability in the supply of juveniles by producing juveniles in hatcheries. Low-lying ponds near the coast vulnerable to sea-level rise and storm surge can be relocated further inland. However, both these adaptations require substantial investment.

## **Vulnerability of aquaculture commodities for livelihoods**

### *Pearls {Chapter 11, Section 11.3.2.1}*

Pearl oysters will be exposed to projected increases in sea surface temperature (SST), decreases in salinity due to changing rainfall patterns in some locations, ocean acidification, sea-level rise and possibly more intense cyclones. Both the black-lipped and white-lipped pearl oysters are sensitive to increases in SST because it increases their susceptibility to pathogens and parasites and affects nacre deposition and pearl quality. Reduced salinity and increased sedimentation associated with rainfall events can cause mass mortality of pearl oysters. Ocean acidification is expected to affect the survival and growth of spat, calcification of shells and pearl quality. The effects of sea-level rise and more intense cyclones may increase the exposure of pearl farm infrastructure to damage. Pearl farming operations have considerable capacity to adapt to the changes ahead. Options include increasing the proportion of spat produced in hatcheries under controlled temperature and pH conditions; placing oysters in deeper, cooler water; harvesting pearls during cooler months to avoid extreme SST; growing pearl oysters at microsites where concentrations of carbon dioxide in sea water are reduced; and designing infrastructure to withstand intense cyclones. Such adaptations will increase operational costs.

### *Shrimp {Chapter 11, Section 11.3.2.2}*

Shrimp farming will be exposed to projected increases in temperature, changes in rainfall, sea-level rise, ocean acidification and possibly stronger storm surge from more severe cyclones. The species of shrimp grown in New Caledonia is expected to be sensitive to increasing, or more variable, water temperature and reductions in rainfall. Potential impacts include the greater risk of temperature-related diseases,

deteriorating water quality during times of extremely high rainfall and problems in drying out ponds between production cycles. Sea-level rise is also expected to impede the draining of ponds, to remove the anoxic sediment layer, which reduces growth and survival of shrimp during the next production cycle. However, shrimp farming may benefit in the shorter term from increasing temperatures that increase growth rates and improve yields. Shrimp farming enterprises can adapt to the effects of sea-level rise by adding soil to the floor of ponds and increasing the height of the walls so that ponds continue to drain efficiently. Ultimately, new ponds may need to be constructed at higher elevations, and shrimp may need to be farmed more intensively. In more tropical areas, the warming conditions may enable the shrimp farming industry to grow a wider variety of species.

#### *Seaweed {Chapter 11, Section 11.3.2.3}*

Seaweed farming is expected to be exposed to projected increases in SST and rainfall, ocean acidification, sea-level rise, and possibly more intense cyclones. The *Kappaphycus* seaweed grown in the region is sensitive to increased SST and reduced salinity, which stress the plants and inhibit growth. More intense cyclones would cause great damage to the equipment used to grow seaweed. The expected increase in SST is likely to result in crop losses due to increased incidence of outbreaks of epiphytic filamentous algae and tissue necrosis. Lower salinities caused by increased rainfall are likely to reduce the number of sites where seaweed can be grown. On the other hand, higher levels of carbon dioxide (resulting in ocean acidification) and sea-level rise may benefit seaweed farming by stimulating growth and promoting water exchange. There is limited scope for adaptation of seaweed farming at the regional level by shifting production to higher latitudes.

#### *Marine ornamentals {Chapter 11, Section 11.3.2.4}*

Marine ornamental aquaculture is expected to be exposed to projected increases in SST, changes in rainfall, ocean acidification, sea-level rise, degradation of habitats and possibly more intense cyclones. The main species used for marine ornamental products, corals and giant clams, are expected to be sensitive to increased SST. Higher temperatures are likely to affect the growth and survival of cultured corals and giant clams grown in the sea (due to more regular bleaching). These species are also sensitive to changes in salinity and turbidity associated with higher rainfall, and reduced aragonite saturation levels caused by ocean acidification. As a result, the conditions for producing the main marine ornamental products are eventually expected to deteriorate. In some locations, sea-level rise could reduce the potential impact by improving water exchange and nutrient supply to oligotrophic sites. Possible adaptations involve transferring operations from the sea to recirculating tanks on land, where water temperature and pH can be controlled, and developing markets for species of coral that are likely to be more tolerant to changing environmental conditions.

### *Freshwater prawns {Chapter 11, Section 11.3.2.5}*

Freshwater prawn aquaculture is expected to be exposed to projected increases in water temperatures and rainfall, and the possible effects of more intense cyclones. Freshwater prawns are sensitive to increases in water temperature and the potential effects include increased growth, provided temperatures remain within thermal limits. The projected increases in rainfall should increase availability of freshwater and provide opportunities to farm freshwater prawns in a greater range of locations. The expected expansion of freshwater habitats should also provide a greater abundance of wild juveniles for grow-out operations. Adaptations to reduce any adverse effects of warmer pond temperatures centre on constructing ponds in locations where they have high water turnover rates.

### *Marine fish {Chapter 11, Section 11.3.2.6}*

The sensitivity of hatchery-based marine fish aquaculture operations to the projected changes in SST is expected to be low because these operations rely on environmentally controlled facilities to mature broodstock and rear the juveniles. However, collection of wild juvenile rabbitfish for grow-out may be sensitive to the effects of SST on the spawning cycle of the adults. The sensitivity of marine fish grown in sea cages to the projected increase in SST is likely to be similar to the responses of demersal fish associated with coastal habitats, i.e. metabolic rates are expected to increase {Chapter 9}. Depending on the species and location of operations, growth could be inhibited under the A2 emissions scenario by 2100. The potential impact of climate change on prospective marine fish species, or the infrastructure needed to produce them, is estimated to be low because the possible effects can be taken into account when assessing the suitability of local and projected environmental conditions for establishment of hatcheries and sea cages. A possible longer-term effect is that once sites are selected, fish may need to be fed a greater daily ration due to their higher rates of metabolism in warmer waters.

### *Sea cucumbers {Chapter 11, Section 11.3.2.7}*

The sea ranching and/or farming of sea cucumbers is expected to be exposed to projected increases in air temperature and SST, increased rainfall, ocean acidification, sea-level rise, changes to seagrass habitats, and possibly increasing cyclone intensity. These operations are expected to be sensitive to many of these consequences of climate change. Higher water temperatures, reduced salinity and ocean acidification could affect the success of sea ranching operations by increasing the mortality of juveniles and degrading the seagrass habitat {Chapter 6} where hatchery-reared juveniles need to be released. Pond farming in subtropical areas is expected to benefit from the faster growth rates of sea cucumbers reared in warmer water. However, sea cucumbers grown in ponds in the tropics may suffer higher mortality due to the increased likelihood of stratification caused by higher rainfall and reduced salinity. In

locations where farming sea cucumbers in ponds proves to be profitable, adaptations can be made to hatchery operations to control the temperature, salinity and pH of the water. The construction of ponds for growing sea cucumbers to market size can be modified to maximise mixing.

### *Trochus {Chapter 11, Section 11.3.2.8}*

The production of trochus for restocking programmes is expected to be exposed to projected increases in SST, lower salinity due to more rainfall, ocean acidification, sea-level rise and possibly increases in cyclone intensity. The future success of restocking programmes based on release of hatchery-reared juveniles is likely to be sensitive to lower salinity, sea-level rise and more intense cyclones. The salinity of the shallow rock pool habitats used by trochus is expected to decrease beyond their tolerance in some locations and sea-level rise is likely to reduce the availability of this habitat where intertidal areas are prevented from moving landward. Powerful waves from cyclones are likely to cause high mortality of trochus released on reefs unless these trochus have reached the size where they move to deeper water. The possible effect of ocean acidification on the strength of trochus shells remains to be determined. The key adaptation for restocking programmes will be to place more emphasis on translocation of mature adult trochus to form breeding populations. Where hatchery-reared animals are required, they should be released at the largest size possible to reduce the need to use intertidal areas as release sites.

### **Overall vulnerability**

When the direct effects of the projected changes to water temperature, rainfall, ocean acidification, sea-level rise, cyclone intensity, and the expected indirect effects of alterations to habitats, are integrated it is evident that:

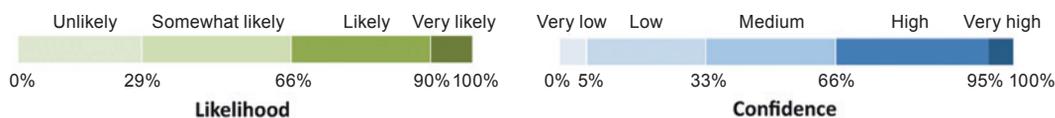
1. existing and planned aquaculture activities to produce tilapia, carp and milkfish in freshwater ponds for food security are likely to benefit from the anticipated changes to surface climate; and
2. aquaculture enterprises producing commodities for livelihoods in coastal waters are likely to encounter production problems due to changes projected to occur in the tropical Pacific Ocean.

Aquaculture operations for tilapia, carp and milkfish are expected to benefit strongly from projected increases in temperature and rainfall, and to cope with other changes to the environment even though some are negative. These projected benefits are expected to be apparent by 2035 (Table 6.15), and well established by 2100, especially under the A2 emissions scenario, when surface temperatures are expected to be 2.5–3.0°C higher, and rainfall 10–20% greater, in tropical areas relative to 1980–1999 {Chapter 2}. A proviso is that the changing climate does not limit access to the ingredients needed to formulate appropriate diets for tilapia, carp and milkfish, particularly fishmeal.

**Table 6.15** Vulnerability of aquaculture commodities to projected climate change under the B1 and A2 emissions scenarios in 2035 and 2100.

Commodity	Vulnerability					
	B1/A2 2035		B1 2100*		A2 2100	
<b>Food security</b>						
Tilapia and carp	L (+)		L-M (+)		M (+)	
Milkfish	L (+)		L (+)		L (+)	
<b>Livelihoods</b>						
Pearls	L (-)		L (-)		M (-)	
Seaweed	M (-)		M-H (-)		H (-)	
Shrimp	L (+)		L (-)		L-M (-)	
Marine ornamentals	L (-)		M (-)		H (-)	
Freshwater prawn	L (+)		L (-)		L (-)	
Marine fish	L (-)		L (-)		L-M (-)	
Sea cucumbers	L (-)		L (-)		L-M (-)	
Trochus	L (-)		L (-)		L (-)	

\* Approximates A2 in 2050; L = low; M = moderate; H = high.



The enhanced conditions for freshwater pond aquaculture expected as a result of climate change by 2035 should also apply to the farming of freshwater prawns. However, the benefits for farming freshwater prawns may be reversed by 2100 due mainly to the temperature sensitivity of the prawns and the effects of higher temperatures on stratification of ponds.

Although some commodities for livelihoods are likely to benefit from the projected changes in specific environmental variables, when the effects of all variables are integrated, most commodities produced in coastal waters are expected have a low vulnerability by 2035 (Table 6.15). The exceptions are shrimp and seaweed. For shrimp farming in 2035, the expected benefits from the projected increases in water temperatures may well improve yields. For seaweed farming, the expected increases in SST and rainfall by 2035 are likely to mean that the industry has a moderate rather than low vulnerability to crop losses due to increased incidence of outbreaks of epiphytic filamentous algae and tissue necrosis.

By 2100, the effects of climate change and ocean acidification on all livelihood commodities are expected to be negative (Table 6.15). Under the A2 emissions scenario, seaweed farming and production of marine ornamentals are likely to have a high vulnerability, and the culture of pearls is expected to be moderately vulnerable to such conditions. Shrimp farming, marine fish culture and sea ranching/pond farming of sea cucumbers are all expected to have a low to moderate vulnerability to the A2 scenario by 2100. The vulnerability of trochus is rated as low until further research elucidates how they acquire calcium carbonate to construct their shells.

Vulnerability does not necessarily imply that there will be overall reductions in productivity of coastal aquaculture commodities in the future. Rather, it indicates that the efficiency of enterprises producing the commodity are likely to be affected (Table 6.16). Total production could still increase if the operations remain viable, and more enterprises are launched. For example, seaweed production targets that have been set for the next decade of 1000–2000 tonnes per year (engaging several hundred households) in both Fiji and Solomon Islands should still be achievable, but not necessarily in the same places or with the methods now in use.

**Table 6.16** Projected changes in efficiency of aquaculture operations under B1 and A2 scenarios in 2035 and 2100, relative to 2010.

Aquaculture commodity	Vulnerability		
	B1/A2 2035	B1 2100*	A2 2100
<b>Food security</b>			
Tilapia and carp	↑ ■■ ■	↑ ■■ ■	↑ ■■ ■
Milkfish	↑ ■■ ■	↑ ■■ ■	↑ ■■ ■
<b>Livelihoods</b>			
Pearls	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■
Seaweed	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■
Shrimp	↑ ■■ ■	↓ ■■ ■	↓ ■■ ■
Marine ornamentals <sup>a</sup>	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■
Freshwater prawn	↑ ■■ ■	↓ ■■ ■	↓ ■■ ■
Marine fish	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■
Sea cucumbers	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■
Trochus	↓ ■■ ■	↓ ■■ ■	↓ ■■ ■

\* Approximates A2 in 2050; a = includes coral fragments, live rock and giant clams.



