SCIENCE AND SOLUTIONS FOR AUSTRALIA

OCEANS

OCEANS

SCIENCE AND SOLUTIONS FOR AUSTRALIA

OCEANS

Editor: Bruce Mapstone

CSIRO

National Library of Australia Cataloguing-in-Publication entry

Oceans : science and solutions for Australia / edited by
Bruce Mapstone.

9781486307937 (paperback)
9781486307944 (epdf)
9781486307951 (epub)

Includes bibliographical references and index.

Biodiversity – Australia.
Biodiversity – Australia – Management.

Ocean – Australia.
Oceanography – Australia.
Marine ecology – Australia.

Mapstone, Bruce D. (Bruce David), editor.

Published by
CSIRO Publishing
Locked Bag 10
Clayton South VIC 3169
Australia

Telephone: +61 3 9545 8400
Email: publishing.sales@csiro.au
Website: www.publish.csiro.au

Front cover (clockwise from top): wave (source: Steven Dillon/Shutterstock); *Investigator* research vessel (source: Marine National Facility/CSIRO); fish spiral (source: Istvan Kovacs/Shutterstock); Sydney, NSW (source: James Porteous/CSIRO)

Set in Adobe Lucida 9/15 and Lucida Sans
Edited by Peter Storer
Cover and text design by Andrew Weatherill
Typeset by Andrew Weatherill
Printed in Australia by Ligare

Original print edition:
The paper this book is printed on is in accordance with the rules of the Forest Stewardship Council®. The FSC® promotes environmentally responsible, socially beneficial and economically viable management of the world's forests.

Foreword

Larry Marshall, CSIRO Chief Executive

Australia is an ocean nation. Our people have a deep sense of connection to the coast and sea that stretches back thousands of years. We identify strongly with the beach and draw on our oceans for food, culture, energy, trade and recreation. We have stewardship responsibilities for the world's third largest marine estate.

This book captures the latest scientific knowledge on the challenges and prospects for Australia's oceans. It describes some of our many ocean challenges and identifies ways in which science contributes to practical responses to those challenges. The authors provide a bridge between the scientific literature and Australia's community, as with other books in this series.

CSIRO's leading ocean scientists describe Australia's marine estate, its many influences on our lives, and the research done to help understand changes in oceans and the ways we interact with them. They outline its physical systems, the biodiversity it supports, its geology, and its roles in Australia and the world's climate. The team also explores how we interact with oceans as a workplace, an economic resource and as a place for culture, leisure and recreation. The blue economy and how we choose to govern this precious resource is assessed along with the industries our oceans support, including fisheries, aquaculture, energy, and coastal development and tourism.

The extent and effects of pollution are discussed, as are some of the tools and technologies used to monitor and measure our oceans, including scientific tools and innovations being developed to balance the competing demands of the multiple uses of our marine estate. The book concludes with a section on the future role of scientific research into our oceans, and the ways in which rapidly developing technologies are changing the research we can do.

CSIRO and its predecessors have been conducting ocean research for close to a century, following Billy Hughes' vision in 1916 and given the economic, social and environmental importance of our oceans to Australia. We cannot do this work without the support of collaborators and partners nationally and internationally. I commend this work as an exemplar of CSIRO's Strategy 2020 using excellent science and solutions in deep collaboration globally to solve Australia's biggest challenges and deliver profound national benefit.

Space may remain the final frontier but Earth's oceans continue to deliver profound influences on our lives every day. Science is key to us understanding those influences and harnessing them to provide solutions to many of the challenges facing Australia, our region and the world. We are the stewards of powerful and influential ocean resources across three of the world's four great oceans and must rely on science and solutions to guide us to a better future.

Contents

Foreword
Larry Marshall, CSIRO Chief Executive v

Acknowledgements ix

List of contributors xi

CHAPTER 1. Introduction
Bruce Mapstone 1

SECTION 1: AUSTRALIA'S MARINE ESTATE

CHAPTER 2. Australia's ocean currents
Stephen R Rintoul, Ming Feng, Nick J Hardman-Mountford and Eric Raes 13

CHAPTER 3. The living ocean
Alan Williams, Nicholas Bax and Karen Gowlett-Holmes 25

CHAPTER 4. Geology beneath our oceans
Joanna M Parr and Andrew Ross 39

CHAPTER 5. The oceans and our climate
John Church, Wenju Cai, Guojian Wang and Andrew Lenton 51

CHAPTER 6. The oceans and our lives
Sean Pascoe, Toni Cannard, Natalie Stoeckl, Ian Cresswell, Samantha Paredes and Amar Doshi 63

CHAPTER 7. The blue economy
Sean Pascoe, Toni Cannard, Ian Cresswell, Natalie Stoeckl, Amar Doshi and Samantha Paredes 69

CHAPTER 8. Governance of Australian seas and oceans
Ian Cresswell and Marcus Haward 77

SECTION 2: SCIENCE AND OCEAN USE

CHAPTER 9. Fisheries and aquaculture
David C Smith and Nigel Preston 87

CHAPTER 10. Energy from Australia's marine estate
David C Smith, Kenneth Lee and Andrew Ross 97

CHAPTER 11. Coastal development
Andrew DL Steven, Simon Apte, L Richard Little and Mat Vanderklift 107

CHAPTER 12. Operational oceanography – security, safety, transport, search and rescue
Peter R Oke and Andreas Schiller . . . 117

CHAPTER 13. Ocean pollution – risks, costs and consequences
Britta Denise Hardesty, Paula Sobral, Simon Barry and Chris Wilcox . . . 127

CHAPTER 14. Tools and technologies for ocean observation
Mark Underwood and Andreas Marouchos . . . 137

CHAPTER 15. Managing multiple uses of our oceans
Beth Fulton, Tony Smith, Keith Sainsbury and Marcus Haward . . . 149

SECTION 3: FUTURE OCEANS SCIENCE

CHAPTER 16. Changes and challenges for future generations
Éva Plagányi, Peter R Oke, Tatiana Rykova and James Innes . . . 159

CHAPTER 17. Ocean changes to come
Richard Matear, Alistair Hobday and Matt Chamberlain . . . 169

CHAPTER 18. Future technologies
Bernadette Sloyan, Pascal Craw, Edward King, Craig Neill, Rudy Kloser and Levente Bodrossy . . . 179

CHAPTER 19. Conclusion
Bruce Mapstone . . . 187

References . . . 191

Index . . . 199

Acknowledgements

The editor and authors are grateful for the support and assistance from many people in the preparation of this book. Andrew Johnson kicked off the project and provided executive support for its gestation. Simon Torok helped with initial project management and final proofread, and Jenny Baxter provided valuable project support throughout. Alex Wonhas and John Manger reviewed the final draft and provided helpful suggestions for improvement, and Dermot Smyth provided valuable assistance with Chapter 8.

We thank all those who contributed images or graphics for the volume, acknowledged throughout, and others who did a lot of leg-work chasing down material, including Asaesja Young, Camille Couzi and Ben Creagh.

Thank you also to Julia Stuthe, Lauren Webb, Briana Melideo, Tracey Kudis and Deepa Travers from CSIRO Publishing who provided valued support and guidance throughout the drafting and production processes. Peter Storer improved the final copy with his keen editorial eye and helpful suggestions.

List of contributors

Editor

Bruce Mapstone
CSIRO Oceans and Atmosphere

Chapter authors

Simon Apte
CSIRO Land and Water

Simon Barry
CSIRO Data61

Nicholas Bax
CSIRO Oceans and Atmosphere

Levente Bodrossy
CSIRO Oceans and Atmosphere

Wenju Cai
CSIRO Oceans and Atmosphere

Toni Cannard
CSIRO Oceans and Atmosphere

Matt Chamberlain
CSIRO Oceans and Atmosphere

John Church
University of NSW (formerly CSIRO Oceans and Atmosphere)

Pascal Craw
CSIRO Oceans and Atmosphere

Ian Cresswell
CSIRO Land and Water

Amar Doshi
CSIRO Oceans and Atmosphere

Ming Feng
CSIRO Oceans and Atmosphere

Beth Fulton
CSIRO Oceans and Atmosphere

Karen Gowlett-Holmes
CSIRO National Collections and Marine Infrastructure

Britta Denise Hardesty
CSIRO Oceans and Atmosphere

Nick J Hardman-Mountford
CSIRO Oceans and Atmosphere

Marcus Haward
University of Tasmania

Alistair Hobday
CSIRO Oceans and Atmosphere

James Innes
CSIRO Oceans and Atmosphere

Edward King
CSIRO Oceans and Atmosphere

Rudy Kloser
CSIRO Oceans and Atmosphere

Kenneth Lee
CSIRO Oceans and Atmosphere

Andrew Lenton
CSIRO Oceans and Atmosphere

L Richard Little
CSIRO Oceans and Atmosphere

Andreas Marouchos
CSIRO Oceans and Atmosphere

Richard Matear
CSIRO Oceans and Atmosphere

Craig Neill
CSIRO Oceans and Atmosphere

Peter R Oke
CSIRO Oceans and Atmosphere

Samantha Paredes
CSIRO Oceans and Atmosphere and
Queensland University of Technology

Joanna M Parr
CSIRO Mineral Resources

Sean Pascoe
CSIRO Oceans and Atmosphere

Éva Plagányi
CSIRO Oceans and Atmosphere

Nigel Preston
Worldfish

Eric Raes
Alfred-Wegener-Institute

Stephen R Rintoul
CSIRO Oceans and Atmosphere and
Antarctic Climate and Ecosystems
Cooperative Research Centre

Andrew Ross
CSIRO Energy

Tatiana Rykova
CSIRO Oceans and Atmosphere

Keith Sainsbury
University of Tasmania

Andreas Schiller
CSIRO Oceans and Atmosphere

Bernadette Sloyan
CSIRO Oceans and Atmosphere

David C Smith
CSIRO Oceans and Atmosphere

Tony Smith
CSIRO Oceans and Atmosphere

Paula Sobral
Universidade NOVA de Lisboa

Andrew DL Steven
CSIRO Oceans and Atmosphere

Natalie Stoeckl
James Cook University

Mark Underwood
CSIRO Oceans and Atmosphere

Mat Vanderklift
CSIRO Oceans and Atmosphere

Guojian Wang
CSIRO Oceans and Atmosphere

Chris Wilcox
CSIRO Oceans and Atmosphere

Alan Williams
CSIRO Oceans and Atmosphere

CHAPTER 1.

Introduction

Bruce Mapstone

Key messages

- Australia has the 3rd largest marine estate in the world, extending from the coast to the abyssal oceans and from the tropics to Antarctica.
- The oceans around us affect almost all aspects of Australian life, including our weather and climate, food and energy, international security, cities and infrastructure, and wellbeing.
- Research is central to understanding our marine estate and managing our activities that depend on it or affect it.

INTRODUCTION

The marine environment exerts diverse influences on terrestrial Australia and the Australian community, both directly and indirectly. Direct effects of seasonal storms, waves and very high tides on coastal communities and infrastructure are familiar to us all. Our marine estate, however, also has long-term and far-reaching links to Australian climate, energy supply, food supply, economy, infrastructure and social wellbeing. The influence of the oceans on our regional neighbours also has implications for Australia's national security and strategic position internationally, as well as affecting the wellbeing of millions of people in our region.

Australia has formal responsibilities under the United Nations Convention on the Law of the Sea (UNCLOS) to manage its vast and diverse marine estate for conservation and sustainable use and also seeks to secure sustainable national benefits from it. We need to know what our marine estate comprises, how it works, its status, and the effects of our activities on it in order to meet our international responsibilities and deliver sustainable national benefits. Marine research is central to establishing that knowledge.

This book provides a brief, accessible description of some of the key features of our marine estate (Section 1), overviews of some areas where primary marine activities are supported by marine research (Section 2) and some predictions of what marine research might look like in the near future (Section 3). The coverage is neither exhaustive nor technical but is intended to provide an introduction for those interested in learning about the extent of Australia's marine territories and the research that we are doing to help care for them and support solutions to existing or emerging challenges.

AUSTRALIA'S MARINE ESTATE

Australia's marine territory is the third largest marine estate on Earth. It covers 13.86 million km^2, (Chapter 8), ~1.8 times the area of Australian sovereign land territories[1] and includes substantial areas of three of the world's four major oceans, with territory in the Indian, Pacific and Southern Oceans (Fig. 1.1). It extends from equatorial waters just south of New Guinea to Antarctica and spans over one-third of the Southern Hemisphere, from 40ºE to 170ºE longitude. Our marine waters reach from coastal estuaries, lagoons and intertidal areas to abyssal plains at over 5000 m depth.

Our marine estate includes a tremendous diversity of plants and animals (Chapter 3) and energy and mineral resources (Chapter 4). The major currents flowing around Australia (Chapter 2) have profound effects on biological productivity and the weather and climate we experience in our region and globally (Chapter 5). Australians derive diverse social, cultural and community benefits from our affinity with the oceans (Chapter 6). National economic contribution from activities depending on our marine estate (the 'blue economy', Chapter 7) was valued at A$47.2 billion in 2012.[2] Australia has a somewhat complicated system of governing our marine estate, stemming from our federal governance arrangements (Chapter 8), but has been considered a global leader in many aspects of oceans governance. Our marine estate plays a role in a great deal of how we live across Australia.

AUSTRALIAN MARINE RESEARCH

The main focus of Australian marine research is within the Australian marine estate, including the waters off the Australian Antarctic Territory, but the challenges facing our country, our region and the globe require research at many scales, from local to regional and international. The world's oceans are all connected and collectively influence global climate, marine biodiversity, transport and fisheries and so we also need to place our marine research in the context of international research, both to benefit from others' work and contribute to understanding of the global oceans. Hence, for example, Australia does fisheries research beyond Australian waters because of the importance of our participation in regional fisheries management and we do oceanographic research internationally because of the key role global oceans play for Australian climate.

Marine research is done around Australia by several universities, some state government agencies and five main federal agencies. The Bureau of Meteorology, GeoScience Australia, the Department of Defence and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) have explicit mandates to do research across the entire marine estate, with CSIRO having the broadest multidisciplinary activity. The Australian Institute of Marine Science (AIMS) is Australia's leading research agency in tropical waters, while the Australian Antarctic Division has national responsibility to lead and manage research in Australia's polar and Antarctic waters.

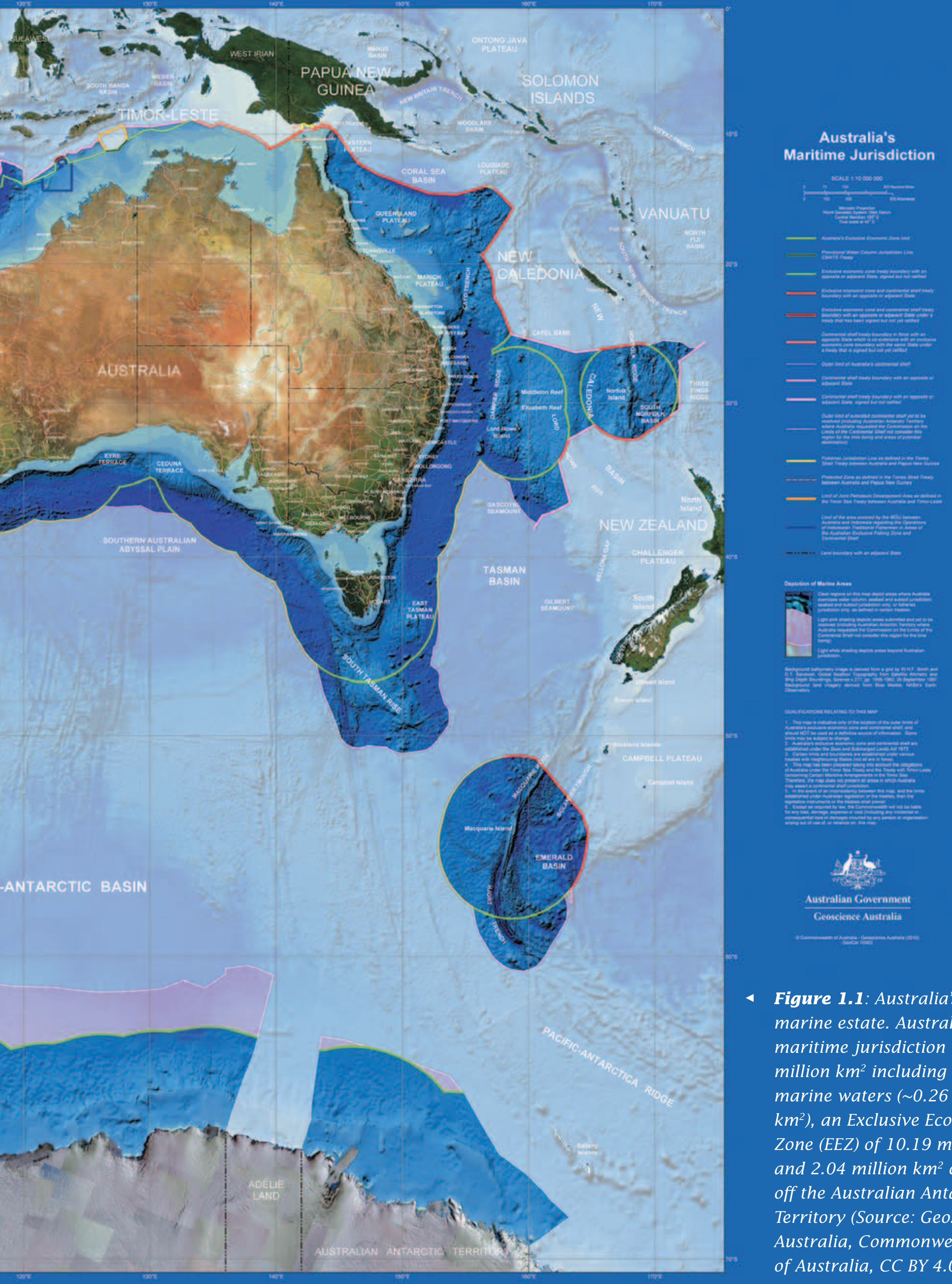
Several Australian universities and the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) also have active marine research and teaching programs and some cover extensive geographic and disciplinary ranges. The universities provide a source of postgraduate research training that is not available otherwise from the Australian innovation system, and so are key contributors to the renewal of Australian marine research capability and capacity.

Each state and the Northern Territory also has some investment in marine research, predominantly focussed in state or territory waters or on resources (e.g. fisheries) under state jurisdiction (Chapter 8).

Marine research is diverse and technologically complex (Chapters 14, 18) and no single institution holds all the capabilities required to tackle the breadth of marine research Australia needs. Collaboration nationally and internationally is central to the research needed to manage our marine estate. Such collaboration partly is supported by several key national infrastructure programs funded by the Australian Government, including the Marine National Facility (MNF), the Integrated Marine Observing System (IMOS), the National Sea Simulator, the National Computational Infrastructure facility and an ice breaker servicing research and other activities around Antarctica. The MNF operates Australia's only blue-water research vessel and a range of specialist equipment for observing and sampling the oceans, available to all Australian researchers and their international collaborators. *Investigator* was commissioned in 2014 as the new MNF vessel and Australia's first ever purpose-built multi-disciplinary research vessel. IMOS has been operating since 2006 to provide a wide range of marine observing facilities and data streams for use by Australian and international researchers and is seen as an international leader of nationally coordinated marine observations.

The Australian Government supports major research infrastructure essential for understanding and managing our marine estate, including the purpose-built research vessel Investigator *that commenced service in 2014 (Source: CSIRO).*


40°E
50°E
60°E
70°E
80°E
90°E
100°E
110°E
0°
10°S
20°S
30°S
40°S
50°S
60°S
70°S
SOMALIA
KENYA
TANZANIA
COMOROS
MOZAMBIQUE
MADAGASCAR
SEYCHELLES
MASCARENE PLATEAU
MAURITIUS
Port Louis
Mauritius Island
Reunion Island
Rodrigues Island
CENTRAL INDIAN RIDGE
CHAGOS-LACCADIVE RIDGE
MALDIVES
Diego Garcia
MID-INDIAN OCEAN BASIN
NINETYEAST RIDGE
COCOS BASIN
INVESTIGATOR RIDGE
Cocos (Keeling) Islands
RAITT RISE
Christmas Island
SUMATRA
SUNDA SHELF
KALIMANTAN
INDONESIA
JAVA
SUNDA TROUGH
LOMBOK BASIN
SUNDA TRENCH
ROO RISE
ARGO ABYSSAL PLAIN
GASCOYNE ABYSSAL PLAIN
EXMOUTH PLATEAU
CUVIER ABYSSAL PLAIN
WALLABY PLATEAU
WHARTON BASIN
ZENITH PLATEAU
BATAVIA SEAMOUNT
PERTH ABYSSAL PLAIN
PERTH
NATURALISTE PLATEAU
BROKEN RIDGE
DIAMANTINA FRACTURE ZONE
SOUTHWEST INDIAN RIDGE
SOUTHEAST INDIAN RIDGE
Amsterdam Island
St Paul Island
CROZET BASIN
DEL CANO RISE
Crozet Islands
NORTHERN KERGUELEN PLATEAU
GALLIERI SPUR
Kerguelen Islands
OB SEAMOUNT
LENA SEAMOUNT
CONRAD RISE
MARION DUFRESNE SEAMOUNT
McDonald Islands
Heard Island
CENTRAL KERGUELEN PLATEAU
WILLIAMS RIDGE
KERGUELEN PLATEAU
ELAN BANK
LABUAN BASIN
SOUTHERN KERGUELEN PLATEAU
AUSTRALIAN
ENDERBY ABYSSAL PLAIN
PRINCESS ELIZABETH TROUGH
BRUCE RISE
FRAM BANK
FOUR LADIES BANK
AUSTRALIAN ANTARCTIC TERRITORY
DRONNING MAUD LAND



◂ ***Figure 1.1**: Australia's marine estate. Australia's total maritime jurisdiction is 13.68 million km² including estuarine marine waters (~0.26 million km²), an Exclusive Economic Zone (EEZ) of 10.19 million km² and 2.04 million km² of waters off the Australian Antarctic Territory (Source: GeoScience Australia, Commonwealth of Australia, CC BY 4.0).*

OCEANS AND OUR LIVES

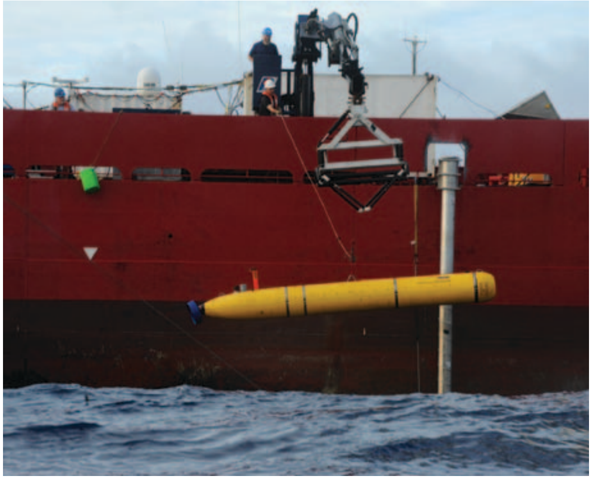
The Oceans Policy Science Advisory Group in 2013 identified six ‘grand challenges’ facing Australia for which the marine environment is central[3] and marine research is important to responding to them. Its successor, the Australian National Marine Science Committee, expanded that list to seven grand challenges and developed a National Marine Science Plan[4] for future research in each of those areas. We do not seek to duplicate that work here, but the challenges identified are woven implicitly through the chapters of this book.

Sovereignty, security and safety

Australia’s economy depends on maritime operations by many industries across a vast region of the globe. Australia also has responsibility for safety and search and rescue over a huge area of oceans. Australia’s security depends on efficient operation of naval and coastal regulatory authorities across vast areas. National assets across the marine estate are exposed to extreme sea conditions associated with severe storms. Safety, effectiveness and efficiency of these operations and others, including search and rescue, all depend on real-time ocean forecasts for which targeted operational research is essential (Chapter 12).

The Australasian Indo-Pacific region comprises many developing nation states with extensive coasts and high dependence on marine food resources (Chapter 9) for which Australia can provide regional research leadership. Australian research is essential to the prognosis for climate change effects across the region and important for assisting nations to prepare for, and adapt to, changes now considered to be inevitable.

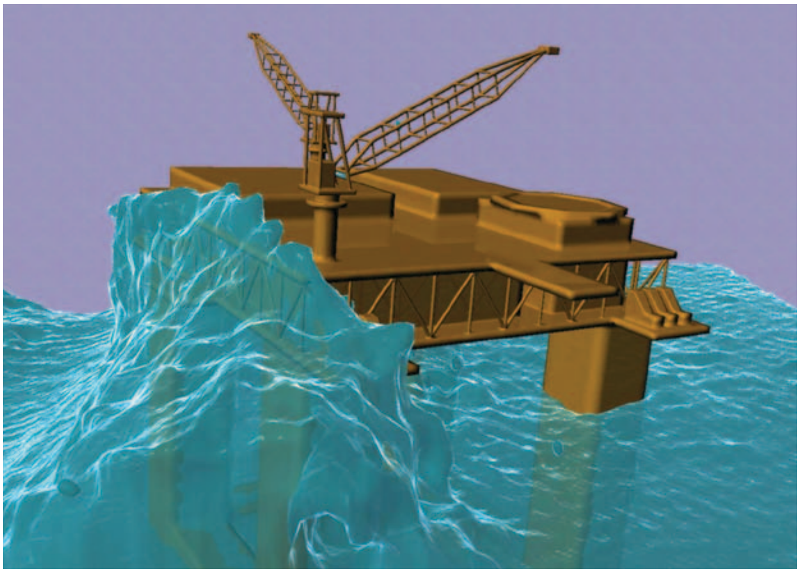
Australia plays leading roles in the Antarctic Treaty System and related international agreements, including the Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Agreement on the Conservation of Albatrosses and Petrels (ACAP) under the Convention on Migratory Species (CMS). These and other international agreements ensure our southern maritime boundary remains an area of peace and international cooperation. Research is a key currency for our participation in them.



An unmanned submarine is lowered from the deck of the Australian offshore support vessel ADV Ocean Shield *as part of an international operation in the southern Indian Ocean to search for the missing Malaysia Airlines aircraft from Flight MH370. Ocean surveillance, defence and search and rescue are essential parts of Australia’s international responsibilities for the vast Australian marine estate and depend heavily on up-to-date ocean research and forecasts and international cooperation (Source: Peter D. Blair, USA Department of Defence 140426-N-OV358–019, Public domain, via Wikimedia Commons).*

Energy

Australia's marine estate sits over abundant non-living resources of economic and social importance, including oil, gas, mineral sands and ore-bearing features (Chapter 4). Sub-seabed oil and natural gas are vital for Australia's energy security and natural gas is set to be a major export from Australia over coming decades, but the oceans of our marine estate also have great potential to supply renewable wave and tidal energy (Chapter 10). Harvesting these massive energy resources is a future necessity requiring research now to understand the options, technologies and challenges of harvesting ocean renewable energy in addition to conventional fossil fuels. Technologies for exploitation and innovations in handling and transport of these resources are important areas of research, together with exploration of the oceans and sub-seabed for potential new resources. There is a high expectation socially that the extraction and transport of these resources will have negligible effect on Australia's marine environment, with clear recognition of the potential for significant impacts from accidents such as oil spills. Informing the actual or potential interaction of the industry with the marine environment is an essential area of marine research.



Offshore oil and gas have been essential for Australia's development but efficiency, safety and environmental effects of exploration and extraction rely on ocean research (Source: CSIRO).

Marine biodiversity

Our marine estate has unique biodiversity over a huge geographic range (Chapter 3). Bioregional marine planning, resource assessment, ecosystem-based management of activities and monitoring the world's largest representative system of marine protected areas all are tasks underpinned by marine research. Balancing the consequences of exploitation with the demands for conservation of the marine estate represents a major policy and regulatory challenge that rests heavily on robust research across the breadth of the marine estate.

Marine tourism and recreation provide direct economic, social and, arguably, health benefits that depend on the 'good health' of the marine environment (Chapter 6). Most Australians live within 50 km of the oceans and even more see the coast as a primary holiday destination. All these people have vested interests in the wellbeing of our oceans. Belief that the marine estate is in good condition also provides vicarious benefit to many Australians and helps fulfil the nation's international marine stewardship responsibilities.

Australia's marine estate is rich in a great diversity of plants and animals, from tropical to Antarctic seas (Source: CSIRO – Matt Curnock, Steve Rintoul).

Food

Australian commercial fisheries and aquaculture industries harvest marine animals and plants, mostly for food, with benefits for the Australian economy and society (Chapter 9). Fishing is an important recreation across Australia and an essential part of the culture and food of many Indigenous Australians (Chapter 6). The direct and indirect effects of all fishing and aquaculture on the status of the marine estate, however, is of material concern nationally and internationally. Research plays major roles in the efficiency and management of these activities in ways that reassure an increasingly concerned community that they are ecologically safe and sustainable. Many of the fish stocks on which we depend are not restricted only to Australian waters and so are effected by fishing practices on the high seas by other nations. Fisheries research is an important enabler of Australia's influence in the multi-national management of these wide-ranging species.

Fishing is important commercially and for recreation and cultural heritage for many Australians (Source: CSIRO).

Coasts

Much of Australia’s coast is low-lying and sandy or muddy. Near-shore marine processes regularly flush estuaries, rework and redistribute coastal sediments and modify the shape of our coasts. Over 80% of Australians live in coastal communities with associated industries and infrastructure (Chapter 11), and many of those communities are built in low-lying areas. Shipping is essential for the national economy, requiring ongoing port development.

Managing coastal development is a profound challenge for Australia and for our regional neighbours. Rising sea levels increasingly will affect Australia’s coastal environments, assets and communities (Chapter 17). Changes in distribution of marine species as the ocean warms (Chapters 3, 5) will present challenges to many fisheries and conservation efforts, possibly also resulting in material shifts in regional marine-based industries. Policy and regulatory responses to these effects are shared across national, state and local jurisdictions and adaptation to coastal risks and changes will be required by diverse communities and industries (Chapters 11, 15, 16). Responses by individuals and communities will hinge on underpinning information about coastal processes and uses delivered at national scale by targeted, large-scale marine research.

Australia has a diverse coastline with many remote areas and others that are integral to many aspects of Australian life (Source: CSIRO – Willem van Aken, Leise Coulter, James Porteous).

Oceans and climate

Australia's climate and weather are influenced profoundly by regional and global processes driven substantially by the oceans. Exchange of heat and moisture between ocean and atmosphere drive key climate features that, in turn, affect directly the weather and climate over Australia's terrestrial environments, including rainfall, temperature, and the frequency and intensity of extreme weather events (Chapter 5). Improving medium- to long-term forecasts of weather and climate for Australia and our region hinges on our ability to capture ocean–climate interactions in Australia's Earth system, climate and weather models.

The oceans affect Australian weather and climate at a grand scale, from the tropics to Antarctica (Sources: NASA, CSIRO – Robert Kerton, Glen Walker).

The oceans are major players in the global carbon cycle and provide a key buffer to the effect of humanity's additions of carbon dioxide to the atmosphere. This benefit comes at a cost, however, because absorbing extra carbon dioxide is leading to acidification of the oceans (Chapter 17). Quantifying this buffering capacity and its consequences is a key international challenge to which Australian marine and atmospheric science is a strong contributor. Equipping Australia to respond to these climate challenges and improving our ability to forecast weather and climate depends on ocean research at a national scale – from the tropical Indo-Pacific to the margins of Antarctica.

Resource allocation

The intensity and diversity of ocean uses is growing rapidly. Different interests often have competing demands for access, resources and approvals to operate across the marine estate. Many of our land-based activities also affect the oceans (Chapters 11, 13). Managing these multiple demands and impacts on the marine estate increasingly requires sophisticated tools to quantify the trade-offs between alternative uses (Chapter 15). Demand for such integrated, multiple-use management strategy evaluations is projected to be a key future challenge for marine science (Chapter 16) and Australia, as an established leader in that field.

CONCLUSION

The oceans around Australia provide both protection and resources in abundance, and influence almost all aspects of Australians' lives either directly or indirectly. Our jurisdiction of enormous areas of those oceans comes with responsibilities to both use the ocean resources and protect the marine environments from damage from such uses. Those responsibilities depend heavily on research. The future of that research will benefit from rapidly advancing research technologies (Chapters 16, 18) but will need to integrate across conventionally separate marine science disciplines and include social and economic disciplines to provide truly integrated support for the stewardship of our marine estate.

CHAPTER 2.

Australia's ocean currents

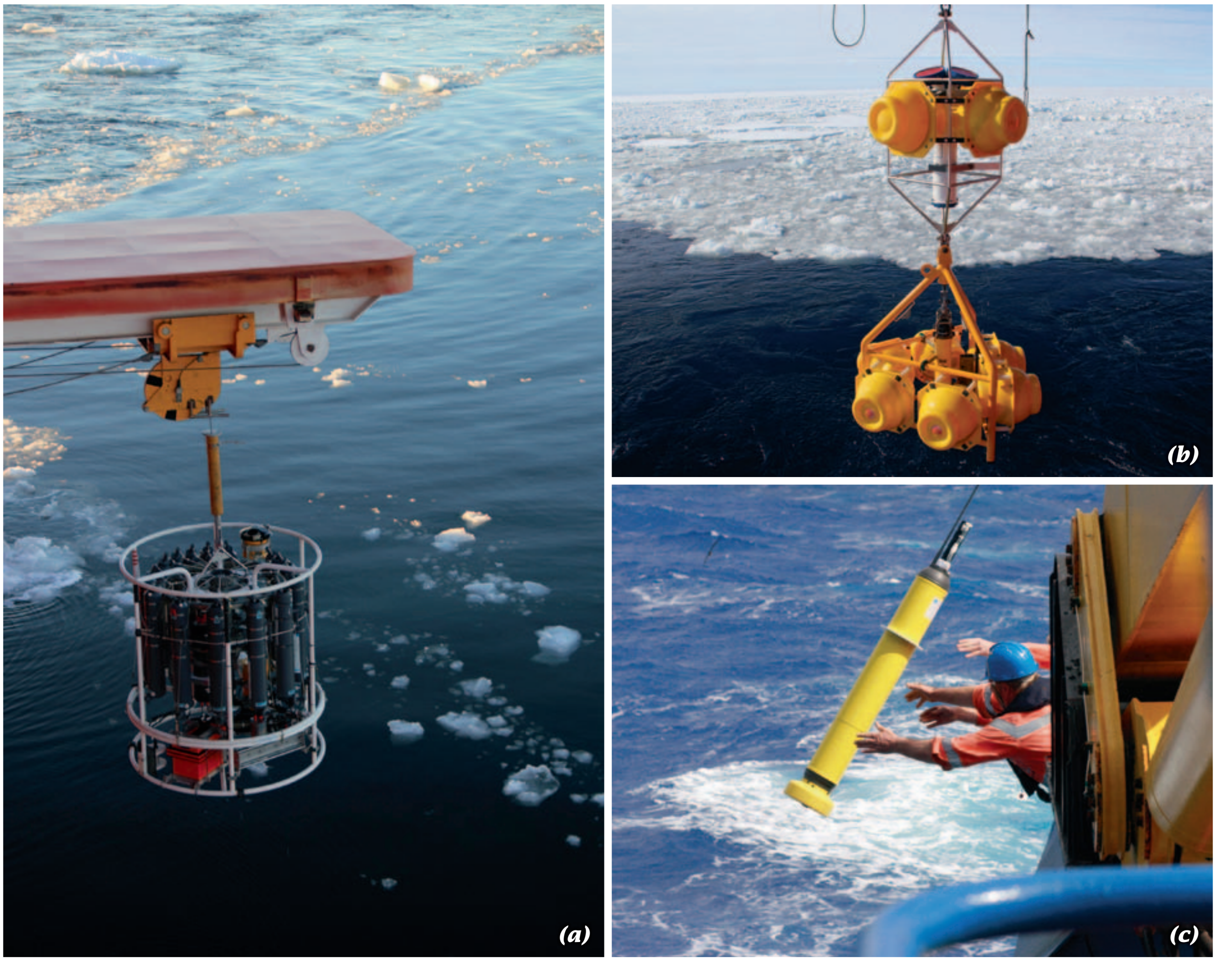
Stephen R Rintoul, Ming Feng, Nick J Hardman-Mountford and Eric Raes

Key messages

- Australia's ocean currents influence patterns of rainfall and temperature on land, the distribution of marine organisms and biological productivity in the sea, and a wide range of marine activities including defence, search and rescue, tourism, offshore structures and transport.
- The major current systems influencing Australia include the East Australian Current in the east, the Leeuwin Current in the west, and currents connecting the Pacific and Indian Oceans through the Indonesian Passages and in the Southern Ocean.
- Ocean circulation varies on many timescales. Notable examples in Australian waters include seasonal extension and contraction of major currents, strong eddies in some locations, southward expansion of warm subtropical waters off the east coast in recent decades and marine heatwaves off the west coast.

INTRODUCTION

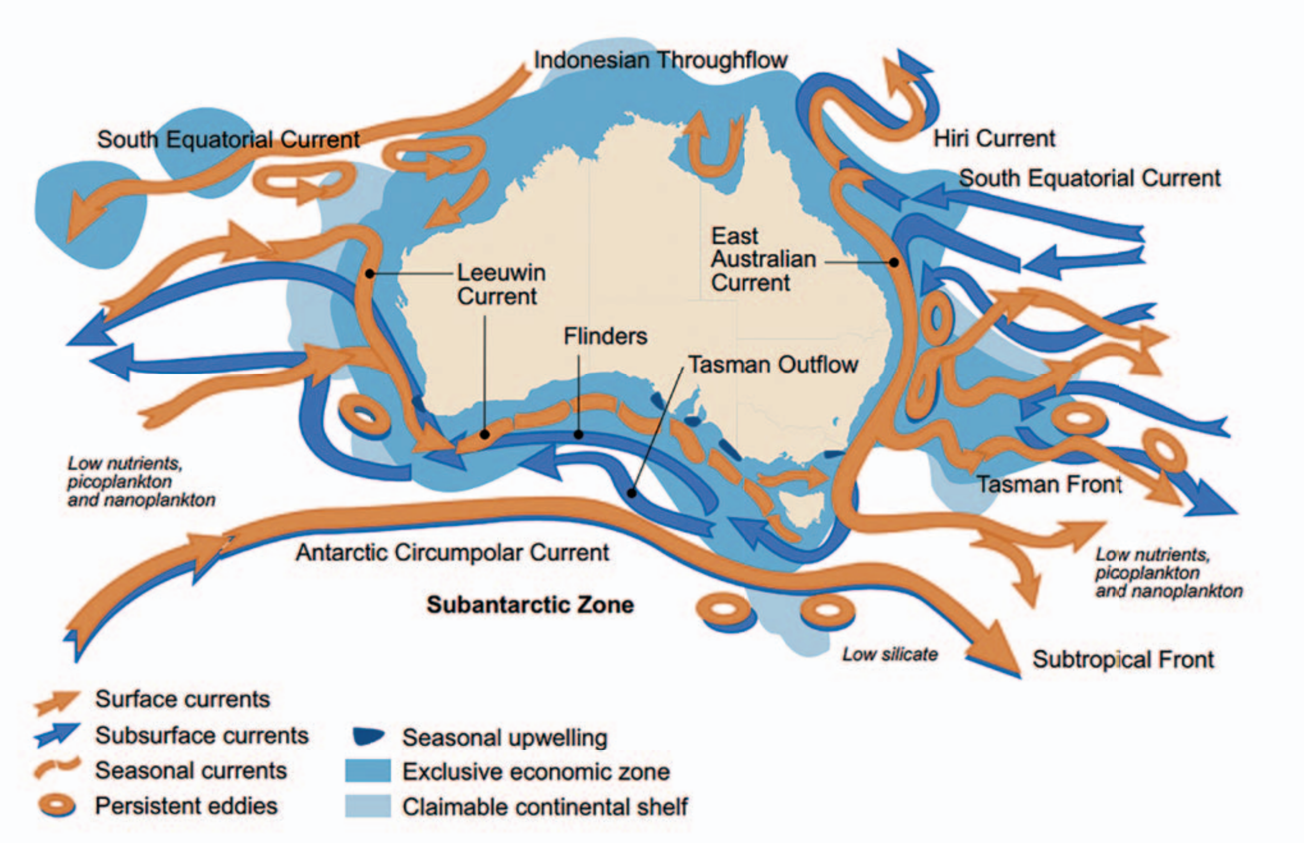
Ocean currents exert strong influences on the terrestrial and marine environment (Chapters 5, 6) and economy (Chapter 7) of Australia by transporting heat, water, nutrients and other properties relevant to climate and marine productivity. Ocean currents along the equator are key players in the El Niño–La Niña cycles that bring droughts and floods to Australia. Variations in the strength of the Leeuwin Current off Western Australia are linked to productivity of the West Australian lobster fishery, while a southward expansion of warm East Australian Current waters has catalysed a shift from kelp forest to urchin barrens along much of Tasmania's east coast. Knowledge of ocean currents is essential for the design of coastal and offshore infrastructure, effective search and rescue, defence operations and sustainable management of marine resources (Section 2, Chapters 9–15). Continued monitoring of ocean dynamics around Australia is important to provide such knowledge, especially as ocean conditions change with changing climate.



Tools for observing the oceans, including ***(a)*** *traditional methods such as lowering instruments from ships,* ***(b)*** *instruments lowered to the sea floor and moored in place to collect data over long periods and* ***(c)*** *robotic Argo floats that drift with ocean currents and transmit oceanographic data via satellite (Source: CSIRO).*

LARGE-SCALE OCEANOGRAPHIC SETTING

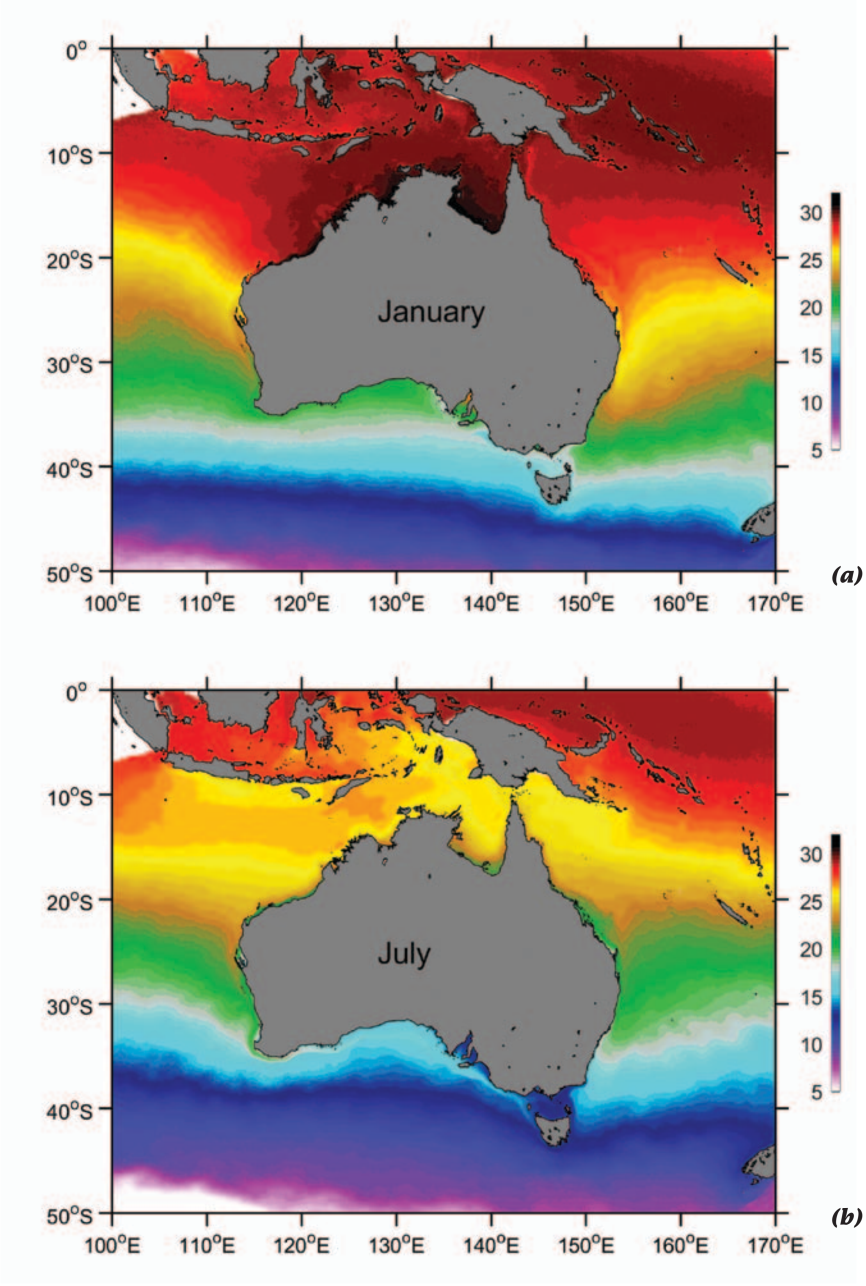
Australia sits at an oceanic crossroads, flanked by the Indian, Pacific, equatorial and Southern Oceans (Fig. 2.1). The Indonesian Throughflow carries relatively fresh water westwards from the Pacific to the Indian Ocean through the Indonesian archipelago. The world's largest ocean current, the Antarctic Circumpolar Current, flows from west to east between Australia and Antarctica. The east coast of Australia is influenced by the East Australian Current, the western boundary current of the large anti-clockwise gyre that spans the subtropical latitudes of the Pacific Ocean. The Indonesian Throughflow feeds the southward flow of the Leeuwin Current off the west coast.



▲ ***Figure 2.1****: A schematic view of the major Australian surface ocean current systems (Source: adapted from the CSIRO report to DSEWPaC, 2011[1]).*

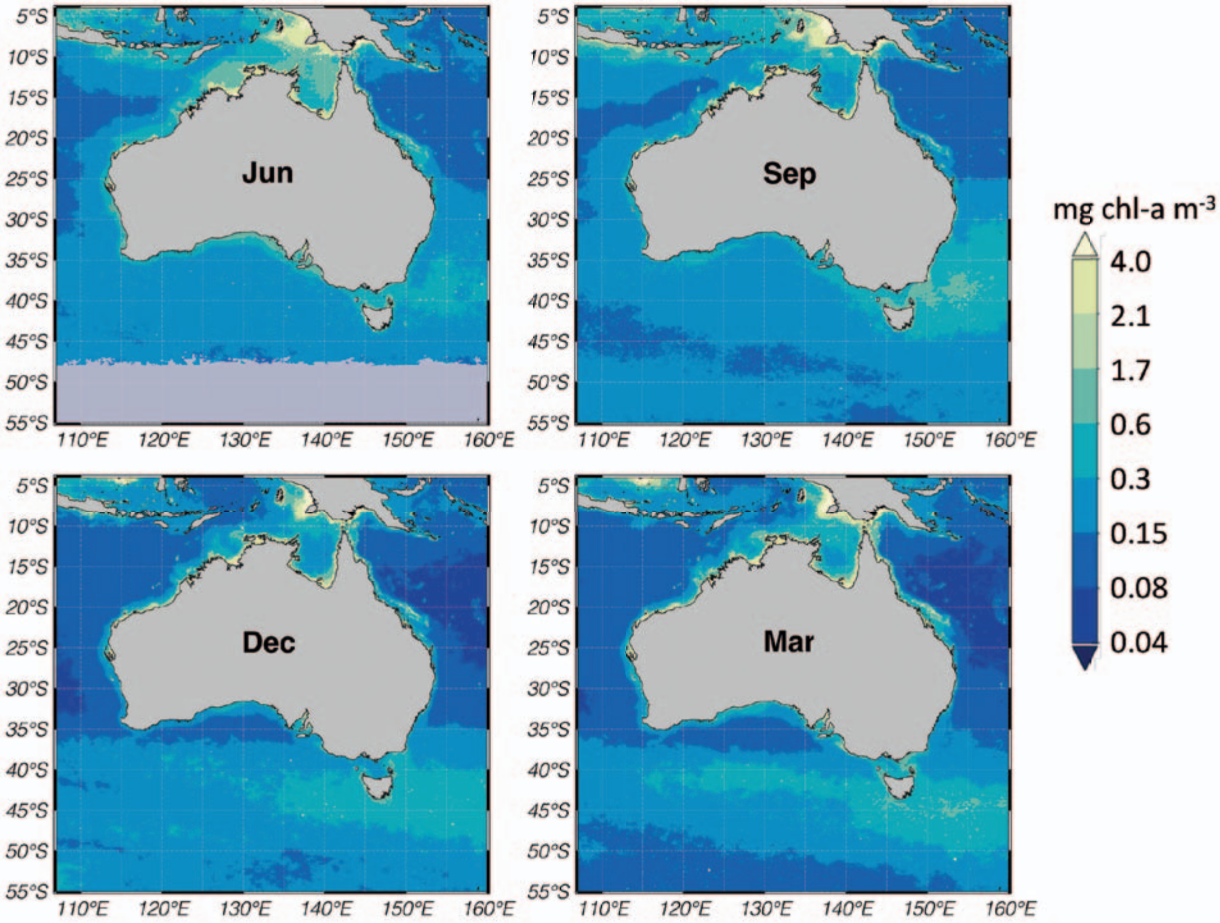
These large-scale ocean circulation patterns are driven by the wind. The easterly trade winds near the tropics and westerly winds further south determine the strength of the subtropical gyres that span the Indian and Pacific Ocean basins. The Indonesian Throughflow and the Leeuwin Current vary mostly in response to winds over the tropical Pacific at inter-annual and decadal timescales. Local winds drive variability of boundary currents such as the East Australian Current, as well as upwelling of nutrient-rich waters in some coastal locations. The current systems near Australia therefore respond to both local and distant changes in wind patterns.

The distribution of temperature, salinity, nutrients and biological productivity around Australia is influenced by atmospheric and oceanic processes. Sea-surface temperature decreases from north to south, warms in summer and cools in winter (Fig. 2.2). Warm waters extend further south along the east and west coasts, reflecting the southward flow of the East Australian and Leeuwin Currents, respectively. Salinity at the sea surface generally is lower in the tropics and far southern latitudes, where precipitation exceeds evaporation, and higher at mid-latitudes, where evaporation is dominant.



◂ ***Figure 2.2**: Average ocean surface temperature in **(a)** summer and **(b)** winter. Warm waters are carried further south off the east and west coasts of Australia by the East Australian and Leeuwin Currents, respectively (Source: climatology by Susan Wijffels, CSIRO, using data from Australia's Integrated Marine Observing System, IMOS. See* the CSIRO Atlas of Regional Seas *(http://www.marine.csiro.au/~dunn/cars2009/) for more maps of ocean properties near Australia.).*

Surface waters surrounding Australia generally are poor in nutrients, resulting in low biological productivity. Exceptions include the northern continental shelves and a wide band south of the continent known as the Subtropical Convergence, where deep winter mixing brings nutrients to the surface layer (Fig. 2.3). Upwelling of nutrient-rich waters occurs off the Bonney coast of South Australia and Victoria in summer and sporadically off the West Australia and New South Wales coasts (Fig. 2.1). Deeper, colder waters tend to be richer in nutrients because of the constant sinking of decaying plant and animal matter from the surface waters to depths where there is little consumption of nutrients, especially below the photic zone. Nutrients thus accumulate at depth and localised upwelling brings these nutrient-rich waters to the surface where they 'feed' shallower water ecosystems.



▲ ***Figure 2.3***: *Average chlorophyll concentration (mg/m³) in surface waters, a measure of phytoplankton biomass, in the Australian sector for the months of June and September (top left and right) and December and March (bottom left and right) (Source: analyses and visualisations produced by Dirk Slawinski with the Giovanni online data system developed and maintained by the NASA GES DISC).*

MAJOR AUSTRALASIAN CURRENT SYSTEMS

East Australian Current System

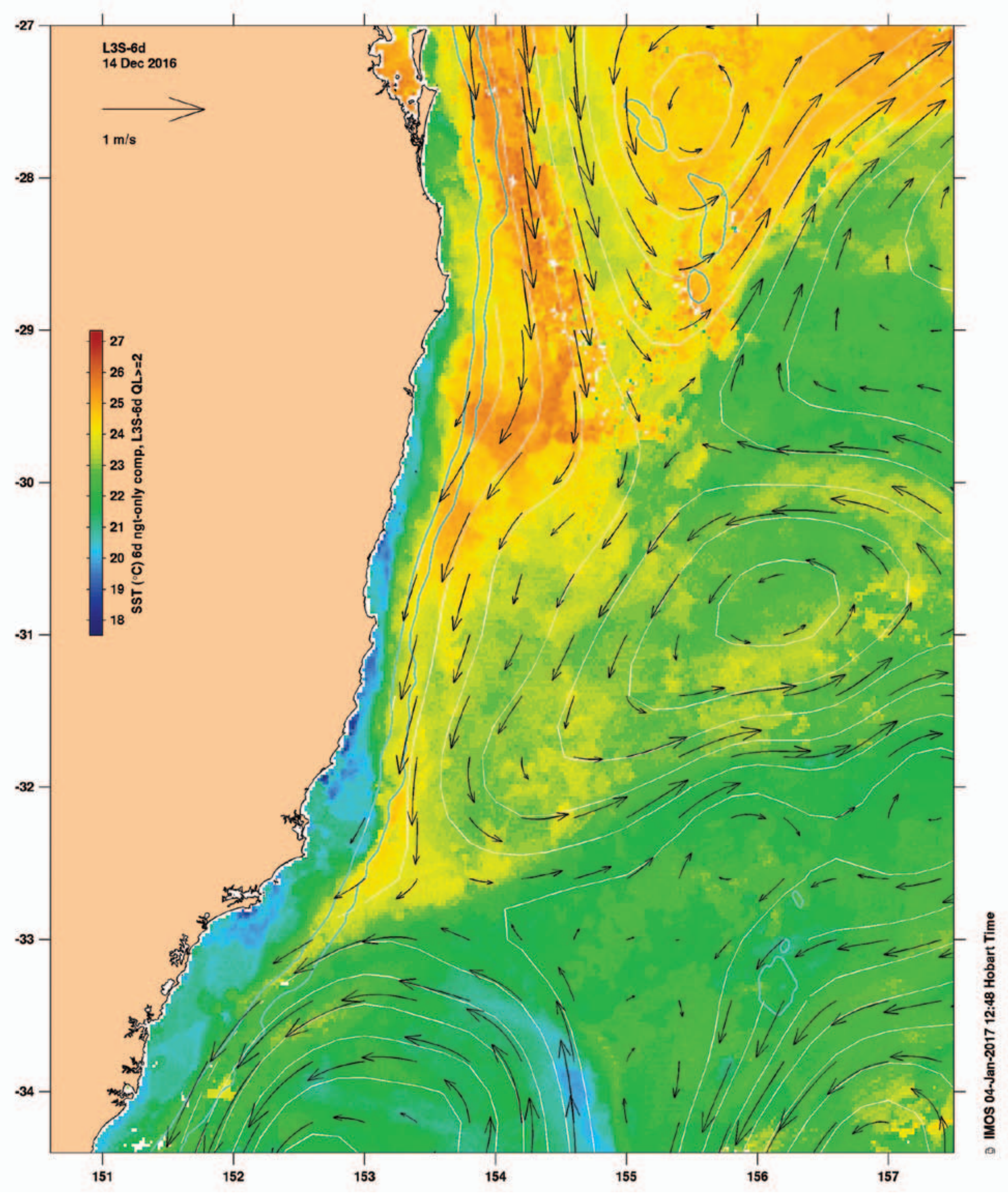
The East Australian Current (EAC) is the western boundary current of the South Pacific subtropical gyre. The South Equatorial Current flows from east to west across the tropical South Pacific to form the northern limb of the gyre. The South Equatorial Current reaches the Australian east coast near 15ºS and splits into two branches. The northern branch feeds the weak Hiri Current that flows north along the western margin of the Coral Sea. The southern branch feeds the EAC, which carries ~22–27 Sverdrups (Sv) (Fig. 2.1) (Sverdrup is a measure of ocean current transport: 1 Sverdrup = 1 million cubic metres per second = 1 billion tonnes per second). Most of the current separates from the coast and turns east near 31ºS to form the Tasman Front (Fig. 2.1), which extends eastwards to New Zealand and connects to the rest of the South Pacific gyre. A portion of the current, however, continues southwards along the coast as the EAC Extension. A deeper branch of the EAC extends past Tasmania, turns west to feed the Flinders Current south of south-east Australia, and ultimately reaches the Indian Ocean. The EAC is highly energetic and strong eddies often dominate the flow (Fig. 2.4).

The EAC Extension reaches further south in summer. The warm EAC waters have extended progressively further south in summer over the past 60 years, driving a strong warming trend in the Tasman Sea and shifts in ecosystems. The changes in the EAC have been driven by wind shifts associated with the ozone hole and increases in greenhouse gases.

The strong flow of the EAC transports large amounts of heat from the tropics to higher latitudes. Interaction of the current with the continental shelf and slope drives episodic upwelling of deeper, colder nutrient-rich waters. Information about the location and strength of the current is used to regulate where fishing for tuna and billfish is allowed off Australia's south-east coast.

Indonesian Throughflow

The Indonesian Throughflow (ITF) provides the only warm water connection between the ocean basins and is therefore a critical link in the global ocean circulation. Recent measurements suggest the ITF carries ~15 Sv from the Pacific to the Indian Oceans, mostly in the top 300 m of the ocean. The ITF enters the Indonesian seas through the Makassar Strait and other passages and exits through the Lombok Strait, Ombai Strait and Timor Passage (Fig. 2.5). The ITF outflow joins the westward-flowing South Equatorial Current in the Indian Ocean, with some of the ITF waters recirculating eastwards to feed the Leeuwin Current. The ITF is stronger during austral winter and weaker during austral summer in response to the Asian–Australian monsoon winds. The transport of warm and fresh water from the Pacific into the Indian Oceans by the ITF has a strong influence on Australian climate variability.



▲ ***Figure 2.4***: *A snapshot of the East Australian Current (EAC) system between Brisbane and Sydney from OceanCurrent, an ocean analysis tool developed by CSIRO and IMOS (http://oceancurrent.imos.org.au/). Colours indicate sea-surface temperature. Black arrows indicate current direction and speed (in m/s). The figure illustrates both the strong jet carrying warm water southwards in the core of the EAC and the complex ocean eddy field. Note patches of cold water near the coast produced by upwelling inshore of the EAC (Source: CSIRO).*

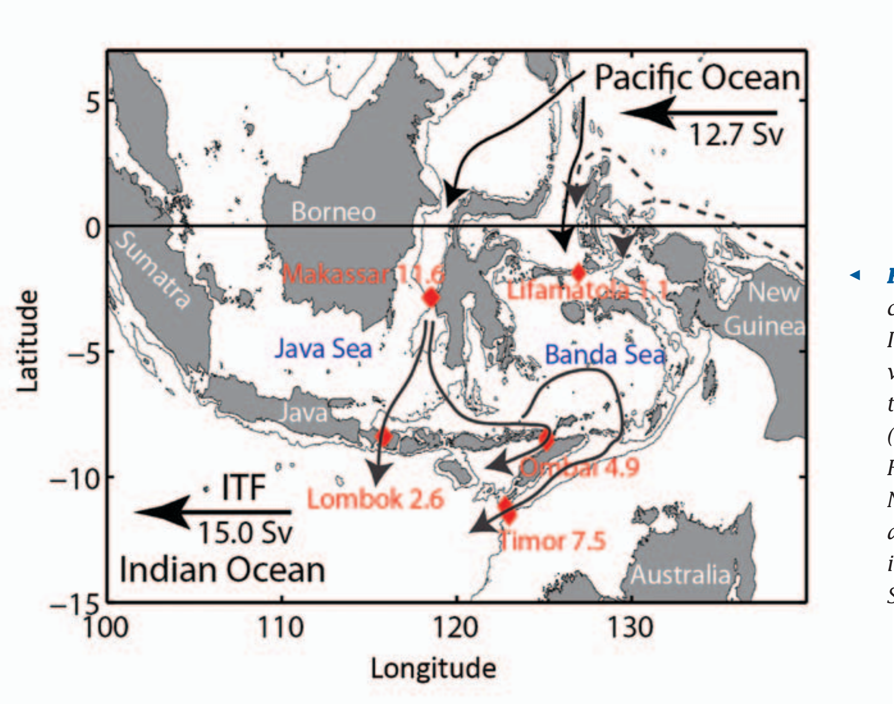


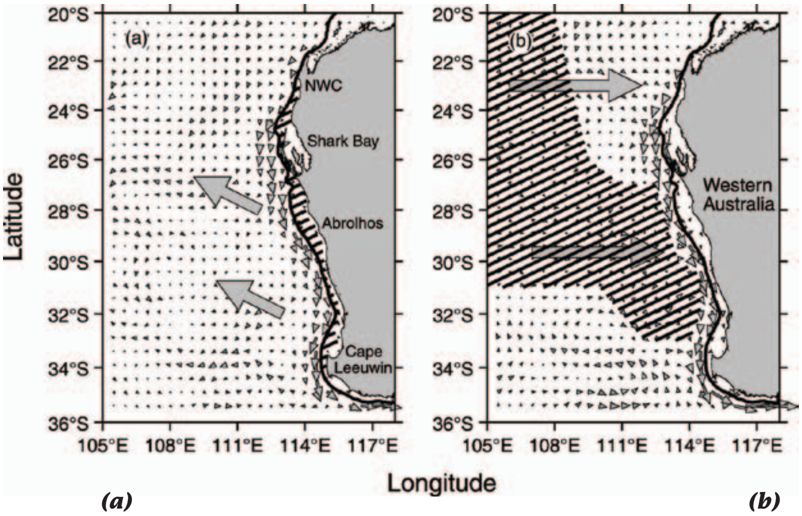
Figure 2.5: *Transport of the currents contributing to the Indonesian Throughflow (ITF) via different passages through the Indonesian archipelago (Source: after graphic by E. Hackert, from Wikipedia). Numbers next to current arrows indicate transport in Sverdrups (Sv) (Source: Sprintall* et al. *2009*[2]*).*

Leeuwin Current system

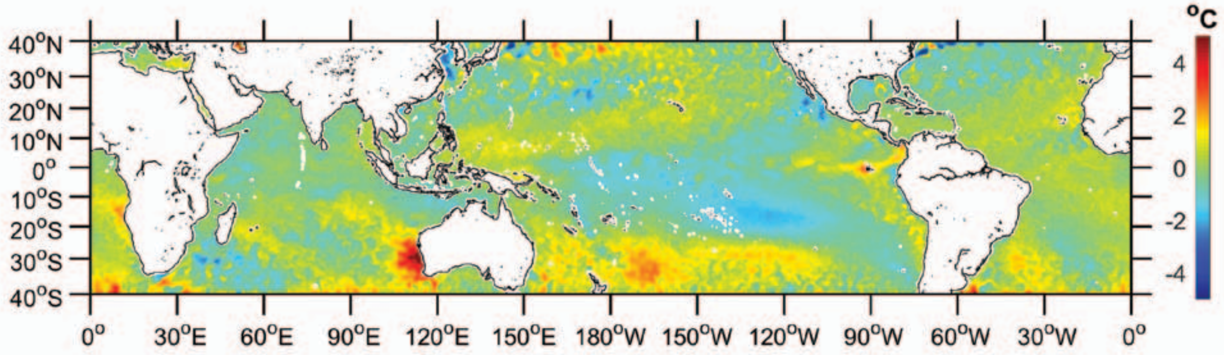
The Leeuwin Current is a narrow eastern boundary current largely forced by the ITF and ocean–atmosphere interactions in the Indian Ocean. Eastern boundary currents in other southern-hemisphere ocean basins flow to the north and support major upwelling systems. The Leeuwin Current, in contrast, is a warm, southward-flowing boundary current that suppresses wind-driven upwelling and productivity off the west coast of Australia. The warm waters carried south by the Leeuwin Current allow the existence of tropical coral reefs as far south as 32°S and the episodic presence of tropical species along the temperate west and south coasts of Western Australia. The Leeuwin Current is weak during austral summer and strong during austral winter, in response to regional wind patterns. The Leeuwin Current during winter is connected with the south-westward-flowing Holloway Current off the north-west coast and the eastward-flowing South Australian Current and Zeehan Current off the south coast, forming the longest boundary current system in the world. The seasonal cycles of the Leeuwin Current and the strong eddies in it play a crucial role in the larval spawning and settlement of western rock lobster, which supports Australia's largest single species fishery (Fig. 2.6).

The ITF and the Leeuwin Current are sensitive to the strength of the Pacific trade winds. Both the ITF and the Leeuwin Current are weaker during El Niño and stronger during La Niña periods. A surge of the Leeuwin Current during one of the strongest La Niña events resulted in an unprecedented marine heatwave off the west coast in 2011 (Fig. 2.7), causing the first-ever recorded widespread coral bleaching event off Western Australia and affecting economically important fishery species and marine habitats.

▸ ***Figure 2.6****: Surface currents along the west coast of Western Australia during* ***(a)*** *the austral summer (December–February) and* ***(b)*** *winter (June–August). The hatched area in panel* ***(a)*** *denotes the coastal habitats of western rock lobster, and the hatched area in panel* ***(b)*** *denotes the June–July distribution of lobster larvae from historical observations. The broad arrows denote general directions of larval transport by ocean currents during the two seasons (Source: Feng* et al. *2011[3]).*



(a) ***(b)***



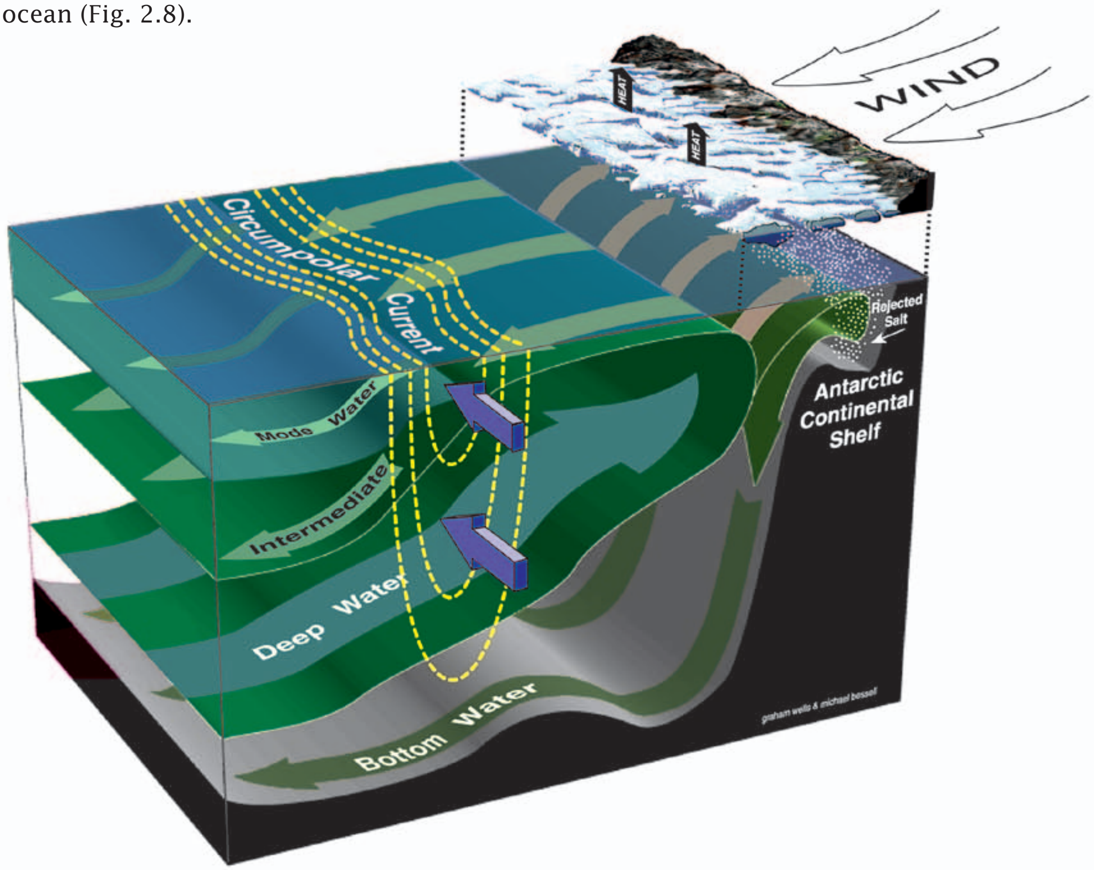
▴ ***Figure 2.7****: Elevation of surface temperatures above normal during the 2011 marine heatwave off Western Australia. Sea-surface temperatures more than 4°C above average were measured during the heatwave (dark red areas) (Source: Feng* et al. *2013[4]).*

Bleached coral at Rottnest Island off Western Australia during the 2011 heatwave (Source: Damian Thomson, CSIRO).

Antarctic Circumpolar Current and Southern Ocean overturning circulation

The Antarctic Circumpolar Current (ACC) is the largest current in the world's oceans, carrying ~150 Sv from west to east around Antarctica – more than 150 times the combined flow of all the world's rivers. The current is made up of multiple streams with many eddies, and extends from the sea surface to the deep sea floor. The deep-reaching nature of the current means that the ACC is strongly steered by the topography of the ocean floor.

The ACC is the primary means of exchange between the Atlantic, Pacific and Indian Ocean basins. This inter-basin connection has a profound influence on global-scale ocean overturning circulation and, in turn, climate. The overturning circulation influences climate by transporting vast amounts of heat and carbon. The Southern Ocean is important particularly because the region takes up and stores more heat and carbon dioxide than any other latitude band. The effectiveness of the Southern Ocean as a heat and carbon store arises from the unique circulation there, where deep water travelling south from warmer latitudes rises to the surface, exchanges heat and carbon dioxide with the atmosphere, and then sinks again to the deep and intermediate layers of the ocean (Fig. 2.8).

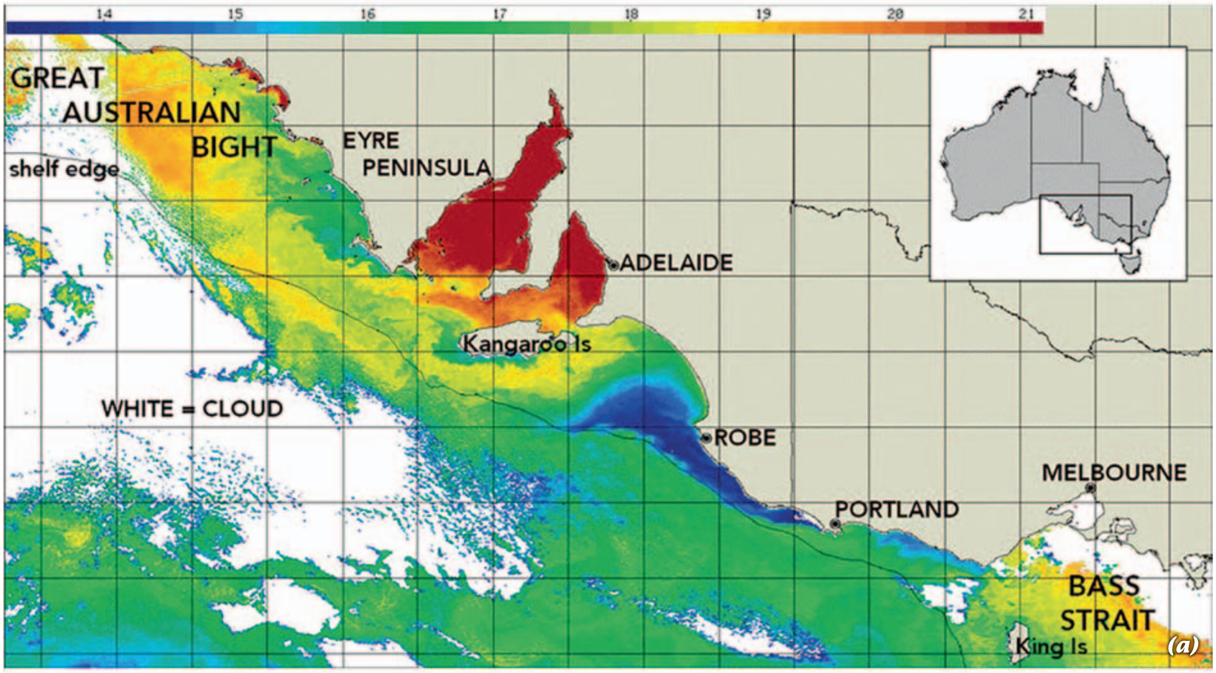


▲ ***Figure 2.8***: *Schematic view of the Southern Ocean overturning circulation. Deep water spreads south and rises as it travels eastward in the ACC. It exchanges heat and gases with the atmosphere at the surface before sinking again, either as dense Antarctic Bottom Water near Antarctica or lighter intermediate water further north. This overturning circulation transfers large amounts of heat and carbon dioxide from the atmosphere to the subsurface ocean (Source: Rintoul 2000[5]).*

Coastal upwelling

Coastal upwelling occurs when winds blow parallel to the coast with the coastline to the right of the wind in the southern hemisphere. Winds in this orientation drive surface waters offshore, resulting in upwelling of colder, nutrient-rich water from below, supporting high biological productivity. Ocean currents also can affect upwelling, either by enhancing it (e.g. when the EAC separates from the coast, as in Fig. 2.4) or suppressing it, as in the Leeuwin Current, where the southward flow of warm, nutrient-poor water usually dominates even though southerly winds are favourable for upwelling.

The most important upwelling zone in Australian waters is the Bonney upwelling off the coast of Victoria and South Australia (Fig. 2.9). Upwelling occurs in summer and autumn (November to May) when the wind blows from the south-east. A narrow continental shelf and several steep subsea canyons help funnel nutrient-rich waters to the sea surface, fuelling phytoplankton blooms that support a highly productive ecosystem, including commercial fisheries and important foraging grounds for seals and whales.



▲ ***Figure 2.9**: **(a)** Sea-surface temperature image showing the upwelling of cold water (blue colours) off the coast of Victoria and South Australia. The upwelling of cold, nutrient-rich water supports a highly productive ecosystem, including a feeding ground for blue whales. **(b)** A blue whale swimming on its right side with its mouth open, feeding on a swarm of krill (*Nyctiphanes australis*) (Sources: a courtesy Dr Pete Gill, Blue Whale Study; satellite imagery courtesy CSIRO; b courtesy Dr Pete Gill, Blue Whale Study).*

CONCLUSION

Australia's ocean currents have a large impact on the terrestrial and marine environment, on biological productivity in the sea, and on human activities as diverse as defence, search and rescue, fisheries, renewable energy, and marine resources (Section 2). These current systems respond to both local and remote changes in wind and are linked to the large-scale circulation of the Indian, Pacific, Southern and equatorial oceans. Variations in ocean currents are linked to cycles of flood and drought on land and to changes in marine ecosystems. Improved knowledge of ocean currents is needed to anticipate and respond to climate variability and change, and for the safe and sustainable use of marine resources.

FURTHER READING

Poloczanska ES, Hobday AJ, Richardson AJ (Eds) (2012) *Marine Climate Change in Australia, Impacts and Adaptation Responses: 2012 Report Card*. CSIRO, Canberra.

Talley LD, Pickard GL, Emery WJ, Swift JH (2011) *Descriptive Physical Oceanography: An Introduction*. 6th edn. Elsevier, Boston, MA, USA.

Tomczak M, Godfrey JS (2003) *Regional Oceanography: An Introduction*. 2nd edn. Daya, Delhi, India.

CHAPTER 3.

The living ocean

Alan Williams, Nicholas Bax and Karen Gowlett-Holmes

Key messages

- Australia's marine biodiversity is highly diverse with many unique components.
- Multi-scale patterns in species, habitats and the environment reflect both geological history and current environmental conditions.
- Australia's marine biodiversity has been mapped to define 'bioregions' for management purposes.
- The distribution and abundance of many marine species are changing in response to local and global drivers including resource extraction, habitat loss, marine pollution, ocean warming and more acidic oceans.
- The consequences of these changes for biodiversity and the marine products and services that currently benefit the Australian community remain unclear.
- Australia has started nationally consistent programs to monitor changes in its marine resources and inform future management of marine biodiversity.

INTRODUCTION

The oceans surrounding Australia and the Australian Antarctic Territories are among the biologically most diverse in the world. Australia's complex geological history and large geographical scale have helped create this wealth of marine biodiversity that spans the tropics to Antarctica, from the inter-tidal zone to abyssal depths. Many of our marine habitats remain unexplored and their biological inhabitants poorly known but we know enough to recognise that our marine estate contains extraordinary biological diversity. Australians value this biodiversity for its aesthetic qualities but marine biodiversity also contributes to a range of commercial values. Marine tourism, for example, contributes about A$11.6 billion to the Australian economy annually, while commercial marine fisheries and aquaculture were valued at A$2.4 billion in 2012–13. Healthy, biodiverse marine ecosystems also deliver services harder to value in monetary units, such as coastal stabilisation by coral reefs, mangroves and seagrasses – the value of which may be realised only following their removal or after major storm events.

THE SCALE, DIVERSITY AND CLASSIFICATION OF AUSTRALIA'S MARINE ESTATE

Australia's marine estate is the third largest in the world (Chapter 8). Some 33 000 marine species, mainly animals, have been recorded from Australian waters. About 17 000 others have been collected but not catalogued, making Australia's marine biota among the most diverse worldwide. Many new species still are being discovered. It is estimated that only 10–20% of Australian marine organisms may have been sampled – so there may be as many as 250 000–500 000 Australian marine species, not including microscopic plants and animals. Biodiversity is known best at depths shallower than 200 m and poorly known at greater depths. There have been few samples of any kind collected beyond 2000 m depth. It is likely that as many as half of all species in new collections from the deep ocean will be new to science.

Australia's marine habitats presently span tropical to polar latitudes and occupy parts of three oceans (Pacific, Southern and Indian) and four marginal seas (Timor, Arafura, Coral and Tasman). Evolutionary processes linked to geological history and modern day processes such as sediment movements, temperature gradients, nutrient input and productivity, and ocean circulation have created the distributional or 'biogeographic' patterns we see today, including strong north–south and depth-related patterns (Fig. 3.1). The northern tropical biota is highly diverse, with many species shared with the 'megadiverse' Indo-West Pacific region. Our southern biota, in contrast, is characterised by a high level of endemism (species found nowhere else).

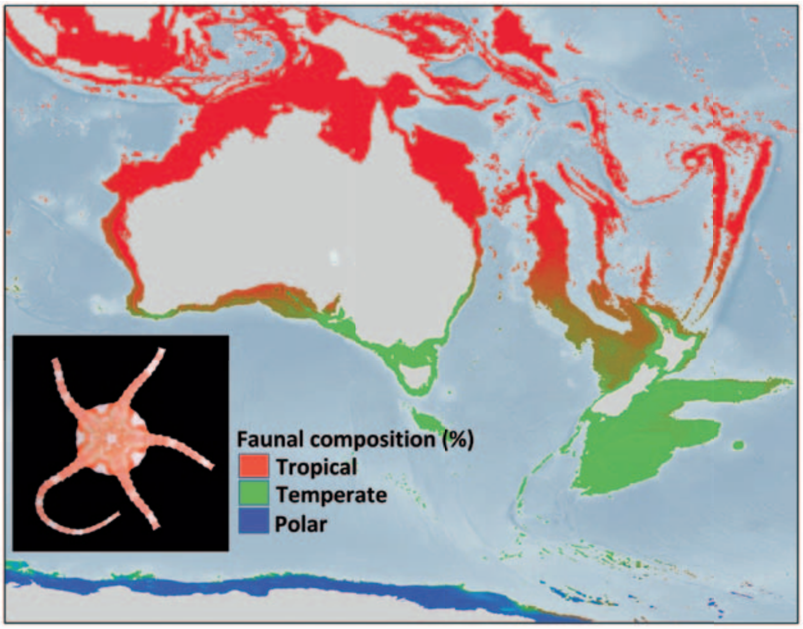


Figure 3.1*: Brittlestar communities show strong north–south and depth-related patterns of species composition and distribution that is typical for Australia's marine biota (Sources: reprinted from O'Hara* et al. *(2011)[1] with permission from Elsevier; inset image courtesy Karen Gowlett-Holmes).*

Biodiversity is influenced by environmental properties at regional scales (100–1000 km^2) and can be modified by particular water column and seabed features at finer spatial scales. Water column features such as oceanic fronts, eddies or upwelling provide areas of enhanced productivity where animals aggregate. Geological seabed features such as submarine canyons or undersea mountains (seamounts) provide scarce rocky substrata in the predominantly muddy deep sea that can support modified or unique biodiversity. These multi-scale patterns have been mapped collectively in a process called 'marine bioregionalisation' that has been used by the Australian Government to define 'bioregions' for management purposes (Fig. 3.2).

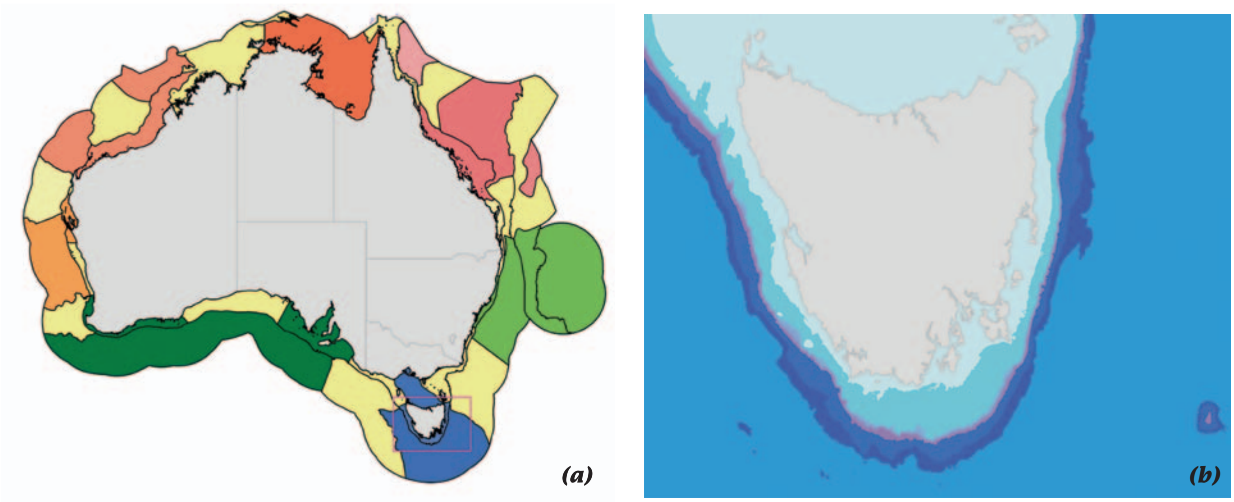
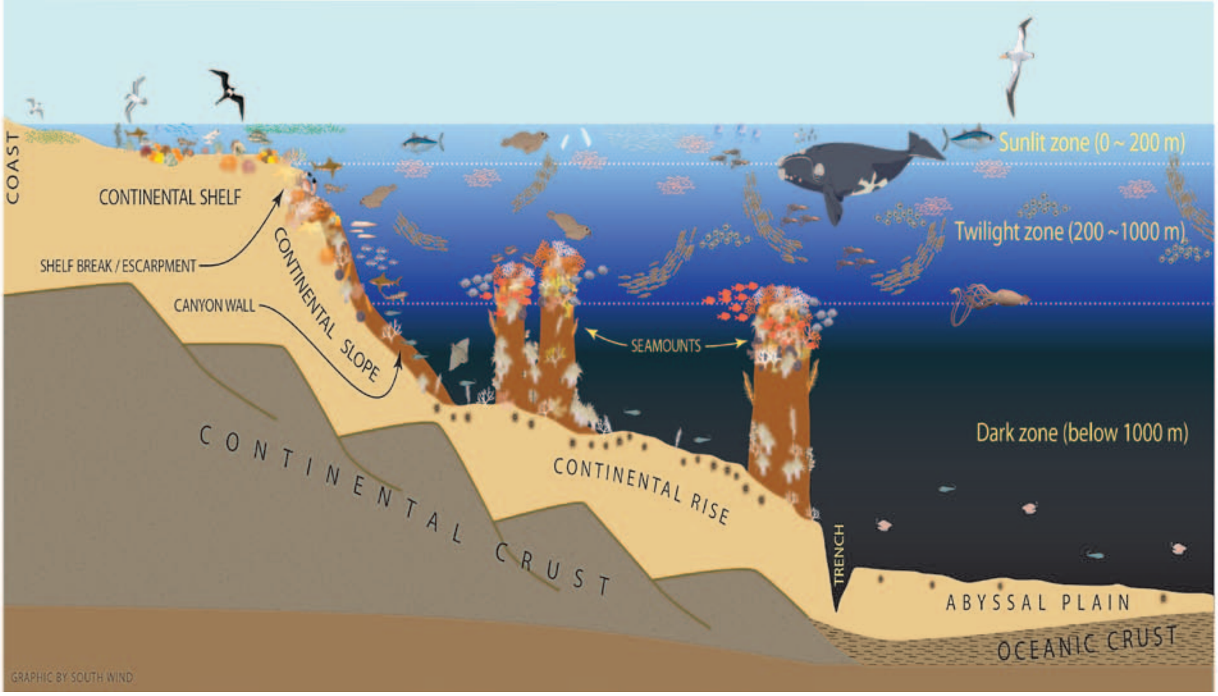


Figure 3.2*: Marine bioregionalisation for Australia showing* ***(a)*** *bioregions at national scale, and* ***(b)*** *finer scale pattern around Tasmania representing the strong influence of depth on biodiversity distribution[2] (Source: CSIRO).*

Most marine life ultimately depends on sunlight for energy, though some ecosystems around geothermal vents at great depths are supported entirely by chemical processes. Two-thirds of the oceans are below the sunlit zone, however, and half below the twilight zone. Adapting to this range of light levels and distance from primary production – the basis of most ecosystems – are key elements structuring marine habitats (Fig. 3.3).

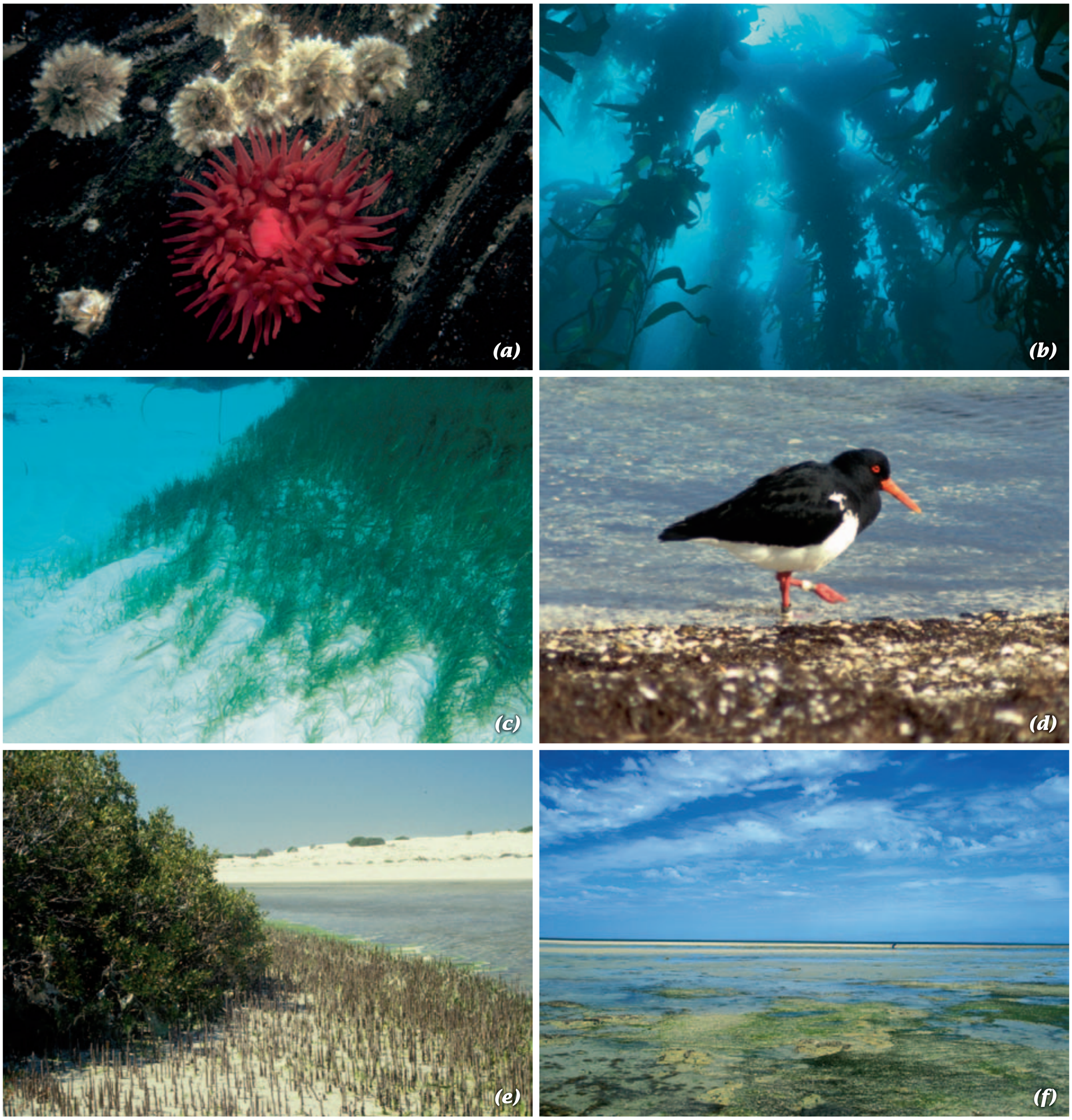


▲ ***Figure 3.3**: Schematic representation of broad habitat types from the coast to abyssal depth in Australian seas (Source: Peter Boyer, South Wind Graphics).*

BROAD HABITAT TYPES AND COMMUNITIES OF THE MARINE ESTATE

Coasts

Australia's coastal marine habitats include rocky shores, cobble and sand beaches, mudflats, mangroves and wetlands. Coastal communities broadly can be considered as 'supratidal', 'intertidal' and 'subtidal'. Organisms in supratidal areas are submerged in sea water only rarely but are exposed to fresh water, large changes in temperature, and a great variety of predators including land animals and seabirds. The intertidal areas between high and low water marks are characterised by varying degrees of submergence and the effects of wave action and turbulence. Mobile aquatic animals are able to forage here at high tide and retreat to deeper water, hide in refuges or seal-up at low tide, while algae and non-mobile aquatic animals living here are adapted to survive short periods out of water during low tides. Subtidal areas are covered in sea water permanently and generally experience more stable environments with lower variation in temperature, salinity and sunlight. Typical organisms in the coastal habitats include molluscs, sea-stars, crabs, urchins, anemones, corals, sponges, fishes, and a great variety of algae, including kelp forests. All of these groups have high diversity in tropical and temperate Australian seas.



Australia's coastal marine habitats include rocky shores, cobble and sand beaches, mudflats, mangroves and wetlands: ***(a)*** *intertidal sea anemone and barnacles in a rock pool;* ***(b)*** *giant kelp forest;* ***(c)*** *seagrass bed;* ***(d)*** *pied oystercatcher foraging on a sandy beach;* ***(e)*** *mangroves at low tide;* ***(f)*** *mudflat at low tide (Source: all images Karen Gowlett-Holmes).*

The continental shelf

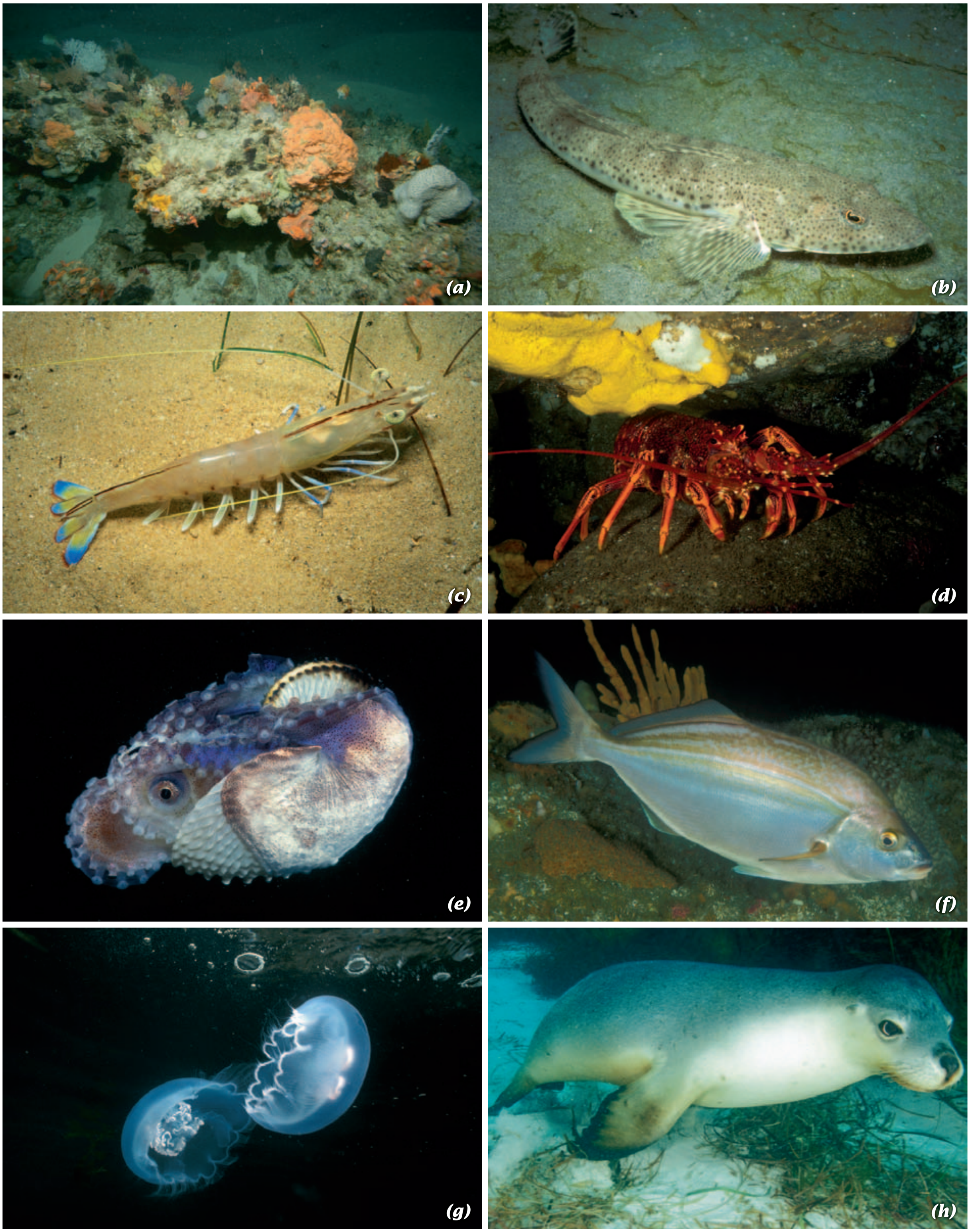
Subtidal habitats change as ocean depth and distance from the Australian coast increases across the continental shelf – the gently sloping seabed that extends to ~140–200 m depth before dramatically steepening at the 'shelf break'. The width of Australia's continental shelf varies considerably, from ~10 km in places such as off the Ningaloo coast of north-west Western Australia and off central New South Wales to 500 km in parts of the Great Australian Bight. Habitat types include rocky reefs and extensive plains of land-derived sediments that typically grade from coarse-grained sands to fine mud as distances from coasts increase and wave influences diminish. Biological production in continental shelf waters is high relative to the deeper ocean because the shelf's sunlit (photic) environment, well-oxygenated water and higher nutrient levels collectively fuel photosynthesis in phytoplankton (free-floating microscopic plants) and algae (seaweeds). This primary production is the base of food webs supporting larger animal plankton and herbivores including euphausids (krill), copepods, jellyfish and amphipods. Many larger carnivorous animals are found in both water column (pelagic) and seabed (benthic) habitats, including many of the species most familiar to Australians as seafood or the targets of recreational fishing (e.g. prawns, lobsters, squids and fishes), megafauna (e.g. turtles, seabirds and mammals) or iconic species (e.g. white shark, seals and whales). Biological diversity and abundance generally are high in shelf waters and on the seabed.

Coral reefs are well-known habitats that extend from the intertidal to subtidal zones in warm, typically nutrient-poor waters. Reefs are formed mostly from calcium carbonate skeletons of stony corals and calcareous algae. Coral reefs are extremely diverse ecosystems that include species from almost all known taxa. Australia's Great Barrier Reef (GBR) is the world's largest reef system, made up of over 3000 individual reefs and shoals and extending over 2600 km from the south coast of Papua New Guinea to just north of Fraser Island. The GBR supports over 1500 species of fish, 30 marine mammal species, six species of sea turtle, 215 visiting or nesting species of birds, and 17 sea snake species. Over 4000 species of invertebrates – including corals, sea cucumbers, sea stars, crabs, shrimps, molluscs and worms – also are known from the GBR, and many more are undescribed. Abundance of reef-forming corals has declined by around 50% over the past three decades, causing great concern nationally and internationally.

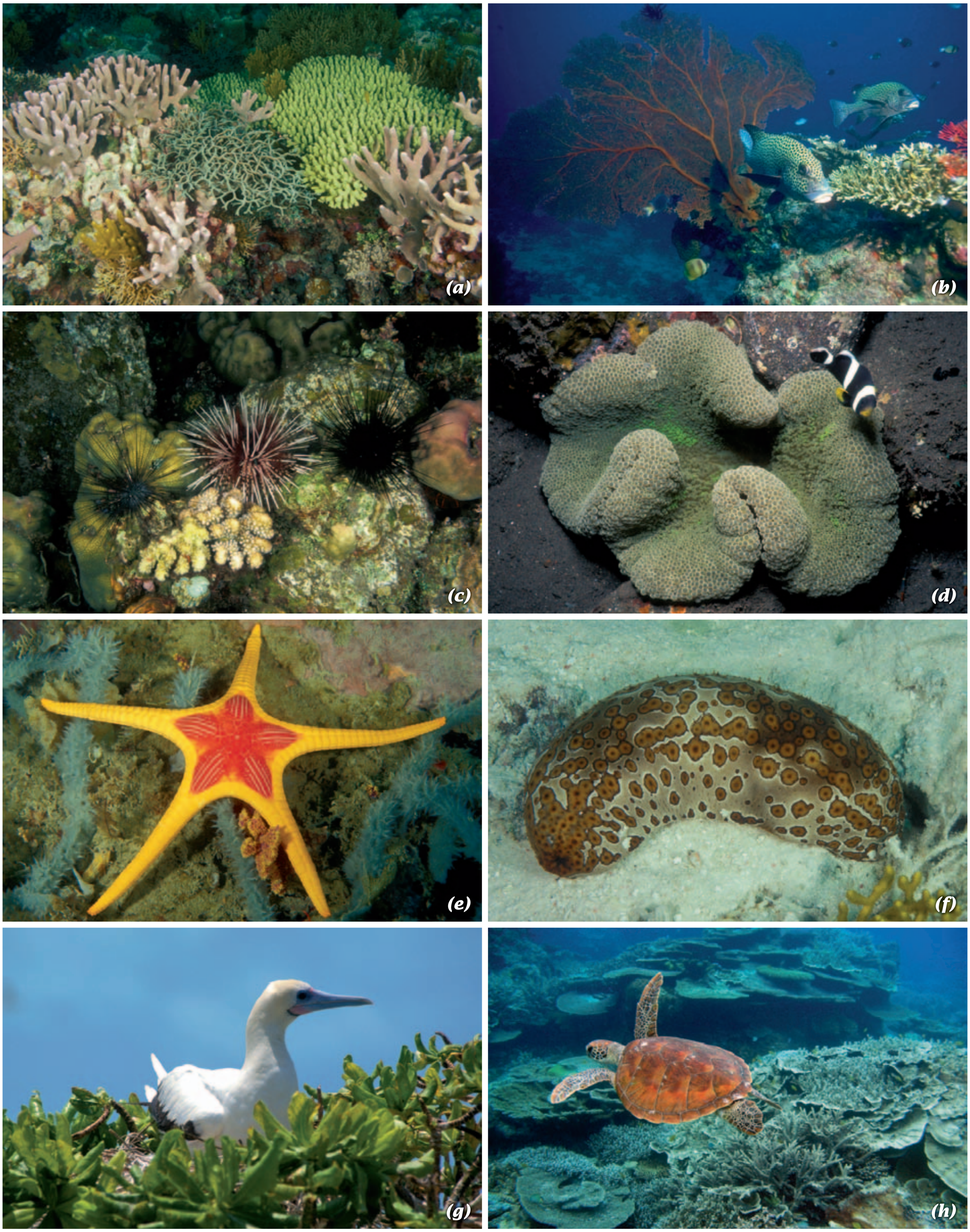
The deep ocean

Most of Australia's marine estate lies beyond the continental shelf break. The seabed drops steeply from the shelf break, at around 200 m depth, through the steep continental slope and deeper continental rise to 3000 m depth. Vast, relatively flat expanses of muddy sediments form the abyssal plain beyond these features in depths exceeding 3000 m.

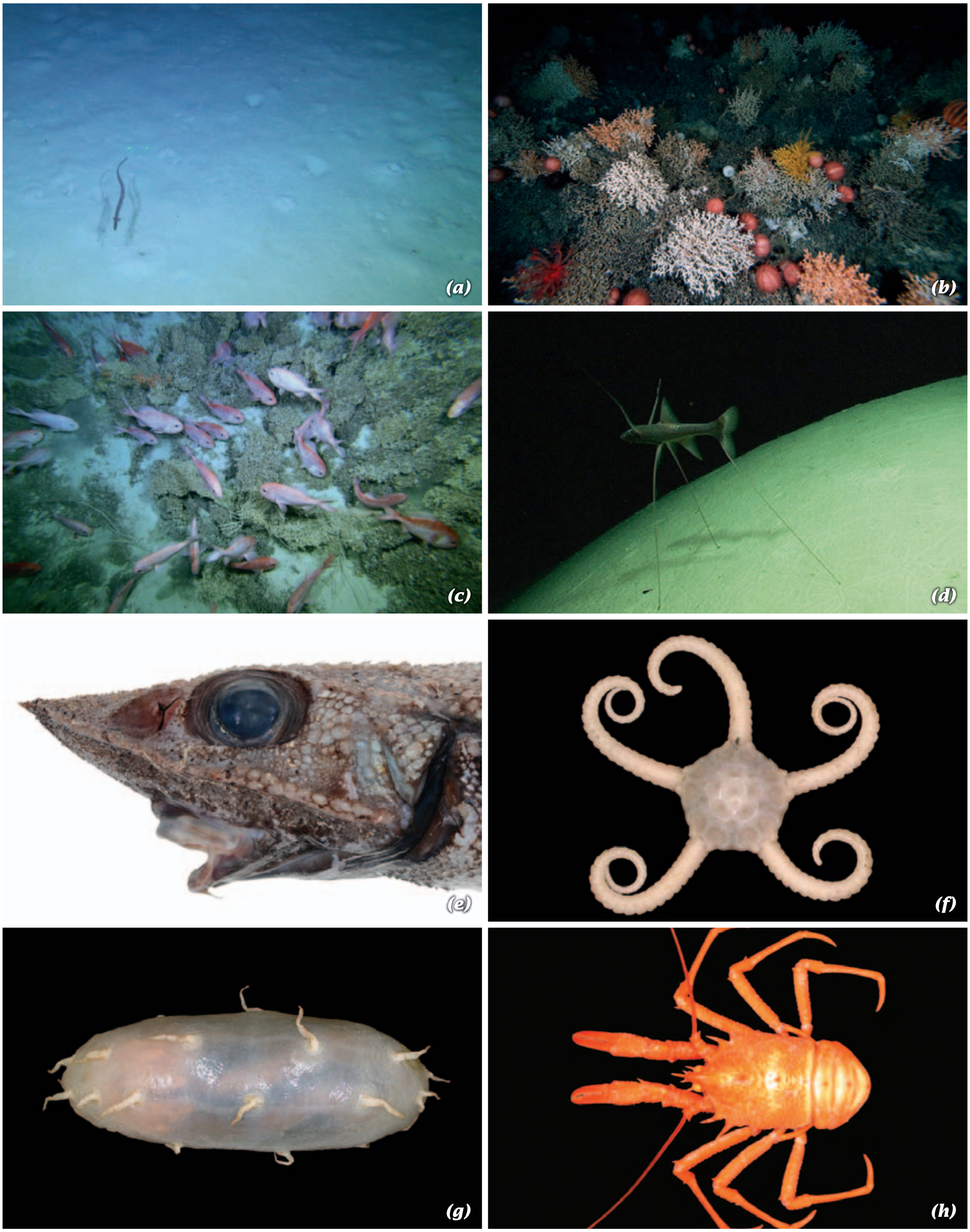
Animals live in total darkness beyond ~1000 m depth, at extreme pressure, with relatively low oxygen levels, and at temperatures of less than 4ºC. No plants live at these depths. Food arrives at the seabed mainly as sinking particulate matter (detritus) composed of bodies and fragments of dead animals and faecal material from the water column above. There typically is an exponential decrease in animal biomass with increasing ocean depth and most biomass in the offshore ocean is in the water column rather than on the seabed.



Australia's continental shelf provides habitats for many familiar marine species: ***(a)*** *sponges on a reef at 100 m depth;* ***(b)*** *southern sand flathead;* ***(c)*** *western king prawn;* ***(d)*** *southern rock lobster;* ***(e)*** *argonaut;* ***(f)*** *bastard trumpeter;* ***(g)*** *moon jellyfish;* ***(h)*** *Australian sea lion (Sources: reef image CSIRO; all other images Karen Gowlett-Holmes).*

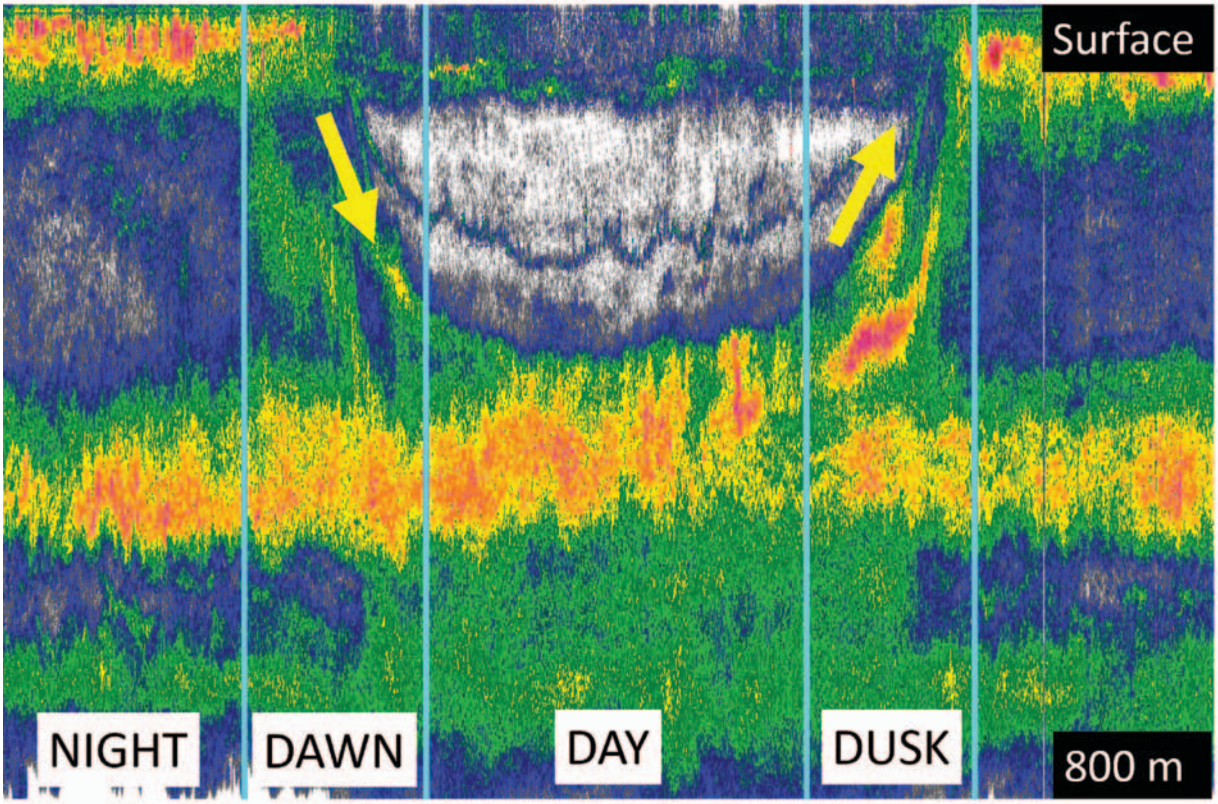


A great diversity of species is associated with coral reefs: ***(a)*** *reef composed of stony corals;* ***(b)*** *fan corals and fishes;* ***(c)*** *coral reef with feeding sea urchins at night;* ***(d)*** *sea anemone with anemonefish;* ***(e)*** *seastar on sponges;* ***(f)*** *tigerfish holothurian;* ***(g)*** *red-footed booby on a nest;* ***(h)*** *green turtle swimming above a coral reef (Sources: green turtle and reef slope vistas GBRMPA, Commonwealth of Australia; all other images Karen Gowlett-Holmes).*



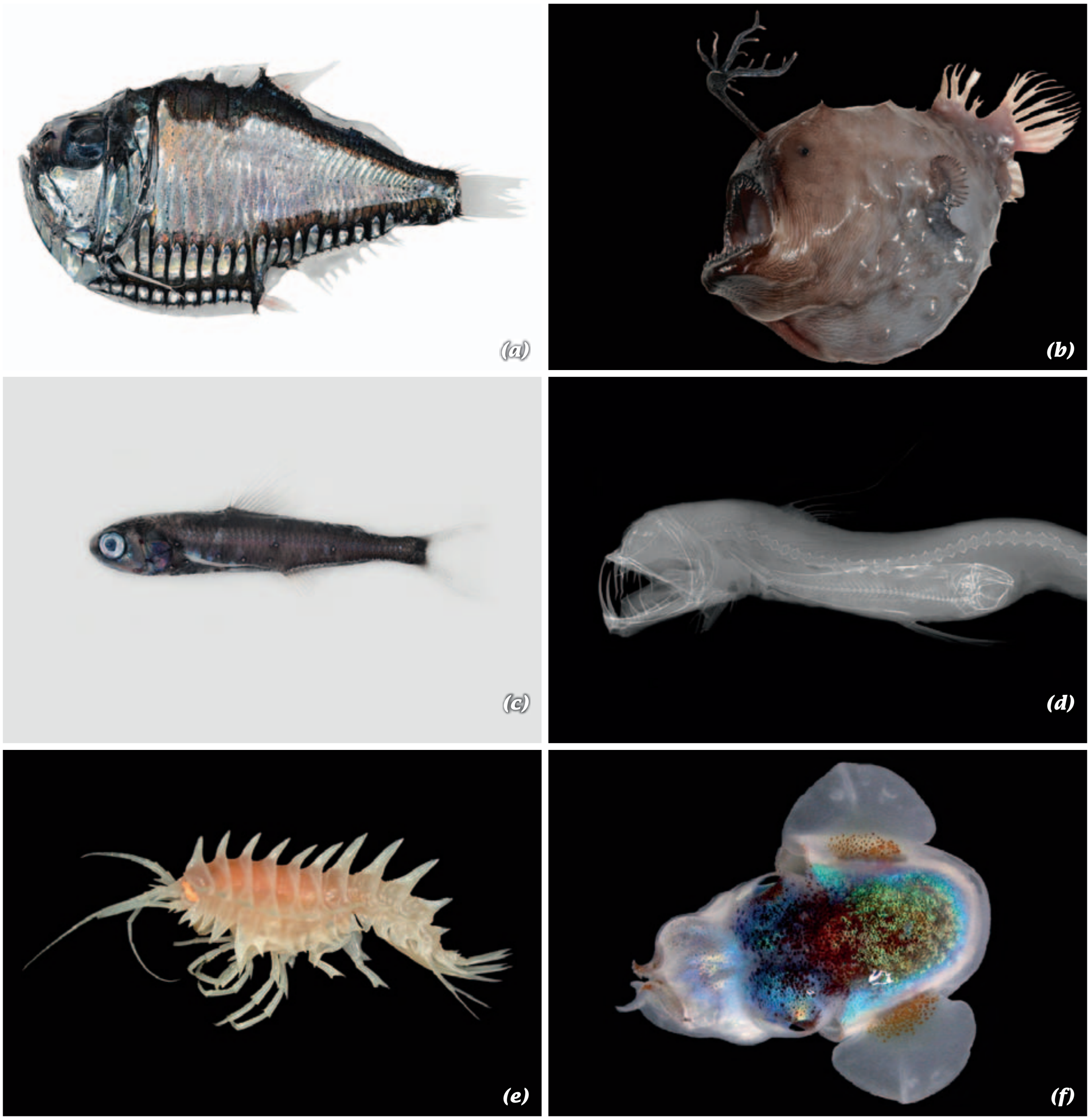
Views of the deep ocean seabed and its biodiversity: ***(a)*** *muddy seabed with an eel at 1600 m depth;* ***(b)*** *reef-forming stony coral with urchins and soft coral on a seamount at 1200 m depth;* ***(c)*** *a small school of orange roughy on a seamount targeted by commercial fishers at 950 m depth;* ***(d)*** *tripod fish;* ***(e)*** *head of a rat-tail fish;* ***(f)*** *brittlestar;* ***(g)*** *seapig holothurian;* ***(h)*** *squat lobster (Sources: a–c CSIRO; d–e National Fish Collection, CSIRO; f–h Karen Gowlett-Holmes, CSIRO).*

Many ocean inhabitants move up and down through the water column daily to either avoid predators or pursue prey. Nighttime ascent of large numbers of animals is seen by ships' echo-sounders and referred to as diel migration of the 'deep scattering layers' (Fig. 3.4); the majority are lanternfishes.



▲ ***Figure 3.4***: *A ship's echo-sounder records the twilight vertical migration (descending at dawn and ascending at dusk, yellow arrows) of a myriad of small organisms making up the 'deep scattering layers' in the upper 800 m of open ocean. The colour gradient from white to blue, green, yellow and red depicts increasing biomass (Source: CSIRO Bioacoustics Group).*

Animals living at great depth show many adaptations and specialisations for finding food, avoiding predators and communicating in near complete darkness. Adaptations of body form are most striking in fishes living in the deep water column, such as the anglerfishes, dragonfishes and their relatives, where lures for prey, large mouths, long teeth and highly distensible stomachs maximise the chances of encountering, capturing and digesting scarce prey.



Examples of biodiversity in the deep open ocean: ***(a)*** *hatchetfish showing large light organs;* ***(b)*** *anglerfish with lure on head;* ***(c)*** *lanternfish with small light organs;* ***(d)*** *dragonfish with large meal as shown by X-ray;* ***(e)*** *amphipod;* ***(f)*** *bottle-tail squid (Sources: a–d National Fish Collection, CSIRO; e–f Karen Gowlett-Holmes, CSIRO).*

Antarctic waters

Australia's Antarctic Territories contain a full range of coastal to deep ocean habitats, albeit in very cold waters (typically below 2ºC). Antarctic biodiversity includes many iconic bird species such as penguins and albatross and marine mammals including many species of whales and seals. The Antarctic krill (*Euphausia superba*) is a keystone species in the marine food web, with biomass measured in hundreds of million tonnes, which is food for many fish, bird and mammal species. Antarctic waters also support diverse benthic communities characterised by sponges, corals, seastars and brittlestars.

Examples of Antarctica's rich biodiversity: ***(a)*** *minke whales;* ***(b)*** *seabed invertebrates;* ***(c)*** *krill;* ***(d)*** *black-browed albatross;* ***(e)*** *elephant seals;* ***(f)*** *king penguins (Sources: a Frederique Oliver, Australian Antarctic Division (AAD); b Cooperative East Antarctic Marine Census Project 2007–09, AAD; c Rob King, AAD; d James Doube, AAD; e Karen Gowlett-Holmes; f Barend Becker).*

HUMAN PRESSURES ON BIODIVERSITY

Human pressures including pollution, climate change and acidification, exploitation, invasive species, and habitat loss are affecting marine communities. Human pressures vary around the Australian and Antarctic coastlines, depending on population densities and locations of industries and land uses, but some pressures, such as ocean acidification and pollution, have effects throughout the ocean over long timescales. Many marine species will adapt to new pressures but some species might not be able to adapt rapidly enough for local survival. Species inhabiting the continental shelf off southern Australia, for example, will have fewer options to respond to warming oceans, such as by range extension, because they already are at the edge of the available habitat or environmental conditions they require. Understanding the nature and amount of both natural and human-induced changes in Australia's marine biodiversity is key to deciding how to conserve and use biodiversity appropriately now and in the future, and to measure the effects of management interventions and changing environment. The quantitative, nationally consistent and long-term monitoring programs and infrastructure required to underpin such understanding are being designed and implemented by the Australian Government, for example through the Integrated Marine Observing System (IMOS) and Marine National Facility new research vessel *Investigator*.

(a) *Australia's new research vessel* Investigator *has enhanced Australia's capacity to understand its marine biodiversity.* ***(b)*** *Biodiversity sampling equipment on the vessel's back deck (Source: CSIRO, Stewart Wilde).*

CONCLUSION

Australia’s marine biological communities are dynamic over a range of timescales that reflect adaptations to the geological past over millions of years and responses to modern day environments. Multi-scale spatial patterns in species and habitats have been mapped to define ‘bioregions’ for management purposes. Increased knowledge and measurement of changes in the distributions of marine species and structure of marine communities are part of Australia’s strategy for managing its biodiversity into the future.

FURTHER READING

Australia’s Antarctic biodiversity: The Biogeographic Atlas of the Southern Ocean, <http://atlas.biodiversity.aq/index.html>.

Australia’s Integrated Marine Observing System (IMOS), <http://imos.org.au/about.html>.

Australia’s marine biodiversity: conservation, management and marine reserves, <http://www.environment.gov.au/marine>.

Biodiversity on the Great Barrier Reef, <http://www.gbrmpa.gov.au/about-the-reef/biodiversity>.

CHAPTER 4.

Geology beneath our oceans

Joanna M Parr and Andrew Ross

Key messages

- ✻ Australia sits within a single tectonic plate and the seafloor of Australia's marine estate is characterised by several large sedimentary basins with rich geological history related to the evolution of the Australian continent.
- ✻ Australia's seafloor contains a variety of geological resources including oil, gas and coal, sands, gravels and shell-sands, and minerals such as rutile, ilmenite, zircon, gold and tin.
- ✻ Several of Australia's offshore sedimentary basins have been producing oil or natural gas since the 1960s but many remain under-explored.
- ✻ Various mineral deposits of commercial potential also occur within Australia's marine estate but there has been relatively little development of them to date and there is only a low level of currently active seabed mining.
- ✻ There are no known active hydrothermal vents or seafloor volcanoes within Australia's marine estate, though some are likely to exist near Heard Island in the Southern Ocean.

INTRODUCTION

Knowledge of current seafloor geology is important to assist bioregional marine planning, where geomorphological features and sediment type can provide proxies for communities of seabed plants and animals. Seafloor features also can focus oceanographic phenomena, such as upwellings associated with deep water canyons. The sediments accumulated on the seafloor over millennia reveal how marine sedimentary basins formed, how the sediments that fill them were transported or deposited, and where they originated. Knowledge of how these sedimentary basins filled, combined with their internal architectures, can be used to determine resource potential, paleoclimate, paleogeography, and the tectonic evolution that has shaped Australia and its marine estate.

Oil and gas resources were identified within Australia's offshore sedimentary basins during the 1960s. Exploration, drilling and production of oil and gas since then has occurred in Bass Strait, followed by offshore north-west Australia. There also are several large under-explored 'frontier basins' (Table 4.1) around Australia that might contain as yet undiscovered hydrocarbon deposits. A marine mineral resource industry also may have growing importance for Australia as (1) technological advances enable more detailed geological exploration and mining of the seafloor, and (2) terrestrial mineral resources, including building sands and gravels, become harder to find and extract.

Table 4.1: Offshore sedimentary basins currently producing oil and gas or under investigation for hydrocarbon potential (the 'frontier basins'). *See also Fig. 4.2.*

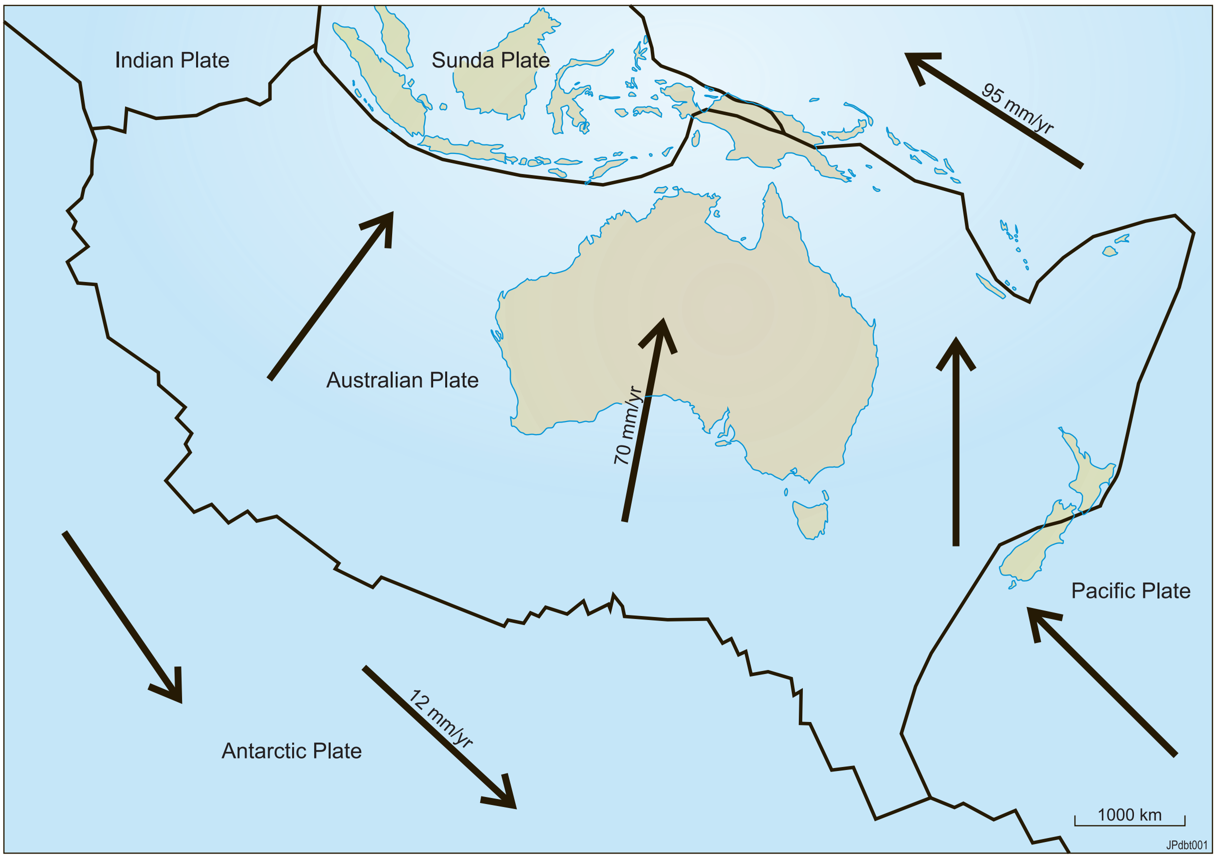
Offshore basin	Age	Status (exploration and production)
Producing offshore basins		
Bass Basin	Mesozoic to Cenozoic[a]	First offshore hydrocarbon producing region; moderate production
Gippsland Basin		Previously major production; in decline
Otway Basin		Small basin, limited production and exploration
Northern Margin Basins (Carnarvon, Bonaparte and Browse basins)	Paleozoic to Mesozoic[b]	Active exploration. High production, ongoing development
Frontier offshore basins		
Sorell Basin	Mesozoic to Cenozoic	Unexplored
Bight Basin (Ceduna Sub-Basin, Eyre Sub-Basin, Recherche Sub-Basin)		Multiple sub-basins with variable prospectivity; region being actively explored
Eastern Margin Basins (Capel Basin, Faust Basin)		Little exploration
Mentelle Basin and Naturaliste Plateau	Paleozoic to Mesozoic	Unexplored
Perth Basin		Limited exploration; recently renewed interest
Roebuck Basin		High exploration interest; largest oil field discovery in Australia in past decade
Arafura Basin	Neo-Proterozoic to Paleozoic[c]	Little exploration

[a] 250 million years to present; [b] 540–250 million years ago; [c] 1000–540 million years ago.

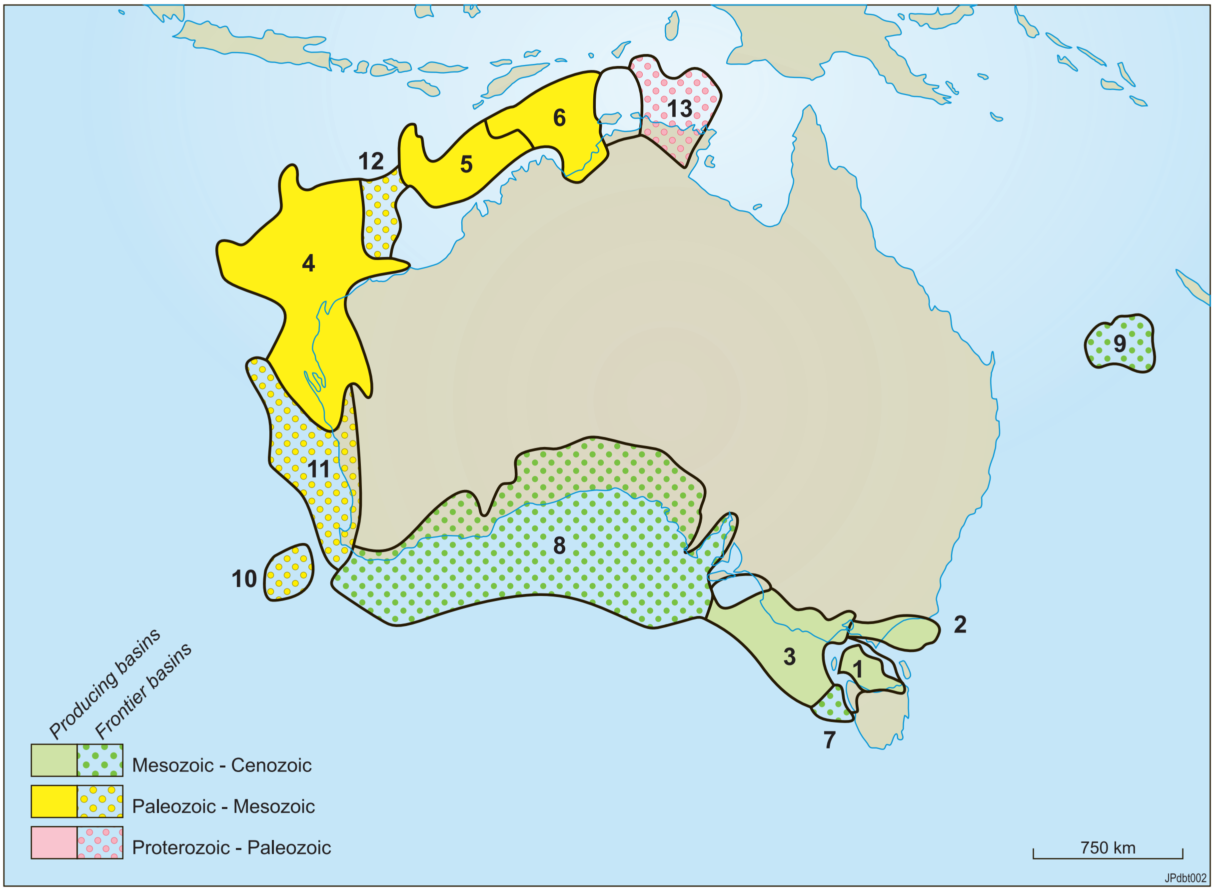
GEOLOGY OF AUSTRALIA'S MARINE ESTATE

Australia forms part of the Australasian tectonic plate (Fig. 4.1) that is moving northwards at ~70 mm/year. The Australasian plate is separating from the Antarctic plate to the south, while colliding with the Eurasian and Pacific Plates to the north and colliding obliquely with the Pacific Plate to the east and south-east (Fig. 4.1). The plate movements have led to variable stresses building up in the Earth's crust, most easily observed to the north of Australia as earthquake and volcanic activity along the Java–Sumatra arc. There was significant volcanic activity around Australia's margins in the geological past, reflected by the remnants of extinct volcanoes in the Great Australia Bight, on the North West Shelf and along the Lord Howe Rise.

The geology of Australia's continental shelf is connected intimately with Australia's terrestrial geology because rock units commonly extend out to sea beneath more recent shoreline sediments. The continental shelf is dominated by large, long-lived sedimentary basins (Fig. 4.2) formed in response to the gradual breakup of the supercontinent Gondwana during the Mesozoic period from 160–65 million years ago. These basins formed foci for sedimentation around the margins of the new Australian continent in which large volumes and depths of sediment accumulated over millions of years, trapping abundant organic matter – the precursor to oil and gas.



▲ **Figure 4.1**: *The Australasian tectonic plate. Arrows show movement of the plates relative to each other, with numbers indicating velocities (millimetres per year) calculated using GPS stations (Source: J. Parr, CSIRO).*



▲ ***Figure 4.2**: Offshore sedimentary basins around Australia that have produced hydrocarbons (solid shading) or are highly prospective for hydrocarbons (stippled shading). (1) Bass Basin; (2) Gippsland Basin; (3) Otway Basin; (4) Carnarvon Basin; (5) Browse Basin; (6) Bonaparte Basin; (7) Sorrel Basin; (8) Bight Basin; (9) Capel-Faust Basins; (10) Mentelle Basin; (11) Perth Basin; (12) Roebuck Basin; (13) Arafura Basin (Source: J. Parr, CSIRO).*

The modern geomorphology of Australia's continental shelf reflects more recent geological processes, primarily since the last ice age that ended around 12 000 years ago. Key features include remnants of ice-age coastlines, from when sea level was over 130 m lower than today, and deeply eroded rift valleys that form canyons up to 1500 m deep across the continental shelf (e.g. the Perth Canyon). The gently sloping continental shelf is largely covered in unconsolidated sediments (muds, oozes, silts and gravels) deposited in river estuaries and then transported offshore and along the coast by wind-driven currents and waves. A good example is the transport of sands northwards from offshore southern New South Wales to Fraser Island in Queensland. Beyond the continental shelf is a steep continental slope that plunges from ~200 m depth to the abyssal plain 4000–5000 m below the open ocean.

EXPLORATION

Australia's territorial waters have been explored since Matthew Flinders' first survey in 1810, but still relatively little is known about the detailed geology and resource potential of much of Australia's extensive marine estate.

Geoscience Australia has completed many marine surveys mapping the geology of Australia's marine estate. A range of techniques (Table 4.2) is used to generate maps of the seafloor, determine the sub-seafloor structure, or do more focussed studies of specific geological features that can be used in pre-competitive analysis of resource potential or habitat structure for oil and gas exploration.

The multi-nation International Ocean Discovery Program (IODP) and its precursor ocean drilling programs (ODP and DSDP) are major international research programs that have increased significantly our knowledge of the deeper seafloor geology in our region. There have been multiple expeditions in our region, including: drilling on the North West Shelf of Australia to understand the variability of ocean currents and their impact on climate through geological history; drilling offshore Antarctica to understand the development of glacial ecosystems; and drilling in the Bismarck Sea to investigate an actively forming mineral deposit related to seafloor volcanic activity.

Many commercial geological surveys also have occurred, either as near-shore studies for infrastructure development (e.g. channel dredging, cable or pipe laying, port construction) or offshore surveys to determine sub-seafloor geology related to potential oil and gas reservoirs.

The IODP (http://iodp.org/index.php) research vessel Joides Resolution *is 143 m long with a drilling derrick reaching 62 m above the water line. Drilling in water depths up to 6 km, it can reach >2 km into the Earth's crust (Source: R. Arculus, IODP-ANZIC).*

Table 4.2: Some techniques used to map the geology and explore for resources on or below the seafloor

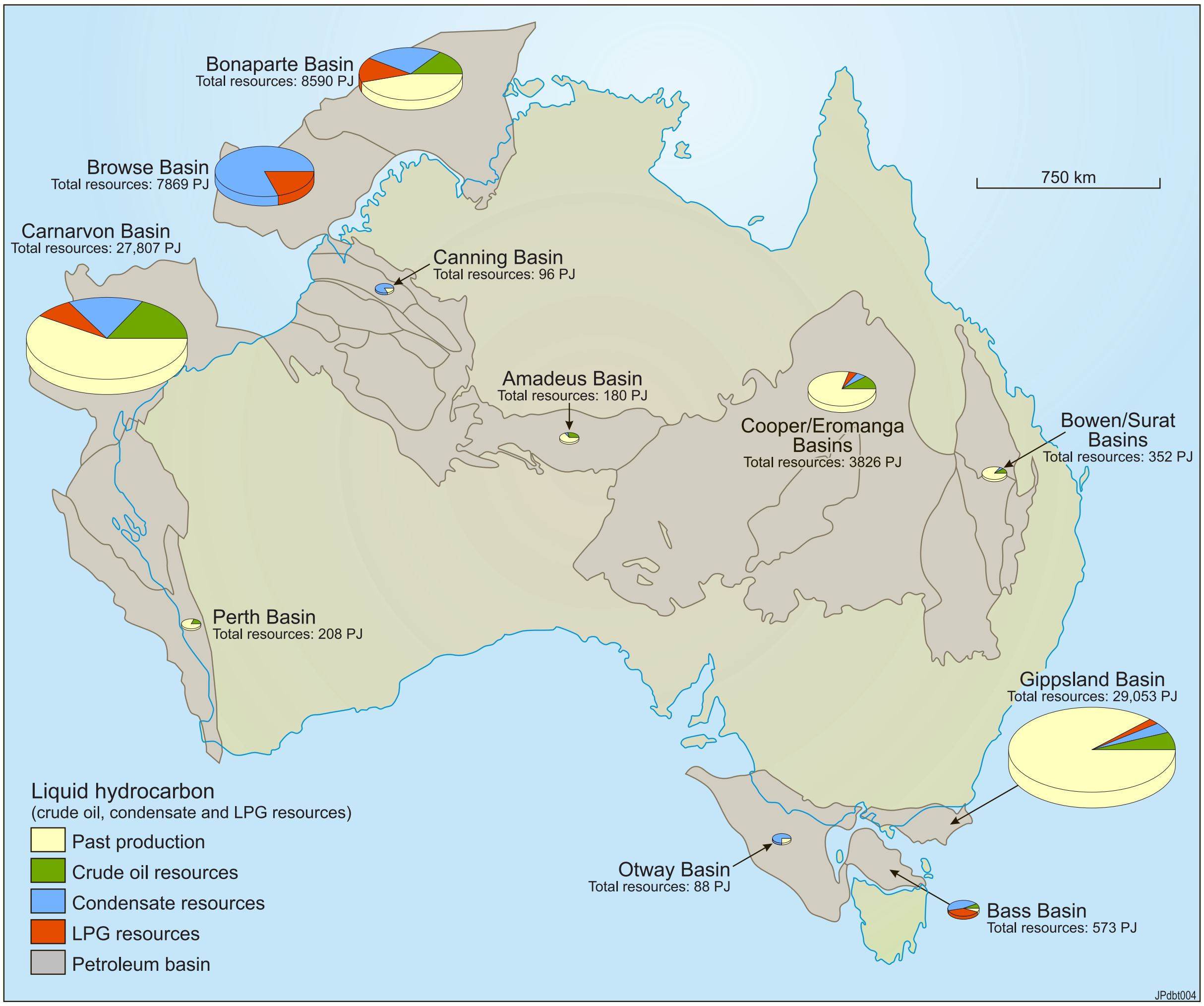
Approach	Technology	Outputs
Bathymetric surveys	Acoustic mapping	Reflected beams of sound (single beam or multibeams, side scan sonar) measure distance to, and reflectivity of, the seafloor below the ship and build seafloor topographic and physical property maps (Fig. 4.3a)
Direct observation	Automated underwater vehicles (AUVs) and remotely operated vehicles (ROVs)	Direct measurements on the seafloor, video observations, and sample collection
Remote sensing and water column observations	Synthetic aperture radar (SAR) remote sensing, in-water acoustic sensing and chemical-physical property sensors	Identifies physical-chemical irregularities in the water column above 'leaky' spots in the seafloor emitting hydrocarbons or hot water and gases
Sampling	Dredging (Fig. 4.3b), shallow coring	Samples rocks and sediments from the seafloor
Geophysical techniques	Seismic exploration (reflection 2D, 3D)	Identifies subsurface structures using reflected energy waves, usually generated as a series of sound pulses from air compressors
	Magnetometry	Measures variations in magnetic properties of subsurface rocks to help identify different rock types
Drilling	Shallow (<10 m deep) using platforms on the seafloor	Preliminary exploration in shallow areas and ground-truthing remote methods
	Deep (kilometres deep) using specialised drill ships or rigs	Exploration of deep geology of the ocean crust to investigate the geology of the ocean crust and delineate oil fields (Fig. 4.3c)

▲ ***Figure 4.3**: **(a)** Bathymetric maps of the seafloor are made by measuring the time taken for sound pulses to travel from a ship's hull to the seafloor and back. Greater accuracy is achieved by using many narrow sound beams spread across an array. This image shows the RV* Southern Surveyor *from the Marine National Facility, CSIRO, using EM300 multibeam to survey paleochannels on the Great Barrier Reef shelf. **(b)** Rock dredges for scientific surveys are dragged along the seafloor to break fragments off outcrops and collect rocky material. **(c)** Scientists examine a drill core on board a research vessel. Cores often are split in half to examine internal structures and mineralogy (Sources: a R Beaman, James Cook University; b CSIRO; c Simon George).*

ENERGY RESOURCES

Australia's offshore sedimentary basins (Fig. 4.2) contain ~2% of world gas reserves and accounted for 8% of world liquid natural gas (LNG) trade in 2011. Australia's total known oil resources in 2012 were estimated at 20 664 petajoules (PJ) or 3376 million barrels of oil equivalent, made up of 55% condensate, 26% crude oil and 19% liquefied petroleum gas (LPG) (Fig. 4.4). Condensate is the portion of hydrocarbon resource that exists as a gas in the subsurface reservoir but condenses to a light oil on extraction due to the decrease in pressure and temperature. Crude oil occurs as liquid in the reservoir and after extraction. LPG is gas extracted from petroleum or natural gas streams as they emerge from the ground.

Australia's first oil fields were identified in the early 1960s in the Gippsland and Bass basins. Additional major oil fields have been developed on the North West Shelf, and in the Carnarvon and Bonaparte basins. The Carnarvon, Bonaparte and Browse basins contain around 92% of Australia's known conventional gas resources. Reserves from the Gippsland and Otway basins are now



▲ ***Figure 4.4***: *Australia's major offshore oil and gas fields and their production. PJ = petajoules = 1015 J, 1PJ equivalent to ~50 megatons of TNT (Sources: data Geoscience Australia and BREE, 2014; map J. Parr, CSIRO).*

nearly exhausted and the now water-saturated reservoirs are being assessed as potential storage containers for geosequestration of anthropogenic carbon dioxide.

The search for oil and gas offshore more recently has focussed on ‘frontier basins’ (Fig. 4.2, Table 4.1) with approval of new exploration access coupled with seismic surveys and preliminary exploration drilling.

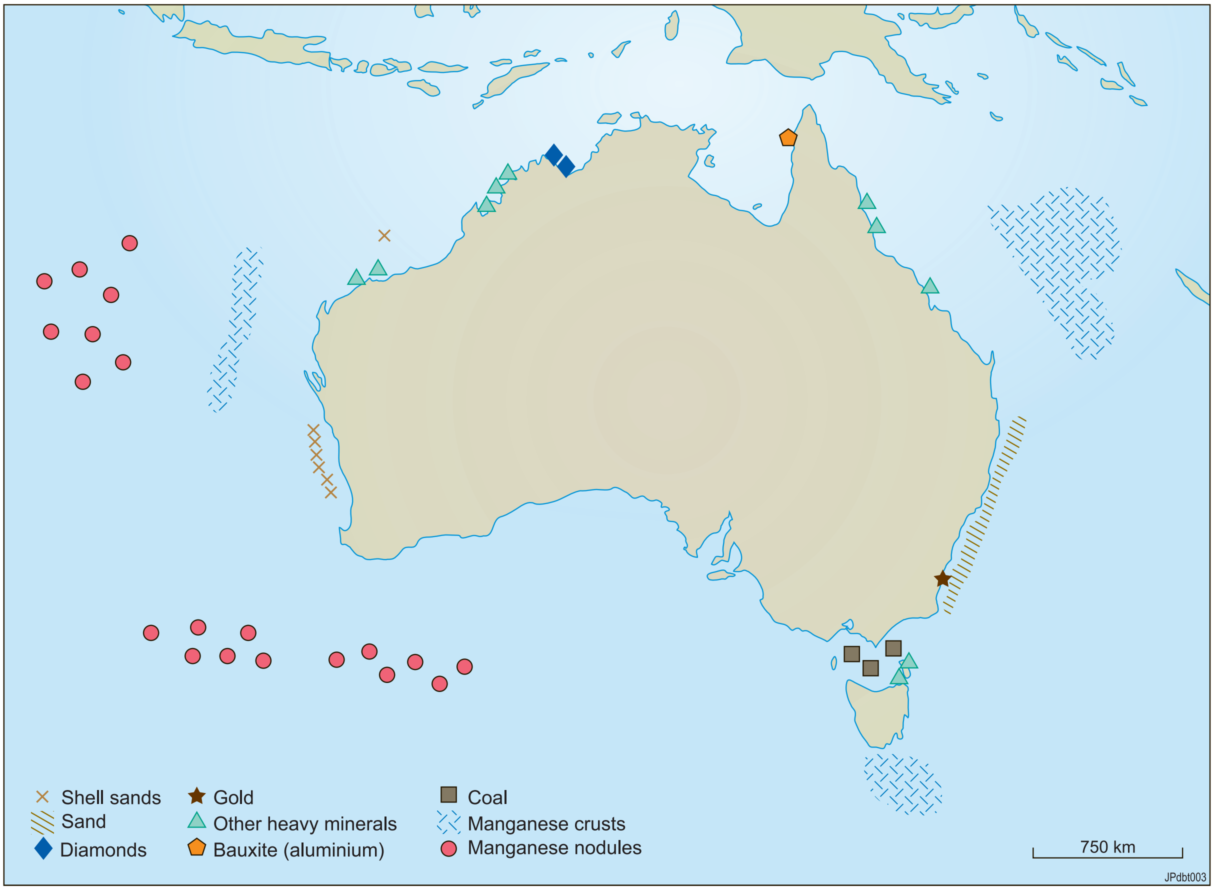
Harriet A Platform drilling for oil north of Barrow Island in the Carnarvon Basin. Waste gas is being burnt off as a flare (Source: CSIRO).

MINERAL POTENTIAL

The concept of sustainably exploiting seafloor mineral resources is not established yet in Australia but is well established internationally, with major marine sand mining operations in Europe, the USA and Japan. Approximately 21% of the sand and gravel aggregate requirement in the UK, for example, is met from marine sources. Drivers for developing marine mineral extraction include decreases in discoveries of high-grade, accessible deposits on land, particularly for construction materials such as bulk sands and gravels. Any development of marine mineral mining activities, like all other resource extractions, needs clear policy and regulatory guidelines to ensure that such activities do not compromise the surrounding marine or nearshore environments or adversely affect coastal communities.

A variety of mineral resources occur in Australia’s territorial waters (Fig. 4.5) and there is potential for developing some near-shore operations. No significant base metal or precious metal deposits have been identified in Australia’s deeper marine environment to date. Australia’s marine estate does not include active volcanoes, except possibly on the seafloor around Heard and McDonald Islands in the Southern Ocean, so there is low likelihood of finding active hot water (hydrothermal) vents rich in base and precious metals, such as those discovered off Papua New Guinea and Tonga. There is some potential for finding ancient, inactive deposits buried by seafloor sediments or along now inactive volcanic arcs and ridges, such as the Lord Howe Rise. Identifying such deposits is a major challenge in very deep water, although new geophysical instruments mean this could be possible in the next decade.

Dredging sand and gravels from offshore deposits in United Kingdom coastal waters (Source: British Marine Aggregate Producers Association).



▲ **Figure 4.5**: *The distribution of known mineral deposits on the seafloor around Australia. Many deposits, in particular manganese nodules and crusts, occur as dispersed fields on the seafloor without well-defined boundaries (Sources: data Geoscience Australia, 2006; map J. Parr, CSIRO).*

Iron and manganese oxides encrust a boulder recovered from the seafloor (Source: Evelyn Mervine).

The potential also exists for ore deposits linked to the movement of fluids through the seafloor. Models for lead–zinc deposits formed by flow of metal-charged groundwater through geological reservoirs (similar to deposits found in the Northern Territory and Mississippi Valley), for example, suggest that sedimentary rocks of the Great Australian Bight could host this type of deposit. That prospect was tested, but not proven, by a CSIRO-led research expedition in 2001.

CONCLUSION

Australia's vast seafloor territory has a wide range of geological features that host a variety of geological resources, including hydrocarbons, heavy minerals and metalliferous deposits. We do not have a clear understanding, however, of either its geological potential or environmental vulnerability. There is growing public debate about the merits of offshore exploration and mining, particularly as pressure grows to discover and exploit new energy and mineral resources and major oil fields are established in increasingly deep and remote waters. Considerable work remains to be done to provide key geological information, such as resource characteristics, depth and size, as well as baseline environmental knowledge, including impact studies, for both petroleum and mineral extraction industries.

FURTHER READING

Blewett RS (Ed.) (2012) *Shaping a Nation: A Geology of Australia*. Geoscience Australia and ANU E Press, Canberra.

Geoscience Australia and BREE (2014) *Australian Energy Resource Assessment*. 2nd edn. Geoscience Australia, Canberra.

Geoscience Australia and Commonwealth Scientific and Industrial Research Organisation (2006) *Australian Offshore Mineral Locations Map, August*. Geoscience Australia, Canberra, <http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_64757>.

Northern Territory Environmental Protection Authority (2012) *Interim Report: Seabed Mining in the Northern Territory*, NTEPA, Darwin, <http://www.ntepa.nt.gov.au/__data/assets/pdf_file/0003/144039/Seabed-Mining-Report.pdf>.

Totterdell JM, Hall L, Hashimoto T, Owen K, Bradshaw MT (2014) *Petroleum Geology Inventory of Australia's Offshore Frontier Basins. Record 2014/09*. Geoscience Australia, Canberra. doi:10.11636/Record.2014.009

CHAPTER 5.

The oceans and our climate

John Church, Wenju Cai, Guojian Wang and Andrew Lenton

Key messages

- The oceans are a major influence on global and Australian climate.
- The oceans currently store over 93% of increased heat accumulating in the Earth's climate system.
- Warming oceans and loss of mass from glaciers and ice sheets are causing sea level to rise.
- Ocean acidification is an inevitable consequence of rising atmospheric carbon dioxide.
- Ocean warming and acidification have significant negative implications for marine environments and ecosystem services.

INTRODUCTION

Australia is a land of weather extremes. Climate variability and change have significant economic, environmental and social effects. Australia lies in the ocean-dominated southern hemisphere and is surrounded on all sides by large oceans that, in concert with the atmosphere, determine Australia's climate.

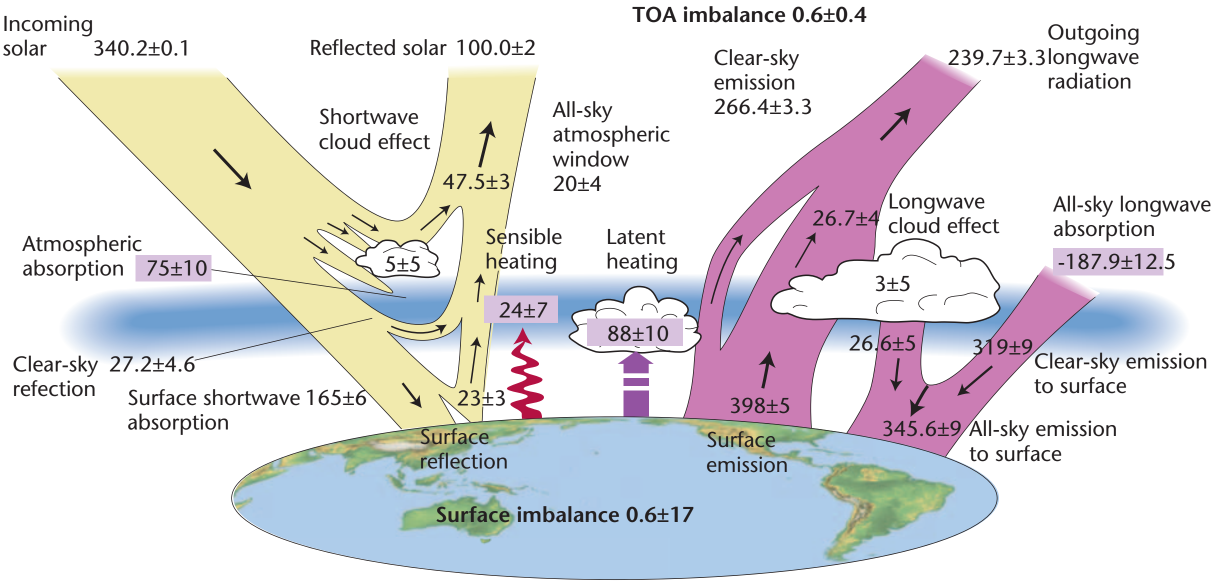
Agricultural and ocean production and the welfare of country and coastal communities are linked to climate variability directly, and are vulnerable to climate change. Coastal regions are subject to dangers from cyclones, storm surges and coastal inundation, erosion and ocean acidification. Cities and urban populations also are affected: drought, bushfires, flood, storm and cyclone damage all affect urban environments as well as rural and coastal areas. Severe water shortages in some major cities have resulted in development of desalination plants to supplement natural water supplies.

We describe the major roles of the oceans in the climate system and climate variability and change, and the effects of climate change on sea-level rise and ocean acidification.

THE OCEANS' ROLE IN CLIMATE AND CLIMATE CHANGE

The oceans' central role in climate is the exchange of heat and carbon with the atmosphere, especially the ability to store vast amounts of heat and transport it thousands of kilometres (see Chapter 2) before releasing it to the atmosphere. Oceans also are sources of much of the water falling as rain or snow in Australia and they absorb excess carbon dioxide (CO_2) from the atmosphere, thereby being key to moderating atmospheric CO_2 levels.

The climate system is fuelled by radiation from the Sun (Fig. 5.1). About 30% of solar radiation is reflected back to space by clouds and the Earth's surface, with the remainder absorbed at the Earth's surface, 70% of which is oceans. The atmosphere is then warmed from below by evaporation and long-wave radiation from the Earth's surface. Some of this long-wave radiation is absorbed by clouds and greenhouse gases in the atmosphere, which then re-emit radiation both back towards the surface and upwards to space. Increasing greenhouse gas concentrations increases the downward re-emission of long-wave radiation, resulting in global warming.



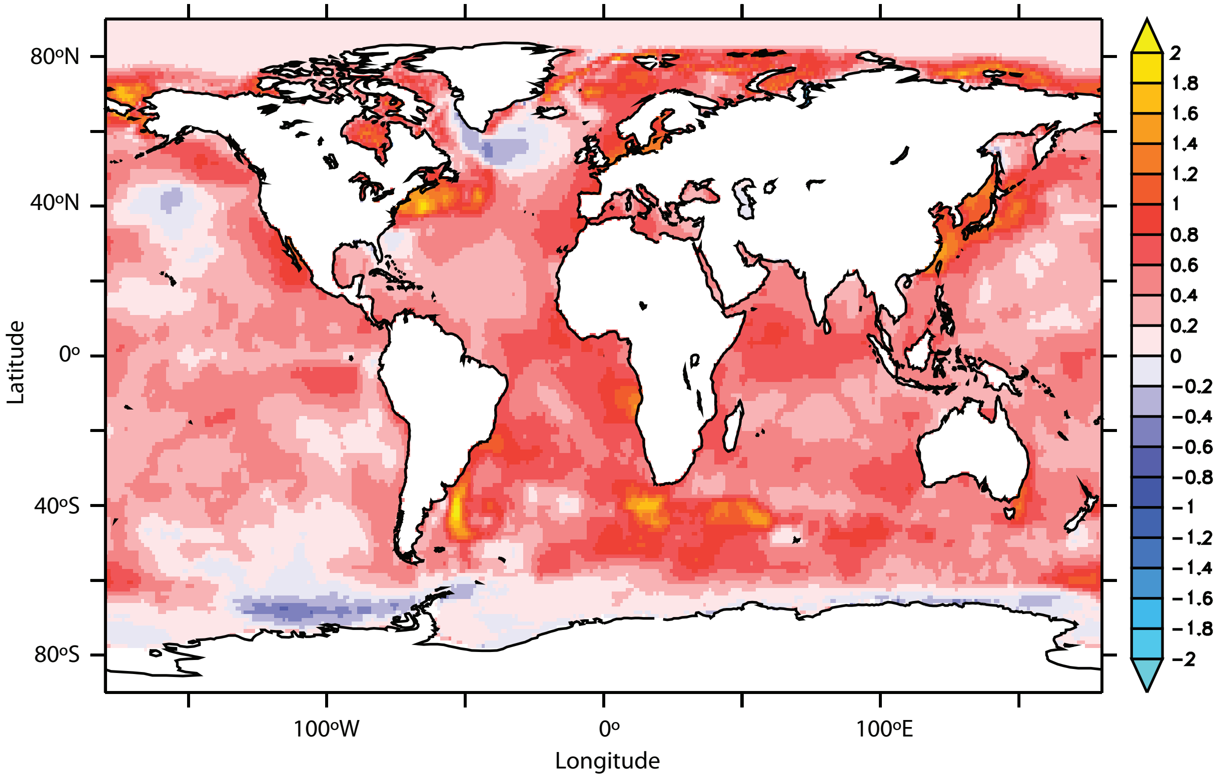
▲ ***Figure 5.1**: The annual energy balance of the Earth with amounts shown in average Watts/m^2 for 2000–2010. Solar fluxes are in yellow and infrared in pink. Numbers with purple background are the main components of atmospheric energy balance (Source: Stephens* et al. *2012[1]).*

Ocean warming

The oceans have a huge capacity to store heat and carbon. The amount of heat required to warm just the upper 3 m of the oceans by 1°C would warm the entire atmosphere by the same amount.

Burning fossil fuels, land clearing and our agricultural and industrial activities release greenhouse gases into the atmosphere, the most important being CO_2. The resulting increase in atmospheric greenhouse gases is warming the Earth. The ocean surface has warmed by 0.11°C per decade from 1971 to 2010.[2]

Ocean warming is uneven (Fig. 5.2) with some regions showing slight cooling and others showing considerable warming. Ocean warming around Australia is greater than the global average and has led to significant changes in marine environments, including southward shifts of tropical fish along the east and west coasts, loss of species in some regions, coral bleaching and reduced coral growth in the Great Barrier Reef and Ningaloo.



▲ ***Figure 5.2***: *Change in sea-surface temperature (°C) since the pre-industrial period based on the Hadley Centre's sea-surface temperature reconstruction (Source: Lenton* et al. *2016,[3] CC BY 3.0).*

Ocean warming penetrates into the deep oceans and affects ocean circulation. The Earth has absorbed a vast amount of heat since 1970, equivalent to that released by ~4 Hiroshima atomic bombs per second. More than 93% of this energy is stored in the oceans, with most of the remainder melting ice and warming land, and less than 1% warming the atmosphere (Fig. 5.3).

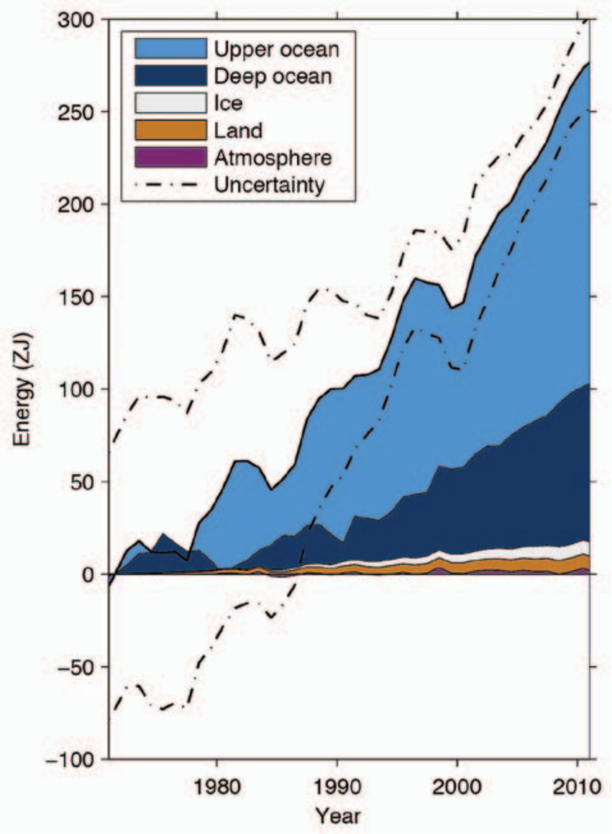
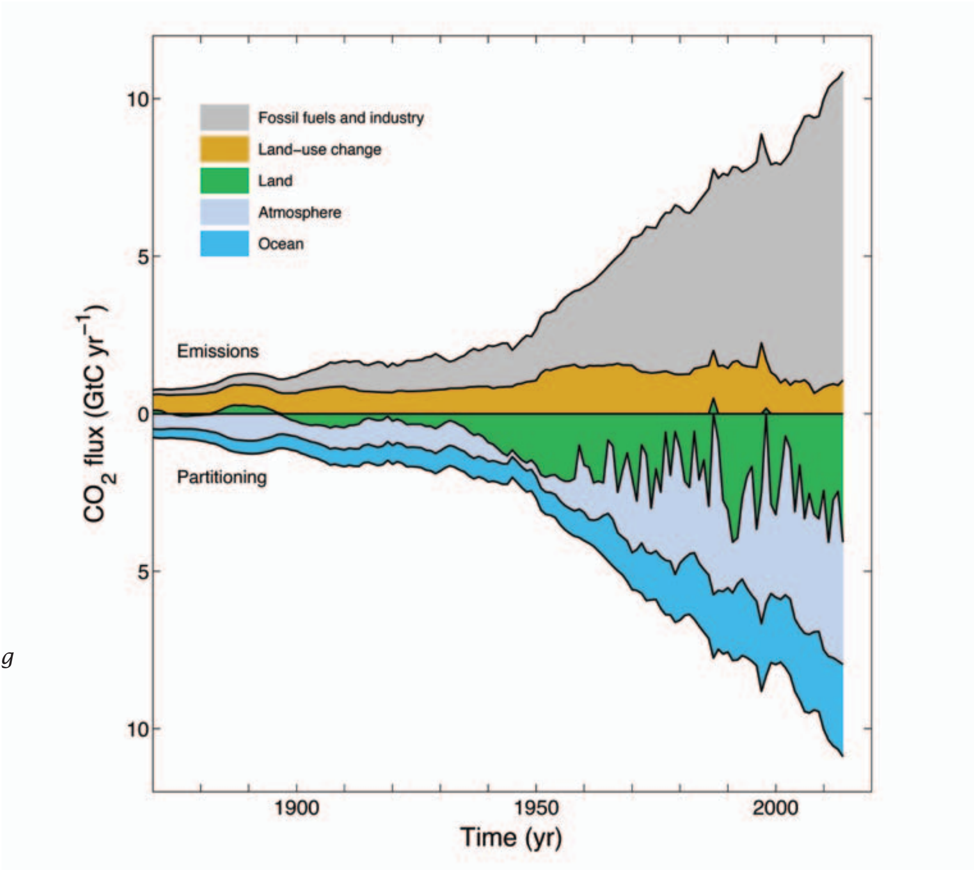


Figure 5.3: *Heat storage in the Earth's climate system. Most heat goes to warming the oceans, with smaller amounts to melting ice and warming the land and atmosphere (Source: from* IPCC Assessment Report 5, Working Group 1*, Box 3.1, Fig. 1*[2]*).*

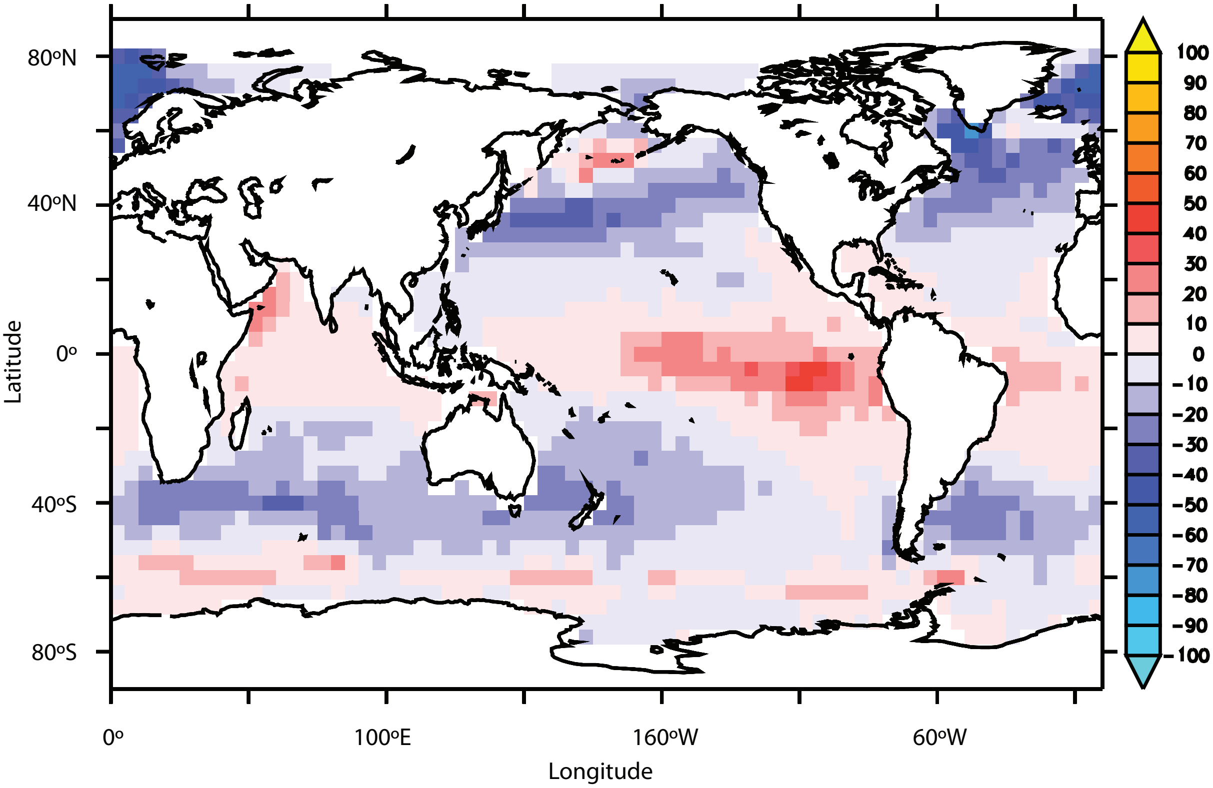
Ocean carbon storage

Atmospheric concentrations of CO_2 were around 280 parts per million (ppm) before the industrial revolution. Atmospheric CO_2 levels have risen since – due to burning of fossil fuels, cement production and land use change – to around 400 ppm in 2015. The concentration would be much higher if it were not for the land and oceans together (roughly equally) taking up ~50% of humanity's annual emissions (Fig. 5.4). Thus the oceans are key in slowing climate change.

Air–sea exchanges of CO_2 (Fig. 5.5) are driven by natural processes and tend to balance over long periods. Atmospheric emissions of CO_2 from human activities, however, have generated an imbalance resulting in increasing amounts of CO_2 being absorbed into the oceans. Continued emissions will drive further increases in ocean CO_2 concentrations. The largest amount of carbon taken up by the oceans is stored in the Southern Ocean between latitudes of ~30ºS to 50ºS, and in the North Atlantic Ocean. Oceans will continue to slow increases in atmospheric CO_2 if we continue burning fossil fuels, but it is unclear by how much, or for how long, oceans can continue mediating atmospheric CO_2 accumulation.



▸ ***Figure 5.4***: *Carbon fluxes (gigatonnes/year) since the pre-industrial period showing sources (positive) and sinks (negative) (Source: after LeQuéré* et al. *2015,*[4] *CC BY 3.0).*



▴ ***Figure 5.5***: *Sea–air CO_2 exchange (grams of carbon per m^2 per year) for the year 2000. Negative values (purple-blue) indicate net uptake into the oceans from the atmosphere and positive values (yellow-red) indicate net release from the oceans (Source: data from Park* et al. *2010,*[5] *CC BY 3.0).*

Ocean transport of heat

Oceans transport heat around the globe. The Earth receives more energy from the Sun than it loses to space at low latitudes (the tropics), and vice versa at high latitudes (nearer the poles). The oceans and atmosphere transport heat from low latitudes to high latitudes to balance these processes. The southward flow of warm water in the East Australian Current and the Leeuwin Currents off the east and west coasts of Australia, respectively (Chapter 2), are examples of this poleward heat transport in the oceans. These heat transports affect sea-surface temperatures and thus regional weather and climate.

CLIMATE IN OUR REGION

Variations in ocean heat transport result in variations in climate over seasons to decades and centuries. East–west transport of heat in the tropical Pacific and Indian Oceans is important for Australian climate variability on seasonal to inter-annual periods. The Southern Ocean becomes increasingly influential on our climate over longer periods.

The best known climate pattern affecting Australia is the El Niño-Southern Oscillation (ENSO) of the tropical Pacific Ocean. A similar temperature oscillation occurs in the Indian Ocean, known as the Indian Ocean Dipole (IOD), with similarly powerful influences on Australian and regional climate.

The El Niño-Southern Oscillation (ENSO)

The Pacific Ocean is central to development of El Niño and La Niña events that alter global weather patterns, affecting ecosystems and agriculture worldwide. An El Niño state increases risk of droughts, heatwaves and bushfires in Australia and a La Niña can induce floods and tropical cyclones in our region.

El Niño conditions arise when easterly winds over the equatorial Pacific weaken and warm sea-surface temperatures move eastwards towards the Americas. These shifts take with them tropical rain-generating convection and result in drought conditions in western equatorial Pacific regions, including parts of Australia, and increased rainfall to eastern Pacific regions. La Niña conditions and increased rainfall over parts of Australia occur when easterly winds strengthen and warm Pacific Ocean surface waters return westwards towards Australia.

There is no consensus yet on how the overall ENSO frequency or strength might change over the 21st century, though recent modelling suggests extreme El Niños and La Niñas are likely to be more frequent with continued global warming.[6,7]

The Indian Ocean

El Niño events in the Pacific Ocean often are accompanied by cool sea-surface temperatures in the eastern equatorial Indian Ocean, warm sea-surface temperatures in the western Indian Ocean and increased easterly equatorial winds. This state is a positive Indian Ocean Dipole (pIOD) and generally results in droughts and bushfires in East Asia and Australia and floods in parts of the Indian subcontinent and East Africa. The pIOD also preconditions south-east Australia for summer bushfires, when seasonal rain is lowest. Examples include the Ash Wednesday (1982) and Black Saturday (2009) bushfires. Negative IODs (nIOD) are associated with increased rainfall in south-east Australia, particularly when nIODs coincide with La Niña events.

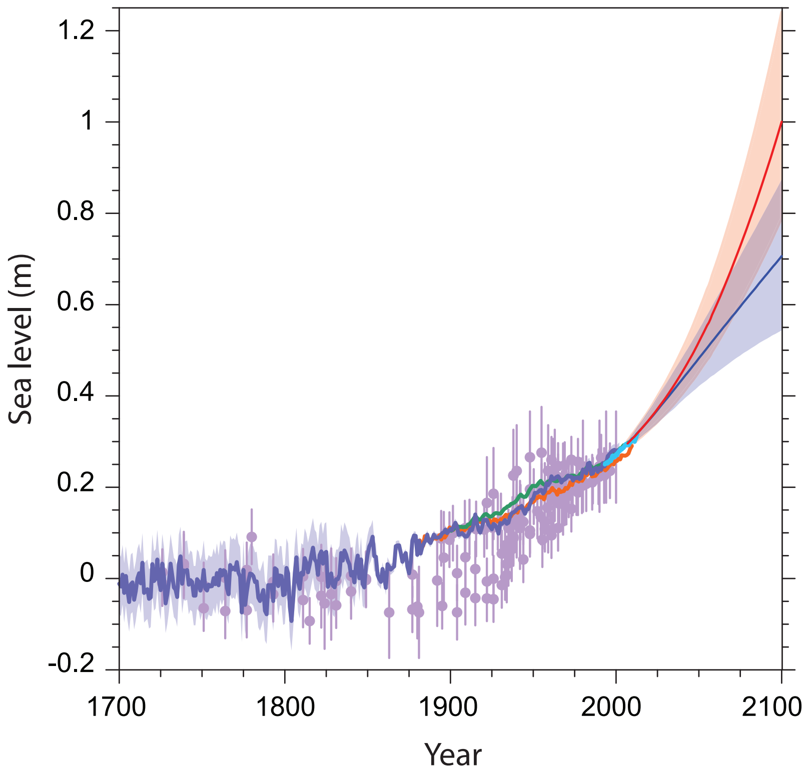
The Southern Ocean and Tasman Sea warming

The Southern Annular Mode (SAM) also affects Australia's climate. A positive SAM occurs when atmospheric pressure is higher than average in mid-latitudes and lower than average at high-latitudes (over the Southern Ocean), indicating a southerly shift of westerly weather systems and reduced rainfall in southern Australia. The SAM has been more positive since the 1970s in response to increasing CO_2 and depletion of Antarctic ozone, with associated long periods of low rainfall in southern Australia, especially in the south-west. Above average warming of the Tasman Sea is attributed partly to the persistent positive SAM. Models suggest the poleward shift in weather patterns will slow as the Antarctic ozone hole diminishes but will persist if global warming continues.

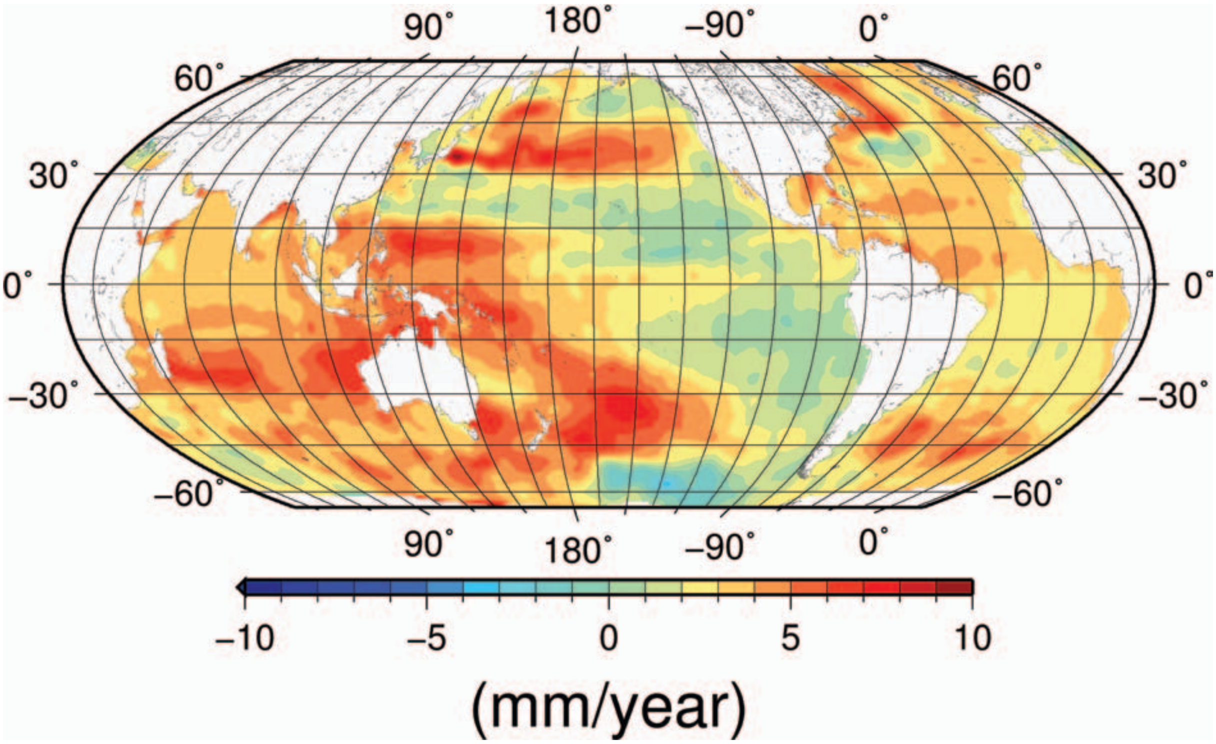
SEA-LEVEL CHANGE

Sea levels vary on timescales from seconds (surface waves), through hours (tides and storm surges), and months to years (related to phenomena such as ENSO) and over longer terms in response to global warming.

The global average sea-level rise over the 20th century was ~1.7 mm/year. Global average sea-level rise has been higher (Fig. 5.6) since 1993, ~3 mm/year, but the rate is not uniform around the world (Fig. 5.7). The largest 1993–2015 rises were in the western equatorial Pacific and along the north and north-west coasts of Australia, partly from natural climate variability.



◂ **_Figure 5.6_**: *Observed and projected global mean sea-level change from 1700 to 2100. Historical estimates come from observations of past events, tide gauges and satellites. Projections are from global climate models and show likely rises for unmitigated emissions of greenhouse gases (red lines and shading) and with significant reductions in emissions (blue lines and shading) (Source:* IPCC Assessment Report 5, Working Group 1, *fig. 13.27*[2]*).*



▴ **_Figure 5.7_**: *Satellite observations of the rate of sea-level rise over January 1993 to December 2015 (Source: CSIRO).*

Why does sea level change?

The two major contributions to 20th century sea-level rise were expansion of oceans as they warmed (like liquid in a thermometer) and the shrinking of glaciers and ice sheets. The ice sheets of Greenland and Antarctica contain enough water to raise global sea levels by 7.3 and 58 m, respectively, and satellite observations indicate their contributions to sea level have increased over 1993–2010. Atmospheric temperatures are key to increased surface melting of glaciers and the Greenland Ice Sheet, but penetration of warm ocean waters under the base of Greenland and Antarctic ice shelves has resulted in the greatest increases in the discharge of ice into the oceans.

These ocean and ice sheet processes have very long timescales and high inertia, meaning global average sea level will continue to rise for centuries, or even millennia, after atmospheric concentrations of greenhouse gases are stabilised.

Impacts of sea-level change

Changes in sea level impact coastal flooding events and the stability of coastlines. Frequencies of coastal flooding from high sea-level events have increased significantly during the 20th century, both around Australia and globally. Such events will become more frequent as sea level rises during the 21st century and beyond. Coastal inundations by extreme sea-level events that have occurred historically about once per century are expected to become decadal or even annual events this century in some areas, including around Australia. Higher average sea levels mean sustained inundation of coastal land, allowing storm surges and surface waves to have greater impacts on coastlines, with resultant impacts on the coastal environment, infrastructure and communities.

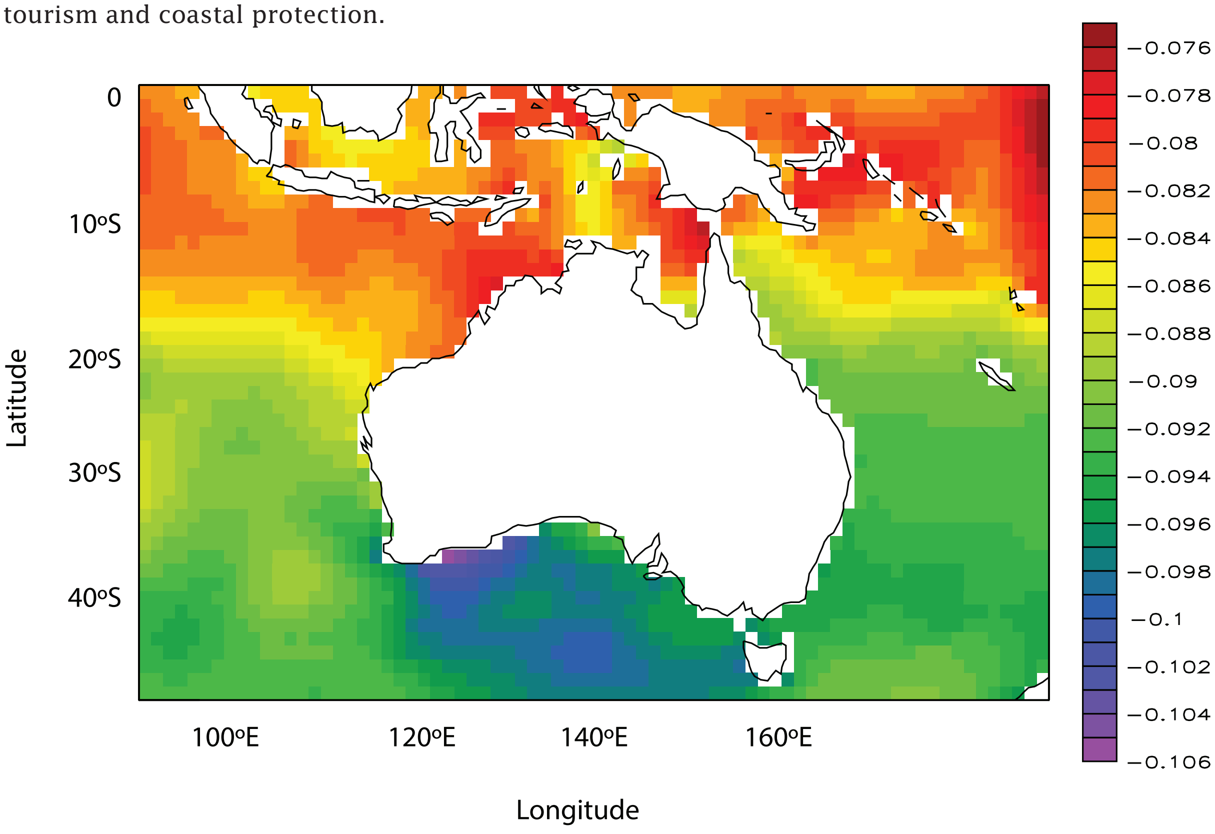
Many populated coastlines will be affected by increasing sea levels over coming decades (Source: CSIRO).

OCEAN ACIDIFICATION

The oceans' uptake of atmospheric CO_2, while slowing climate change, leads to changes in ocean chemistry. CO_2 reacts with seawater as it is absorbed by the oceans to form carbonate and bicarbonate ions. A direct consequence of rising atmospheric CO_2 is a net reduction in carbonate (ion) concentration and a consequent reduction in seawater pH (smaller values are more acidic), collectively known as ocean acidification. There has been a 0.09 drop in pH around Australia and a global drop of 0.1 since pre-industrial times, corresponding to about a 30% increase in ocean acidity. The largest Australasian changes are around southern Australia (Fig. 5.8).

Ocean acidification impacts the entire marine ecosystem, from plankton at the base of food webs to fish at the top. Factors affected include reproductive health, organism growth and physiology, species composition and distributions, food web structure and nutrient availability. Carbonate is used (with calcium) by corals and some algae to form reef structures and by other organisms such as oysters, crabs, starfish and some plankton to make hard shells. Reduced carbonate in the oceans means it will be harder for these creatures to make shells and for corals and algae to form reefs.

Ocean acidification and warming are the physical changes predicted to have greatest direct impact on marine environments and the key ecosystem services the oceans provide, such as food, tourism and coastal protection.



▲ ***Figure 5.8**: Changes in pH around Australia since the preindustrial period. A decrease in pH value of 0.09 from historical average ocean values reflects approximately a 30% increase in acidity (Source: Lenton* et al. *2016[3]).*

CONCLUSION

Oceans are central to Australian and global climate through their ability to store, transport and exchange with the atmosphere vast amounts of heat and CO_2. Ocean–atmosphere interaction is the key driver of Australia's climate variability over seasonal–inter-annual periods. Oceans are slowing climate change by absorbing heat and CO_2. Heat uptake by the oceans, however, contributes to sea-level rise and uptake of CO_2 increases ocean acidity. Ocean warming and ocean acidification are affecting marine ecosystems in fundamental ways. Improving predictions of climate variability over months to years and climate change projections through the 21st century and beyond will depend significantly on ocean observations and our ability to understand and model global oceans' interactions with the atmosphere, ice-sheets and glaciers.

FURTHER READING

Cleugh H, Stafford Smith M, Battaglia M, Graham P (Eds) (2011) *Climate Change: Science and Solutions for Australia*. CSIRO Publishing, Melbourne.

CHAPTER 6.

The oceans and our lives

Sean Pascoe, Toni Cannard, Natalie Stoeckl, Ian Cresswell, Samantha Paredes and Amar Doshi

Key messages

- Oceans play an important role in almost all parts of our society.
- We depend on the oceans for water, air and food.
- Oceans support employment opportunities and the means to trade with other nations.
- Oceans provide us with recreational and cultural benefits.

INTRODUCTION

Oceans affect nearly all components of our lives. Eight of the world's 10 largest cities are located on the coast and over half the world's population lives within 200 km of the coast, and around one-quarter within 100 km. Nearly nine in 10 Australians live within 50 km of the coast. Australia is connected to the rest of the world through a global maritime highway through which most of our trade passes.

Oceans provide us with food, with opportunities to work and play, and help control the environment in which we live. Oceans ultimately provide the water we drink and the air we breathe, which in turn underpins the production of food we eat and export. Oceans have cultural values for many people, contributing to their wellbeing. 'Sea country' is a key part of the culture and economy of many Indigenous Australians.

FOOD

Australians have a well-established love of seafood, with over half the population eating seafood at least once a week. Australia is a relatively small producer of seafood, however, producing around only 233 000 tonnes annually (see Chapter 9). Much of our seafood is high-valued (e.g. prawns and lobster) and exported to Asia, Europe and the USA, while much of the fish we consume is imported, even though we harvest a wide variety of species locally.

A few of the wide variety of fish species from Australian fisheries and aquaculture and consumed domestically (Source: Sean Pascoe, CSIRO).

Most wild-caught fisheries are fully exploited globally and in Australia, so much of the future growth in supply of fish is likely to come from aquaculture. Australian aquaculture was negligible in the 1970s but now is a major producer of seafood, largely focussed on high-value species. Australian farmed fish species such as Atlantic salmon and barramundi increasingly are available through supermarkets and other retail outlets and are becoming main components of the Australian fish diet.

Consumption of other marine products such as seaweeds is increasing globally and it is likely that these will play an increasing role in future Australian consumption. These species also lend themselves to mariculture (the marine version of agriculture). Recent research focussed on these products has developed a seaweed variety that tastes like bacon, as well as being high in protein, vitamins and other nutrients. Such varieties are likely to lead to increased acceptance of seaweeds and other marine vegetation as future food sources.

WORK

Oceans provide major sources of employment and livelihoods, particularly in developing countries. Around 260 million people globally rely on marine fishing for employment, either directly in the industry or indirectly in upstream industries such as boatbuilding and transport and downstream industries such as processing and marketing.[1] Most (80%) of fishing-related employment occurs in Asia, with much of the remainder (15%) in Africa.[2] The Australian fishing industry is relatively small by global standards but is a key industry underpinning many coastal communities, with each dollar produced in fishing resulting in between two to three additional dollars generated in the local economy (see Chapter 7).

Oceans provide more employment opportunities than just fishing, with ocean and coastal tourism one of the fastest growing areas of contemporary tourism and a key part of many regional coastal economies. Tourism provides an additional livelihood opportunity in coastal regions and often exceeds the value of fishing. Tourism accounts for around 75% of marine-related employment in Australia.

Mining industries in Australia, such as offshore oil and gas and land-based mining of products such as coal and iron ore, depend on the oceans for shipping transport of products (Chapter 7). These industries are capital intensive, so often provide fewer direct employment opportunities than fishing and tourism, but play significant roles in Australian society when indirect employment in ports, offshore islands and transport is taken into account.

PLAY

The coast and near-shore are major areas for leisure, recreation and tourism (e.g. Box 6.1). Coastal tourism in particular has been identified as a major source of income in many developing countries, with South-East Asia currently one of the most important and fastest growing tourist destinations in the world.[3] This is beneficial to the tourists and tourism industry but causes challenges in some areas in terms of waste disposal and ensuring adequate supplies of drinking water. Lack of understanding of coastal processes in some cases has led to increased beach erosion through poorly planned development. Increased pressure on coral reefs, if not properly managed, could reduce their attractiveness to tourists.

Beaches are one of Australians' most valued natural recreational environments, with popular recreational activities including walking, swimming and surfing. Recreational fishing also is popular, with around one-third of beach goers fishing at least once a year. Balancing resident and tourist beach access needs is challenging. Residents are more frequent users of the beach but tourists bring additional economic benefits to an area.

Box 6.1: The Great Barrier Reef

The catchments adjacent to the Great Barrier Reef (GBR) are home to more than 1 million people. This coastal environment provides communities with numerous recreational opportunities, with beach access, fishing and boating major contributors to the benefits derived by local residents. The GBR is also a major tourism drawcard for the region, responsible for more than 80% of the area's overnight visitors.[4] Even those who visit the region primarily for business are motivated to stay longer to enjoy the natural attractions of the region. Tourists, like residents, enjoy spending time at the beach and more than 60% go to the offshore islands or reefs.[5] Tourists also come to the region for specialist activities including SCUBA diving and whale-watching.

(a) *Residents, resorts and beach, Port Douglas and* ***(b)*** *diving on the Great Barrier Reef (Sources: a Fiona Henderson, CSIRO; b eGuideTravel.com, CC BY 2.0, www.flickr.com/photos/eguidetravel/2920392008).*

(a) *North Stradbroke Island, Queensland;* ***(b)*** *surfing on the Gold Coast (Sources: a Paul Welding, CC BY 2.0, https://www.flickr.com/photos/paulweldingphotography/15818616155; b Camila Sé, CC BY 2.0, https://www.flickr.com/photos/136092741@N07/20673667543).*

CULTURE AND WELLBEING

The marine environment holds very high intrinsic value for many in Australia. Many people are concerned that the marine estate is conserved and in 'good shape' even if they rarely (or never) use it. Knowing that reef fish, coral cover and mangroves are healthy and iconic marine species are abundant, for example, are considered by many to be more important to quality of life of GBR residents than the jobs and incomes associated with key regional industries.[6]

Coastal and estuarine ecosystems also contribute to spiritual or religious values in some cultures. Spiritual significance and resource extraction such as traditional fishing activities form important parts of cultural heritage for many coastal Indigenous groups. Indigenous fishing rights and access to biocultural resources are recognised in multiple ways in Australian waters (Chapter 8) and in recent years the High Court of Australia has upheld cultural fishing rights under the *Native Title Act 1993*. Indigenous Australians have a strong connection to their sea country that long-preceded European settlement, as a source of food, as well as featuring in creation stories and as ceremonial places.

Indigenous Australians have had strong connections with the oceans from long before European settlement (painting by Joseph Lycett, ca 1817) (Source: National Library of Australia, http://nla.gov.au/nla.pic-an2962715-s17).

Beaches and oceans also play major roles in the culture of non-indigenous Australians, though less of a spiritual role than for many Indigenous Australians. Beach use, for example, is embedded in the broader Australian culture, as well as providing recreation, with many beaches having cultural iconic status (e.g. Bondi Beach and Surfers Paradise). Recreational activities such as surfing, SCUBA diving and recreational fishing also have generated their own values and cultures that extend beyond the activities themselves.

Areas of outstanding natural beauty that include water also have been found to be strongly associated with human health and wellbeing. The high value placed on coastal amenity is reflected in property prices and recreational pursuits, with local residents and tourists alike placing great value on beaches and coastal environs as places of relaxation, recreation and appreciation of natural beauty.

OTHER ECOSYSTEM SERVICES

Over two-thirds (by value) of the world's ecosystem services are produced in the marine environment, with around half in the coastal region.

It is estimated that 50–80% of the oxygen in the atmosphere is produced by marine plants. Most of the water vapour in the atmosphere, which becomes rain onshore, derives from the oceans, meaning that the oceans are responsible indirectly for most terrestrial agricultural production through water supply.

The oceans play a major role in regulating weather and El Niño, La Niña and other climate processes (Chapter 5) that have major influences on agricultural production and the weather and climate Australians experience.

The oceans also are central to moderating climate change through absorbing heat and carbon dioxide (CO_2). The oceans have absorbed much of the atmosphere's excess heat trapped by greenhouse gas emissions and a large proportion of human CO_2 emissions (Chapter 5). The concept of blue carbon (or coastal carbon) refers to the carbon from CO_2 captured and stored by marine plants, including mangroves, saltmarshes, coastal wetlands, seagrass meadows and planktonic plants.

CONCLUSION

Oceans play a role in nearly all parts of our lives, from the water we drink, the air we breathe and the food we eat to our enjoyment and social and physical wellbeing. They provide us with employment and recreation opportunities, and increasingly will provide energy and pharmaceuticals. Oceans also have played significant roles in people's daily lives, culture and heritage for millennia and are likely to continue to do so for future generations.

FURTHER READING

Larson S, Stoeckl N, Farr M, Esparon M (2015) The role the Great Barrier Reef plays in resident wellbeing and implications for its management. *Ambio* **44**, 166–177. doi:10.1007/s13280-014-0554-3

World Ocean Review (2010) *Living with the oceans, World Ocean Review 1*. Maribus gGmbH, Hamburg.

CHAPTER 7.

The blue economy

Sean Pascoe, Toni Cannard, Ian Cresswell, Natalie Stoeckl, Amar Doshi and Samantha Paredes

Key messages

- The blue economy represents the range of commercial activities that are dependent on the marine environment and a wide range of non-monetary ecosystem services provided by the oceans.
- Growth in the blue economy is likely to exceed that of the terrestrial economy in coming decades, with the development of new industries and expansion of existing industries.
- Benefits may dissipate, resulting in substantial opportunity cost to Australia, unless developments are managed to ensure economic and environmental sustainability.

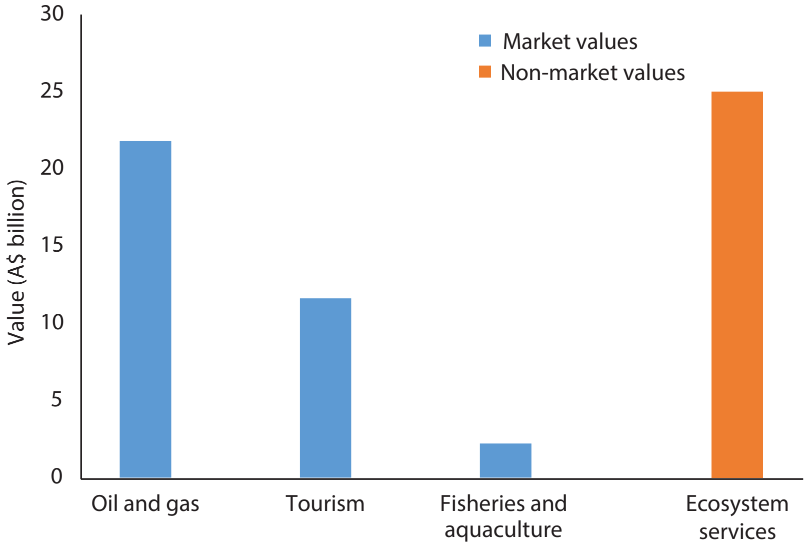
INTRODUCTION

People have been using marine resources for millennia for food, transportation, recreation and cultural purposes (Chapter 6). Advances in technology over recent decades have made it technically and economically feasible to access and use a wider range of living and non-living marine resources. Current annual ocean economic activity globally is estimated to be US$3–5 trillion, while the value of annual ocean economic activity in Australia has been estimated to exceed A$42 billion.[1] This economic activity is expected to grow at a faster rate than terrestrial economic activity, more than doubling in value over the next decade.[2]

The term ‘blue economy’ recognises the substantial wealth generation potential that the oceans provide and highlights the importance of ensuring economic and environmental sustainability when developing and managing ocean resources. The blue economy encompasses those industries that are dependent on the oceans and ocean resources. Oceans represent economic powerhouses for many nations, including Australia, supporting a wide variety of industries. Potential conflicts between these industries present significant management challenges to ensure future opportunities are maximised. Oceans provide more than just commercial benefits, however: they also provide substantial non-market benefits in the form of ecosystem services – environmental, social and cultural services – that do not have monetary values *per se*, but are at least as important as commercial industries in maintaining and enhancing the overall welfare of Australians.

COMPONENTS OF THE BLUE ECONOMY

The main components of the Australian blue economy currently are shipping, oil and gas, tourism, ship building, and fisheries and aquaculture, although potential exists for development of several new industries. Their relative values are illustrated in Fig. 7.1, along with ecosystem services which provide substantial non-market benefits from the ocean environment. Shipping is not presented in Fig. 7.1 because it is difficult to 'value' shipping *per se* to Australia directly given the international nature of most shipping businesses. Ecosystem services reflect production from natural assets, including: provisioning services such as the production of food and water; regulating services such as the control of climate and carbon sequestration; supporting services such as the production of oxygen; and cultural services such as spiritual and recreational benefits (Chapter 6). Ecosystem services generally cannot be increased through policy or regulatory decisions, but poor management of other sectors in pursuit of economic development may lead to reductions in non-market values from ecosystem services.



◂ ***Figure 7.1***: *Relative value of key ocean industries and ecosystem services attributed to Australia's marine estate.*

CURRENT INDUSTRIES STATUS AND OPPORTUNITIES

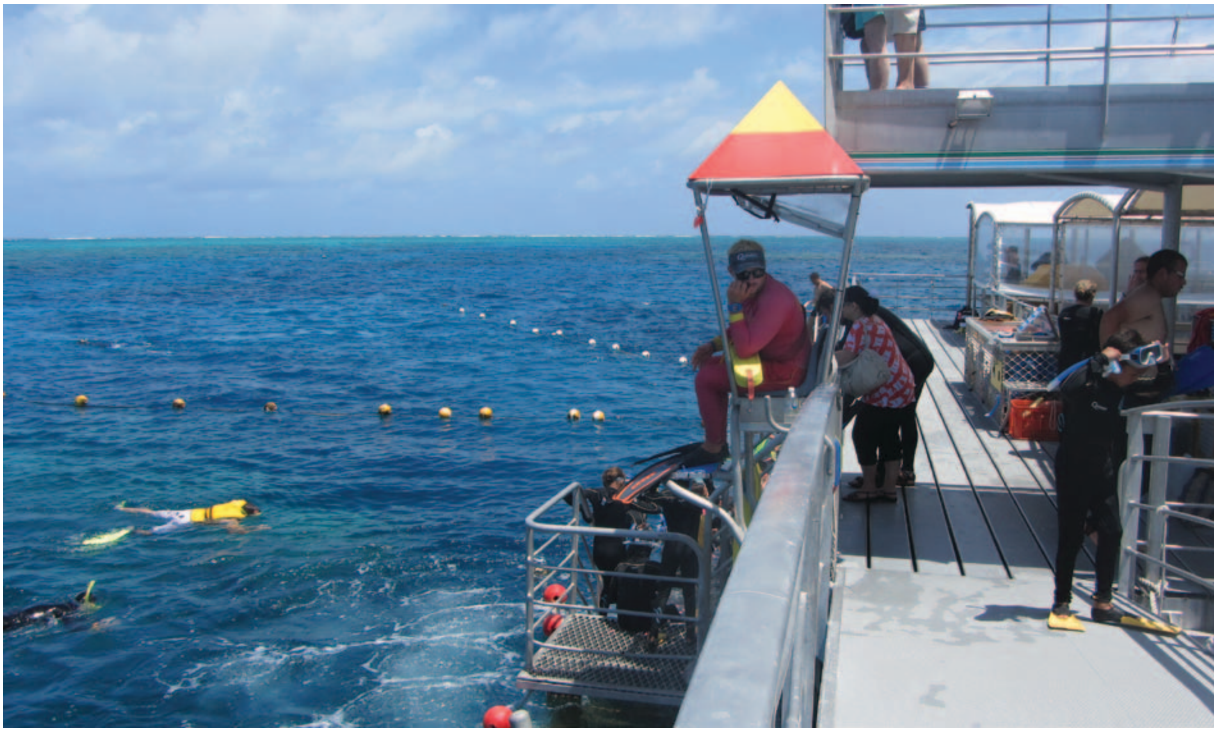
Shipping is the most cost- and energy-efficient mode of international transport. Goods valued at $US18.9 trillion were traded internationally in 2014, over 90% of which was by ship. Exports from Australia by sea in 2012–13 exceeded A$220 billion, which represented ~90% of total exports and ~14% of the total Australian Gross Domestic Product, while shipping also delivered imports worth A$184 billion. A further 101 million tonnes of freight were shipped around the Australian coast in interregional trade, representing 17% of domestic freight movements.

A coal bulk carrier entering Port Hunter, New South Wales (Source: Nick Pitsas, CSIRO).

There is growing interest in the extraction of oil, gas and mineral resources offshore as demands for these resources increase globally and onshore resources decline. The offshore oil and gas industry has expanded globally, with around one-third of oil and gas coming from offshore sources worldwide valued at approximately US$1.7 trillion in 2014. Offshore oil and gas contributes roughly one-third of the value added from all ocean-based industries globally.

The oil and gas industry in Australia currently produces over A$20 billion worth of resources a year with the potential to increase three-fold within the next decade[1] (see also Chapter 10). More than 22 000 full-time equivalent workers were employed directly in the sector in 2013, with 65 000 additional positions in associated contract work. Australia is currently the world's third largest exporter of liquid natural gas. Over 90% of the gas resources lie in offshore basins, most of which are yet to be exploited (Chapter 4).

Marine-based tourism globally contributes around one-third of the total value added from all ocean-based industries, about the same as the global oil and gas industry. Marine tourism in Australia is estimated to generate over A$11 billion a year to the largely regional economies in which it occurs. The Great Barrier Reef (GBR) World Heritage Area, for example, is a major tourism drawcard for the adjacent coast, attracting over 80% of the area's overnight visitors, injecting an estimated A$5–6 billion into the economy and generating around 64 000 full-time equivalent jobs.[3] Growth in this sector is expected to increase over coming decades, particularly as incomes in China increase and more Chinese people travel internationally. China is forecast to be Australia's biggest source of tourists by 2020, with coastal and nature-based tourism highly attractive to this group. Many iconic marine tourist destinations such as the GBR, however, are under increasing pressure from climate change and port development. These pressures may adversely affect future tourism growth to those areas but may stimulate new opportunities for other coastal regions that retain less disturbed environments to capture the growing coastal tourism market.

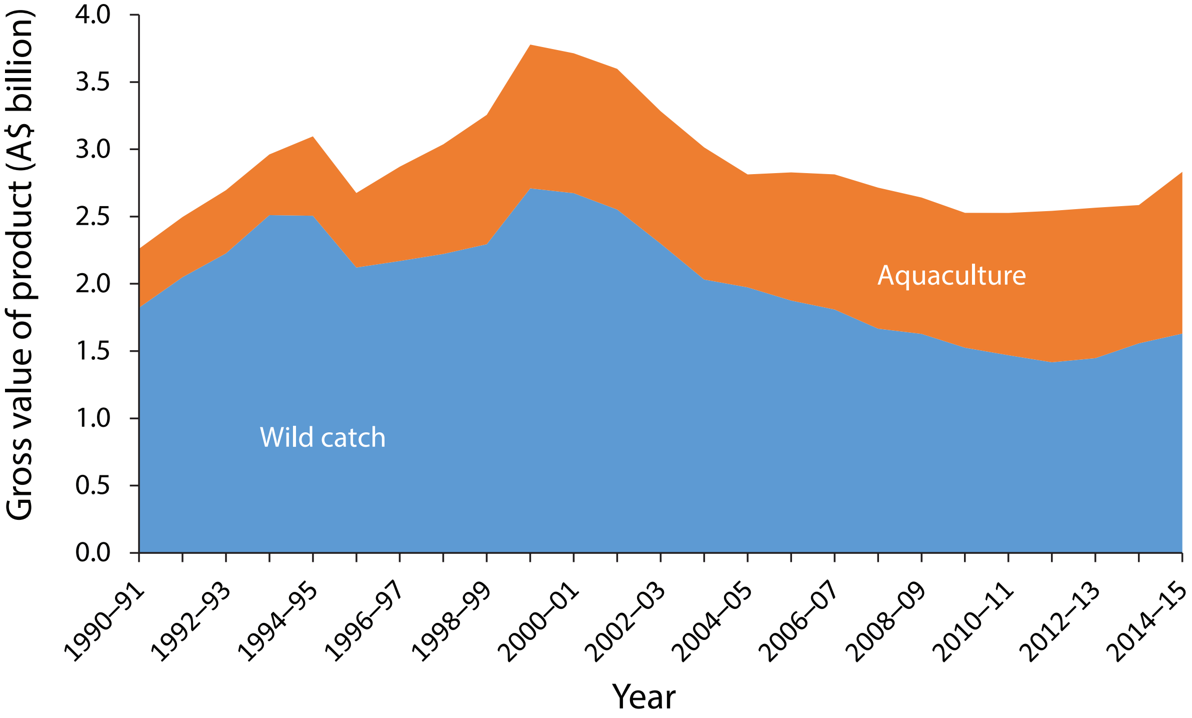


Tourist operation on Agincourt Reef, Great Barrier Reef (Source: Robert Linsdell, CC BY 2.0, www.flickr.com/photos/boblinsdell/9440742113).

The global direct value of fishing is estimated to be US$80–85 billion a year[4] but total value is estimated to be US$225–240 billion when associated industries are included.[5] Wild-catch fisheries in Australia play a vital role in supporting many regional coastal communities and play an important role socially through access to high-quality, locally produced seafood. The potential for growth of wild-caught fisheries is naturally limited by the fish stocks, with modern management largely now focussing on ensuring the sustainability of the resource while maximising its value to the Australian community (Chapter 9).

Global aquaculture has grown substantially since the 1980s and now comprises almost 50% of the world supply of aquatic protein for human consumption. This has had a negative impact on many wild-caught fisheries as increased global supply of seafood has resulted in lower prices received by traditional wild-harvest suppliers. Similar aquaculture growth has been seen in Australia (Fig. 7.2), with a general decline in the value of wild-caught seafood offset by the growth of aquaculture. Aquaculture is expected to continue to increase both within Australia and globally (Chapter 9) as new technologies and management processes decrease the cost of production, reduce reliance on wild-caught species as feed-stock, and increase the range of species and areas in which aquaculture can operate, both onshore and offshore.

Fishers haul a catch of orange roughy (Source: Mark Lewis, CSIRO).



▲ ***Figure 7.2****: Value of production from Australian aquaculture and wild-catch fisheries (real values, 2011–12 dollar equivalents) (Source: Sean Pascoe, CSIRO).*

DEVELOPING INDUSTRIES AND OTHER OPPORTUNITIES

There remains potential for oceans to provide further benefits. New industries are developing that use Australia's ocean resources and offer considerable opportunities for the future. Marine biotechnology has potential to provide a wide range of new products. Coastal and ocean environments have a large diversity of marine microorganisms, the biochemical potential of which is unknown for most species. Components from such organisms could lead to many new bioactive products: at least four drugs are on the market currently, with many more clinical trials underway, largely on cancer-targeting compounds or new antibiotics.[6] Such microorganisms also may offer more than just medical benefits. Marine micro-algae have been shown to be a new 'crop' for biofuel production, with the additional advantage that they also could reduce future net CO_2 emissions. New algae strains can be engineered from existing algae to supply larger quantities of biofuels than traditional biofuel crops (e.g. corn, soybean) from the same land area. These algae can thrive in less favourable growth conditions than terrestrial crops, including in saline, brackish or waste water and on non-arable land. They therefore have the potential to complement other industries such as aquaculture and sewage treatment, absorbing nutrient-rich effluent for their own production.

Algae used to treat wastewater in Christchurch, New Zealand. The algae are collected and used to generate biofuel (Source: Sustainable Initiatives Fund Trust, CC BY 2.0, www.flickr.com/photos/siftnz/4170457412).

Ocean renewable energy production also is expected to be a major growth area in coming decades. The oceans store enough renewable energy, in various forms, to exceed current total global energy demands, but only a fraction of this potential is currently realised. Offshore wind energy already is operating in several countries and research is underway to improve the efficiency of wave, tidal and thermal energy systems. More than 100% of the energy demand in Denmark, for example, is met by offshore wind farms, with any surplus being exported. There is opposition to wind farms in Australia, particularly offshore wind farms, largely because of their potential impact on migratory seabirds. Major other new Australian energy initiatives have started, however, such as the development of wave energy technology that converts ocean swell into renewable power (Chapter 10).

Availability of fresh water is limited in many areas of Australia. Desalination of sea water can mitigate this issue. Australia currently has over 66 operational desalinisation plants, ranging from small-scale plants supplying water to islands such as Hamilton and Christmas islands to large-scale plants supplying 15% of Sydney's water supply. A key challenge facing the further development of desalination plants in Australia is their energy demand, although the development of ocean renewable energy technologies may complement future development of desalination plants.

The ocean contains a wide range of mineral resources other than oil and gas. Offshore mining of other minerals currently is limited in Australia but is increasing globally. The availability of resources in Australia is largely unknown, with only limited exploration having been completed (Chapter 4). An extensive area of ferromanganese nodules, containing manganese, nickel, copper and tin, has been identified in deep waters off south-west Australia but has not yet been exploited. New technologies will be required to map and extract these minerals without damaging the marine environment.

The marine environment provides many ecosystem services (Chapter 6) of considerable value (Fig. 7.1). Potential to further exploit some of these services is limited, but enhancing some services, such as seagrass and mangrove restoration to support carbon capture, provides opportunities for development of new industries, provided appropriate market incentives can be generated (e.g. a carbon trading scheme to allow such new industries to sell carbon credits). Maintaining such services through appropriate environmental management is essential, however, particularly as other industries (such as marine mining, urban and port development) develop that may affect the marine environment negatively.

CONCLUSION

Future blue economy growth has the potential to far exceed most terrestrial economies, provided its benefits are not subverted by poor management and degradation of the associated environments. The potential of the blue economy is still emerging and improvements in regulatory frameworks are necessary to balance economic development with environmental protection. Australian fisheries provide a good example where the benefits of good management have been substantial, especially in avoiding or redressing resource overexploitation.

Science and research will play a vital role in blue economy development over the coming decades, including new production technologies, appropriate risk assessments and design of integrated monitoring and decision-support systems (Chapters 15, 16).

New ways of using the oceans to meet human needs continue to develop. The oceans are tremendous sources of wealth and wellbeing, but more than two-thirds of the gross value of the blue economy is dependent on healthy marine ecosystems.[7] Careful management of the activities in the marine environment, not only for the biological-based resources, is critical for long-term sustainability, market growth and future emergence of blue economy innovations. Increasing development comes with risks. The continued expansion of exploitation of marine resources could lead to damage of ocean ecosystems. Effective management and policy is required to ensure sustained access to both the resources and non-market values of our oceans that Australians expect for themselves and future generations.

FURTHER READING

Economist Intelligence Unit (2015) *The Blue Economy: Growth, Opportunity and a Sustainable Ocean Economy, Briefing Paper Prepared for the World Ocean Summit*. The Economist Group, New York, USA.

FAO (2014) *The State of World Fisheries and Aquaculture: Opportunities and challenges*. Food and Agricultural Organisation of the United Nations, Rome, Italy.

Hoegh-Guldberg O (2015) *Reviving the Ocean Economy: The Case for Action – 2015*. World Wildlife Fund International, Geneva, Switzerland.

Oceans Policy Science Advisory Group (2013) *Marine Nation 2025: Marine Science to Support Australia's Blue Economy*. Australian Institute of Marine Science, Townsville.

OECD (2016) *The Ocean Economy in 2030*. OECD Publishing, Paris, France.

CHAPTER 8.

Governance of Australian seas and oceans

Ian Cresswell and Marcus Haward

Key messages

- ✻ Australia has a vast and diverse marine estate.
- ✻ Australia's marine domain is governed by strong domestic management as well as commitments to international and regional arrangements.
- ✻ Governance and management involves multiple agencies and jurisdictions with coordination mechanisms to deal with conflicts.

INTRODUCTION

How we manage oceans is different from how we manage our land. The sea is considered a common property resource and is administered by governments under international agreement, unlike land where individuals can own exclusive rights to particular areas. Australia's history of development has led to the system by which we govern our oceans.

Australia's total maritime jurisdiction is 13.86 million square kilometres (km^2), the third largest in the world, and extends from the tropics to Antarctic waters, including approximately 0.26 km^2 of 'internal' marine waters landward of the Territorial Seas Baseline along the coastal low water line[1] (Fig. 8.1; Chapter 1). This is a large and diverse marine jurisdiction with equally diverse rules governing management in different areas. Over 100 laws and policy instruments have been established by Australia's Federal and state governments. Australia has jurisdiction providing it with rights to the natural resources (living and non-living) of the water column, seabed and subsoil within our Exclusive Economic Zone, initially declared on 1 August 1994. The Federal Government has overall responsibility for the marine estate but over the course of the past 115 years since federation a series of complex state–federal arrangements have been established to manage the estate. This chapter outlines Australia's ocean governance arrangements and identifies key future challenges for implementing nationally cohesive governance.

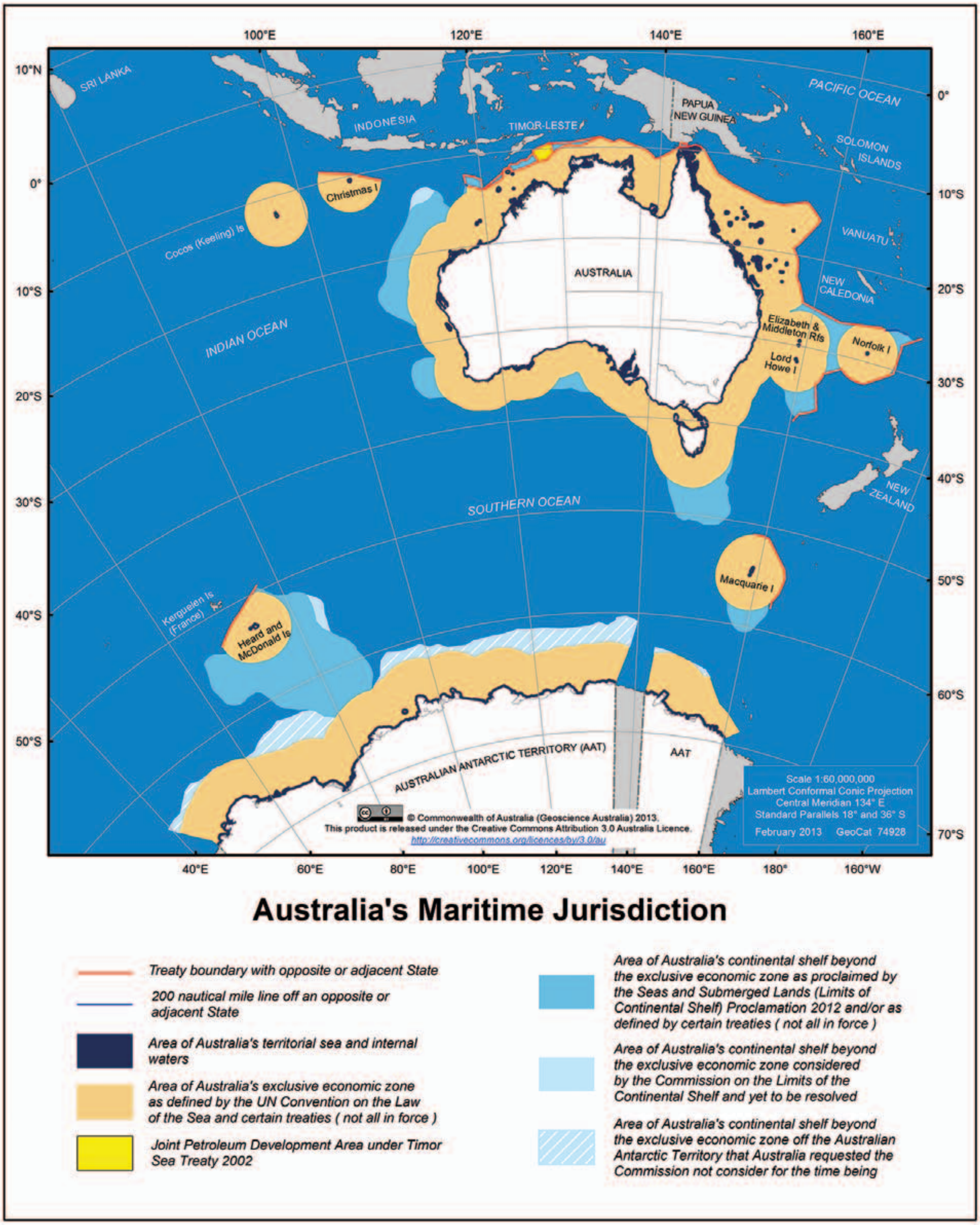
ZONES OF OUR MARINE ESTATE

Australia has a range of maritime zones formalised under the *Seas and Submerged Lands Act 1973*, with three main jurisdictional areas recognised internationally. First, the 'Territorial Sea' (generally) is the sea within 12 nautical miles of the shore. Second, the 'Exclusive Economic Zone' (EEZ) is an area from the Territorial Sea out to (mostly) 200 nautical miles from shore. Third, a 'Contiguous Zone' extending 24 miles from the shore and overlapping the Territorial Sea and inner EEZ that allows Australia to 'exercise control necessary to prevent and punish infringement of its customs, fiscal, immigration or sanitary laws and regulations within its territory or Territorial Sea'. Australia, unlike other countries, also has a 'Coastal Waters' zone extending 3 nautical miles seaward of the shore, within the Territorial Sea.

The Federal Government has sovereignty over Australia's entire marine estate but under the Offshore Constitutional Settlement (OCS, below) many responsibilities in Coastal Waters are regulated or managed by the adjacent state or territory government. Most Australians' engagement with their marine domain is within Coastal Waters.

OUR NEIGHBOURS AND INTERNATIONAL WATERS

Australia shares maritime boundaries with six neighbours: Indonesia, East Timor, Papua New Guinea, Solomon Islands, France (Kerguelen Islands and New Caledonia) and New Zealand. Also adjacent to Australian waters lie international waters sometimes called the 'High Seas'. Non-living resources of the seabed and subsoil in the High Seas, beyond any nation's jurisdiction, are considered 'the common heritage of mankind'. This area is defined by the United Nations Convention on the Law of the Sea (UNCLOS) as 'the sea-bed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction' – that is, beyond the EEZ or extended continental shelf of all maritime nations. The extended continental shelf is that area considered to be a contiguous part of a nation's continental shelf that a coastal state can claim beyond 200 nautical miles from its coast under Article 76 of the UNCLOS.[2] Obligations from the UNCLOS also may affect Australian fisheries within its EEZ, particularly through regional fisheries agreements (e.g. Box 8.1) that, as international law, can have obligations for Australian nationals and industry. Australia is engaged in key regional bodies in the Indian, Southern and Pacific Oceans. Australia also has key bilateral arrangements in northern waters such as the Torres Strait, with Papua New Guinea, and the Timor and Arafura Seas, with Timor-Leste and Indonesia.



▲ ***Figure 8.1****: Australia's maritime jurisdiction (Source: Geoscience Australia, Commonwealth of Australia).*

Australia is party to several other multi-lateral environment agreements covering issues such as pollution, migratory shorebirds, dugong and turtles. Australia maintains involvement with the International Whaling Commission and the Convention on Trade in Endangered Species of Wild Flora and Fauna (CITES), including supporting initiatives to promote sustainable management of shared stocks.

Box 8.1: The Convention for the Conservation of Southern Bluefin Tuna

Southern bluefin tuna (SBT) is one of Australia's most valuable tuna fisheries, with current exports of A$150 million per annum of SBT caught live off South Australia and 'grown out' to market size in sea-cages. The fishery is subject to international management by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) under the Convention for the Conservation of Southern Bluefin Tuna (1994). CCSBT manages catch allocation to member states under a global total allowable catch. Australia and Japan are the two largest harvesters of SBT, followed by the Republic of Korea, Taiwan, New Zealand, Indonesia and South Africa. Regional management of SBT has been challenging, but early disputes over stock status have given way to greater confidence in stock assessments and a robust management procedure, leading to recovering stocks. Past disputes within CCSBT centred on alleged under-reporting of catch by Japan, concerns about the method of calculating weight of SBT caught by Australian fishers for grow-out, and assessment of Australian recreational SBT catch. Challenges also arise from illegal high-seas catch by 'flag of convenience' vessels, unregulated catch by members of CCSBT and catches by nations that are not CCSBT members.

A brown booby overhead a shipwreck at Cato Island, in the Coral Sea (Source: Benjamin Cohen, Scottish Universities Environmental Research Centre).

HISTORY

The Federal Government assumed some responsibilities for offshore matters following federation in 1901 but ownership of marine resources remained unclear because the states retained legislative and administrative responsibilities developed as former colonies. The Federal Government eventually assumed jurisdiction over all seas beyond low water mark through the *Seas and Submerged Lands Act 1973*. The legislation was challenged by the states in the High Court of Australia. The court upheld the legislation but the Federal Government opted to seek a formal way to share offshore jurisdiction with the states. The Offshore Constitutional Settlement (OCS) was negotiated between 1976 and 1979 and took effect in February 1983 with proclamation of the *Coastal Waters (State Titles) Act 1980*, following earlier proclamation in January 1982 of the companion legislation the *Coastal Waters (State Powers) Act 1980*. The OCS provided the states with jurisdiction from low water to 3 nautical miles offshore in the 'Coastal Waters' zone and provided the means to share responsibility between governments through 'agreed arrangements'.

Management traditionally was focussed on living marine resources (e.g. fisheries) but the greatest driver for the OCS was to develop an agreed framework for use of offshore oil and gas. The OCS is based on sector-specific management and does not provide mechanisms for integration of oceans management or resolving conflicts among sectors. Various attempts to improve oceans governance through marine planning have followed. One response was through the *Fisheries Administration Act 1991*, which set objectives for cost-effective management and also required fishing to work under principles of ecologically sustainable development (ESD).

There has been increasing public concern since the 1970s about degradation of the marine environment. Policy responses by government have included inquiries such as the Resource Assessment Commission (RAC) Coastal Zone Inquiry report (1993) that led to establishment of Federal and state governments' coastal policies in the late 1990s. The Federal Government also released an 'Oceans Policy' in 1998, which sought to integrate across sectors and jurisdictions through ecosystem-based management (EBM) approaches and included ESD principles in the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*. The EPBC Act requires sustainable fisheries assessments for all fisheries that export produce and environmental assessments for major projects that potentially significantly impact matters of 'national environmental significance', which include Commonwealth marine areas and the Great Barrier Reef.

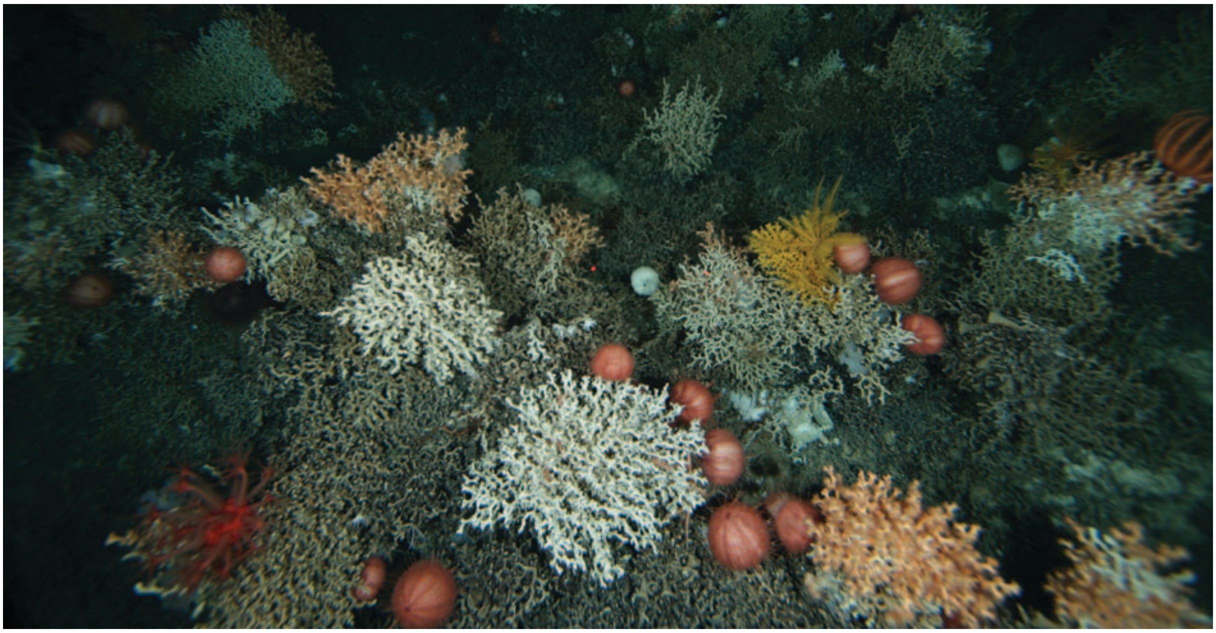
How we govern our oceans is (by its nature) subject to a multitude of international agreements, with key ones being: the UNCLOS (1994), the United Nations Conference on Environment and Development (UNCED, 1992), multiple regional agreements for managing highly migratory fish stocks and stocks straddling multiple EEZs, Regional Fishery Management agreements and several multilateral environment conventions such as the Convention on World Heritage, the Convention on Migratory Species, the CITES and the Convention on Biological Diversity.

AUSTRALIAN ENVIRONMENTAL MARINE MANAGEMENT

Australia has been seen as a leader in marine ecosystem-based management, the best-known examples being the Great Barrier Reef (GBR) Marine Park (*Great Barrier Reef Marine Park Act 1975*) and ongoing improvements to management of land-based inputs into the GBR waters. Specific governance arrangements were established to coordinate activities between the Federal and Queensland governments to deal with the complex issues facing the GBR. The park employs ecosystem-based management, such as zoning, that includes multiple-use areas and no-take zones.

Successive Federal Governments have sought to implement Australia's Oceans Policy (AOP) through Regional Marine Plans that were later redefined as Marine Bioregional Plans (MBPs). These are based on large-scale classifications of marine ecosystems and document marine environment and conservation values of each region, set out broad biodiversity objectives, identify regional priorities, and outline strategies for managing use of Australia's Territorial Sea and EEZ beyond Coastal Waters. Another major program, linked to MBPs, is establishment of a National Representative System of Marine Protected Areas that links all jurisdictions to achieve marine conservation in Australian waters.

The Federal Government established the National Offshore Petroleum Safety Authority in 2005 to regulate the health and safety of workers on offshore facilities, which in 2012 became the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA). The NOPSEMA now brings together existing state, territory and national regulations for health and safety, structural integrity, environmental plans and day-to-day operations associated with petroleum activities in the EEZ beyond Coastal Waters.



Coldwater coral habitat formed by Solenosmilia variabilis *on a seamount in the Huon Commonwealth Marine Reserve at 1300 m depth. The coral matrix provides habitat for other corals, urchins, glass sponges and crinoids (Source: CSIRO Biodiversity Surveys).*

SURVEILLANCE

Australia's marine domain poses significant challenges for monitoring, control and surveillance of activities that occur within it. Australia has been active in dealing with illegal movement of people, criminal activity and illegal, unreported and unregulated (IUU) fishing within its marine jurisdiction and internationally. It has worked hard with neighbouring countries to tackle the problem of IUU fishing, especially in the Southern Ocean. It has a treaty with France to deal with particular problems with enforcement in the waters around the French Kerguelen Island and Australia's Heard Island and McDonald Islands. The Australian Border Force, in collaboration with the Australian Defence Force, provides surveillance and enforcement capability in Australia's EEZ. The Australian states are responsible for enforcement of marine environment and resource management laws and regulations within Coastal Waters adjacent to their coasts. Those state activities are undertaken variously through resource management agencies or by police services and coordinated among the states through intergovernmental arrangements.

Australian Border Force vessels Ocean Protector *(red) and* Ocean Shield *(blue), which support enforcement and search and rescue activities across Australia's marine estate (Source: Australian Department of Immigration and Border Protection, CC BY 3.0).*

INDIGENOUS GOVERNANCE

Australia's Aboriginal and Torres Strait Islander peoples have complex connections to the coastal and marine areas that pre-date the current (6000 year-old) sea level by tens of thousands of years. 'Sea country' is a term denoting traditional coastal and marine estates of Indigenous Traditional Owner groups around the Australian mainland and offshore islands and also is shorthand for the combination of cultural rights, obligations, knowledge and resource management practices that characterise the relationship between Aboriginal and Torres Strait Islander peoples and their coastal and marine environments. Political and policy recognition of sea country has been growing since the 1980s as a formal element of Australian marine governance. Claims to sea country under native title legislation have been the basis of several High Court cases since native title was recognised in Australian law in 1992. The Court has recognised co-existence of native title with other existing marine rights (shipping, fishing, etc.) but has not supported exclusive native title to offshore marine areas. The Blue Mud Bay case in 2008 confirmed exclusive Aboriginal rights over intertidal areas under existing land rights legislation that applies only to the Northern Territory. Indigenous Protected Areas (IPAs) have been declared that contain large marine components that are managed through Indigenous-led collaborative governance arrangements with government agencies, commercial fishers and other interested parties. The Dhimurru IPA (2000) in the Northern Territory was the first IPA to include some inshore marine areas, with an additional 400 000 ha of sea country added in 2013. Formal Indigenous land and sea management plans have been implemented in other areas, enabling traditional practises to form the basis of contemporary, collaborative environmental and resource management governance. The rapid expansion of Indigenous ranger programs over the past 15 years also has increased formal governance of near-shore marine areas and marine resources.

*Tropical rock lobsters (*Panulirus ornatus*) are harvested by commercial, Indigenous and recreational fishers in Queensland, the Torres Strait and the Gulf of Papua (Source: CSIRO).*

FUTURE CHALLENGES

A key challenge for governance of our marine estate is growing demand for resources, including through use of new technologies. Mismanagement of the environment could result in potential benefits not being realised. New technologies in fisheries internationally, for example, have outstripped governance systems, leading to sub-optimal management and resource overexploitation. Global change, including increased climate variability and change, also has demonstrated impacts on Australia's marine environment.

The current OCS arrangements and the lack of property rights over ocean resources are not considered world's best practice. Developing a balance between use and conservation of ocean resources is a challenge for policy makers, industries and broader communities. Improved appropriate regulatory and incentive-based management systems to reduce adverse environmental impacts while allowing reasonable development is a key priority.

Australia led the world in introducing oceans policy in the 1990s and has improved sectoral management since then. Implementation of an Australian Oceans Policy has largely stalled, however, and Australia has had limited success in implementing integrated oceans management. The substantial challenge remains of providing the right mix of governance tools to allow integrated management across sectors that balances social, economic and environmental objectives.

CONCLUSION

The governance of Australia's marine estate is controlled through the division of powers and responsibilities among federal and state jurisdictions as well as a strong adherence to multiple international agreements. Australia has developed considerable capacity to manage its vast marine estate with the skills needed to take into account future opportunities and challenges in resource management and marine conservation.

ACKNOWLEDGEMENTS

The authors thank Dr Dermot Smyth for his invaluable input.

FURTHER READING

Butterly L (2013) Changing tack: Akiba and the way forward for Indigenous governance of sea country. *Australian Indigenous Law Review* **17**, 2–22.

Fogarty MJ, McCarthy JJ (Eds) (2014) *The Sea: Ideas and Observations on Progress in the Study of the Seas. Volume 16: Marine Ecosystem-based Management*. Harvard University Press, Cambridge, MA, USA.

Geoscience Australia (2015) Website. Geoscience Australia, Canberra, <http://www.ga.gov.au/ausgeonews/ausgeonews200903/limits.jsp>.

Haward M, Vince J (2009) Australian ocean governance-initiatives and challenges. *Coastal Management* **37**, 1–16. doi:10.1080/08920750802475368

Holland G, Pugh D (Eds) (2010) *Troubled Waters: Ocean Science and Governance*. Cambridge University Press, Cambridge, UK.

Smyth D, Isherwood M (2016) Protecting sea country: Indigenous peoples and marine protected areas in Australia. In *Big, Bold and Blue: Lessons for Australia's Marine Protected Areas*. (Eds J Fitzsimons, G Westcott) pp. 307–325. CSIRO Publishing, Melbourne.

Vince J, Smith ADM, Sainsbury KJ, Cresswell ID, Smith DC, Haward M (2015) Australia's oceans policy: past, present and future. *Marine Policy* **57**, 1–8. doi:10.1016/j.marpol.2015.02.014

CHAPTER 9.

Fisheries and aquaculture

David C Smith and Nigel Preston

Key messages

- ✻ Australia's wild fisheries are relatively small by global standards but have an important ecological, social and political footprint. They generally are acknowledged as well managed.
- ✻ There are considerable interactions among fisheries and between fisheries and other sectors.
- ✻ The breadth of fisheries research has increased considerably to meet the objectives of ecosystem-based fisheries management.
- ✻ Aquaculture is the fastest growing global food production sector.
- ✻ Australia's aquaculture industry is valued at A$1.1 billion and is growing by 11% per year.

INTRODUCTION

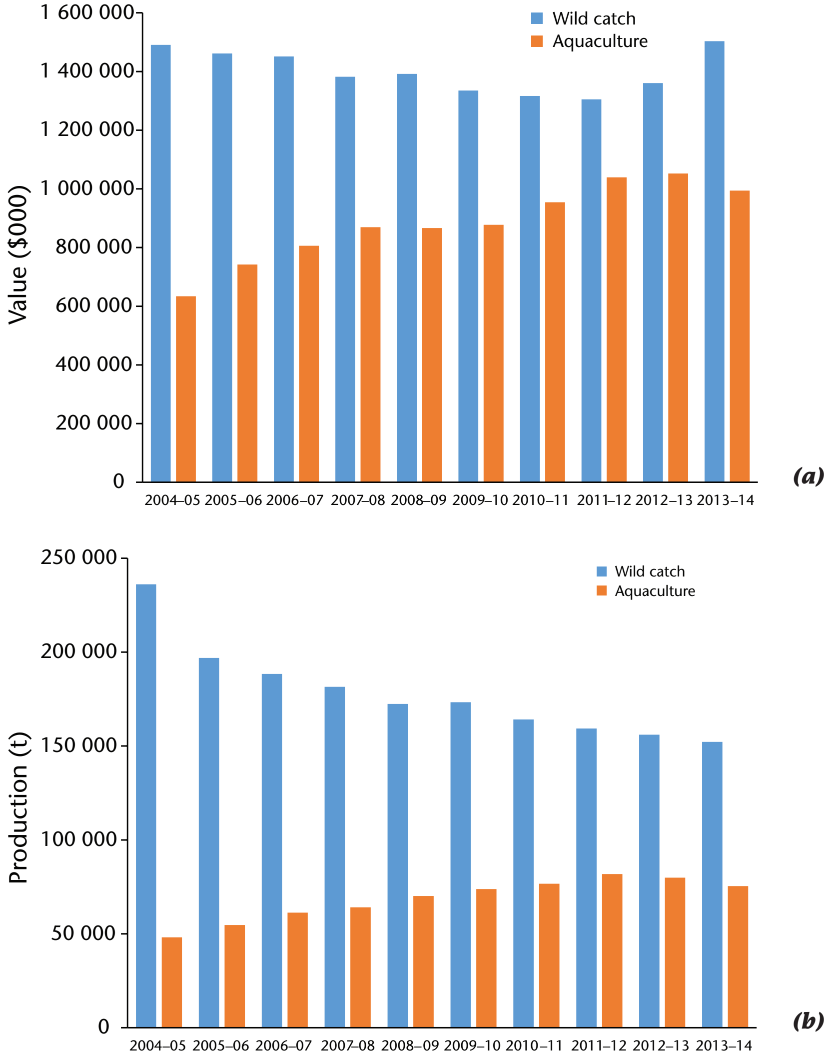
Fisheries and aquaculture are important for food and economic security. Marine fisheries and aquaculture produced 104.4 million tonnes of product globally in 2012, 79.7 million tonnes from wild-harvest marine fisheries and 24.7 million tonnes from marine aquaculture.[1] These are the primary sources of protein for 17% of the world's population and nearly a quarter of protein consumption in low-income food-deficit countries.

Australia's fisheries and aquaculture industries are small by global standards but generally are regarded as well managed and at the forefront of ecosystem-based management. Australia is ranked 4th in terms of compliance with the FAO Code of Conduct for Responsible Fisheries,[2] and 7th in overall performance in terms of Ecosystem-Based Fisheries Management (EBFM).[3]

Recreational fishing is a major social and economic activity in Australia, unlike many other nations, with up to four million people participating per annum and catches of many species exceeding commercial catches.[4] Indigenous fishing also is important, with growing recognition of the cultural, economic and nutritional importance of this sector.[5]

STATUS OF AUSTRALIAN FISHERIES AND AQUACULTURE

Australia's fisheries and aquaculture production has generated, on average, A$2.4 billion a year over the past decade (Fig. 9.1). Fisheries and aquaculture produced ~227 123 tonnes of seafood for domestic and export markets in 2013–14, with wild-capture fisheries contributing 152 210 tonnes worth A$1.5 billion and aquaculture producing 74 913 tonnes worth A$1 billion.[6] Approximately 14 000 people are employed directly in fisheries and aquaculture-related industries, including processing and seafood wholesaling.



◂ ***Figure 9.1***: ***(a)*** *Average annual value and* ***(b)*** *volume of Australia's fisheries and aquaculture production 2004–2014 (Source: CSIRO, data Australian Fisheries and Aquaculture Statistics, ABARES[6]).*

Wild-catch fisheries

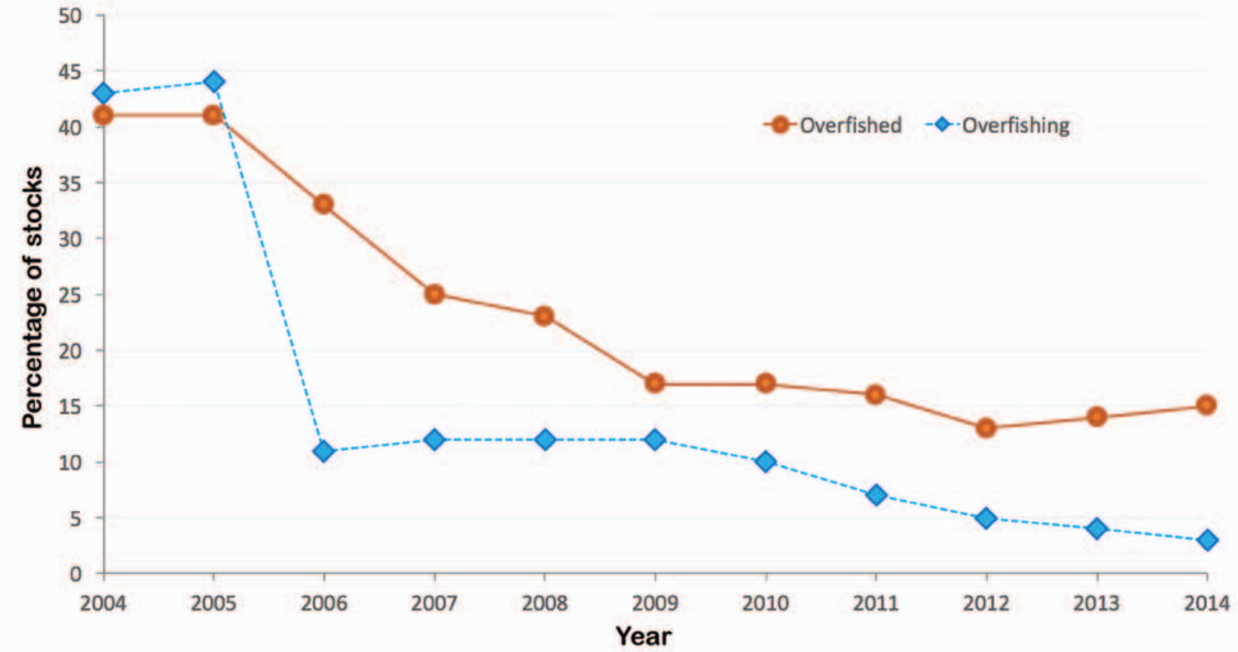
Australia's wild-catch fisheries comprise three sectors: commercial, recreational and Indigenous. Commercial fisheries operate from the tropics to sub-Antarctic waters. The bulk of the catch is from coastal and marine waters, with small amounts from estuaries and negligible catches from freshwater systems. Marine fisheries exploit depths to over 1500 m. Several methods are used including trawl, pots, traps, line, nets and collection by divers.

A large proportion of the catch is high-value species that mostly are exported, including rock lobsters, prawns, tunas and abalone. Australian marine fisheries account for only 0.2% of landed volume from global marine fisheries but 2% of marine fisheries' landed value. Fishery product imports, however, are greater in volume and value than local production, with Australia importing over 70% of its seafood consumption.[7]

Prawn trawler at sea (Source: CSIRO).

The Commonwealth Harvest Strategy Policy implemented in 2008 has seen a rapid improvement in the status of Australian fish stocks currently managed by the Commonwealth (Fig. 9.2).[8]

Two hundred and thirty-eight stocks were assessed nationally recently for their status in light of ongoing harvest.[9] Only 5% of stocks were determined to be overfished, comparing favourably with a global figure of around 30% overfished.



▲ ***Figure 9.2****: Percentages of species or stocks managed by the Australian Fisheries Management Authority (AFMA) overfished (orange) or subject to overfishing (blue) from 2004 to 2014. Overfished refers to stocks below the biomass considered to be a minimum acceptable level and overfishing refers to fishing mortality rates that are higher than considered sustainable (Source: CSIRO, after Smith* et al. *2014[8]).*

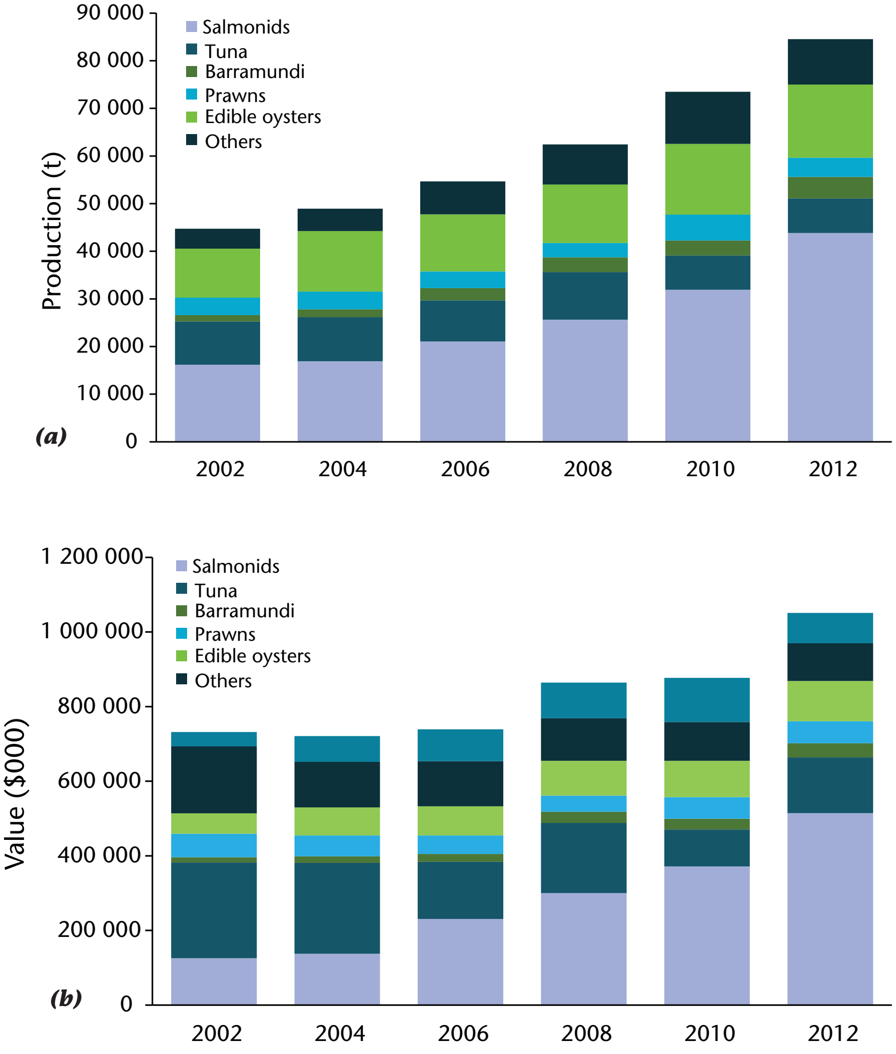
The estimated Australian recreational fisheries catch is around 48 400 tonnes with a retained catch of ~30 000 tonnes. The total direct and indirect value of recreational fishing in Australia was estimated to be A$2.56 billion in 2013.[4] It generally is acknowledged that catching success of recreational fishers is increasing through application of new technologies but there also are indications that participation rate is declining.[4] It is estimated that Indigenous customary fishing harvests ~2000 tonnes per year[5] across all species.

Aquaculture

Australia's aquaculture industries include tropical, subtropical and temperate water species. Production systems include near-shore cages, rafts and lines and onshore ponds. The volume of Australian aquaculture production has increased at an average of around 11% annually over the past 20 years (Fig. 9.3).

The gross value of Australian aquaculture production increased by A$100 million to $1.1 billion in 2012, including wild-caught southern bluefin tuna that are subsequently reared to market size in cages by the South Australian tuna farming sector. Australian aquaculture production in 2012 was 84 605 tonnes and accounted for 46% of the gross value of Australian fisheries production.[10]

The main aquaculture species in cooler water regions of Australia are Atlantic salmon, Pacific oysters, Sydney rock oysters and wild-caught, cage-reared southern bluefin tuna, with smaller



▸ ***Figure 9.3**:* ***(a)*** *Volume and* ***(b)*** *value of production from Australia's main aquaculture species 2002–2012 (Source: CSIRO, data Australian Fisheries and Aquaculture Statistics, ABARES[6]).*

production of blue mussels, yellowtail kingfish, green lip and black abalone, freshwater trout and marron (a freshwater crayfish). The Atlantic salmon sector has grown most over the past decade, with production reaching 44 000 tonnes and a value of A$513 million in 2012 when it accounted for 49% of the total value of Australian aquaculture and 22% of the total value of fisheries production.[10]

Pearl oyster production is the most valuable sector in warmer Australian waters, with farmed prawns and barramundi the other significant warm-water sectors that are increasing in production volume and value (Fig. 9.2). Other warmer water species include red-claw crayfish, beche-de-mer and cobia. The Australian aquafeed sector is often excluded from aquaculture statistics but is a key aquaculture industry with an estimated value of A$120 million per annum in 2012.

Salmon pens off the south-east coast of Tasmania (Source: CSIRO).

GOVERNANCE, POLICY AND MANAGEMENT SYSTEMS

Wild-catch fisheries

Australia has a large and diverse marine jurisdiction with complex intergovernmental arrangements shaping management of its fisheries.[11] The final adoption in 1983 of the Offshore Constitutional Settlement (OCS) clarified shared responsibility between the state and Federal governments (Chapter 8). States and territories generally have jurisdiction over fisheries operating from low water mark to 3 nautical miles offshore and the Federal Government generally has responsibility over fisheries beyond 3 nautical miles out to the edge of Australia's Exclusive Economic Zone, typically 200 nautical miles offshore.

A consensus has emerged among jurisdictions that fishery managers should take an EBFM approach that considers the broader ecological impacts of fishing.[12] This is consistent with the growing international demand for environmentally sustainable food production. All Commonwealth fisheries and export-based state fisheries also are assessed for their environmental performance under the *Environmental Protection and Biodiversity Conservation (EPBC) Act 1999*. Australia has well-established participatory processes that see stakeholders actively engaged in the fisheries management system.

Aquaculture

Governance, policy and management systems vary across the aquaculture sector according to the location, species and production systems. All Australian aquaculture enterprises require a licence to operate. The states and territories have responsibilities for most elements of the regulation and licensing.[13] The Federal Government also has responsibilities under the EPBC Act, which provides an overriding requirement for ecological sustainability of all activities. The Federal Government also has several functions in relation to research, quarantine, aquatic animal health, food safety and market access and trade. Other statutory organisations, including the Great Barrier Reef Marine Park Authority (GBRMPA), are involved in the regulation of aquaculture activities that occur within their jurisdiction.

Australia's states and territories are at various stages in the development of aquaculture zones and associated operating conditions, but the rapid growth of aquaculture in Tasmania and South Australia is reflected in the most advanced development of policies, legislation and regulations to facilitate the sustainable growth of aquaculture.

MONITORING, ASSESSMENT AND RESEARCH

Fisheries research has been done in Australia for over a century, with greatest focus on target species and their management. Community expectations, international requirements and market forces over recent decades have resulted in greater emphasis on considering the broader ecosystem impacts of fishing. This shift has seen the development of new observational methods, risk-based approaches to management advice, and greater consideration of economic and social dimensions of fisheries.

Australia's aquatic science institutes and universities also have a long history of supporting aquaculture expansion, including for development of oyster farming, tropical prawn culture in land-based ponds, Tasmanian Atlantic salmon and southern bluefin tuna farming in sea-cages and, more recently, full life-cycle culture of yellowtail kingfish. Current research includes: applications of new technologies to improve species production; selective breeding programs to enhance growth, disease resistance and market quality of farmed fish, crustaceans and molluscs; development of new nutrition and feed technologies and products; and environmental assessment and mitigation. New sensor-based technologies are being developed to monitor in detail environmental conditions and individual health and production on aquaculture farms and new decision-support systems are supporting integrated ecosystem and multiple-use management across uses, including aquaculture (see also Chapter 15).

Significant challenges for Australia's wild fisheries and aquaculture include increasing community requirement for government and industry accountability, poor social licence to operate for the industry, and maintenance of resource access provisions that include recreational and Indigenous sectors while still maintaining a viable commercial industry. Current challenges to sustainable management are likely to be compounded by long-term changes in the ocean environment, which limit the value of past experience and historical patterns for predicting future sustainability of harvests.

Research has a major role in tackling these challenges. Advances in ocean observation systems such as improved ecological and genetic techniques and use of advanced micro-sensors will improve our ability to monitor fishery and aquaculture production and environmental conditions and impacts. New methods to assess the status of data-poor species and fisheries will help fill the gap between small production, low-value fisheries and the high costs of research needed for their management. Innovative decision-support tools that incorporate 'whole of system' modelling, including ecological, social, economic and management information, will underpin successful EBFM.

Key opportunities, focus and targeted impacts of aquaculture research include: step-changes in genetic improvement via advanced selective breeding technologies that increase the value of Australian aquaculture; novel aquafeeds and feed technologies that increase the value of the Australian and global aquafeed industries and reduce global aquafeed reliance on wild-harvest fishmeal; advanced disease detection and prevention technologies that minimise or prevent stock losses to disease and enable the full economic potential of breeds and feed technologies to be realised; and fully integrated aquaculture production systems incorporating sensor-based monitoring and management technologies, climate modelling and decision-support systems to transform production efficiency and sustainability.

Climate variability and change pose widespread challenges to some fisheries and aquaculture. Recent development and application of dynamic seasonal ocean forecasts are enabling Tasmanian salmon farmers to develop strategies to improve the resilience of their industry to such changes.[14] Similar forecasting techniques are being developed to improve the resilience of pond aquaculture elsewhere in Australia and further afield.

Aquatic animal health and biosecurity is a major field of research activity that had little attention in Australia until 1981 when a national fish health reference laboratory was established. That facility was moved to CSIRO's Australian Animal Health Laboratory (AAHL) at Geelong in 1989.

CONCLUSION

Fisheries and aquaculture are important industries for Australia. A growing population, increasing demands by other users for marine resources, long-term changes in the environment due to climate change and increasingly crowded marine and coastal environments will characterise the challenges faced by Australian fisheries and aquaculture.

Fisheries management often is contentious and, in Australia, also complex because of the multiple state and federal management jurisdictions, legislations, and variety in reporting and assessment methods. Development of national standards for fisheries management and coordinated national approaches to harvest strategies and reporting of fishery status have commenced, but still have a way to go.

The Australian aquaculture industry has significant potential to respond to the national and global demand for safe, high-quality seafood produced under strictly controlled environmental management practices. Research will continue to support aquaculture enterprises through improving production processes, selecting the best individuals and bloodlines for culture, developing new feeds that enhance production at lower environmental cost, and improved animal health and disease resistance.

FURTHER READING

FAO (2014) *The State of World Fisheries and Aquaculture: Opportunities and Challenges*. Food and Agricultural Organisation of the United Nations, Rome, Italy.

Finn M, Flood M, Stobutzki I, Maloney L, Ward P, *et al*. (2015) *Status of Key Australian Fish Stocks (SAFS) Reports 2014 and Beyond*. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

Pitcher TJ, Kalikoski D, Short K, Carkey D, Pramod G (2009) An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. *Marine Policy* **33**, 223–232. doi:10.1016/j.marpol.2008.06.002

Ridge Partners (2015) '2014 Australian F&A sector overview. A report supporting the development of Working Together: the National Fishing and Aquaculture RD&E Strategy'. Fisheries Research and Development Corporation, Canberra.

Energy from Australia's marine estate

David C Smith, Kenneth Lee and Andrew Ross

Key messages

- Australia's marine estate contributes significantly to our energy needs and exports.
- There are future growth opportunities in offshore oil and gas, ocean renewable energy, and carbon capture and storage as technologies further develop.
- Research agencies work across the whole value chain from exploration to production and decommissioning.
- There has been increasing focus in recent years on baseline environmental characterisation and oil spill response and preparedness.

INTRODUCTION

Australia's vast marine estate contributes significantly to our energy needs. Australia has abundant energy resources, with net energy exports worth over A$331 billion in 2013–14, including A$31.7 billion of petroleum products,[1] though Australia imports ~80% of its oil requirements. Total energy generation and domestic consumption are shown in Fig. 10.1.

Offshore oil and gas is the most important marine industry, valued at A$25 billion in 2011–12.[2] Future growth opportunities with advances in technology include ocean renewable energy, particularly wave energy, and the reduction of carbon dioxide emissions from conventional power generation and gas production through carbon capture and storage.

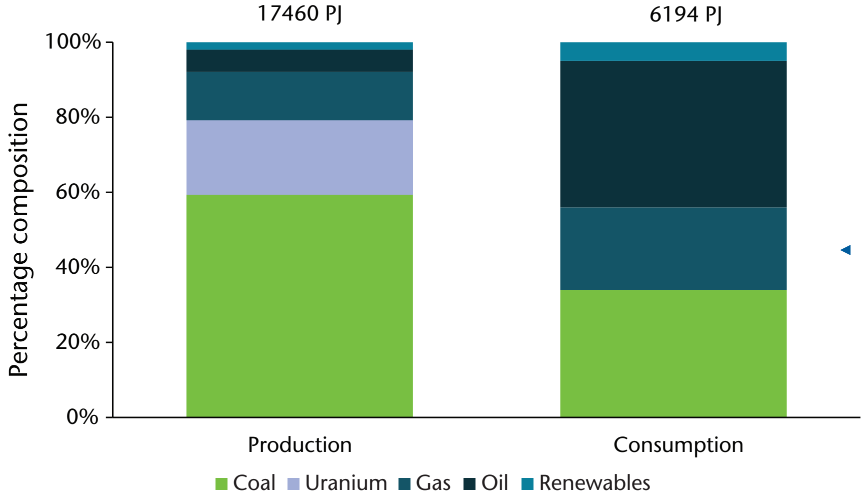


Figure 10.1*: Energy production and primary energy consumption, 2011–12 (Source: Geoscience Australia and Bureau of Resource and Energy Economics[3]).*

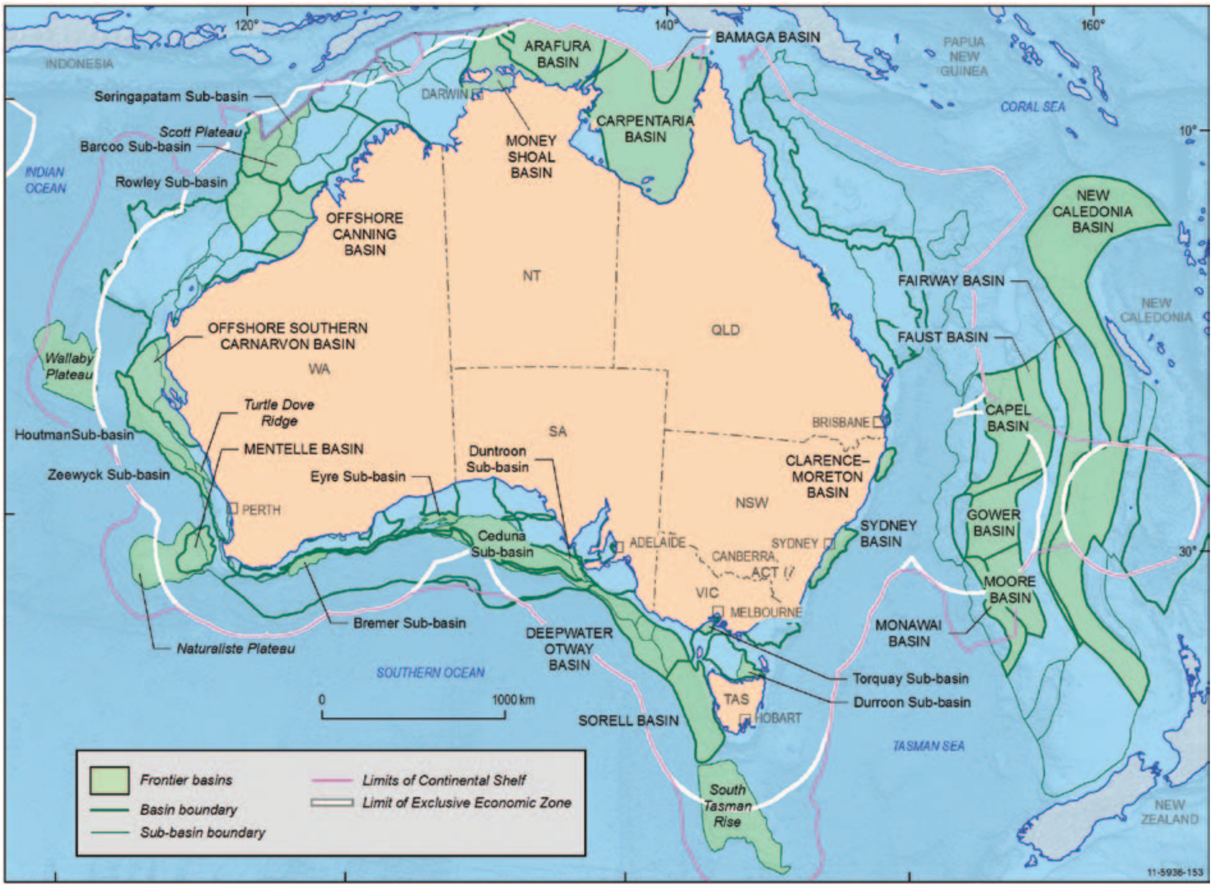
Many Australian research institutions contribute to the science supporting the marine energy sector, including Commonwealth agencies such as CSIRO, Geoscience Australia (GA), the Australian Institute of Marine Science (AIMS) and the Bureau of Meteorology (BoM), some state agencies and several universities.

OFFSHORE OIL AND GAS

Exploration

Australia's marine estate is poorly understood and remains largely underexplored. There are at least 40 offshore geologic basins, but less than 20% (by area) are under current permits for oil and gas exploration or production (Fig. 10.2, also see Chapter 4). Australia produced 79.4 million barrels of crude oil in 2014.[4] Production of liquid natural gas (LNG) has more than doubled since 1998, with exports of LNG reaching 30.4 million tonnes in 2015 with a value of A$16.5 billion. The oil and gas industry's annual contribution to Australia's economic output is expected to more than double from A$32 billion in 2012–13 to A$67 billion by 2029–30, based on the expectation that the north-west shelf region will have an operational life of 45 years.

GA takes the lead in pre-competitive mapping of seabed and subsea geology and regional basin geology. Geophysical data from ships and satellites (seismic, magnetic and gravity data) define the shape and structure of the sub-seabed sedimentary basins and sub-sea basin rocks are sampled to validate the geology of offshore sedimentary basins through dredging and coring or drilling from research or exploration vessels. The detection of natural seepage produced from oil and gas reserves also is used to identify prospective areas for production[5] and also provides essential information on naturally occurring background levels of hydrocarbons in our marine waters to support risk assessments. The Marine National Facility new research vessel *Investigator* – with its state-of-the-art systems for sediment and water column sample collection, seabed mapping,



▲ ***Figure 10.2***: *Australia's offshore frontier basins (Source: Geoscience Australia, Commonwealth of Australia, 2016, CC BY 4.0).*

sub-bottom profiling and chemical and geophysical analysis – has advanced our capability to characterise sub-seabed structures and identify potential hydrocarbon reserves. Advances in satellite technologies are enhancing the frequency of detection and differentiation of sea-surface anomalies in Australia's marine estate such as natural oil seeps, biological events and accidental spills of crude oil and its refined products or other hazardous and noxious substances.

Recent technological advances have enable petroleum activities to extend into deeper waters across the globe, including around Australia. Woodside Energy Limited, for example, in 2014 drilled an exploration well (Steel Dragon-1) at a depth of 2037 m off north-western Australia.

Environmental regulation and research

The Federal Government established the National Offshore Petroleum Safety and Environmental Authority (NOPSEMA) in January 2012 as a single unified regulator to enforce compliance with offshore safety, well integrity and environmental management across the industry, largely in response to the Montara (oil spill) Commission of Enquiry (2011) and a Productivity Commission Report (2009). Responsibility for reporting on offshore environmental practices previously sat with state and territory designated authorities. Those responsibilities were transferred formally to NOPSEMA with the passing of the *Offshore Petroleum and Greenhouse Gas Storage Amendment (National Regulator) Act 2011*. The National Plan for Maritime Environmental Emergencies (the National Plan) led by the Australian Maritime Safety Authority (AMSA) provides the over-arching policy framework and national arrangements for the management of maritime environmental emergencies, including those arising from offshore energy activities.

Australian research agencies work across the entire value chain of oil and gas production, including exploration and production, transport and, more recently, decommissioning, to meet regulatory needs. Research areas include: environmental characterisation and baselines; oil spill response (including for shipping spills); ocean state forecasting; foundation engineering; and coastal infrastructure. Recent advances also have incorporated technologies provided by the oil and gas industry, such as autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs), with great potential to enhance significantly the value of scientific studies in deep water.

There is little doubt that the recent Deepwater Horizon and Montara oil spills have changed dramatically public perceptions of how the industry and government should operate in terms of technology, risk assessment, on-site management and policy. One consequence of the publicity following these major events is that there is a much greater focus on baseline characterisation and modelling of the environments in which oil production occurs (see Box 10.1), and where oil spill preparedness, response and recovery capacity is required. AMSA, for example, released an updated *Oil Spill Monitoring Handbook* in 2016 for use across the Australian marine estate.[6]

Response to spills includes: monitoring impacts; predicting oil fate, behaviour and transport; development of remediation technologies; and methods to assess damage and validate recovery of affected areas.

Areas of required improvement remain across the industry, however, and a greater focus needs to be given to field studies that can verify modelled impacts from production activities, investigations into cumulative impacts at the appropriate temporal and spatial scales, and improved facilitation of information sharing across common environmental risks.

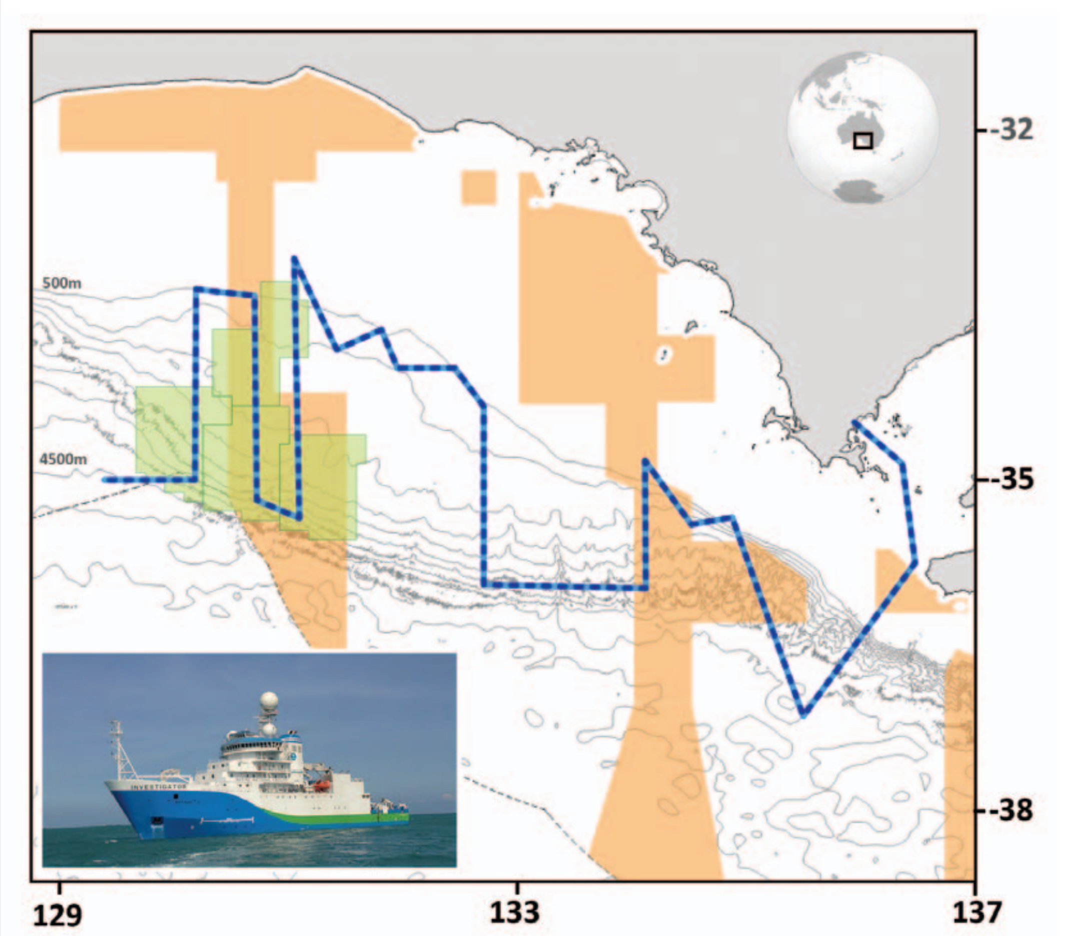
Seismic surveys that are central to geological exploration for potential oil and gas fields often are contentious, with concern regarding impacts on marine systems, particularly iconic species such as whales and dolphins. Impacts of noise on other sectors such as fisheries target species are poorly understood but still generate considerable controversy. Several research agencies are engaged in studying the impacts of marine noise on marine mammals and commercially important fishery species such as southern rock lobsters.

Box 10.1: The Great Australian Bight Research Program

BP planned to invest A$1.43 billion and drill four exploratory wells in the hope of discovering a new deep-water oil and gas province in the Great Australia Bight (GAB), though those plans were put on hold in 2016. The GAB is one of Australia's most valuable marine ecosystems. It supports globally significant populations of seabirds and marine mammals, diverse and endemic seabed communities and important fishing, aquaculture and ecotourism industries.

Two research agencies (CSIRO and the South Australian Research and Development Institute) and two South Australian universities (Adelaide and Flinders) entered into a A$20 million collaborative research partnership with BP Australia to undertake an integrated study of the ecological processes and socio-economic importance of the GAB. The program is one of the few whole-of-system studies ever undertaken in Australia, the first such study before an Australian exploration activity, and the first large-scale, integrated study of the ecosystems, resources and socio-economic values of the GAB (Fig. 10.3).

The Research Program comprises seven themes: physical oceanography; pelagic ecosystem and environmental drivers; benthic biodiversity; ecology of iconic and apex predators; petroleum geology and geochemistry; socio-economic values; and data integration and ecosystem modelling.



▲ ***Figure 10.3***: *Map of RV* Investigator *planned cruise track (blue line) from December 2015, with Commonwealth marine reserves (orange), the BP exploration permit area (green), the Exclusive Economic Zone (dashed black line) and 500 m depth contours also shown. Inset photo of RV* Investigator *(Source: CSIRO).*

Decommissioning

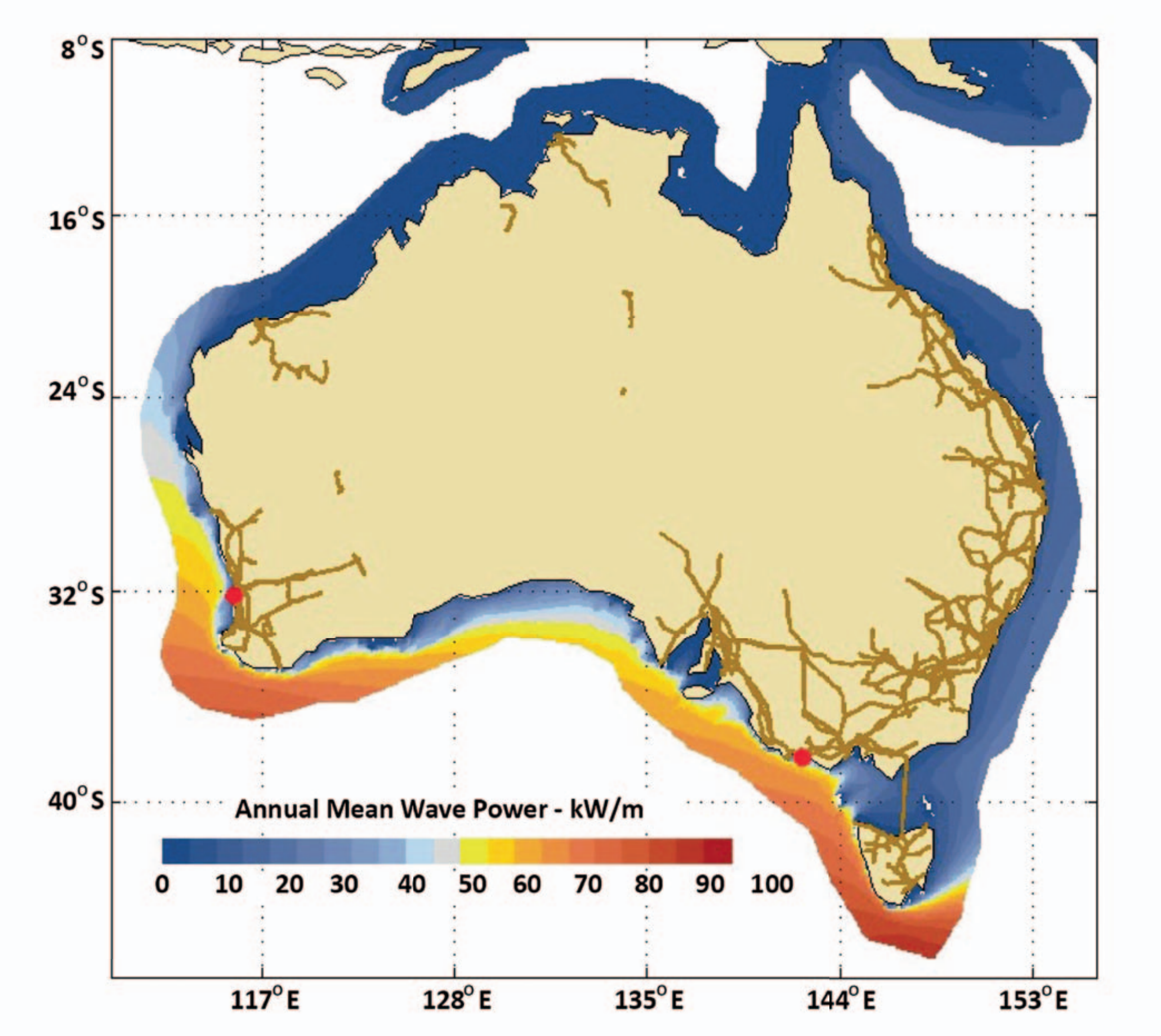
Those offshore oil and gas structures approaching obsolescence will require decommissioning. Decommissioning of facilities may leave unwanted, long-lasting environmental, societal and economic legacies or risks if not properly managed. An oil or gas well that has come to the end of its useful life typically is plugged to prevent leaking of fluids and gases into the ocean. NOPSEMA administer regulations under the *Offshore Petroleum and Greenhouse Gas Storage Amendment (National Regulator) Act 2011* covering safety, well integrity and environmental management, including decommissioning. Risks to the integrity of the well must be reduced to as low as practicably possible.

Removal policies are based on returning the seabed to the condition in which it was found, but some structures develop extensive marine communities around them during their production lives. It has been argued recently that removal of structures may not represent the best environmental practice.[7] One suggested approach is to leave such structures in place as artificial reefs ('rigs-to-reefs') and there now is substantial debate around decommissioning activities.

Oil rigs need to be decommissioned at the end of their operating lives, raising long-standing issues of securing disused wells and new issues about the effects of removing structures that have been in place for decades and now support marine communities (Source: photo of Rankin A, courtesy Horizon International Images).

MARINE RENEWABLE ENERGY

The marine renewable energy industry is an emerging industry globally. Marine renewable energy generation in Australian waters is at a fledgling stage that is predominantly focussed on wave energy,[8] primarily across the southern coasts of Australia (Fig. 10.4). Deployments of marine energy generators in Australian waters are limited to two pre-commercial scale (less than 500 kW) power stations off Perth, Western Australia and off Port Fairy, Victoria and a few experimental or prototype deployments. There is a smaller tidal energy sector located in tropical northern waters and areas adjacent to the Bass Strait Islands. It remains unclear whether these activities are likely



▲ ***Figure 10.4***: *Wave energy atlas of Australia. Red dots show locations of two mature wave energy projects at Port Fairy, Victoria, and Perth, Western Australia. Brown lines on the land indicate Australia's primary existing electricity grids (Source: CSIRO).*

to be suitable for large-scale deployment (more than 100 MW capacity). Australia is not a member of the International Energy Agency's working group on Ocean Energy Systems. Wave, current, and wind energy assessments depend on oceanographic data provided by the BoM and CSIRO and digital elevation data for the seabed and adjacent land, as well as regional infrastructure information related to likely energy demand.

There is a considerable resource of wave energy around Australia (Fig. 10.4) that is non-limiting and a viable means of adding to Australia's future low-emission energy production once appropriate technologies become available at financially viable cost. CSIRO has undertaken early assessments of the wave resource and recently commenced a project funded by the Australian Renewable Energy Agency (ARENA) to develop an Australian wave energy atlas and do experiments to assess impacts of energy extraction from waves on surrounding hydrodynamics.

Research on the efficiency and environmental effects of ocean energy technologies (based on the recovery of energy from waves, tides and wind) largely has been driven by technology developers and regulatory agencies in the Northern Hemisphere. Understanding impacts of ocean renewable energy technologies (including offshore wind) on the marine seabed and biological features is required. Potential research areas include the assessment of the ecological risks associated with changes in hydrodynamic and physical or chemical properties of the ocean (including marine noise) that might impact directly the biota or their habitat.

CARBON CAPTURE AND STORAGE

It is anticipated that fossil fuels will remain the world's and Australia's dominant source of energy for the next two to three decades, despite recognised concerns about the climatic effects of fossil-fuel emissions of greenhouse gases. There is ongoing interest in capture and disposal of the produced carbon dioxide (CO_2) from conventional energy production such as from coal and oil or gas power stations to reduce atmospheric emissions.

Assessment of the potential for secure carbon capture and storage (CCS) in offshore basins, potentially following oil or gas extraction, has been a recent new objective for marine science and policy in Australia. The secure containment of geologically sequestered CO_2 is an important component of effective emissions reductions. Detailed seafloor and water column baseline studies are required before any injection of CO_2 into the ocean floor, and natural seepage surveys are essential to map out prospective areas, as well as areas that should be rejected for CO_2 storage. Ongoing monitoring and long-term surveillance also is required to validate storage security.

Australia was the first country to release offshore acreage for the safe disposal of CO_2 and one block in the offshore Gippsland Basin, Victoria, is being evaluated currently as a major CSS site. Pre-competitive data on potential storage areas elsewhere, off the Northern Territory and Western Australia, are being studied by GA and results are being released to industry for commercial evaluation. This work is part of Australia's assessment of methods to reduce greenhouse gas emissions from conventional energy sources.

CONCLUSION

Australia has large offshore reserves of natural gas and substantive reserves of oil. Petroleum exploration and production is extending into deeper waters farther from shore following recent technological advances.

Australian research agencies work across the entire value chain from exploration, to production, transport and decommissioning to meet regulatory needs. Accidents continue to represent a key risk, however, despite advances in technologies and best available operational safety protocols. Such unplanned events have the potential for significant physical and biological environmental consequences. Knowledge of the risks and impacts from oil spills, and how to prevent or minimise such effects, has increased dramatically following significant spill incidents both in Australia and internationally over recent years.

There are significant future growth opportunities in ocean renewable energy and carbon capture and storage as technologies develop further, and associated research opportunities to support the safe and well-managed development of those opportunities.

FURTHER READING

APPEA (2015) *Key Statistics 2015*. The Australian Petroleum Production and Exploration Association, Canberra.

Geoscience Australian and BREE (2014) *Australian Energy Resource Assessment*. 2nd edn. Geoscience Australia, Canberra.

Hemer MA, Zieger S, Durrant T, O'Grady J, Hoeke RK, *et al.* (2016) A revised assessment of Australia's national wave energy resource. *Renewable Energy*, <http://www.sciencedirect.com/science/article/pii/S0960148116307406>.

CHAPTER 11.

Coastal development

Andrew DL Steven, Simon Apte, L Richard Little and Mat Vanderklift

Key messages

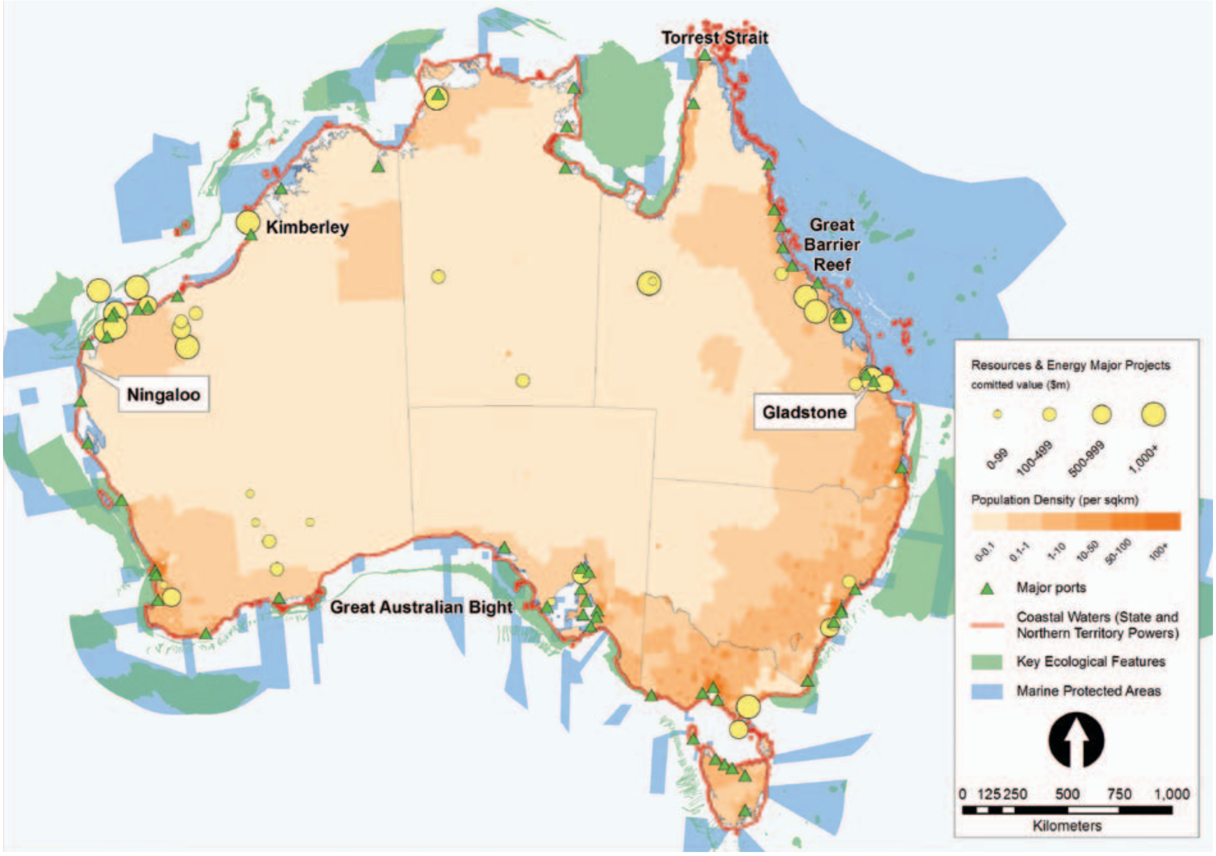
- ✻ Our social, economic and ecological dependence on the Australian marine estate will increase as human populations grow and commercial use of coastal resources expands.
- ✻ A key challenge will be to balance the multiple competing uses and the impacts of those uses to ensure opportunities are realised and needs are met in environmentally, economically and socially sustainable ways.
- ✻ Research on coastal development is important to support informed decision making.

INTRODUCTION

More than 80% of Australians live within 50 km of the coast, many in our coastal capital cities and, increasingly, in regional coastal towns. The ‘coast’ or ‘coastal zone’ means many things to different people: an ecosystem with intrinsic values; a commodity to be bought and sold; a community place where people meet; a landscape with aesthetic appeal; a productive system generating profits; a waste disposal service; a property to be managed; or a spiritual realm.[1] The multiplicity of these constructions illustrates the competing demands for the services derived from our coastal assets. Coasts are defined in this chapter as the zone of interface between terrestrial, aquatic and marine environments, incorporating those marine environments within 3 km of the shoreline low water level (see Chapter 8) and extending landwards, nominally 50 km but noting that the size of that interface is different for different issues and processes.

Australia's continental coastline is ~36 000 km long and spans 35° of latitude (Fig. 11.1). Coastal biodiversity and habitats vary greatly and are shaped by a range of climates, prevailing wave and tidal regimes from three surrounding oceans, the varied geology of the Australian continent and the consequences of severe events such as cyclones and floods. These coastal environments include more than 900 estuaries, 10 000 sandy beaches and 8000 diverse islands and vary latitudinally from World Heritage-listed coral reefs around northern Australia to temperate rocky and sandy shores in the south.[2] We do not discuss in this chapter the coasts of Australia's Antarctic Territory since that coast mostly is unpopulated and subject to international treaty arrangements.

Our social, economic and ecological dependence on urban coastal environments will increase as human populations and commercial maritime activities continue to expand. Sustainable management of Australia's coastal domain will need to take into account the full range of economic, social, cultural and environmental values. Ensuring that opportunities are realised and needs are met in an environmentally, economically and socially sustainable manner will need to be underpinned by short- and long-term strategic research that supports informed decision making.[3]



▲ ***Figure 11.1**: The Australian coast showing areas of key ecological features, marine protected areas and coastal development patterns including population density, port, and resource and energy developments (Source: CSIRO).*

(a) *Mangroves occupy large stretches of the coast in northern Australia.* ***(b)*** *Granite outcrops of the coastline in Torndirrup National Park, Western Australia reflect a coast heavily influenced by exposure to waves (Sources: a Mat Vanderklift, CSIRO; b Jo Myers, CSIRO).*

Pressures on the coastal zone

The main contemporary pressures on the Australian coastal zone are: nutrient and chemical contaminant inputs from diffuse and point sources; urban development and population growth; coastal industrial development; port expansions and dredging; shipping traffic; tourism; and fishing and aquaculture.

Parts of Australia's coast, such as Cockburn Sound in Western Australia, face challenges associated with use by heavy industry (Source: CSIRO).

There has been substantial degradation to ocean coasts, bays and estuaries in the east, south-east and south-west of Australia.[4] Water quality is considered poor in over half of the estuaries in New South Wales, for example. Many have double the natural levels of sediment and nutrient inputs, and around one-third of catchments have lost over 50% of their natural vegetation through land clearing.[4] Much of the impact occurred in the mid–late 19th and 20th centuries and arose from unregulated or poorly regulated human activities in river catchments, urban and coastal developments, and fishing.

Many of these current pressures co-occur and give rise to a complex mix of stressors and resulting impacts that will intensify as our activities in the coastal zone grow. Research focusses on understanding the risks to marine ecosystems, predicting impacts of existing and proposed activities and developing mitigation options. The issue of multiple use and the cumulative effects of multiple coastal developments on an area is illustrated in Box 11.1 for Gladstone Harbour.

HOW DO WE MANAGE COASTAL ECOSYSTEMS?

Coastal governance is carried out across three levels under the Australian system: federal, state, and municipal. The Federal Government typically plays a relatively minor role in most coastal governance due to its delegation of coastal waters responsibilities to the states under the Offshore Constitutional Settlement (Chapter 8) and because most terrestrial coastal areas sit under state and municipal jurisdictions. The Federal Government has endorsed the concept of Integrated Coastal Zone Management (ICZM), which recognises that multiple use of the coastal zone needs to be balanced with environmental stewardship. States retain responsibility for coastal waters within 3 nautical miles of the low tide level but delegate much of the onshore management and planning to municipal governments.

State governments manage conservation and recreation ‘on the water’ within their coastal waters. State marine protected areas, in the form of marine parks or reserves, are a common tool used for this purpose. Indigenous Protected Areas are a more recent initiative, where Traditional Owners and ranger groups manage activities including use of sea country by Indigenous people.

State governments also manage commercial and recreational fisheries operating within Coastal Waters. These activities are governed in two broad ways: by limiting fishing effort through limited entry, licences, gear restrictions, and time of fishing; and by limiting catch, through quotas, bag limits and size limits. Aquaculture, infrastructure and urban development are managed through planning authorities.

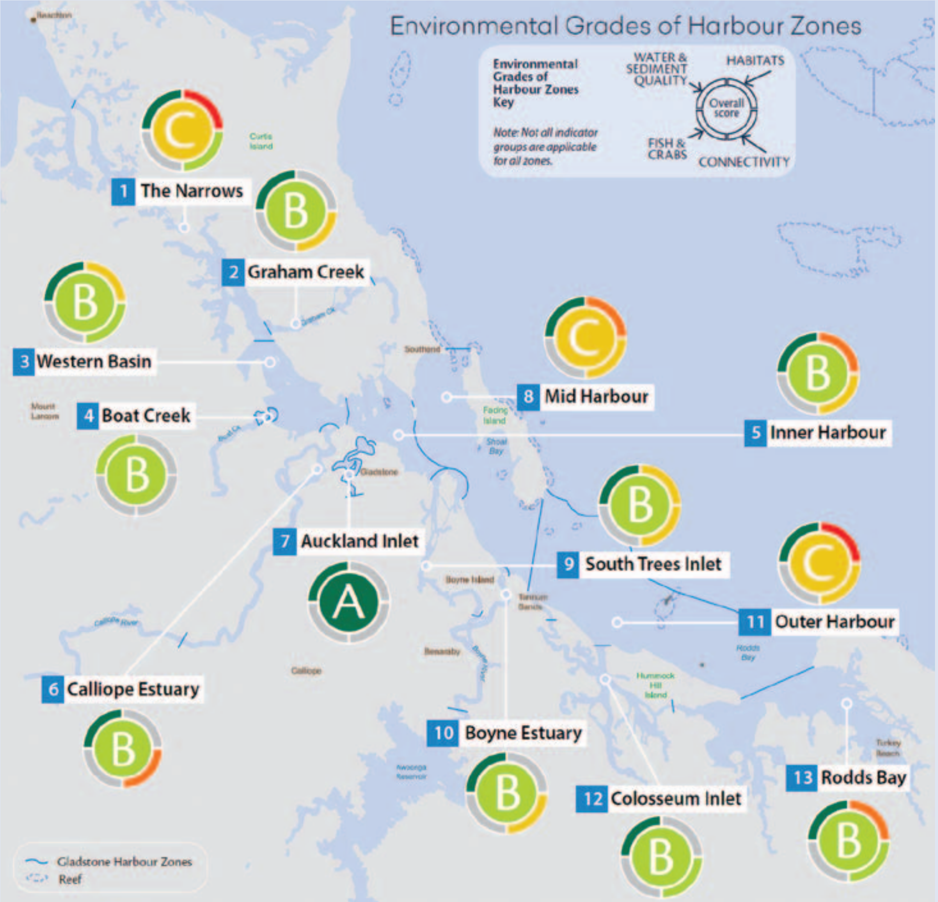
State and municipal governments increasingly are looking to new institutional arrangements in managing coastal areas to deal with institutional failures arising from overlapping and unclear jurisdictions in the coastal zone. Stakeholder partnerships are being used to bring together a range of stakeholders including municipal councils, industries and environmental managers to monitor coastal use (Box 11.2).

Box 11.1: Cumulative pressures in the coastal zone: Gladstone Harbour

The central Queensland town of Gladstone has been an industrial hub since the 1960s. The shores of the harbour are home to a range of industries including two of the world's largest alumina refineries. It is also the fifth largest multi-commodity port in Australia and the world's fourth largest coal exporting terminal. The western parts of the harbour basin have been expanded recently, primarily to allow increased exports of liquefied natural gas (LNG).

Gladstone harbour is within the World Heritage Area of the Great Barrier Reef, and historically has supported a thriving seafood industry and is a focal point for recreational fishing. A large-scale dredging operation was conducted recently in the harbour and controversially was blamed for fish kills and fish disease, which harmed the local fishing industry.

The Gladstone Healthy Harbour Partnership – an alliance of government, community and industry – has been formed to advise management of the multiple uses of the coastal zone. The partnership applies best-practice science to understand and manage the growing pressures. They have commissioned research that includes development of predictive models that can be used to run future scenarios of various regional developments and possible environmental impacts along with an annual report card (Fig. 11.2), which evaluates environmental, social, economic and cultural performance.



▲ ***Figure 11.2***: *Gladstone Healthy Harbour Partnership report card for 2015. The environmental, social, economic and cultural health of the harbour is assessed each year and regions graded from A (very good) to E (very poor) (Source: courtesy Gladstone Healthy Harbour Partnership).*

Box 11.2: Ningaloo Reef: where municipal, state, federal and international governance meet

Ningaloo Reef is a large fringing coral reef system on Australia's west coast and a hotspot where the challenges of balancing the interests of conservation, recreation and economic opportunity are intense. Ningaloo is a World Heritage Area and a marine park under both Western Australian and federal legislation. It attracts hundreds of thousands of visitors each year who participate in activities such as swimming with whale sharks and recreational fishing. Fishing, along with climate change, is considered one of the main threats to the conservation values of Ningaloo. Production wells for oil and gas not far from the boundary of the World Heritage Area add to the complexity of managing the system. The information needed to manage the needs of conservation, recreation, industry and the local economy is significant. Several large research initiatives have been undertaken, including within the Western Australian Marine Science Institution, the Ningaloo Collaboration Cluster, the Pilbara Marine Conservation Partnership and Ningaloo Outlook. This research investment has provided maps of the seabed and seabed communities, understanding of the ways that ocean currents move, assessments of the state of valued and ecologically important species and the pressures on their populations. This information has been brought together in evaluations of the trade-offs among various management actions, from size and placement of sanctuary zones to modified bag limits for recreational fishers to the social and environmental impact of different types of tourist accommodation.

Tourists come from all over the world to swim with whale sharks at Ningaloo, just one of the species of megafauna that are characteristic of this World Heritage Area (Source: Mat Vanderklift, CSIRO).

FUTURE RESEARCH CHALLENGES

Coastal research encompasses a broad range of biophysical and socio-economic disciplines and is carried out by scientists and engineers employed by universities, museums, federal and state fisheries, and environment, planning and climate agencies.

The National Marine Science Plan 2015–2025[5] identifies the science required to underpin development of Australia's blue economy (Chapter 7). *Urbanising coastal environments* is one of seven grand challenges identified in the plan. This challenge must balance multiple competing uses and the impacts of those uses, because the decisions we make now will have profound consequences for future generations (Box 11.3). Applied and basic strategic coastal research, such as that listed in Table 11.1, is required to underpin the repair and ongoing management of these high-value ecosystems for improved productivity and enhanced cultural and conservation values.

Table 11.1: Ten science challenges for the urban coastal zone identified in the National Marine Science Plan.[6]

1.	Better characterise coastal habitats, environment processes and define envelopes of natural variability.
2.	Understand catchment contaminant pathways and define thresholds of concern.
3.	Address cumulative impacts and identify important stressor interactions.
4.	Develop bio-observing technologies.
5.	Understand the impacts of degradation and loss of coastal habitats, including the loss of productivity and ecosystem services.
6.	Incorporate quantitative and qualitative social and cultural perspectives into coastal decision making.
7.	Develop, test and apply eco-engineering approaches.
8.	Develop methods to mitigate coastal hazards.
9.	Improve data coordination and discoverability.
10.	Support the development of urban/coastal industries.

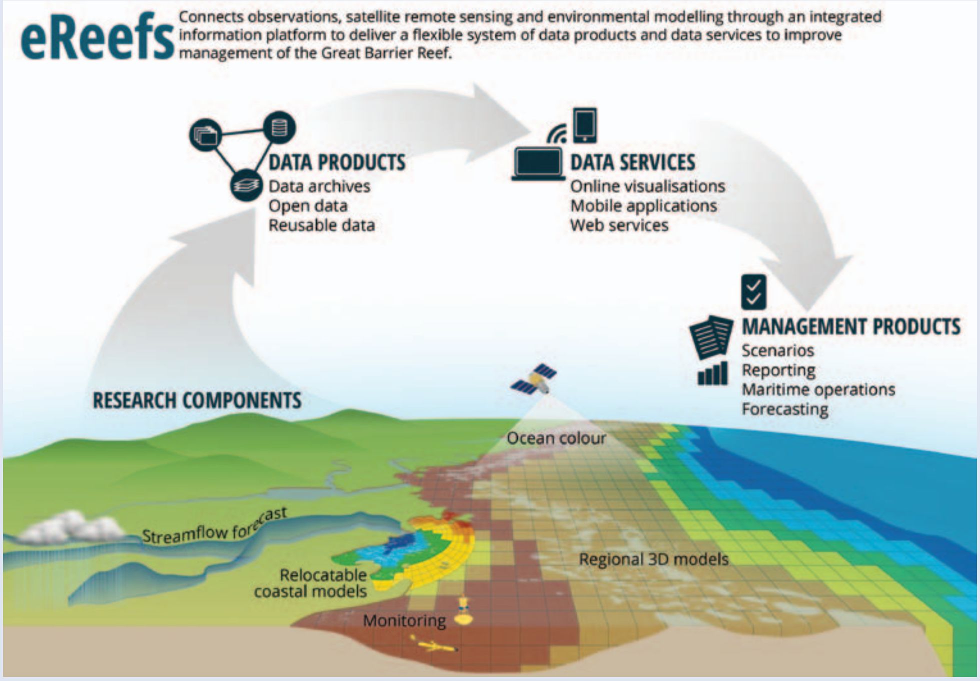
Box 11.3: eReefs: an information management system for the future of the Great Barrier Reef

eReefs is a collaborative project that contributes to the protection and preservation of the iconic Great Barrier Reef (GBR). eReefs is built upon an integrated system of data, catchment and marine models, visualisation, reporting and decision-support tools that span the entire GBR and adjacent coastal areas – from paddock to catchment, estuary, reef lagoon and ocean. It provides the first comprehensive information platform capable of meeting the many and varied needs of users for access to improved environmental intelligence, allowing them to assess past, present, and future conditions and management options to mitigate the risks associated with multiple, and sometimes competing, uses of the GBR and adjacent land areas. Importantly, it also forms the first step in building comprehensive coastal information systems for Australia.

The centrepiece of the eReefs information platform is a whole-of-region, shelf-scale, numerical marine modelling system. The modelling system comprises hydrodynamic models to predict the physical state of the GBR, sediment transport models predicting the fate of suspended fine sediments and a biogeochemical model to predict water column and benthic production, water quality and nutrient cycling. A web-based modelling environment called RECOM (RElocatable Coastal Model) can be accessed by users to establish models quickly at the scale of individual estuaries, embayments or coral reefs.

Automated sensors are used that can make near-continuous measurements of water quality and quantity variables to provide better data for users and for models. Access to satellite-derived synoptic daily maps of water quality for the GBR is available through a marine water quality dashboard (http://www.bom.gov.au/marinewaterquality/).

The backbone of the eReefs information platform is an innovative information architecture that enables access to data from a range of data custodians. This information can be discovered dynamically, making it much easier to develop end-user products. Access to these models and datasets has been simplified thorough the development of a visualisation portal (http://portal.ereefs.info/) that allows users to interact with eReefs products easily via the web (Fig. 11.3).



▲ ***Figure 11.3***: *Conceptual diagram of eReefs information platform for managing the Great Barrier Reef (Source: CSIRO).*

CONCLUSION

Australia’s social, economic and ecological dependence on our coastal estate will increase as human populations grow and commercial use of coastal resources expands. A key challenge for Australia’s future will be to balance the multiple competing uses, and the impacts of those uses, to ensure opportunities are realised and needs are met in environmentally, economically and socially sustainable ways.

FURTHER READING

Short AD, Woodroffe CD (2009) *The Coasts of Australia*. Cambridge University Press, Cambridge, UK.

SoE (2011) ‘State of the environment 2011. Australia state of the environment 2011’. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. Australian Government, Canberra.

Stocker L, Kenchington R, Kennedy D, Steven ADL (2012) Introduction to Australian coasts and human influences. In: *Sustainable Coastal Management and Climate Adaptation*. (Eds R Kenchington, L Stocker, D Wood) pp. 1–28. CSIRO Publishing, Melbourne.

CHAPTER 12.

Operational oceanography – security, safety, transport, search and rescue

Peter R Oke and Andreas Schiller

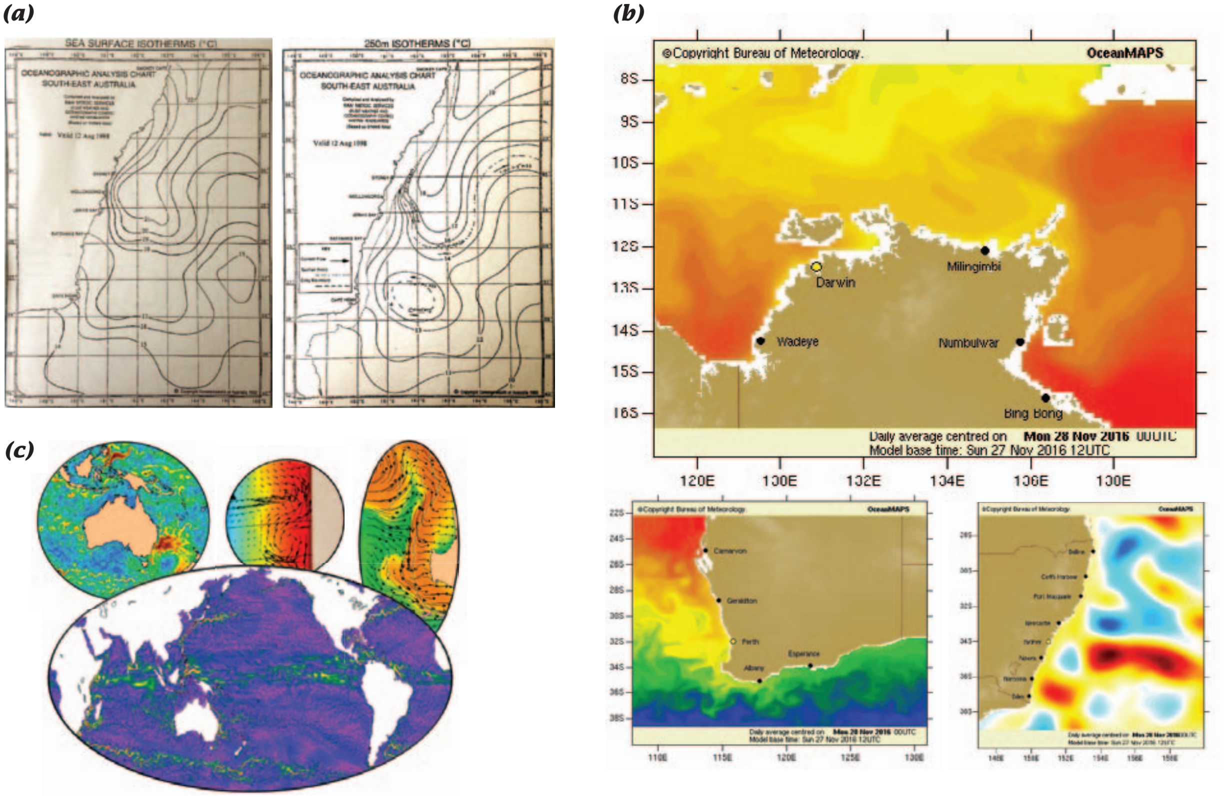
Key messages

- Near-real-time forecasts of ocean conditions are possible now as a result of advanced new technologies and a history of oceanographic research.
- Ocean forecasts are key to defence operations and play key roles in optimising vessel passages, search and rescue and operations of many marine industries.
- Ocean observations and detailed ocean models are essential for ocean forecasts.
- Continued improvements in ocean forecasts will accrue with further advances in technology and future oceanographic research.

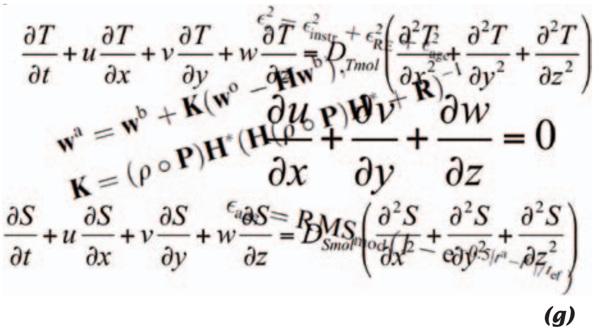
INTRODUCTION

Operational oceanography is the application of ocean data to provide estimates of the current and future ocean state, usually via ocean models that use data from satellites, ocean buoys and other sources. Operational oceanography now delivers forecasts and analyses of the three-dimensional ocean circulation and ocean properties in near-real-time. The emergence of operational oceanography follows a revolution in ocean observations and the proliferation of supercomputing for scientific research. Continued improvements in the accuracy and comprehensiveness of oceanographic forecasts are anticipated (Chapter 16). Operational oceanography has proven to be an indispensable service to the Australian and international community through provision of economic, social and environmental benefits to the general public, to marine industries and to defence. It provides near-real-time support for shipping, marine search and rescue, defence and border security, and marine industries, including fishing, offshore oil and gas and tourism.

The value of ocean forecasts has been long recognised by defence forces. Oceanographic information available to navies and the public up to the 1980s and 1990s was minimal – limited to hand-drawn maps of ocean properties based on sparse observations (Fig. 12.1a). Operational ocean services delivered today, by contrast, include a range of products (Fig. 12.1b and c) that



▲ **Figure 12.1**: *Schematic diagram showing the progress of operational oceanography, contrasting* ***(a)*** *the hand-drawn maps of the 1980s and 1990s and earlier with* ***(b)*** *a range of three-dimensional, near-real-time forecasts and analyses, and* ***(c)*** *maps of ocean properties available today (Sources: a Commonwealth of Australia, 1999, reproduced with permission of the Australian Hydrographic Service; b Bureau of Meteorology, Commonwealth of Australia; c Peter Oke, CSIRO).*



Various modern ocean observation and modelling platforms and instruments: ***(a)*** *deploying an XBT device;* ***(b)*** *Argo robotic floats ready for deployment;* ***(c)*** *deploying the 'seasoar' instrument from RV* Franklin*;* ***(d)*** *Australia's national supercomputer;* ***(e)*** *satellite remote sensing of sea level;* ***(f)*** *retrieving deep ocean observational moorings from the Antarctic resupply vessel* Aurora Australis*; and* ***(g)*** *a depiction of the types of equations used to underpin ocean forecasting and previously requiring laborious manual calculation (Sources: a R. Cowley; b Bruce Miller, CSIRO; c NASA; d National Computational Infrastructure, Australian National University; e–f CSIRO; g Peter Oke, CSIRO).*

estimate the past, present, and future properties of the ocean in great detail, often with near-real-time updating. Some of the information now delivered routinely includes ocean circulation, wave heights, sea level, and water properties – including temperature, salinity and chlorophyll-a (a measure of phytoplankton).

Applications of operational oceanography include the provision of up-to-date information of ocean circulation to competitors in yacht races, such as the Sydney-to-Hobart race (Fig. 12.2, left). Ocean forecasts and analyses can help competitors plan their path and avoid accidents (e.g. iceberg encounters at high latitudes in round-the-world races).

Some applications of ocean forecasts are surprising. For example, analyses of a 20-year ocean hindcast – a model simulation of the historical ocean circulation – helped support the successful search in 2009 for the Australian Hospital Ship *Centaur*. The *Centaur* sunk off eastern Australia in May 1943 resulting in the deaths of 268 of the 332 crew. The ship's captain survived the incident and precisely reported the location of the sinking, indicating that the survivors of the *Centaur* had drifted north-eastwards for 36 hours before their rescue. Many at the time doubted this report, citing the dominance of southward flow of ocean currents in the region. Analysis of historical oceanographic conditions, however (Fig. 12.2, right), indicated that the captain's account was plausible if an eddy was present at the time of the sinking. An expedition to locate the sunken hospital ship was conducted armed with such analyses and the confidence that the captain's report could be true. The remains of the AHS *Centaur* were found near the captain's reported position, solving a long-standing maritime mystery.

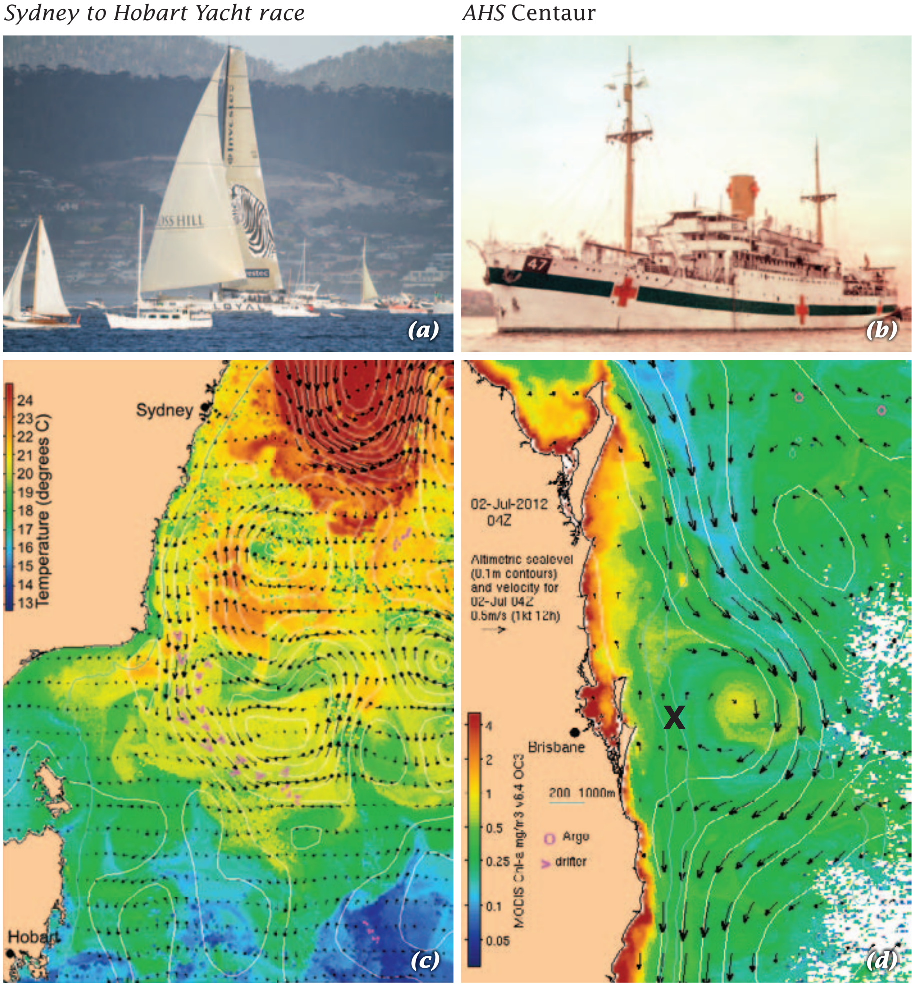
Other applications of operational oceanography include the support of search and rescue operations, promoting security, assisting safety at sea and enabling efficiency for a range of marine industries.

SECURITY

Australian oceanographic research is important in maintaining Australia's presence and sovereignty in the Southern Ocean. Oceanographic research in the Southern Ocean and around Antarctica is an important component of Australia's international standing and maintenance of our southern margins as a demilitarised region of peace and research under the international Antarctic Treaty. Unlawful fishing and other activities that threaten Australia's Southern Ocean and Antarctic interests require the Australian Defence Force and Customs to monitor activity in the region and operate for long periods at sea. Ocean forecasts are central to those operations.

Ocean forecasts play a key role in supporting naval operations. Competing navies typically have more or less equivalent hardware (ships, submarines) and knowledge of the current and future ocean environments can provide real tactical advantage in combat and surveillance situations. Ocean forecasting supports naval operations in deep and shallow water.

Predictions of conditions in shallow water (e.g. off beaches) are important for support of amphibious operations. Forecasts of ocean currents, waves, and beach shape are used for planning operations – often providing critical information in determining the 'go' or 'no go' decision for



Sydney to Hobart Yacht race

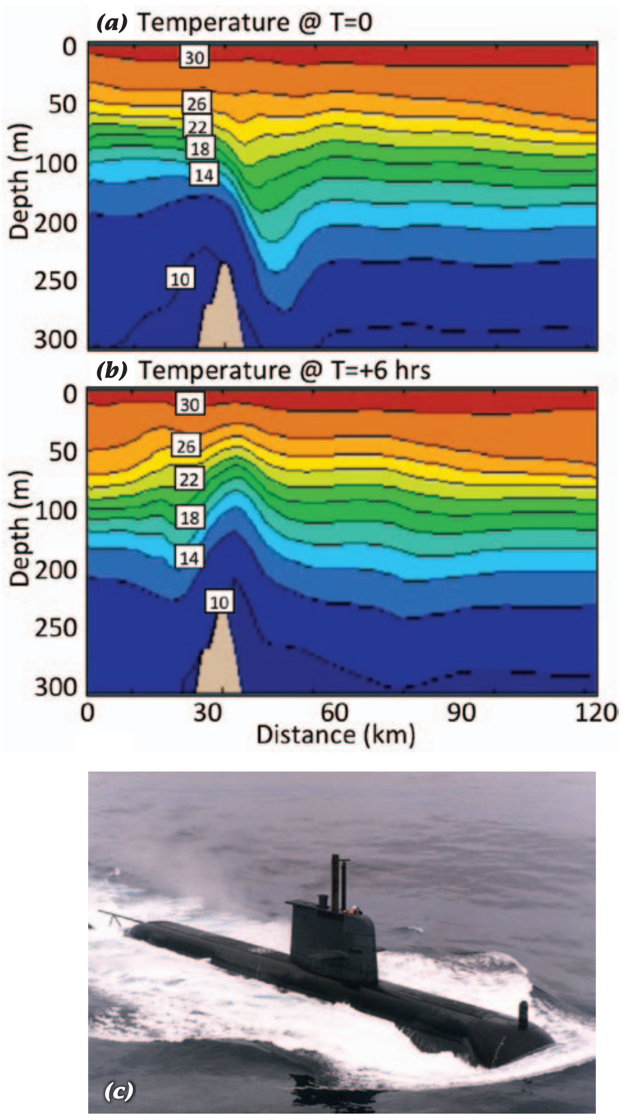
AHS Centaur

▲ ***Figure 12.2***: *Operational oceanography supports:* ***(a)*** *competitors in yacht racing; and* ***(b)*** *expeditions searching for shipwrecks. The maps were taken from OceanCurrent Integrated Marine Observing System (IMOS) and show:* ***(c)*** *sea-surface temperature and surface velocities during the 2014 Sydney to Hobart yacht race; and* ***(d)*** *ocean chlorophyll-a and surface velocities showing an eddy off Brisbane, such as the one believed to have been present when the AHS Centaur was sunk in 1943, at the location indicated by 'X' (Sources: maps courtesy IMOS, www.oceancurrent.imos.org; left photo JJ Harrison, CC BY 3.0, https://commons.wikimedia.org/w/index.php?title = File:Investec_Loyal_about_to_win_2011_Sydney_to_Hobart.jpg&oldid = 228431356; right photo National Archives of Australia, <http://memento.realviewtechnologies.com/default.aspx?iid = 37502&startpage = page0000015): NAA: B6416, 280>).*

a planned mission. Forecasts can inform decision makers about whether planned landings of personnel and vehicles are feasible. The presence of large waves, strong rip currents or offshore sandbars, for example, can make a beach landing unachievable.

Navies often engage in a form of 'hide and seek' in deep water and understanding underwater acoustics is central to success. Sound is emitted by ship and submarine engine noise and other on-board activities. The passage of such sound emissions (acoustic signals) through water is influenced by temperature layers in the ocean, depth (and so pressure) and the amount of particulate matter in the water. A submarine's acoustic signals propagate directly to the surface and the ocean floor under 'good conditions', rendering the submarine almost undetectable, except from immediately above. The same submarine's acoustic signals under 'bad conditions', however, can be channelled hundreds, and even thousands, of kilometres away from the vessel. A poorly located submarine effectively broadcasts its location to enemy vessels, much like whales that communicate over vast distances in the ocean. Submariners use ocean forecasts of sub-surface temperature to 'hide' in regions where detection is least likely. Navy surface ships, conversely, often use oceanographic information to maintain positions with the greatest 'range of detection' so they can 'hear' acoustic signals over large distances in all directions.

Safe passage of submarines also is supported by operational oceanography. Some parts of the ocean, particularly narrow straits and passages, experience large internal waves that can be hundreds of metres in size. Figure 12.3 shows an example of subsurface temperature fields in a narrow strait during a period when an internal wave is present and oscillating over ~6 hours. The difference in shape of the isotherms (depths of the same temperature) between the two snapshots indicates potential vertical displacement of a submarine, which in this case could be up to 200 m. Hitting the seabed or surfacing unexpectedly poses significant safety and security risks for submarines, and so advance warning of the likelihood of internal waves is important for safe passages.



▲ ***Figure 12.3**: **(a)**, **(b)** Fields of subsurface temperature (different colours show layers of different water temperature) in a narrow strait at two times, spaced 6 hours apart, showing large-amplitude internal waves that could displace a submarine by up to 200 m; and **(c)*** HMAS Collins *(Sources: a–b Peter Oke, CSIRO); c AB Kockums, <https://en.wikipedia.org/wiki/HMAS_Collins_(SSG_73)#/media/File:HMAS_Collins_Kockums_photo.jpg>).*

SAFETY

Environmental disasters at sea are common. The Montara oilrig in the Timor Sea, for example, leaked oil and gas continuously into the ocean for 74 days following an accident in 2009. The spill is regarded as Australia's worst oil disaster. The Deepwater Horizon oil spill in 2010 captured the world's attention as oil leaked into the Gulf of Mexico unabated for 87 days, seriously damaging the Gulf's marine environment and coasts. Operational ocean forecasts were used in these, and many other, cases to support oil spill response coordination and planning activities. The movement of spilt crude oil was estimated using predicted ocean currents at various depths. This information allowed decision makers to plan and coordinate activities to contain spills and limit environmental damage.

Oceanography also has an important role in planning and approval processes for oil and gas exploration. Consideration of the likely dispersal of oil if a spill occurred can be used to influence where oilrigs are placed to minimise the risk of oil reaching populated regions or regions of high conservation value. Australia's north-west shelf, for example, is ideal in some respects because the surface currents in that region are almost always directed towards the centre of the Indian Ocean, away from the Western Australian coastline that includes valuable fisheries and high-value conservation areas such as the Ningaloo Coast World Heritage Area.

Oil and gas exploration and operations also depend on regular forecasts of ocean surface currents and waves to determine when conditions are safe and efficient for drilling and transport activities.

Predictions of wave conditions are used by commercial fishing fleets routinely to identify regions of safe operation. Fishers also use forecasts of ocean properties such as temperature or chlorophyll to identify regions that are likely to be good fishing grounds, knowing that specific fish populations prefer certain conditions. Operational oceanography thus promotes safety and efficiency at sea, while lowering costs by minimising time at sea and raising profit by maximising catch prospects.

The international community has developed a global array of sensing devices anchored to the sea floor to monitor continuously for sea-level fluctuations that might indicate imminent tsunamis. This global tsunami warning system both collects real-time data of tsunamis and uses models to predict the times, places and magnitudes of most likely impacts, facilitating early responses to minimise loss of life. Most meteorological agencies now provide full-time continuous operational services to detect and forecast tsunamis worldwide.

Similarly, tropical cyclones are destructive natural events, not just because of their damaging winds but also because of the storm surge they can cause. Scientists use models of the coupled ocean–atmosphere system to predict the likelihood and extent of tropical cyclone events, including the likely location of landfall, the intensity of the cyclone and the likelihood of any resulting storm surge. Such forecasts provide the public with the advice needed to decide whether to stay and endure the storm or to evacuate, such as when tropical cyclone Yasi caused a storm surge of 5 m along the Queensland coast in 2011.

TRANSPORT

Transport and shipping industries routinely use forecasts of winds, waves and ocean currents to optimise ship routeing and to identify safe (or to be avoided) passages. Ships can take advantage of forecasts of favourable winds and currents to avoid unfavourable conditions and 'catch the current', so reducing travel time and costs. The shipping industry also uses ocean forecasts to assess under-keel clearance at some ports with large tidal ranges or relatively shallow passages.

Oceanographic research also plays a role in responding to natural and introduced pollution (Chapter 13). Invasive species, for example, have the potential to damage native marine habitats. Shipping can act as a vector for carrying invasive marine species from their natural habitat into foreign waters. Oceanographic forecasts help identify where an introduced marine species is likely to go once released in a new environment, supporting detection and eradication measures, such as occurred when Asian black-striped mussels were introduced accidentally into Darwin harbour in 1999 and the Asian green mussel was discovered in the port of Cairns in 2001.

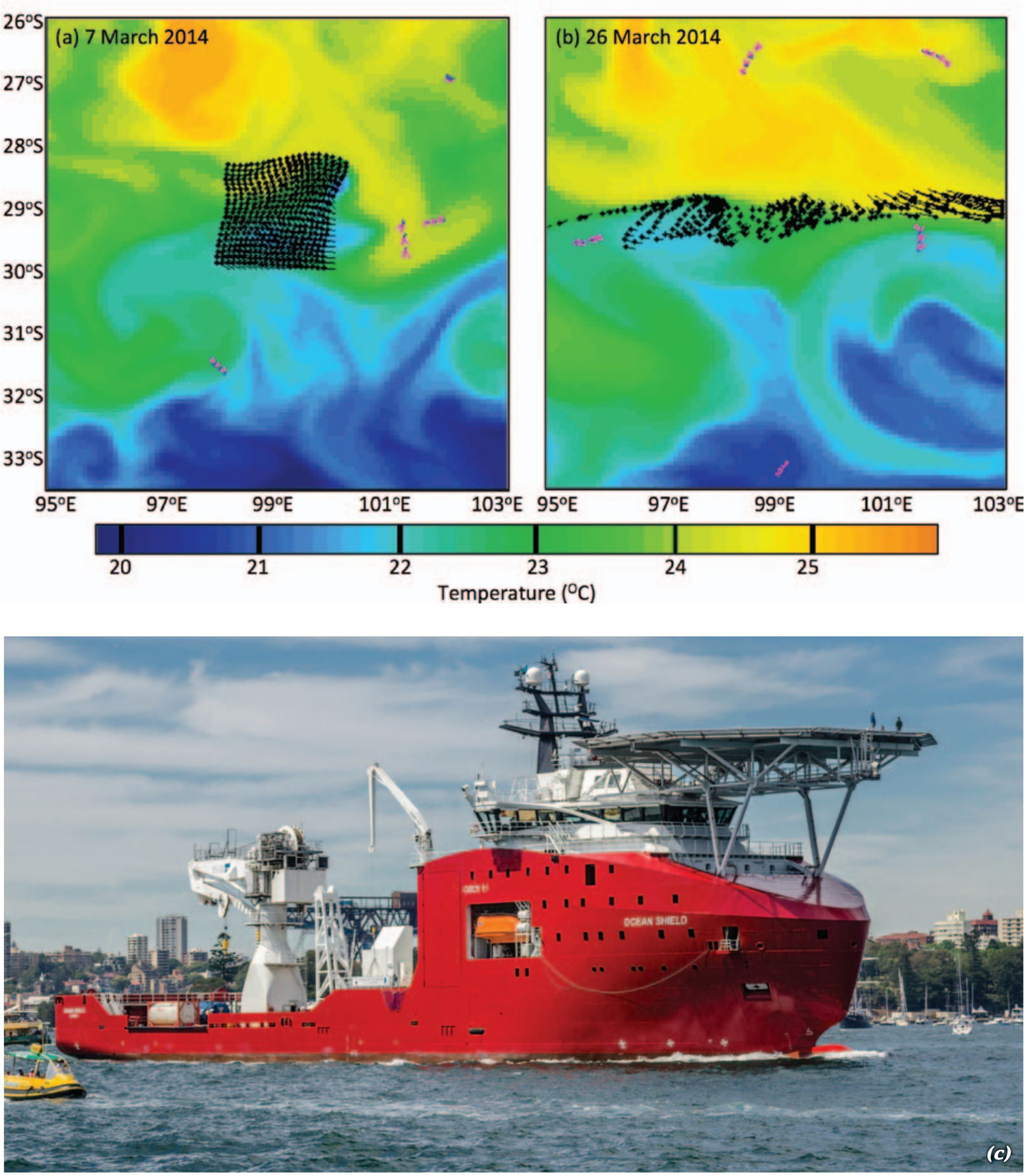
SEARCH AND RESCUE

The United Nations Convention on the Law of the Sea requires all coastal member states to 'promote the establishment, operation and maintenance of an adequate and effective search and rescue service' for their ocean territories (Article 98). Australia, as a member state, has a duty of care to provide operational services for search and rescue at sea over vast areas of the Pacific, Indian and Southern Oceans.

Australia has had a significant role, for example, in the search for wreckage of the plane from flight MH370 that crashed into the Indian Ocean in early March 2014. Ocean analyses including forecasts and hindcasts of ocean currents have been used to focus and support the search by planes and ships (Fig. 12.4). Such activities are expensive and time-critical. Accurate ocean forecasts can reduce the search area significantly, saving time and money and improving chances of success.

CONCLUSION

Oceanographic research and operational oceanography provide important services and benefits to the Australian community by: providing tactical advantage and promoting safety with the Australian Defence Force; supporting safety at sea for marine industries and the public; and providing important capabilities to support search and rescue at sea. Australia's ability to deliver these services is underpinned by ocean observations and sophisticated ocean models, leveraging off national research efforts and supercomputing facilities.



▲ ***Figure 12.4**: Examples of predicted sea-surface temperature (colour) and the distribution of model particles (black dots) tracking the possible paths of surface debris originating at a possible crash site of the MH370 plane in the Indian Ocean. Fields are shown for: **(a)** 7 March 2014, when MH370 is believed to have crashed; and **(b)** 26 March 2014, allowing the search to focus on the narrow band of area most likely to contain floating debris. **(c)** The Australian Defence Force (later Australian Border Force) vessel* Ocean Shield *participated in the search for wreckage from flight MH370 (Sources: a–b CSIRO; c Hpeterswald, CC BY 3.0, https://commons.wikimedia.org/w/index.php?title = File:ADV_Ocean_Shield.jpg&oldid = 121132749).*

FURTHER READING

Bell MJ, Schiller A, Le Traon PY, Smith NR, Dombrowsky E, Wilmer-Becker K (2015) An introduction to GODAE OceanView. *Journal of Operational Oceanography* **8** (supplement 1), s2–s11. doi:10.1080/1755876X.2015.1022041

National Marine Science Committee (2015) Marine sovereignty, security and safety. In *National Marine Science Plan 2015–2025: Driving the Development of Australia's Blue Economy*. pp. 16–17. National Marine Science Committee, Canberra, <http://www.marinescience.net.au/>.

CHAPTER 13.

Ocean pollution – risks, costs and consequences

Britta Denise Hardesty, Paula Sobral, Simon Barry and Chris Wilcox

Key messages

- The world's oceans are impacted by pollution and translocation of marine organisms, with economic, food security, human health and ecosystem implications.
- Ocean pollution results from waste from the general population, agricultural activities, shipping and transportation, ocean exploration and other industries.
- Movement of organisms results from transport on ships' hulls, as larvae in ballast water and by rafting.
- Marine debris has been identified as a key threatening process for marine fauna.
- Reducing marine pollution will require integrated management across governments, industries and the community.

INTRODUCTION

The oceans are some of the planet's few remaining diverse and mysterious places. They constitute a vast area, but the influence of human activities has been shown to affect ocean systems globally. These effects arise from several sources, including pollution and the transport and establishment of marine pests.

Pollution from human activities affects oceans locally, regionally and globally. Impacts have been reported on pelagic and seabed organisms from plankton to marine mammals. Impacts have been linked to oil spills and other chemical contaminants, entanglement in abandoned, lost or derelict fishing gear, and ingestion of persistent human-generated litter such as plastics.

Marine pests also have wide-ranging and enduring impacts on ecosystems. Marine species have hitchhiked with humans for centuries as fouling on ships or associated with ship ballast, and have been moved intentionally for aquaculture. These transported species can have direct impact by disrupting existing communities or exacerbating effects of pollution that alter ecosystems.

LAND-BASED SOURCES OF OCEAN POLLUTION

Most pollution in the oceans comes from land-based sources including recreational activities, oil wastes, fertiliser runoff, septic tanks, farms, fisheries, vehicles and dumping of household refuse. Tonnes of waste and trash are lost or dumped into the oceans daily and it is estimated that the oceans may contain upwards of 150 million metric tonnes of plastic alone, with recent research estimating that around 8 million tonnes of waste enter our oceans each year.[1]

Inputs of contaminants such as fertilisers, pesticides, heavy metals and other chemicals from river runoff, wastewater and mismanaged litter and oil spills have resulted in an extensive loss of marine life and habitat. Organic pollution entering the oceans can build up excesses of nitrogen, phosphorus and other chemicals. This build up can result in a lack of oxygen in marine waters, particularly in coastal ecosystems such as the Great Barrier Reef, a globally recognised World Heritage Area. Oxygen-deficient conditions generally are harmful to the marine environment and have already resulted in extensive 'dead zones' in coastal areas around the world.

Non-degradable pollutants, such as many pesticides and heavy metals, can persist for long times in the oceans and are toxic to marine organisms. Science shows that pollutants may even disrupt biological functions, such as hormone production, resulting in shifts in population sex ratios that ultimately can compromise the survival of species and communities.

Historically, the world's oceans were considered the ultimate dump for many wastes and effluents from land-based activities.[2] Dumping of industrial, nuclear and other waste into oceans once was common practice in many countries but became regulated by international agreements in the 1970s. Legacy pollution from persistent organic pollutants (POPs), such as PCB and DDT, which were banned in the late 1970s and 1980s, can still be found on oil films and plastic particles in our oceans and in the tissues of long-lived animals. Waste losses into the marine environment still occur illegally or accidentally, despite preventative legislation. Sources of discharges, such as those from industrial plants, now are well regulated in many countries but sources of pollution from the many non-point sources are of growing concern because they are difficult to identify, manage, regulate and control. Laws in Australia restricting discharge of certain types of garbage have been in place since the 1980s under the *Environmental Protection (Sea Dumping) Act 1981* and Amendment (1986) but illegal and unintentional discarding of waste at sea continues.

Dead fish in the coastal zone, likely due to local pollutants (Source: JB Manning, Shutterstock).

Economic and biodiversity consequences from ocean pollution are continuing to increase.[2] Biodiversity loss is expected to result in further declines in marine life, including commercially important food fish, marine mammals, seabirds, turtles and many other organisms. It now is recognised widely, for example, that litter entering our oceans is both significant and increasing and causing harmful impacts on the marine environment and resources, including marine and coastal biodiversity, ecosystems and related ecosystem services. Human-generated debris has detrimental effects on economic sectors including fisheries, aquaculture, merchant shipping and tourism, and has potential human health and safety risks. Marine litter therefore is the focus of growing political attention nationally and internationally.

FISHERIES AND SHIPPING ASSOCIATED WASTE

Aquaculture and fisheries can be contributors to marine pollution through the accidental loss or intentional discarding of buoys, fishing nets, ropes and other equipment. Fishers historically also were allowed to dump waste overboard but international maritime law largely forbids the dumping of rubbish at sea and the Australian Maritime Safety Authority has run significant campaigns promoting proper waste disposal (Fig. 13.1). Providing appropriate shore-based facilities to accept fisheries garbage, waste and non-functioning gear is a key way of ensuring appropriate disposal rather than at-sea dumping or discharge.

STOW IT, DON'T THROW IT

DISCHARGE OF GARBAGE INTO AUSTRALIAN WATERS IS PROHIBITED

Australian Government
Australian Maritime Safety Authority

No discharge permitted within:

- 3nm from the nearest land*
- the Great Barrier Reef (GBR) area and waters up to 3nm from the outer boundary of the GBR area*

No discharge permitted, except food wastes processed to less than 25mm at a distance more than:

- 3nm from the nearest land*
- For the GBR area - 3nm from the outer boundary*

No discharge permitted, except unprocessed food wastes at a distance more than:

- 12 nm from the nearest land*
- For the GBR area - 12nm from the outer boundary*

MARPOL Annex V details the limited exceptions that may apply to the discharge of other ships' garbage*

RETAIN GARBAGE ON BOARD AND DISPOSE OF RESPONSIBLY ONSHORE

VIOLATIONS MAY RESULT IN PENALTIES

REPORT ALL MARINE POLLUTERS TO 1800 641 792 OR
www.amsa.gov.au/environment/reporting-ship-sourced-pollution

*Visit www.amsa.gov.au/environment/regulations for information on nearest land, including the GBR area, and other garbage regulations

AMSA 440 (2/17)

▲ ***Figure 13.1****: The Australian Maritime Safety Authority has run a 'stow it don't throw it' campaign highlighting government restrictions on discharge of waste into the oceans (Source: Australian Maritime Safety Authority).*

Commercial shipping also is a source of marine litter through accidental releases such as plastic pellets from 'plastic' blasting in shipyards or illegal disposal of wastes at sea. Estimates suggest that shipping is responsible for 12–20% of global discharges of waste at sea. Increased shipping traffic brings increasing risk of accidental discharges of material into the sea (e.g. shipping containers, cargo) as a result of accidents, bad weather or negligence.

The fisheries and shipping sectors also suffer economic impacts from marine pollution.[3] Lost or abandoned gear, for example, can end up catching target and non-target fish for decades after it is lost or dumped, a phenomenon called 'ghost fishing'. These ghost catches are unavailable to fishers and potentially can affect the productivity of fished populations. Pollutants found in the tissues of fished species can prevent sale of product or even closure of fisheries either temporarily or indefinitely in the interests of protecting human health. Chemical contamination can affect the reproductive biology of harvested species and result in degradation of fish spawning success, potentially affecting fish catch rates in the long term.

Indigenous ranger with floating and submerged derelict fishing net (Source: Riki Gunn, GhostNet Australia).

Floating objects can be caught in engine cooling systems, can entangle propellers and can be navigation hazards. Disentangling lines from gear and engines can cost valuable time and resources and may result in damage to vessels, with significant economic losses to industry and the community if damaged vessels require search and rescue services.

INVASIVE SPECIES TRANSPORT AND BIOSECURITY ISSUES

The movement of marine organisms by people has been occurring for hundreds of years, primarily associated with shipping. Different waves of biological invasion have been associated with changes in shipping technology. Wooden vessels with solid ballast mostly transported organisms as fouling attached to their hulls.[4] Replacement of solid ballast with water ballast means that modern vessels can transport organisms either as fouling on hulls or as larvae in ballast water. Identification of the threats to the environment posed by these movements has led to international conventions controlling management of ballast water, including making it illegal to dump ballast water in coastal waters in many circumstances.

Prevention of incursions is the most practical approach to controlling this problem. Eradicating marine pests once established is difficult logistically and biologically and rarely has been successful.

Biofouling and the passive transport of fouling organisms on debris has been recognised as potentially the most important vector for the spread and establishment of marine pests but there currently is no agreement internationally to set standards around best practice management of fouling on ships’ hulls and no prospect of a mechanism for limiting passive dispersal on flotsam.

Transport of potentially invasive fouling species on containers found in ***(a)*** *Brazil and* ***(b)*** *the Azores Islands. Such fouled containers are transported across all ocean regions, including those around Australia (Sources: a Martin Thiel; b P. Sobral).*

MARINE DEBRIS FROM LAND-BASED SOURCES

Most of the population in Australia lives within 50 km of the ocean and Australians have a close affinity with the sea, but inappropriate waste-management practices and irresponsible human behaviour result in litter and waste entering our oceans, in spite of this affinity. Litter includes consumer items such as glass or plastic bottles, cans, bags, balloons, rubber, metal, fibreglass, cigarettes and other manufactured materials that end up in the oceans and along the coast, and other materials intentionally or unintentionally discarded at sea.[5]

Plastic comprises the largest quantity of litter in our oceans. Nearly three-quarters of the waste found on coastlines and more than 90% of waste found floating offshore is plastic. A recent national study estimated there are more than five pieces of litter along the coastline for every person living in Australia.[5] Plastic debris can accumulate pollutant chemicals that have entered the ocean, concentrating them on the surface of the plastics. Most plastics float and often are mistaken for food by marine organisms. Most plastics do not degrade naturally but break down into progressively smaller pieces without disappearing. The smaller and smaller pieces of plastic are accessible to smaller and smaller organisms in the food chain. Even microscopic planktonic animals have been found to eat plastic.

Consumed plastic often accumulates in the digestive tracts of animals, increasingly affecting their capacity to feed, their health and, ultimately, causing death. Retained plastics also are passed up the marine food chain, meaning that animals at the top of the food chain could have contamination hundreds of thousands of times higher than the surrounding sea water.

Coastal and marine litter that has washed ashore on just a small area of Christmas Island (Source: CSIRO).

Plastic fragments, bottle caps, toys, balloons, cigarette lighters, plastic resin pellets and other items are found in the digestive tracts of seabirds such as Flesh-footed shearwaters (shown here) on Lord Howe Island (Source: CSIRO).

OIL POLLUTION

Oil spills are one of the most immediate and evident forms of ocean pollution due to the large areas covered and the immediately visible impacts on seabirds and other marine animals and plants. Most maritime oil spills are associated with transportation mishaps, accidents on drilling rigs or, less frequently, sunken vessels and discharges of oil-containing ballast and bilge water. Only a small percentage of oil that ends up in the ocean, however, is a result of maritime spills. Oil in the ocean more commonly is a result of drainage from land. Oil in the ocean can suffocate marine animals and plants, and contamination can lead to behavioural changes and a breakdown in animals' insulation ability as their skin and feathers are clogged with oil.

Negative effects of oil on habitats and marine life may be immediate and obvious when oil covers the sea surface and shoreline. Less obvious toxic effects may persist long after clean-up activities, however, causing long-term negative effects on breeding, growth and development for marine plants and animals. The release of oily mixtures from vessels into the sea is prohibited under international maritime legislation and there are several recommended measures suggested to reduce oil release into the oceans.

ECONOMIC AND SOCIAL COSTS OF OCEAN POLLUTION

Pollution in the oceans has high economic costs that affect many different sectors, including human health, fisheries, transport and tourism. It is estimated that litter in the marine environment costs approximately US$13 billion each year – and this is increasing despite growing public concern over plastics, particularly micro-plastics, and the potential impacts on marine animals and human health.[6]

Litter, oil spills and other forms of ocean pollution may have adverse consequences for coastal communities. A 2009 oil spill from the MV *Pacific Adventurer* off the coast of south-east Queensland, for example, affected more than 60 km of the coastline and resulted in an oil slick in the mouth of the Brisbane River, as well as resulting in oil-covered beaches, reefs, coastal wetlands and mangroves. Coastal areas were restricted and public access was limited and the clean-up cost millions of dollars and took nearly 2 years.

Ocean pollution associated costs to tourism may be high because recreational activities such as bathing, boating, angling, snorkelling and diving may be reduced or restricted. Studies have shown that people will travel further and spend money in areas with cleaner waters and shorelines, pointing to significant economic consequences locally associated with improper waste management and infrastructure.

The human-associated health costs to swimming in contaminated waters has been estimated to be billions of dollars annually, even without including financial impacts of lost wages and affected livelihoods. Long-term illnesses and poor health associated with prolonged exposure to pollution and environmental contaminants are increased where sewerage discharge or agricultural runoff into the oceans is high, which is a problem particularly for developing nations.

CONCLUSION

The oceans have long been a place where humans have discarded waste, with the public perceiving oceans as unending and able to accept the refuse of society without consequence. Indiscriminate dumping has occurred for centuries. Understanding of the consequences of ocean pollution has improved in recent decades, however, and national and international legislation has been implemented to protect the world's oceans from intentional and unintentional pollution. Protecting the oceans' natural resources is critical for biosecurity, economic prosperity and biodiversity for future generations.

FURTHER READING

Clark RB (2001) *Marine Pollution*. 5th edn. Oxford University Press, Oxford, UK.

Hardesty BD, Wilcox C (2011) 'Understanding the types, sources and at-sea distribution of marine debris in Australian Waters'. Final report to the Department of Sustainability, Environment, Water, Health, Population and Communities. Australian Government, Canberra, <http://www.environment.gov.au/marine/publications/understanding-distribution-marine-debris-australia>.

Rothwell DR (1996) The legal framework for ocean and coastal management in Australia. *Ocean and Coastal Management* **33**, 41–61 doi:10.1016/S0964-5691(96)00044-0

Weis JS (2014) *Marine Pollution: What Everyone Needs to Know*. Oxford University Press, Oxford, UK.

CHAPTER 14.

Tools and technologies for ocean observation

Mark Underwood and Andreas Marouchos

Key messages

- Collecting data on the current state of the oceans is difficult but important.
- New technologies and sensors are being developed continually to reduce gaps in our knowledge of the oceans.
- Australia is well-connected with coordinated international observing programs and has an active community focussing on regional observing efforts.

INTRODUCTION

Taking observations to gain a meaningful understanding of the ocean is not easy and there are particular challenges in the Australian context. Our population and resources are modest, but our marine estate is the third largest in the world. Australia's continental coastline (including Tasmania) is around 36 000 km long, with an additional over 24 000 km of island coastlines. Our maritime domain spans ecological regimes from the Antarctic to the tropics and from shallow coastal zones to abyssal waters over 4000 m deep. The oceans are complex: water masses are three dimensional, heterogeneous and constantly moving. Understanding ocean states and processes requires collecting data at a range of spatial and temporal scales, as well as careful interpretation.

The number of ocean variables that are of interest to scientists and that can be observed is large. The most common of these are physical parameters such as water temperature and salinity, with records at some locations extending back to the 19th century. Other variables include optical parameters (colour, clarity), biological variables, chemical properties (pH, alkalinity), dissolved gases (carbon dioxide, oxygen), nutrients and measurement of ocean currents. Other parameters of interest can be inferred through the measurement of a separate proxy parameter. The levels of fluorescence in a water sample, for example, can be used to estimate the abundance of phytoplankton in that water sample, because phytoplankton contain the fluorescent chemical chlorophyll. Ocean observing also can include observations of marine plants and animals via acoustic devices, sampling with nets and dredges, imaging with camera systems and mapping of the ocean floor using acoustic sonar systems. These observations inform us about the past and present state of the oceans while contributing to models used to forecast future ocean conditions (Chapter 12), enabling the prediction of how management decisions we make today will influence the oceans in the future (Chapter 16).

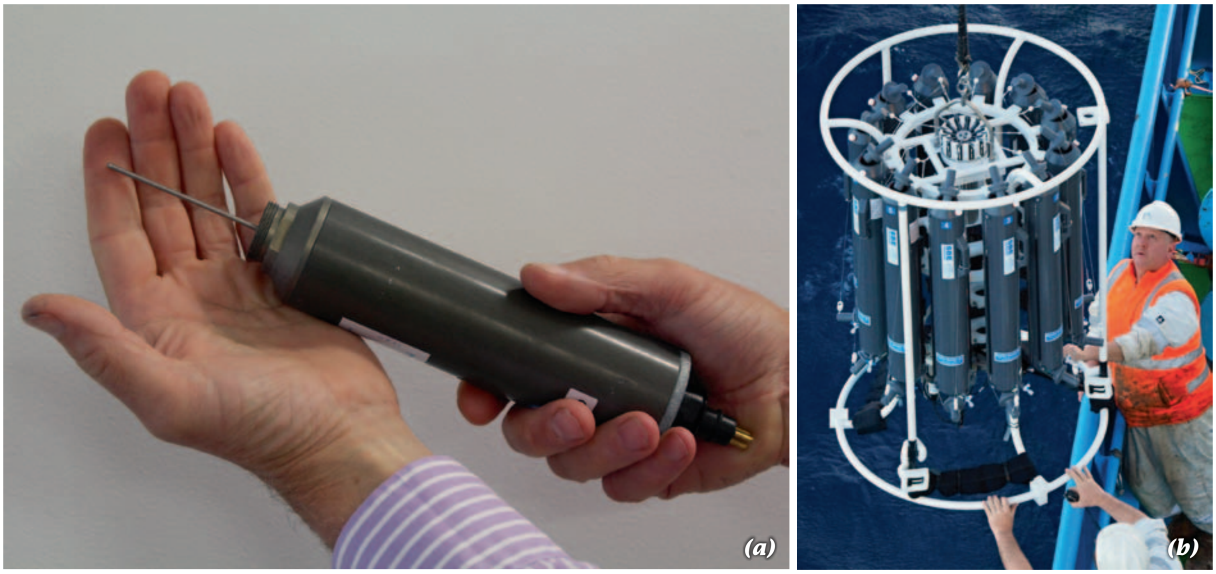
CONVENTIONAL TOOLS FOR OBSERVATIONS

Ships

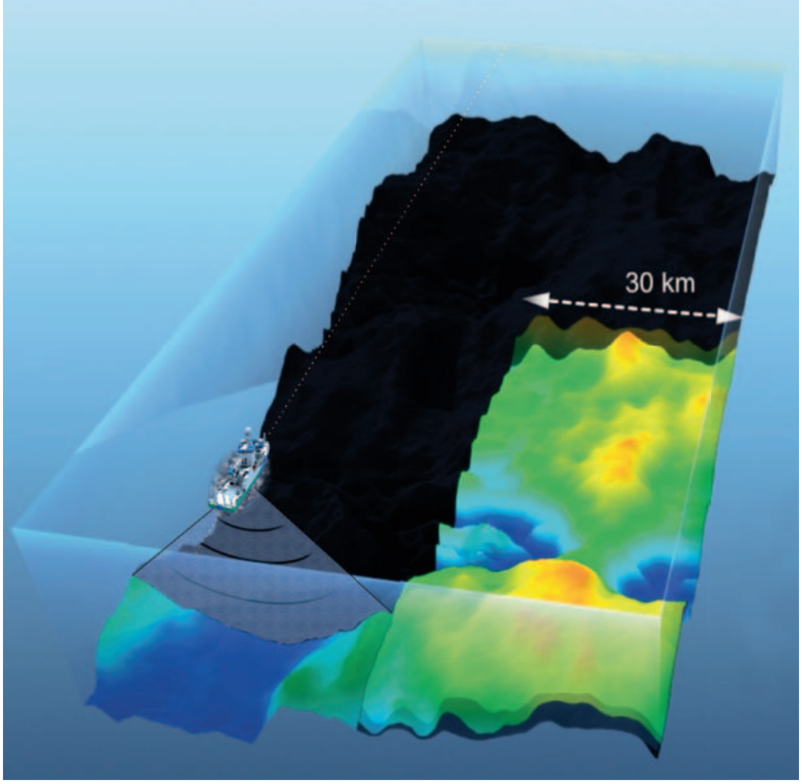
Scientific oceanography gained impetus in the late 19th century, in particular with the HMS *Challenger* expedition from 1872 to 1876. The tools used to collect ocean data then, and for some time after, were rudimentary. Ocean surface temperature was measured by placing a mercury thermometer in a bucket, lowering it over the side to collect a sample of sea water and then reading the thermometer once the bucket was brought back on deck. The depth of the ocean beneath a vessel was measured by lowering a weighted line to the sea floor.

Technological advances have increased the amount of data collected, with higher accuracy and over a broader range. Sea-surface temperature and salinity are measured continuously from modern research vessels with electronic instrumentation fitted to inline water-collection systems. High-quality data are collected routinely from the full water column by lowering specialised instruments from a vessel to the sea floor. Temperature measurements can have accuracies approaching ±0.001ºC and salinity measurements are approaching parts per million resolution. Further variables such as dissolved gases and nutrients can be measured by collecting water samples from the depths for analysis in the laboratory.

Measurements continue to improve through incremental advances in technology, while in some areas the development of new sensing techniques has opened up new fields of study. The development of acoustic sounders, for example, allows the study of depth and topography of the ocean floor (Fig. 14.1), measuring locations, abundances and types of marine life and measurement of ocean currents at depth.



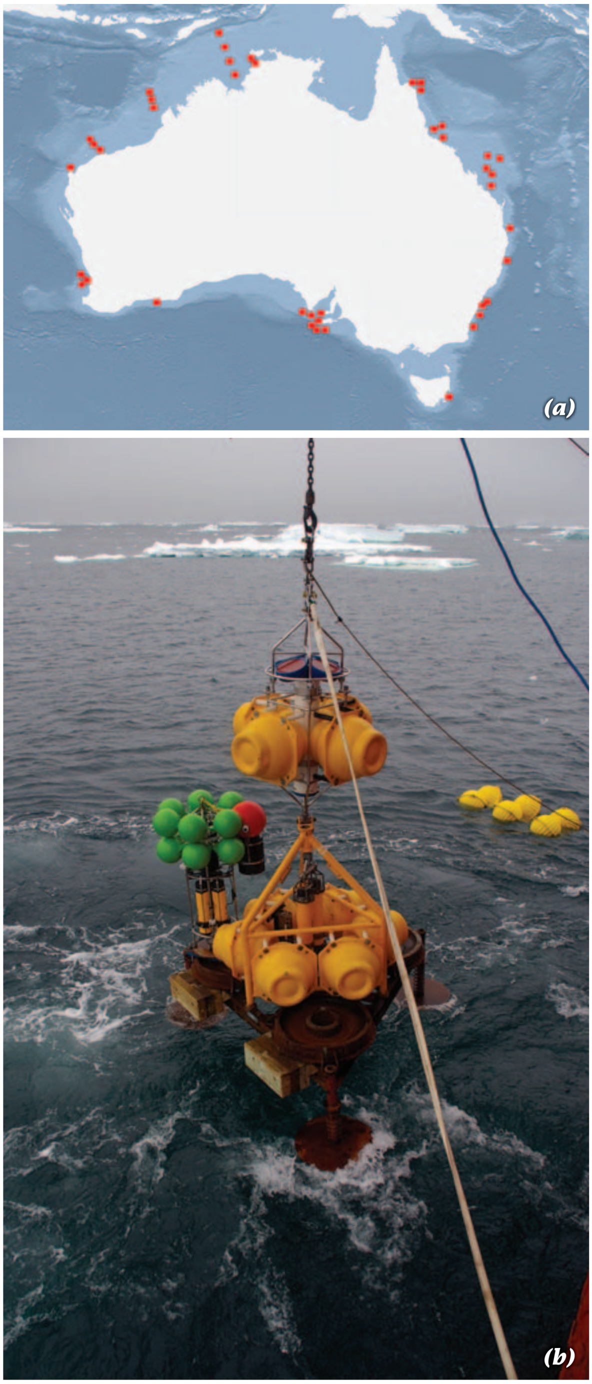
(a) *A high-resolution temperature sensor is one of the sensors employed on CTD (conductivity, temperature and depth) instruments.* ***(b)*** *A CTD instrument being deployed from a research vessel. These systems are fitted with a range of sensors, with data being transmitted to the surface ship in real-time. Sample bottles allow for collection of water samples at prescribed depths, which enable data validation as well as chemical analysis in the laboratory to deliver data on parameters for which sensors are not currently available (Sources: a Robert Kay; b Stewart Wilde, CSIRO).*



▸ ***Figure 14.1****: Sea floor mapping via an acoustic multibeam technique (not to scale). Bathymetric maps of the seafloor are made by measuring the time taken for sound pulses to travel from transducers mounted on a ship's hull to the seafloor and back. Greater accuracy and coverage is achieved by using many narrow sound beams spread across an array. 'Swaths' up to 30 km wide can be collected in one pass over very deep water (Source: CSIRO).*

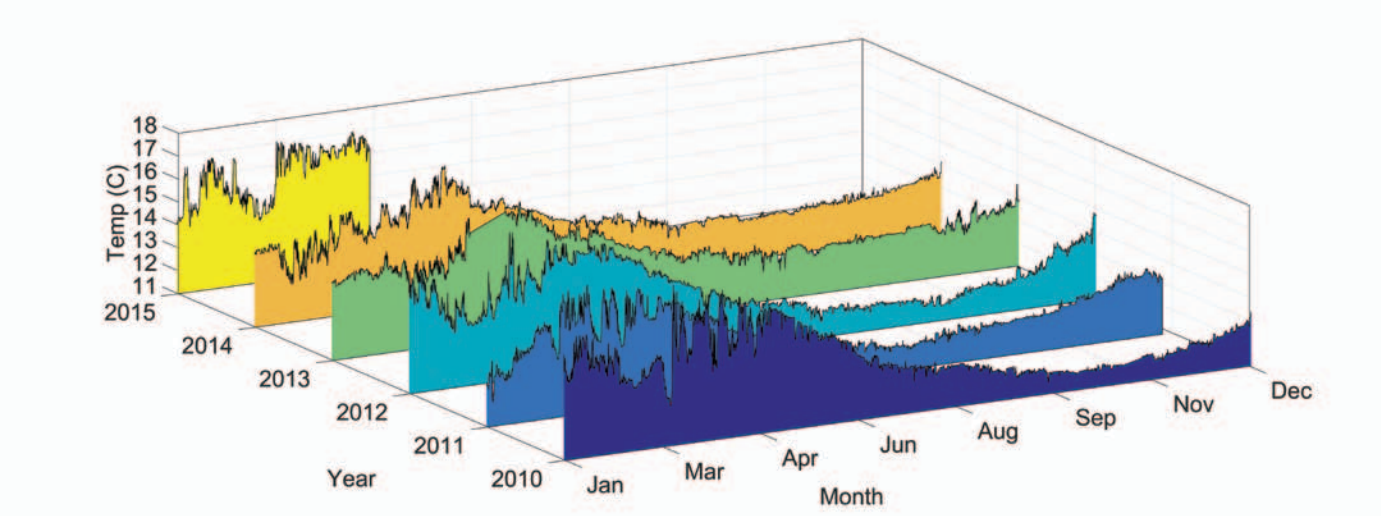
Scientific moorings

Arrays of instrumentation can be installed on ocean moorings at any depth to collect data autonomously for periods spanning several years. Moorings with surface floats can send data back to researchers in real time by radio or satellite communications while those without surface floats can store data internally until they are recovered by ships. There are several mooring arrays around Australia across the continental shelf and into the deep ocean (Fig. 14.2).



◂ ***Figure 14.2**: **(a)** Locations of Australian coastal and shelf moorings deployed as part of the Integrated Marine Observing System (IMOS). **(b)** The deployment of the anchor and science package for an instrumented mooring being set in Antarctic waters. This mooring package was placed to measure water temperature and currents near an ice sheet, improving our understanding of the influence of warm ocean currents on melting ice sheets (Sources: a CSIRO, IMOS; b Steve Rintoul, CSIRO).*

Some sites have been monitored for long periods, enabling a time series of data to be acquired. Maria Island, for example, off the east coast of Tasmania has had periodic sampling and measurement since 1944. A specialised scientific mooring was designed and installed there in 2005 that delivers near continuous data streams of physical and biological variables (Fig. 14.3).



▲ ***Figure 14.3***: *Example showing more than 5 years of data from scientific moorings at Maria Island off the east coast of Tasmania. This image shows a series of yearly plots of the water temperature at 85 m depth (Source: data collected by CSIRO for the Integrated Marine Observing System (IMOS). IMOS is a national collaborative research infrastructure supported by the Australian Government).*

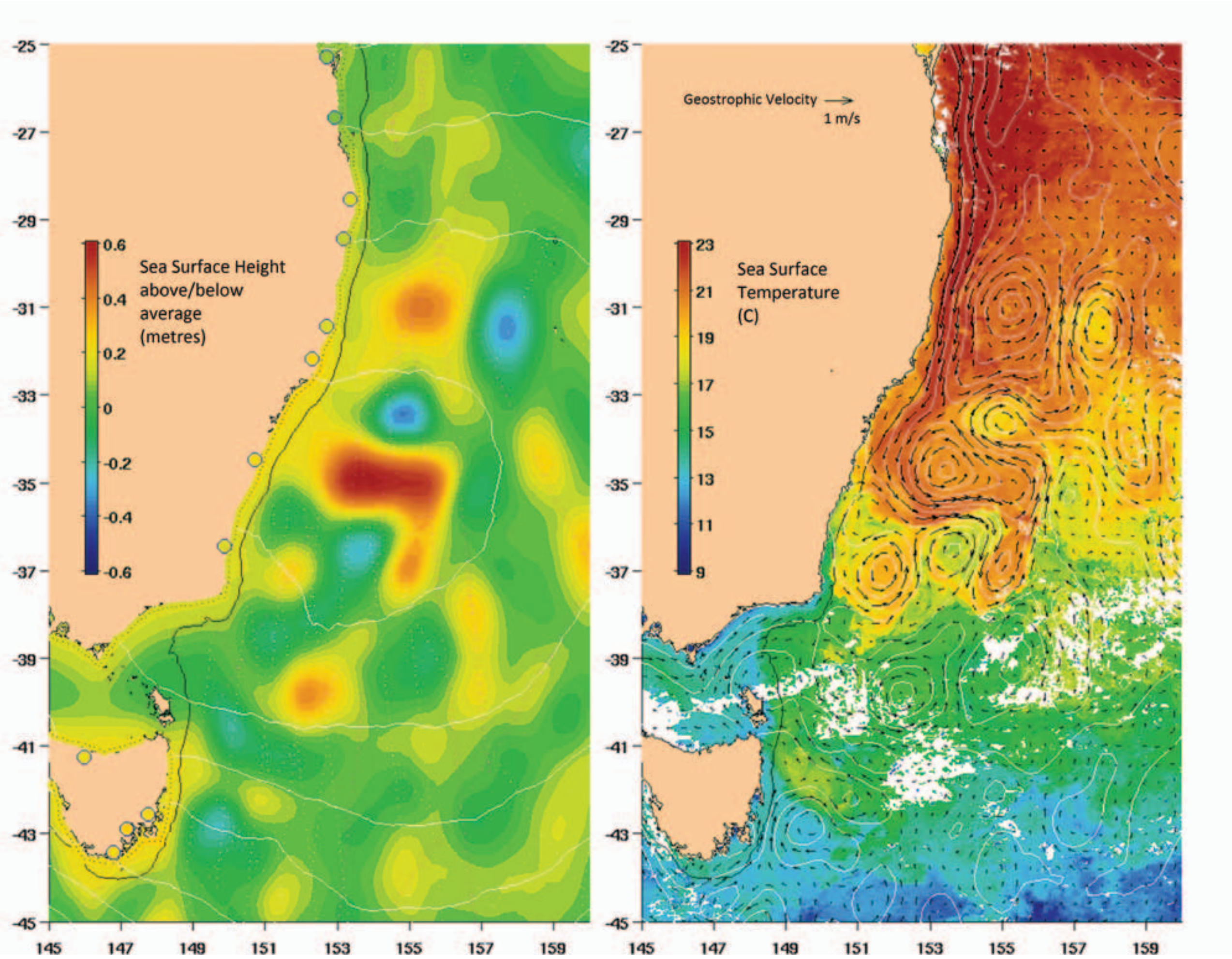
EMERGING TOOLS FOR OBSERVATIONS

The cost of sending people to sea in boats to collect data or install instruments is high, and limits the amount of data that can be collected by such conventional approaches. Technology has been developed increasingly to tackle this challenge. The future of scalable and sustainable ocean science lies in system autonomy and remote sensing.

Remote sensing

A growing array of satellite-based sensors since the 1970s has added considerably to ocean observations. Satellites have a very high capital cost but provide data streams that are not available from any other methods, over long periods and often with broad spatial coverage (Fig. 14.4). Satellite remote sensing of the oceans generally is limited to observations of the oceans' surfaces and use of these remotely sensed data needs to be calibrated periodically with in-situ observations.

The range of variables that can be measured from satellites currently includes ocean surface temperature, ocean currents, ocean height and sea level, surface plankton, ocean colour, wave and wind regimes, and salinity.

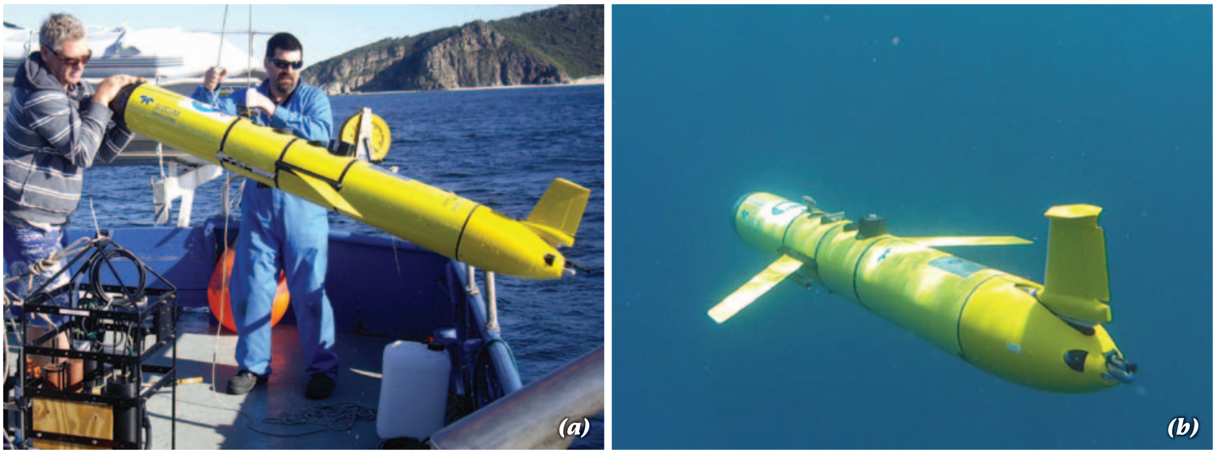


▲ ***Figure 14.4****: Examples of remote sensing data products. Representation of local sea-surface height (left) and sea-surface temperature and currents (right) (Source: CSIRO, IMOS http://oceancurrent.imos.org.au/index.php).*

Autonomous sensing

Autonomous sensing platforms aim to retain the benefits of high-quality, direct measurements by researchers without the need for staff to travel to the measurement site. This is achieved through use of robotic vehicles that can operate on their own and do not require close continuous supervision by researchers. The reduced operating cost of such systems compared with ship-based research can enable institutions to deploy more vehicles and collect more data.

Unmanned vehicles also can transit to remote or otherwise inaccessible locations (such as under ice shelves), remain on location for extended periods and operate in hazardous areas, delivering new datasets that are otherwise difficult or impossible to obtain. Some of these platforms also are scalable – having the ability to be linked together into ‘fleets’ that collect data from multiple locations concurrently.



(a) *An underwater glider being deployed from a small vessel near Tasmania. Underwater gliders are one form of autonomous system that can be used to make observations in the water column.* ***(b)*** *A glider moves by changing its buoyancy and adjusting its centre of mass, thereby gliding up and down through the water in a zigzag fashion. It is programmed to follow a specific path guided by GPS, and can transmit data via satellite when it reaches the surface (Source: CSIRO).*

Passive autonomous devices

The simplest autonomous systems are drifters. These devices originated from the 'message in a bottle' concept that yielded basic information on the average velocity of ocean currents derived from knowing its release point and the time and location of its eventual recovery. Modern drifters now include electronic sensors that can measure the environment (e.g. temperature and salinity) and regularly send this information along with their locations back to a central data centre via satellite.

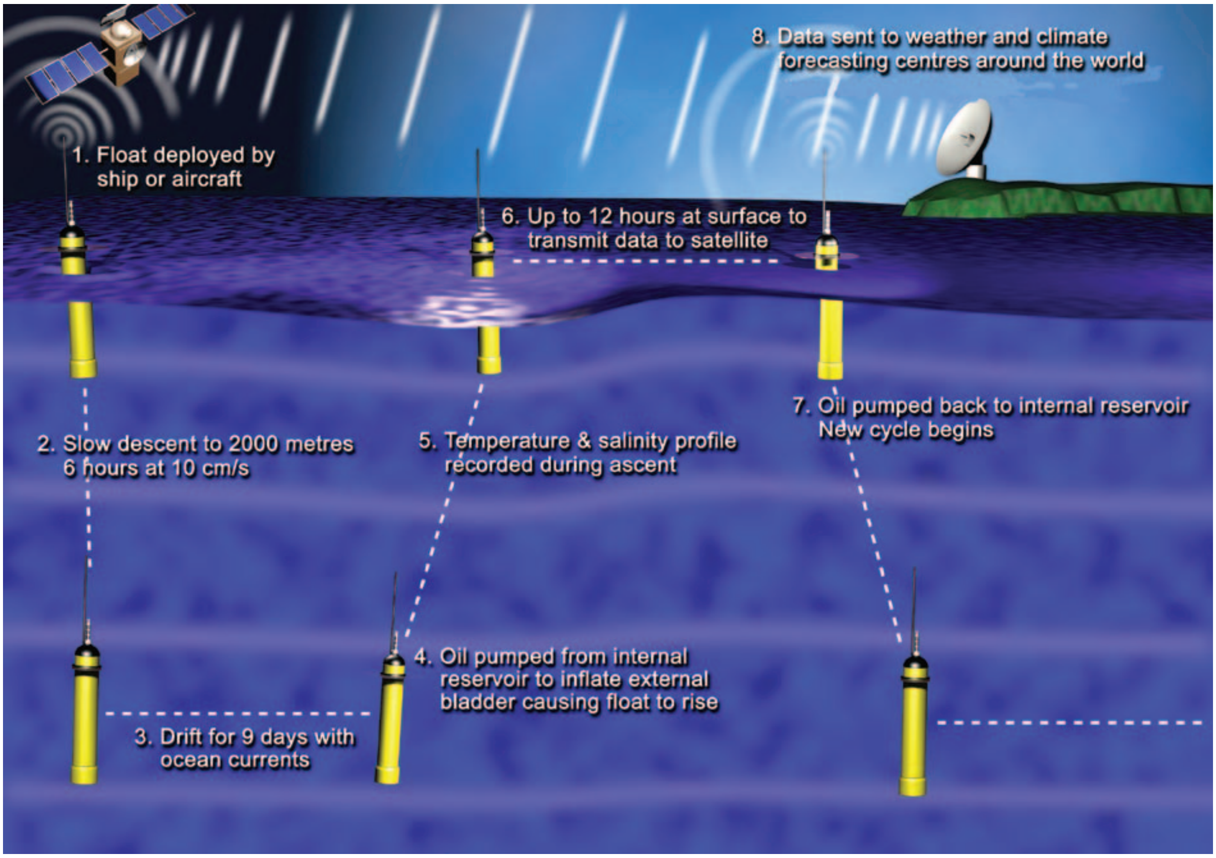
There have been significant advances in drifting autonomous sensor technology in recent years, in particular with the very successful Argo program (Fig. 14.5). More than 3500 active Argo floats currently are deployed across the world's oceans. Argo floats last ~5 years transmitting high-quality data profiles back to scientists every 10 days.

Developments are underway to increase the number and type of sensors installed on Argo floats, including sensors for dissolved gases, optical properties and nutrients, and to design floats that can sample much deeper than 2000 m and others to operate in the polar sea-ice zones.

Autonomous surface vessels

The past decade has seen commercial development of a variety of autonomous surface vessels (ASVs) that can be used to take ocean observations. ASVs can support a suite of ocean science instruments collecting data about the ocean surface, with some water column information also being collected using acoustic sensors.

Some ASVs use solar, wind or wave energy for their long-term operation and have completed missions spanning an entire ocean or maintained functionality for several months of continuous operation.

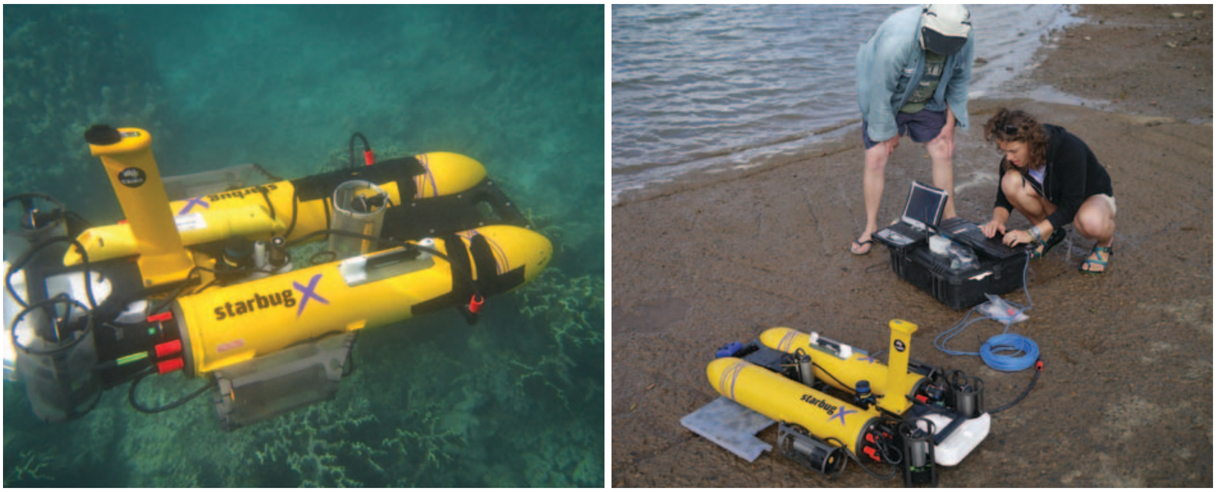


▲ ***Figure 14.5****: Most Argo floats operate on a repeating 10-day cycle following deployment from ships or aircraft. Each Argo float descends to a 'parking depth' of 1000 m or 2000 m where it spends 9 days drifting with ocean currents. Floats parked at 1000 m descend to 2000 m at the end of this period of drift. On the 10th day, the Argo float ascends from 2000 m depth to the ocean surface, collecting data along the way. The data are transmitted to a central collection station via satellite once the float is on the surface and then the Argo float sinks back down to the parking depth and the cycle starts again (Source: Alex Sen Gupta, UNSW).*

Autonomous underwater vehicles

Autonomous underwater vehicles (AUVs), equivalent to unmanned mini submarines, can be used to collect data in areas where it is difficult to sample otherwise or make extended subsurface observations. Data from beneath sea ice, ice sheets and glaciers, for example, are key to understanding ocean-ice dynamics but are difficult to collect using traditional methods. These vehicles also are starting to take the place of human divers to collect data in shallow water.

AUVs are typically battery-powered and can carry a payload of sensors that measure temperature, salinity and depth, record acoustic data, biological variables and map the sea floor or undersides of ice sheets. AUVs come in many shapes and sizes and increasingly are becoming standard tools for collection of large spatial and temporal ocean datasets.



The Starbug X is a small autonomous underwater vehicle developed by CSIRO to collect data from the shallow sea floor. Its primary function is to take photos of the seabed and coral reef areas to enable scientists to evaluate the health of Australia's coastal waters. The system is equipped with a range of sensors that help scientists build a complete picture of coastal seabed conditions (Source: CSIRO).

Animal-borne instruments

Continued miniaturisation of sensors and data telemetry systems have made it viable to build self-contained data acquisition systems small enough to be mounted on animals such as whales and seals, but also on smaller animals including birds and fish. These applications bring value particularly in remote and difficult environments such as sea-ice zones. The resulting datasets are useful particularly when studying an animal's behaviour and their interactions with the environment, but this technique can also act as a means to collect environmental data from a region without the need to place researchers in the field.

Elephant seal fitted with a micro-sensor measuring ocean conductivity, temperature and depth. The data can be transmitted to researchers via satellite when the seal surfaces to breath (Source: Clive R. McMahon, Integrated Marine Observing System, Satellite Animal Tracking, Sydney Institute of Marine Science).

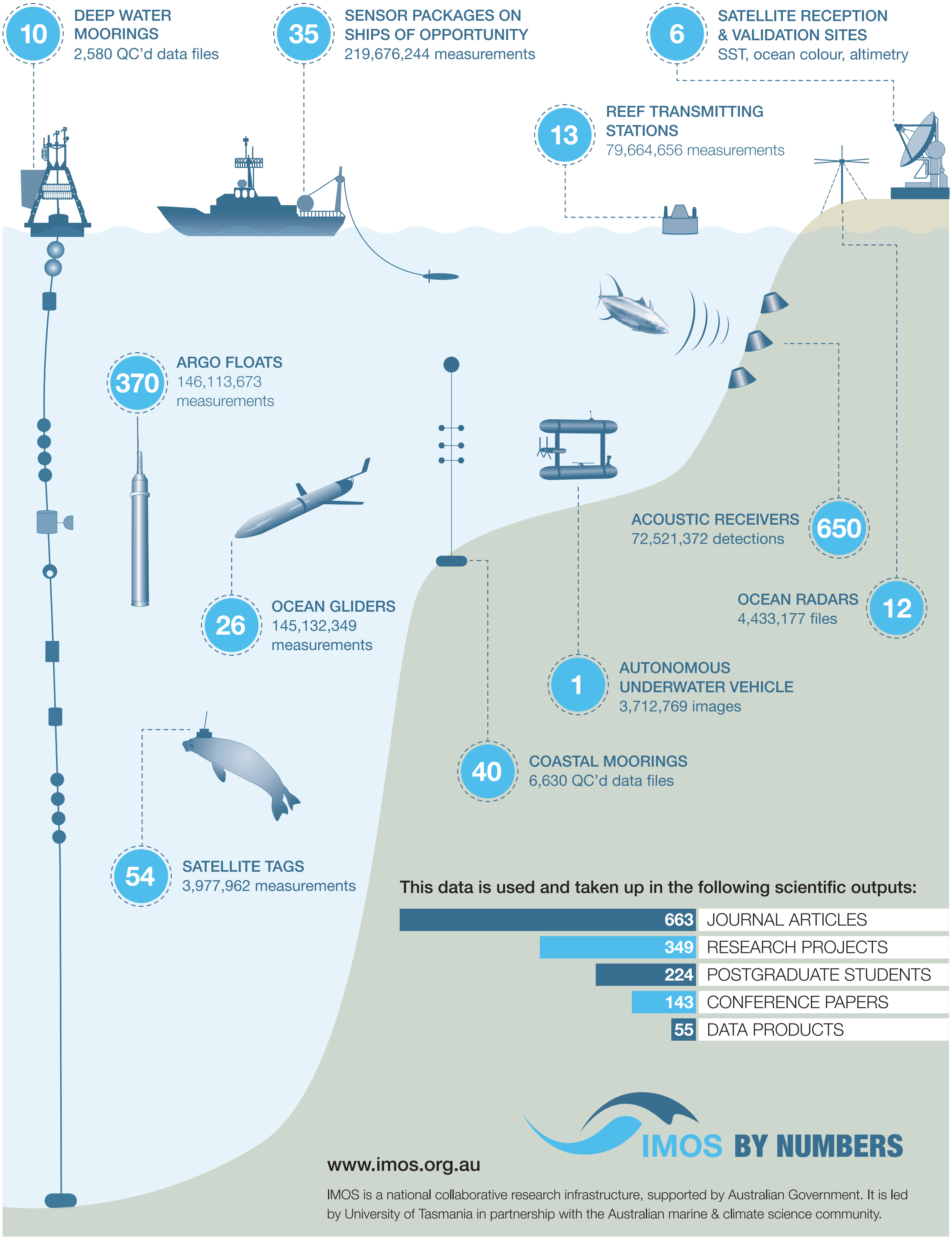
AUSTRALIAN MARINE OBSERVATION INFRASTRUCTURE

Australia has several government agencies and universities that do marine research and there are several national programs with a remit to deliver marine research broadly across institutions. Two of these are the Marine National Facility (MNF) and the Integrated Marine Observing System (IMOS). These are funded by the Australian Government to deliver technical research infrastructure that enables Australian and international researchers to access world-class marine research platforms across the Australian marine estate.

IMOS coordinates and funds a range of programs of ocean observations through marine research organisations that include the Australian Institute of Marine Science (AIMS), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australian Antarctic Division (AAD), Australian Bureau of Meteorology (BoM), Geoscience Australia (GA), Sydney Institute of Marine Science (SIMS), South Australian Research and Development Institute (SARDI) and several Australian universities. Scientific infrastructure supported by IMOS includes scientific moorings, autonomous vehicles, remote sensing via satellite and high frequency radar, marine animal tagging and ship-based observations (www.imos.org.au, Fig. 14.6).

The Marine National Facility (MNF) provides access to a world-class blue water research vessel for Australian researchers and their international collaborators. It is owned and operated by CSIRO on behalf of the Australian nation. The current vessel is *Investigator*, a purpose-built research vessel equipped with the latest available technology and launched for the MNF in 2014. Research voyage time on *Investigator* is granted via a competitive application process that also provides scientists access to a comprehensive set of observing tools. The MNF also holds and distributes a catalogue of more than 30 years of data collected from previous MNF vessels (www.mnf.csiro.au).

Australia's Marine National Facility vessel Investigator *is owned and operated by CSIRO to provide world-class ocean research capabilities to Australian scientists and their international collaborators (Source: CSIRO, Marine National Facility).*



▲ ***Figure 14.6**: IMOS plays a key role in funding marine research infrastructure in Australia. The multi-organisational delivery model fosters links among Australian research agencies and provides a central data delivery portal through the Australian Ocean Data Network (AODN) (IMOS). The schematic illustrates some of the activities coordinated by IMOS and some of the research outputs up to 2016 (Source: IMOS).*

CONCLUSION

Technology increasingly is changing the way we collect measurements of the oceans. New sensors deployed in innovative ways have reduced the cost of collecting data significantly and increased both measurement capability and area of observation. Satellite remote sensing of the oceans has given us new insights into large-scale ocean processes. Autonomous platforms have delivered a step change in the amount of high-quality data now available in near-real-time. National coordination and engagement with international programs gives us more information that improves our understanding of regional issues, as well as global questions. These new data streams, coupled with ever-improving ocean models, enable exciting new research and allow us to look into the future of our climate and oceans in ways not possible previously.

FURTHER READING

Corfield R (2003) *The Silent Landscape: The Scientific Voyage of HMS Challenger*. National Academies Press, Washington DC, USA.

CSIRO website, <http://www.csiro.au/en/Research/OandA>

IMOS website, <http://imos.org.au/>

MNF website, <http://www.csiro.au/en/Research/Facilities/Marine-National-Facility>

CHAPTER 15.

Managing multiple uses of our oceans

Beth Fulton, Tony Smith, Keith Sainsbury and Marcus Haward

Key messages

- Australia's oceans involve a mix of nature and human activities, with multiple users often having conflicting objectives.
- Simple, inflexible, one-solution management options are no longer appropriate.
- Integrated management approaches have been developed to help people understand the complexities of connections among ocean ecosystems and human uses, and what cumulative impacts might result from multiple human uses.
- Decision-support toolboxes have been developed to explore opportunities and consequences of different management and use options.

INTRODUCTION

Australia is a nation that loves the sea. Coasts, and oceans more broadly, are important as loci of human activity and attract many competing human users, often with conflicting objectives. Little of the oceans is completely untouched by human influences,[1] although most human activities are concentrated along coastlines. Near-shore waters also are where most ocean production and food webs are concentrated.

Marine and coastal systems are complicated and changeable, and management decisions need to account for uncertainty as well as political and social acceptability. This chapter focusses on integrated management of Australia's coasts and oceans, the associated challenges and the scientific tools available to support improved decision making for sustainable management.

Australians live along the coasts and use marine environments in many ways – commercially, recreationally and culturally (Source: Nick Pitsas, CSIRO).

INTEGRATED MANAGEMENT OF COASTS AND OCEANS

Earlier views of ocean use focussed on fisheries and shipping. The view has grown to include aquaculture, recreation and tourism and some of the downstream pressures, such as pollution coming from land uses including farming, mining and urbanisation. Even this view is becoming out-dated, however, as the oceans 'fill up' with an increasing diversity of uses, including mining, energy generation, transport, leisure, cultural inspiration, hunting and sea-farming. This diversity is evident most clearly around Australia's major coastal population centres and trade ports.

Ocean and coastal uses typically have been managed separately, sector-by-sector, informed by sector-specific science. Sector-by-sector approaches, however, are becoming less adequate. Increasingly busy coastal regions present expanding economic opportunities that must be balanced against growing pressures from existing uses and concerns over global ocean changes that threaten biodiversity and food security. Australian research has shown that an important approach to achieving this balance is integrated management that aims to balance human activities and environmental stewardship and provide equal support to social, economic and environmental objectives wherever possible.

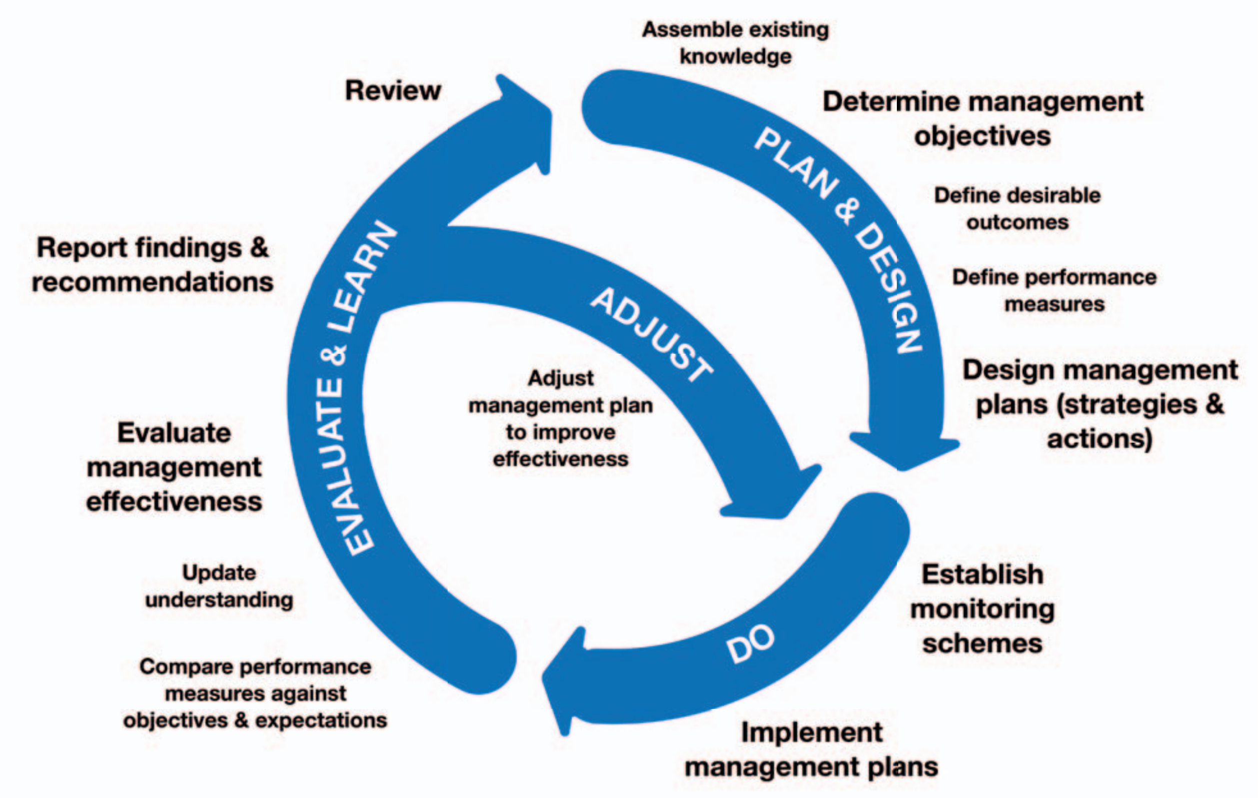
Integrated management is relatively new, and directly recognises connections among marine, coastal and terrestrial systems, as well as between ecosystems and human societies. It is based on understanding cumulative effects of various activities and the different (and sometimes conflicting) objectives of different people seeking to use and enjoy Australia's marine environment in diverse ways. It is not a replacement for sector-based management, but a complementary approach focussed on dealing with the complexity and uncertainty that spans sectors, especially when and where they interact.

Sydney and Port Headland both have busy harbours reflecting the mix of uses coming to dominate populated Australian coastlines (Sources: Taras Vyshnya and Adwo, Shutterstock).

CHALLENGES FACING INTEGRATED MANAGEMENT

Management across so many interacting parts is challenging, particularly given the dynamic nature of marine ecosystems that are less familiar and more rapidly changing than terrestrial ecosystems.[2] Achieving such management without being overwhelmed requires melding many different kinds of knowledge. Integrated management draws on research across physical environments, ecosystems, economic systems, livelihoods and communities and information from industries and Traditional Owners.

Some management can operate within an adaptive cycle of 'learning by doing' where objectives are stated, plans made, actions taken and lessons learned for next time (Fig. 15.1). This is not possible for some long-lived decisions, such as major infrastructure developments (e.g. ports), which are relatively infrequent but not readily reversible. It is important to evaluate decisions across multiple scales from short term and local up to long term and regional (or even global) because a poor decision now may lead to future problems or close down future options. It is important to provide a formal framework that allows lessons learned in one case (e.g. port development) to be applied to similar cases (e.g. other ports) elsewhere or at other times.



▲ ***Figure 15.1***: *The adaptive management cycle, which emphasises making management decisions using best available knowledge and then learning by doing. Management plans and actions are updated based on new understanding from monitoring how a system responded to previous implementations of management plans (Source: modified from Jones 2005[3] with permission from Oxford University Press).*

Uncertainty about the present or future state of a system, however, should not preclude making decisions. Rather, potential outcomes of any decision (including to do nothing) should be compared against what might result from alternative decisions. The pros and cons of the different options then can be laid out transparently with any trade-offs between uses or objectives made clear. Some of these lessons have been learned already in managing individual sectors, such as fisheries. Australia has a world-leading reputation for taking an ecosystem-based approach to fisheries management and for using decision-support tools to explore alternative options.[4]

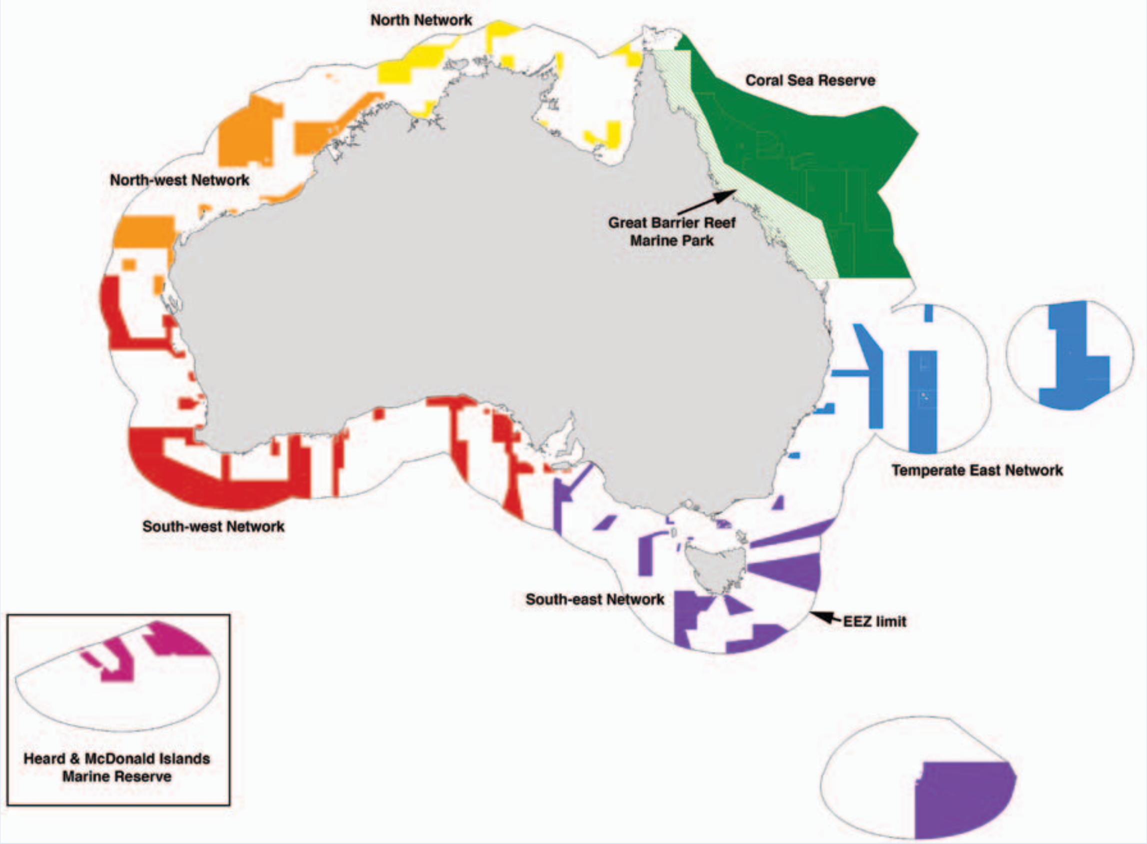
Australia has had successes and failures, however, in applying integrated ecosystem approaches to oceans management. Australia was one of the first countries to adopt a national oceans policy intended to operate across all ocean uses to produce truly integrated oceans management (Box 15.1). Attempts to implement the policy fell short of expectations, however, perhaps because it was too ambitious and ran ahead of science and governance structures needed to support it. Management of the iconic Great Barrier Reef (GBR), in contrast, is regarded widely as a model for integrated multiple use management within an ecosystem approach (Box 15.2).

Box 15.1: Australia's Oceans Policy

Australia was second only to Canada in attempting to establish integrated oceans management, announcing the Australian Oceans Policy (AOP) in 1998, 2 years after Canada and before similar initiatives in the USA and Europe. The policy was intended to include all levels of government, but ultimately only involved the Federal Government, leaving coastal zone management to the states. A considerable governance structure was set up to support the policy, including a Council of Ministers and a National Oceans Office (NOO), with the intention of effecting the policy through development of Regional Marine Plans (RMPs).

The lack of integrated assessment tools at the time, however, meant there were significant scientific challenges in providing information to support management needs. Substantial effort since has been put into developing a toolbox of decision-support tools, and Australia is now much better placed to deliver integrated management.

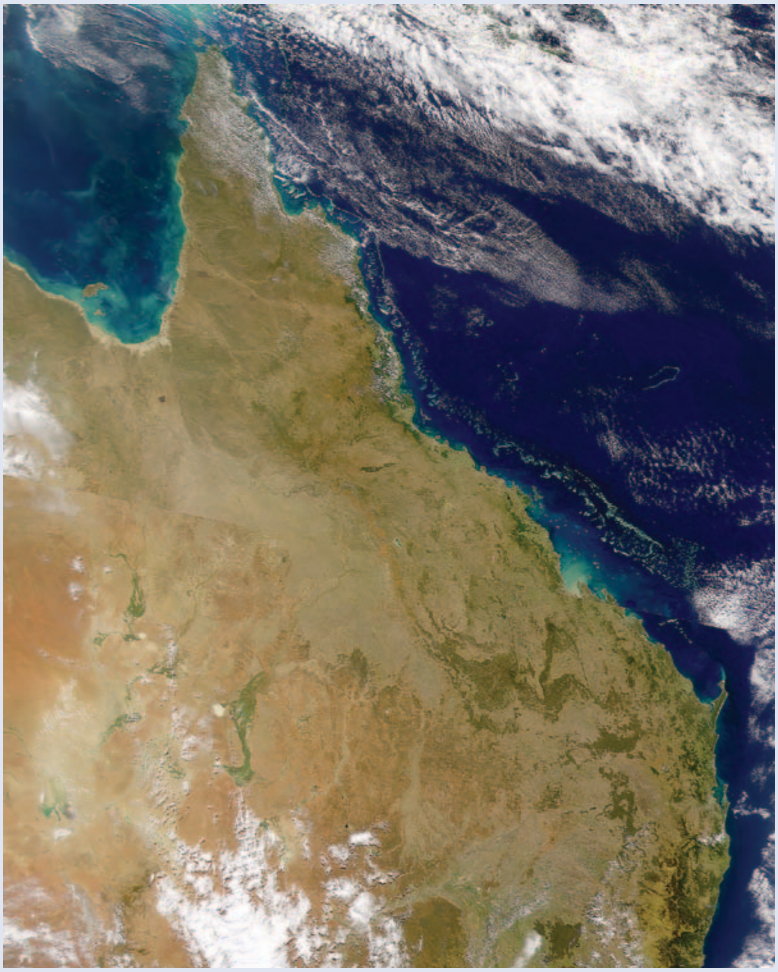
The toolbox came too late for the AOP, however. A review of AOP in 2004 resulted in a large change in direction after only one RMP had been implemented in south-eastern Australia. Governance shrank, the NOO was disbanded and the RMPs shrank from being multiple-use plans to being focussed almost entirely on environmental issues. Ecosystem protection was to be provided by establishment of a National Representative System of Marine Protected Areas (NRSMPA, Fig. 15.2). A key lesson from this history is that integrated management must be pragmatic if it is to be feasible, and take into account existing power and authority structures to secure the support it needs to succeed.[5] It is clear that science and policy must work hand-in-hand for a successful outcome.



▲ ***Figure 15.2**: Map of Australia's National Representative System of Marine Protected Areas, coloured by region (Source: CSIRO, data from Australian Department of the Environment and Energy).*

Box 15.2: The Great Barrier Reef

Australia's Great Barrier Reef (GBR) stretches over 2000 km along the Queensland coast. It is the largest coral reef ecosystem on Earth,[6] with around 3000 reefs and shoals. Integrated management of the GBR began with the *Great Barrier Reef Marine Park Act 1975* and the region was recognised as a World Heritage Area in 1981. The act pre-dated a formal definition of integrated or ecosystem-based management but embodied several key principles, including allowance for sustainable multiple use and enjoyment of the region consistent with conservation of the natural environment. The Marine Park generates A$5 billion annually for the Australian economy through a mix of tourism, shipping and commercial, charter and recreational fishing. More than a million residents live adjacent to the park, along with major ports, mining and agricultural activities. Pressure from these activities, as well as large-scale processes such as ocean warming and acidification, have put the environmental values of the Park under threat.[7]



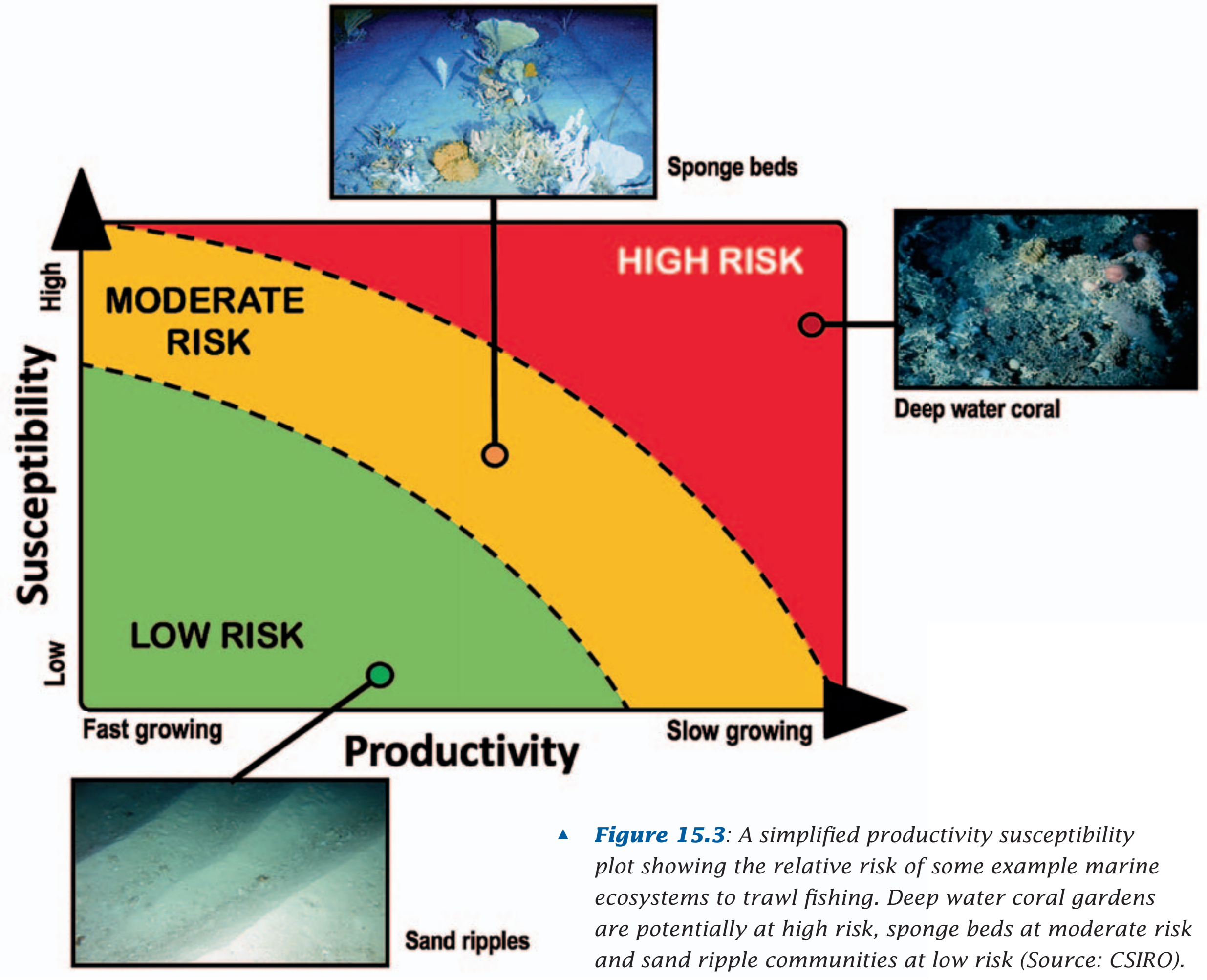
Satellite image of the Great Barrier Reef, which generates A$5 billion per year and is recognised for its integrated management efforts (Source: Visible Earth, NASA).

Spatial zoning to allow different uses in different areas is an important management tool. Governance is further strengthened by publicly inclusive development of management plans (e.g. the Reef 2050 Long-Term Sustainability Plan) and strong monitoring and research efforts.

The current zoning plan resulted from the GBR Representative Areas Program (RAP 2004) undertaken in response to concerns about levels of biodiversity protection within the GBR. The RAP was integrative in terms of its use of scientific information (geology, morphology, ecology, bioregionalisation), use mapping (fisheries, tourism, recreation, shipping) and inclusion of Indigenous values and a public participatory planning process. Different information layers were overlayed to ascertain key locations for biodiversity protection while minimising potential negative social, economic or cultural impacts on those using the region. Deterioration of the GBR since the RAP process has highlighted the importance of tools that deal with dynamically cumulative pressures (e.g. from agricultural runoff, ports and shipping, coastal development and climate change) rather than simpler static information overlays. New tools are being developed that allow such dynamic evaluation of cumulative impacts (Chapters 11, 16).

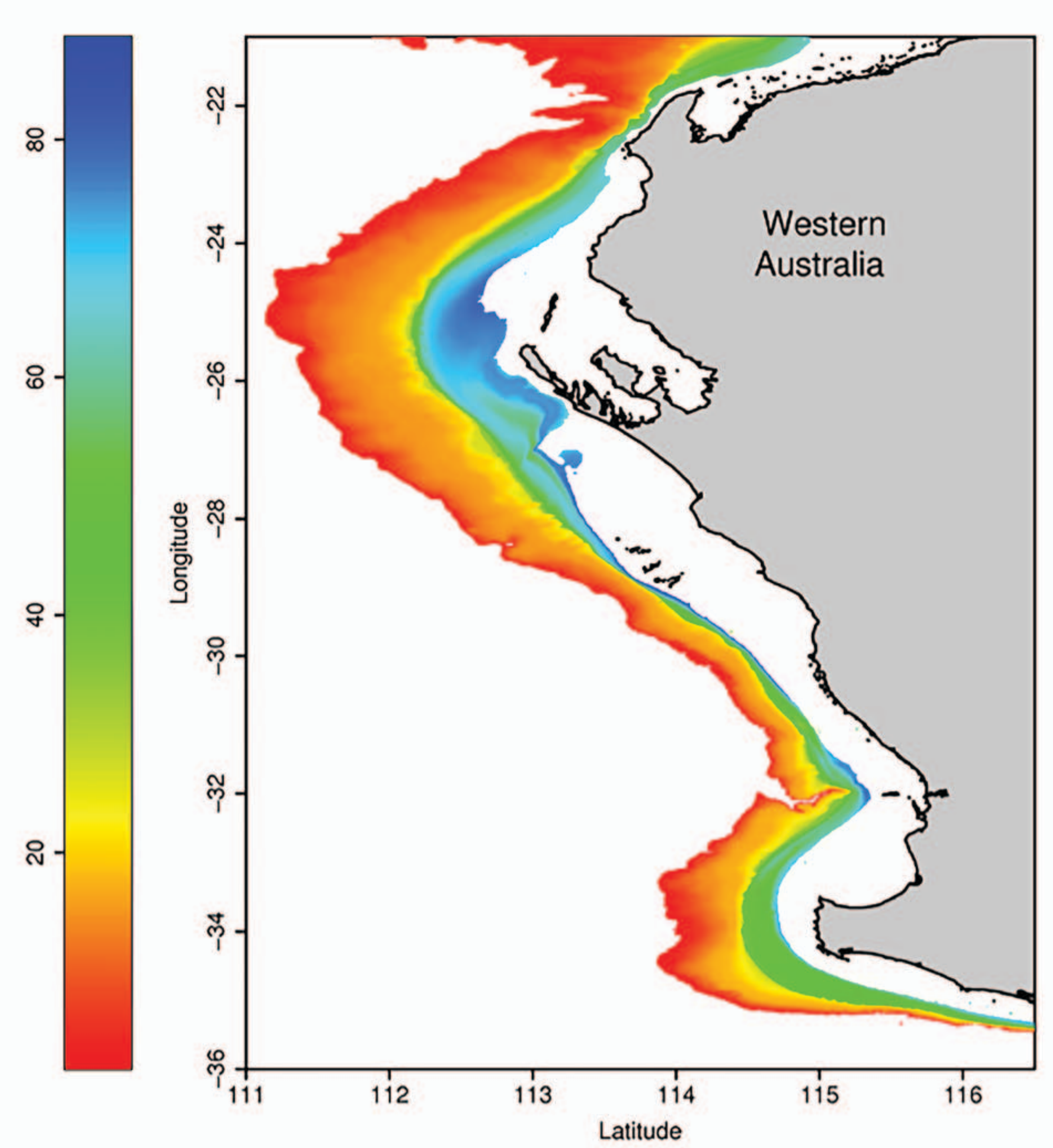
INTEGRATED MANAGEMENT TOOLBOXES

The complexity of the problems that must be tackled in ocean and coastal zones has spawned a diversity of scientific decision-support tools (Fig. 15.3). Some of these help synthesise information (e.g. mapping overlays to find hotspots of pressure) or help identify vulnerability of systems, or specific parts of a system, to particular threats (such as climate change) or uses (such as fishing). Alternative management options (e.g. different zoning combinations) can be explored by assessing how these maps or vulnerabilities may shift over time with different combinations of use and management.



▲ ***Figure 15.3**: A simplified productivity susceptibility plot showing the relative risk of some example marine ecosystems to trawl fishing. Deep water coral gardens are potentially at high risk, sponge beds at moderate risk and sand ripple communities at low risk (Source: CSIRO).*

The vast size of Australia's marine estate means that documenting the entire area in detail is not possible with current methods. Statistical models are used to relate ecosystem components to depth or physical ocean properties (such as temperature or geology, Chapter 4) that can be measured more comprehensively, such as by bathymetric surveys or by satellite remote sensing. These models can then be used to make national maps of potential habitats or biodiversity (Fig. 15.4), which can be used to help decide where to put protected areas and where to allow various uses.



▲ ***Figure 15.4****: Example map of marine species richness (number indicated by different colours) estimated using relationships between the abundance or number of species and environmental properties such as depth or temperature (Source: Dunstan and Foster 2011 with permission of John Wiley & Sons).*[8]

Another set of tools uses simulation models to represent the biological and physical system and predict how that system may change under different management and use options. These tools represent each part of the system (the natural world, human users and management decision making) and act like 'flight simulators' for users and managers, allowing people to explore options interactively and providing a common talking point for finding negotiated management and development solutions.

These tools also allow for exploration of what people value about an ecosystem, what is acceptable and unacceptable to them, and how they will respond to management decisions. This simulation-based approach is known as management strategy evaluation, or structured decision making. It has been used to help shape sustainable fisheries management in Australia and around the world and has been extended recently to integrated management.[9]

CONCLUSION

Demands on our oceans from diverse uses and increasing coastal populations are increasing. Making wise decisions and finding sustainable solutions to issues can be exceptionally challenging because decisions increasingly need to take into account many competing objectives, economic pressures, social desires and political feasibility, as well as ecosystem sustainability. They also need to deal with the fact that ecosystems are ever-changing.

Integrated management is the best means of dealing with the complex and interconnected nature of Australia's coasts and oceans. Integrated management ideally requires knowledge of all parts of the system – climate, food webs and habitats, human uses, economic and social values, and governance – but it can be applied with limited knowledge to explore the consequences of assumptions we must make when we have limited knowledge and associated uncertainty. Science and evidence-based tools help support integrated decision making, synthesising the available information and explicitly incorporating patchy and imperfect understanding, resource limitations and multiple competing priorities.

FURTHER READING

Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D (2012) *Structured Decision Making: A Practical Guide to Environmental Management Choices*. Blackwell Publishing, Oxford, UK.

Haward M, Vince J (2008) *Ocean Governance in the Twenty-first Century: Managing the Blue Planet*. Edward Elgar, Cheltenham, UK.

Ogier E, Macleod CK (2013) *'Your marine values – public report 2013'*. IMAS Technical Report. University of Tasmania, Hobart.

Walters C (2002) *Adaptive Management of Renewable Resources*. The Blackburn Press, West Caldwell, NJ, USA.

CHAPTER 16.

Changes and challenges for future generations

Éva Plagányi, Peter R Oke, Tatiana Rykova and James Innes

Key messages

- Observation and analysis of oceans will become increasingly automated and global.
- Widespread real-time data collection will inform search and rescue, oil and gas, and fisheries operations.
- Future science will need to address uncertainty of forecasts and seek solutions to adapt to climate change.

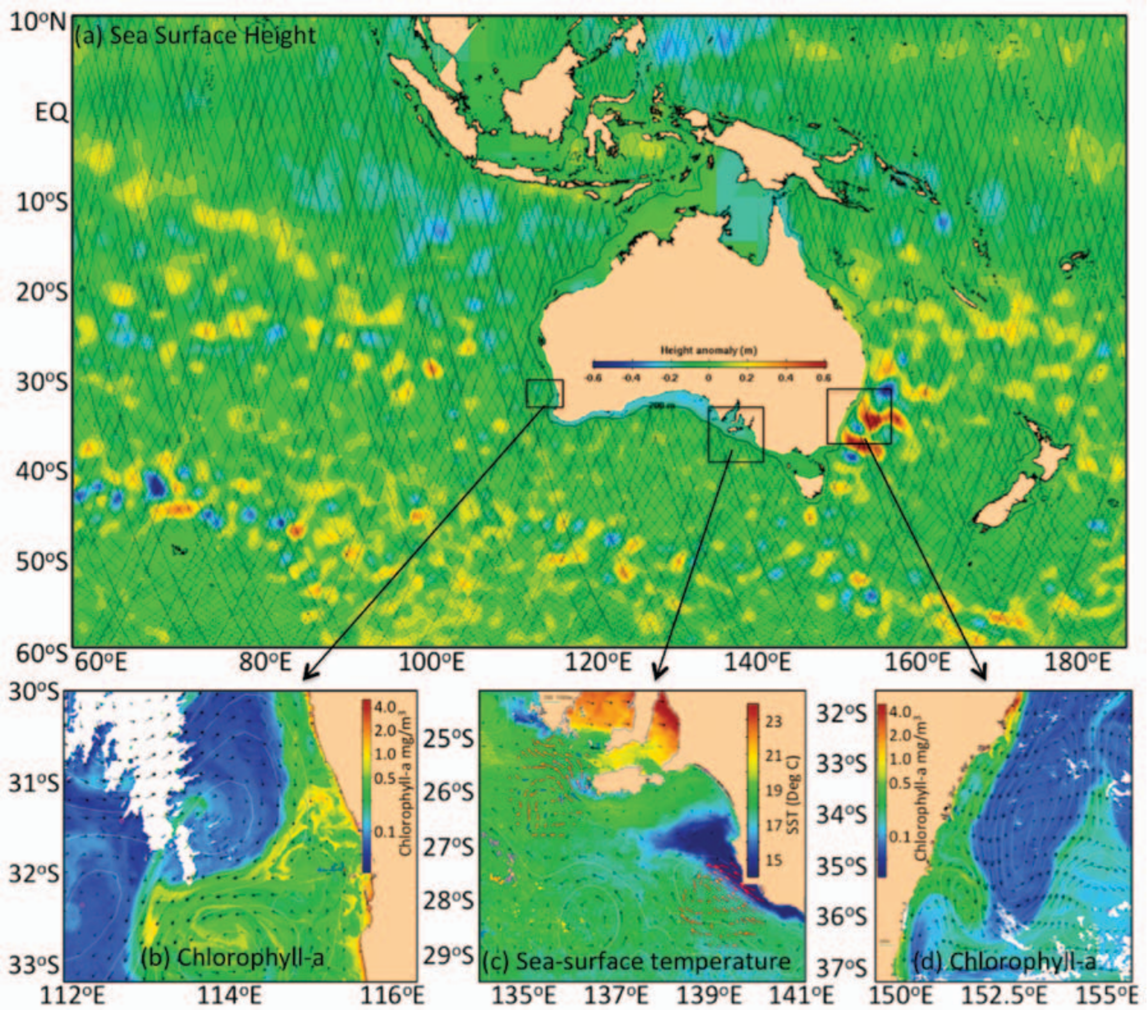
INTRODUCTION

The oceans and the way we research and use them may be at a turning point. Ocean scientists face lots of challenges to provide up-to-date information and advice to policy makers. This challenge is exacerbated by predictions of ongoing and intensifying climate change,[1] growing multiple-use conflicts, and globalisation of markets. Marine science already has undergone many parallel developments to facilitate monitoring, prediction and management of the ocean environment, and those changes will continue.

Technical improvements continue to expand the realm of what we are able to study and understand, ranging from fine-scale measurements to sophisticated genetics methods capable of providing answers to previously impenetrable questions. Increases in computing power and the development of state-of-the-art, multi-disciplinary modelling tools have enabled complex simulations of many aspects of the oceans and our use of them. We describe in this chapter some anticipated changes and challenges in how ocean science might meet Australia's future needs.

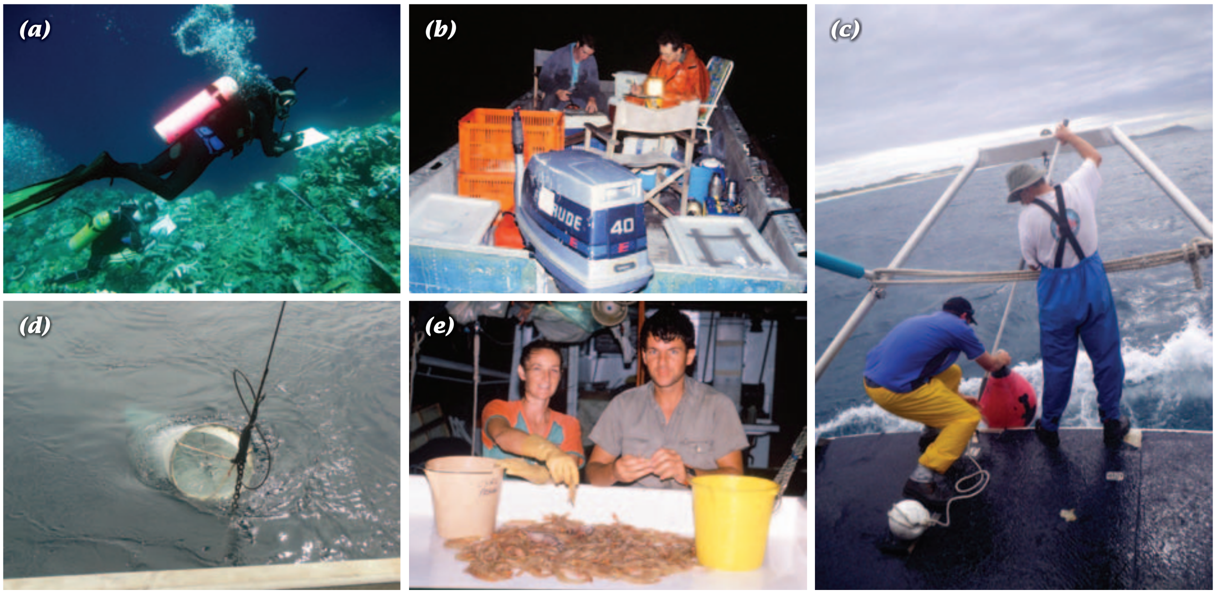
PRESENT AND PAST OBSERVATIONS AND MODELS

Ocean science historically has relied on sparse observations of only a few variables of the water column (e.g. temperature) to understand ocean circulation, ecosystems, fisheries and human impacts on the oceans. Satellite observations have demonstrated that oceans are more complex than previously thought, with rich fields of swirling eddies, filaments and inter-related communities of plant and animal populations (Fig. 16.1).

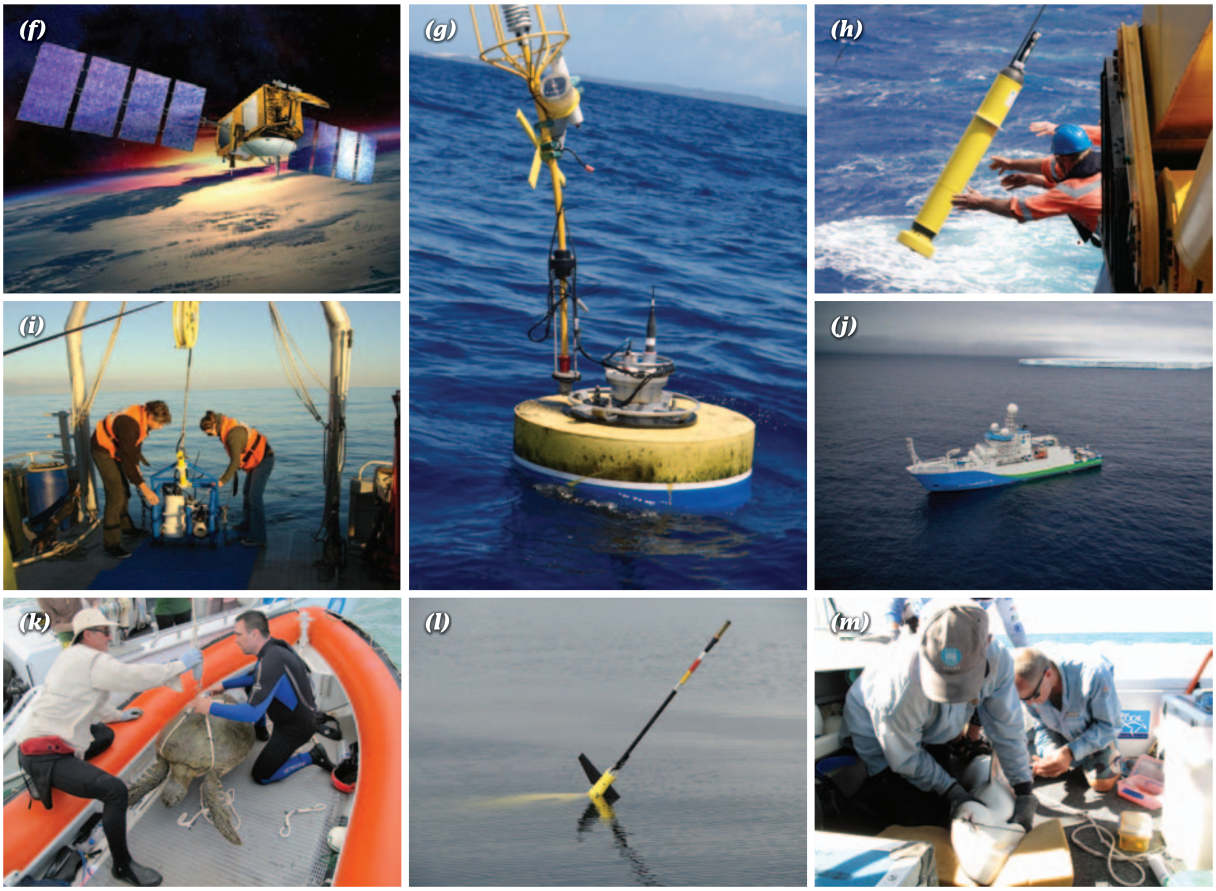


▲ ***Figure 16.1***: ***(a)*** *Sample fields of satellite-derived sea-surface height (green is lower and red is higher);* ***(b, d)*** *chlorophyll-a from ocean colour providing an index of production of planktonic plants; and* ***(c)*** *sea-surface temperature. The black dotted lines in panel a show some of the satellite tracks, the black and red arrows in panels b, c and d indicate surface currents (Source: CSIRO).*

Manual



Automated

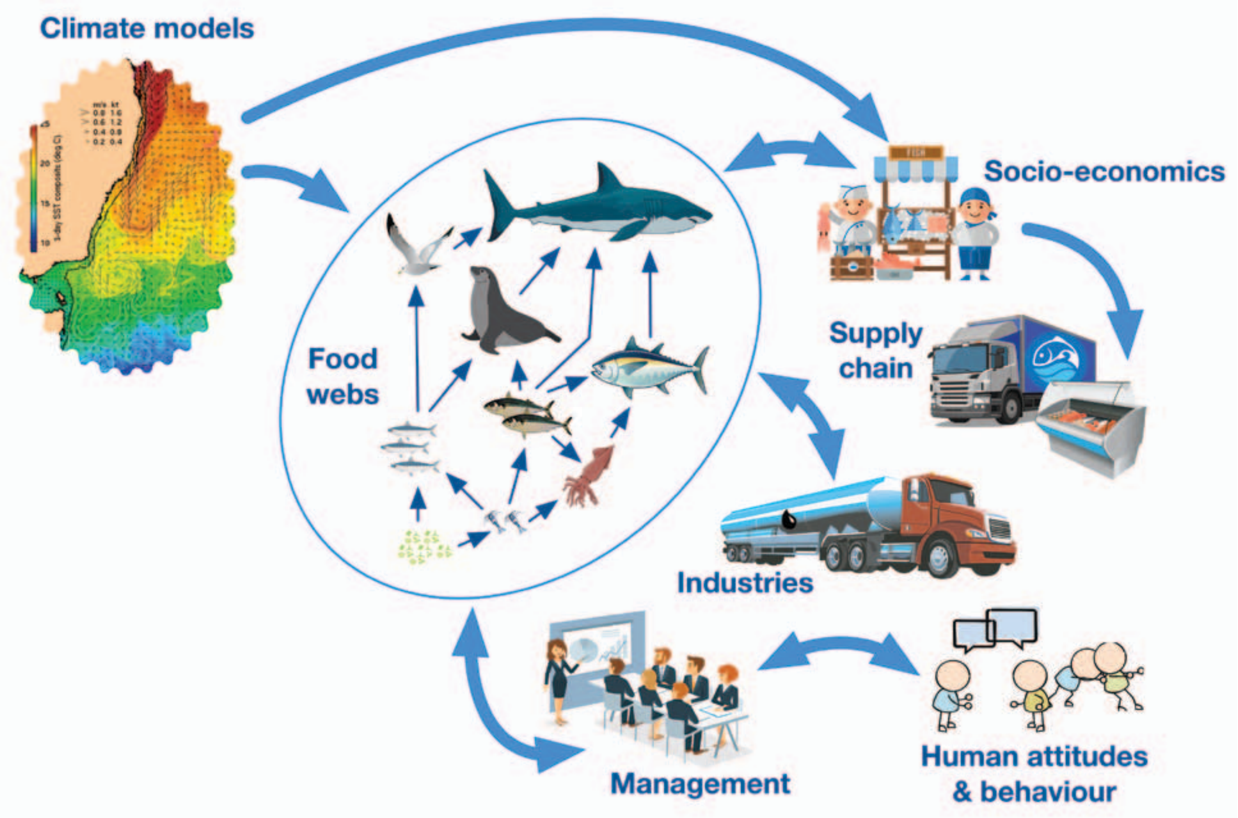


Images depicting changes in methods for observing the oceans showing the manual approaches such as divers, counting samples and physically observing, and automated approaches involving satellites, ship-borne sensors and autonomous platforms (Sources: a–e, g–k, m CSIRO; f NASA; l Matthew Grund, CC BY 3.0).

Our increased ability to observe the ocean environment has influenced the way we conduct business at sea. Commercial and recreational fishers, for example, routinely use satellite observations as decision-making tools to identify where and when to fish most efficiently. The oil and gas industry also uses ocean observations and forecasts to inform more efficient and safer exploration, extraction and transport activities (Chapter 12).

Current global ocean models typically are eddy-resolving, representing circulation features at scales of tens of kilometres or smaller. These detailed models became commonplace in the 2000s and the complexity of embedded ecosystem models increased significantly. Advances in our ability to model and process ocean data stem from ongoing improvements in computing technologies and advances in modelling skills. These improvements have been essential in transforming Australia's marine industries, providing unprecedented information to promote safety, efficiency and sustainability.

The current state-of-the-art in ocean science involves a combination of observations and models. Forecasts of the ocean on timescales of days to months are produced in near-real-time and the outputs are coupled to models of biological and ecosystem components of marine environments. Economic and social models of human activities now also are linked to models of ocean physics and biology to explore potential future consequences of interactions between human activities and ocean environments (Fig. 16.2, Chapter 15).



▲ ***Figure 16.2***: *The connections and complexity built into ecosystem models such as CSIRO's Atlantis*[2] *(Sources: E. Fulton, CSIRO; embedded images Shutterstock).*

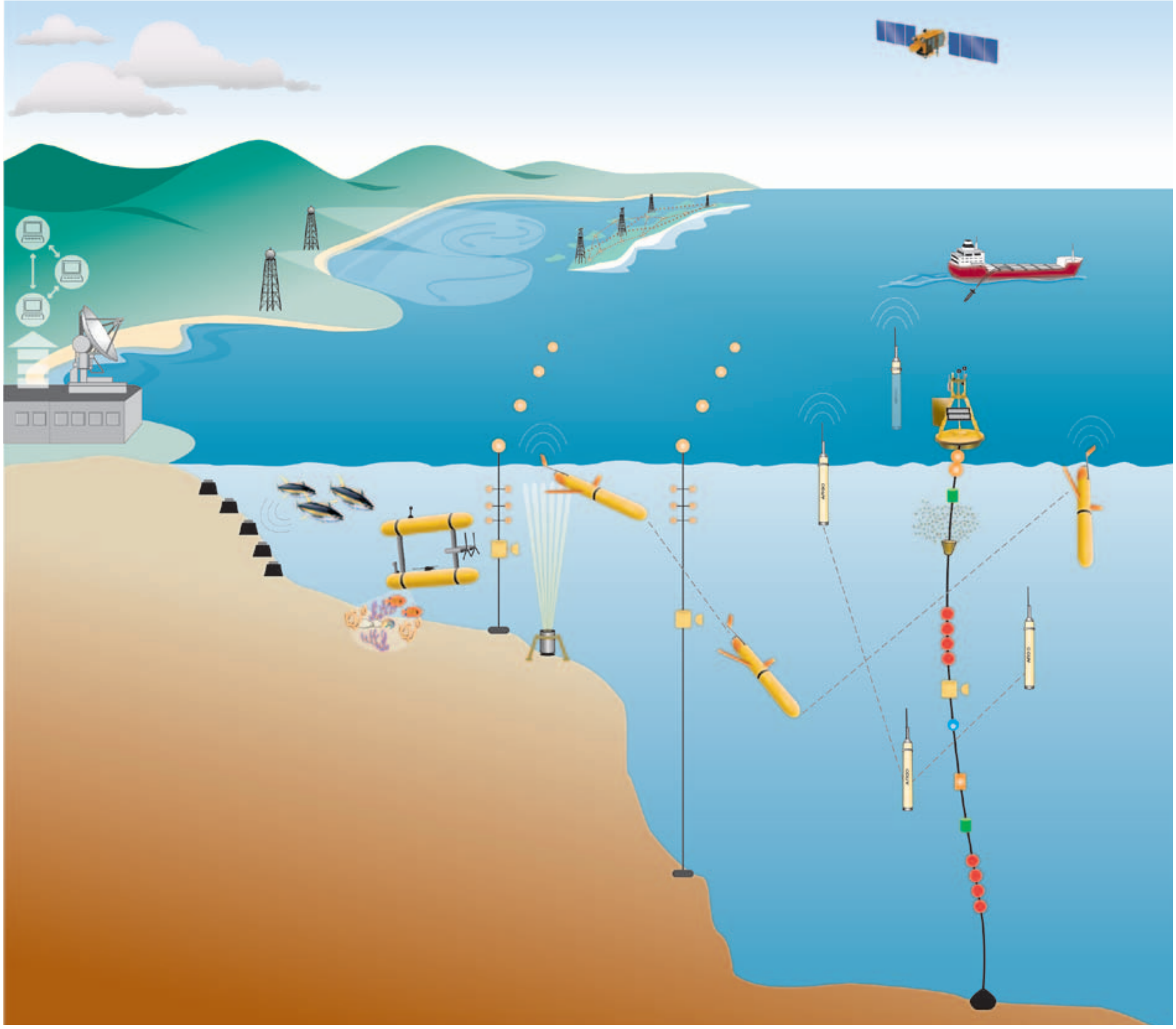
FUTURE OF OBSERVATIONS – ROBOTICS AND REAL-TIME DATA

A revolution in ocean observations seems imminent. Satellite observations are delivered at higher resolution in both time and space, now returning ocean surface measurements on spatial scales of metres rather than tens of kilometres and on timescales of minutes rather than hours. New variables are being measured from space, including sea-surface salinity and more diverse optical properties of the oceans, providing insights into more aspects of ocean variability on finer scales. Wide-swath altimetry, where sea-surface height is measured across large sweeps of the ocean at once, is set to allow monitoring of unprecedented details of ocean currents. Observations at depths are performed by autonomous gliders and Argo floats (Fig. 16.3, Chapter 14). Automated observations are extending to the full depth of the ocean and under polar ice shelves: areas that previously were inaccessible or difficult to observe. These new devices are collecting more variables than ever, yielding new insights into how the oceans work.

Monitoring methods are becoming automated and better coordinated (Chapter 14). The Integrated Marine Observing System (IMOS, http://www.imos.org.au/), for example, supports and coordinates many ocean observation programs by multiple research agencies across the Australian marine estate. Australia's Marine National Facility's new research vessel *Investigator* (http://www.mnf.csiro.au/) includes a wealth of technologies to monitor the oceans from the surface to the sea floor. CSIRO's Starbug is an example of a miniature autonomous underwater vehicle that can use robotic vision to navigate complicated terrain, capturing images of marine species in the open oceans and along the sea floor without the need to be tethered to a surface vessel. These technological advancements in robotics are expected to increase in skill and availability, facilitating exploration of physical and biological characteristics of the oceans as well as supporting compliance and defence monitoring on scales not possible previously.

Biological observations also are more sophisticated, enabling studies of biology, life history, movement, interaction and population structures of marine species in greater detail than was possible just a few years ago. Genetic methods are predicted to become indispensable in determining how closely related are fish stocks from different regions, for understanding organisms' responses to climate change and for improving aquaculture production. New 'close-kin' methods developed by CSIRO, for example, use 'genetic fingerprinting' to estimate abundances of marine fished species, as well as species of conservation interest.

Greater spatial resolution of ocean-use data that are valued by stakeholder groups will allow more informed assessments of how best to allocate resources among these groups (Box 16.1). More accurate, near-real-time data collection in fisheries (such as catch and economic data) via new technologies will provide data needed to further improve economic performance and reduce fisheries by-catch (e.g. by redirecting fishers away from areas where by-catch species are predicted to occur). It is anticipated that improvements in monitoring and technology will lead to lower-impact use of both renewable ocean resources (e.g. less by-catch) and non-renewable resources (e.g. oil and gas extraction), as well as other uses such as energy generation and waste disposal.



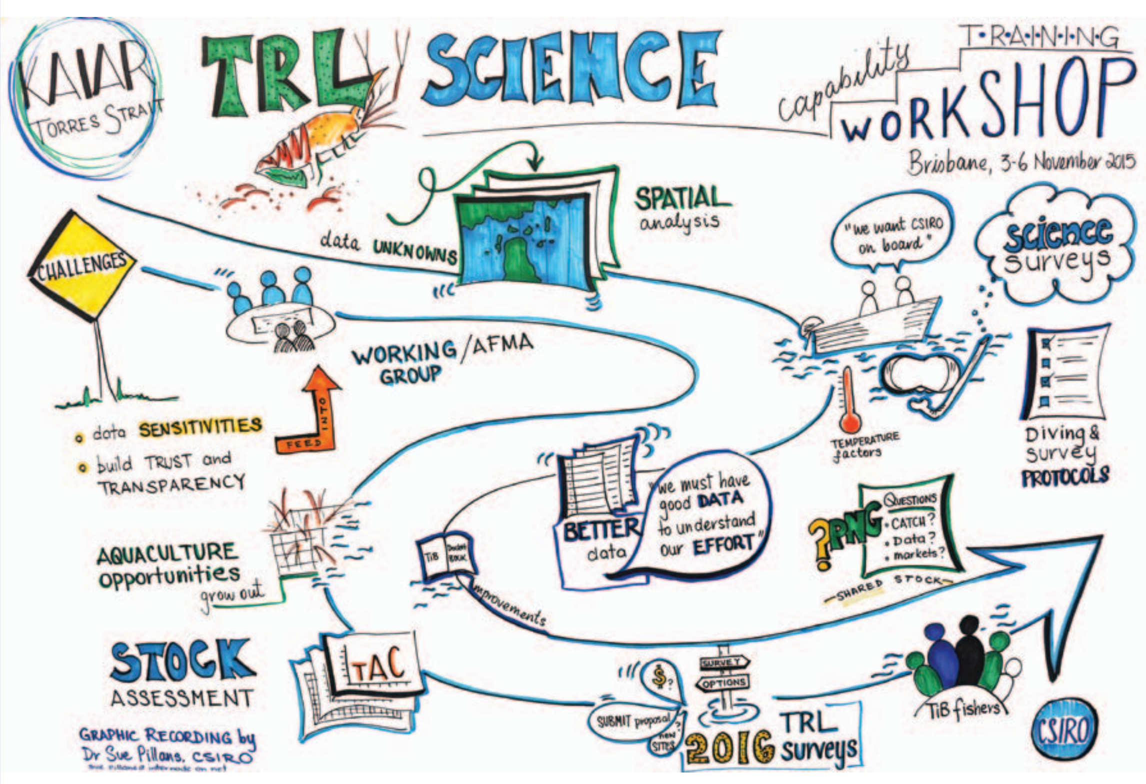
▲ ***Figure 16.3**: Diagram illustrating how the national IMOS program works, depicting observation platforms including Argo floats (cream cylinders), gliders (yellow with wings), moorings (black string with multi-coloured circles at right), and other observing platforms (Source: adapted from* IMOS Marine Matters *newsletter, issue 2, July 2007).*

FUTURE OF MODELS

Forecasting always has been an uncertain science, as evident from weather forecasts. Ocean forecasting is following weather forecasting with a set (ensemble) of predictions, rather than a single forecast, providing probabilities of extreme events under expected ocean and weather conditions. Future models of biological systems will integrate complex processes such as fish behaviour, two-way socio-ecological feedbacks with human systems and feedbacks between physical and biological systems in ensemble runs. It is anticipated that the next generation of such integrated models will close the loop in modelling feedbacks between biology of the oceans and

Box 16.1: Collaborative approaches to advancing science

Future challenges include growing expectations by a better informed Australian community that increasing use of our coasts and oceans is managed appropriately. Citizen science programs such as REDMAP (http://www.redmap.org.au/) are facilitating local data collection that otherwise would be difficult or impossible. These data provide valuable insights into the impact of climate change in shifting species distributions. Volunteer recreational anglers similarly contribute to data collection, as do stakeholders from a range of other marine sectors. Integrated fisheries management in the Torres Strait is built on strong involvement of Traditional Owner communities (Fig. 16.4).



▲ ***Figure 16.4**: Graphic illustrating the involvement of Torres Strait Indigenous communities in mapping the way forward in integrated fisheries management in Australia's Torres Strait (Source: CSIRO, Dr Sue Pillans, www.drsuepillans.com).*

the Earth's climate system. Such modelling will need to account for changes in biological systems due to differing sensitivities of species to human pressures, including fishing and climate change, as well as conservation outcomes (e.g. recoveries in baleen whale and shark populations).

Oceans are becoming crowded, and truly integrated management of the marine environment will require more comprehensive bio-economic models that incorporate not only fisheries but uses from all sectors (e.g. oil and gas, shipping, defence and recreation). Determining optimal allocations of resources among alternative, and potentially competing, sectors is central to optimising society's use of the ocean environment. New approaches will allow this to be done transparently while formally accounting for the inevitable trade-offs associated with different options and demonstrating the effects of uncertainties in our knowledge[3] (Chapter 15).

An important future challenge will be how to include adequately changing societal concerns and complex governance, policy and socio-cultural frameworks in such models. Bio-economic analyses also will need to stretch their theoretical underpinnings to represent non-market and non-use future values in integrated models as communities increasingly exert influence over how oceans are used.

FUTURE UPTAKE OF RESEARCH

Marine industries are becoming smarter and demanding more information to improve safety at sea, efficiency and productivity. Oil and gas companies will demand operational forecasts around the clock. Shipping companies will use ocean forecasts to schedule their fleet movements for greatest efficiency and defence forces and fishing fleets alike will depend more and more on forecasts of the physical and biological properties of the oceans in their decision making. Governments will require precise information on climate mitigation (how to avoid, slow or reverse climate change) and adaptation (how to adjust to it). New ocean uses will continue to emerge, including for energy generation and pharmaceutical production, and coasts will be characterised by continued land reclamation and growing numbers of floating structures, or ‘seasteads’, such as floating cities.

Methods for forecasting ecosystems will become more sophisticated, accurate and precise. This is particularly important, for example, to assess sustainable catches that can be taken from wild fisheries as demand for seafood increases and technology improves fishing efficiency. The relatively narrow conventional definitions of sustainability will be replaced with broader views of sustainability that take into account social values and broader ecological effects of fishing. Societal pressure will play a larger role in driving the need for solutions to the challenges of maintaining biodiversity in the face of ocean use. The emergence of new technologies will improve understanding of the oceans’ rich range of species, potentially fuelling greater demands for targeted marine conservation. New species will continue to be discovered at the same time as climate change and other human pressures drive some existing populations downwards. Active mitigation and translocation strategies will help to ameliorate negative consequences of climate change. In many cases, changes in the oceans and their inhabitants will occur rapidly and unexpectedly and adaptive strategies will be needed to meet the challenges.

The ‘blue economy’ (Chapter 7) recognises that the oceans have a major economic role in humanity’s future and visualises a holistic development framework with sound planning for conservation, sustainable energy production, oil and mineral wealth extraction, bioprospecting, marine transport and other uses. This entails respecting ecological parameters throughout production cycles, using cleaner technologies, creating viable employment and producing high-value commodities. Food security is one of the biggest future challenges on the planet, and the need to use the oceans optimally to grow aquaculture and seek alternative food sources is likely to be a central focus of future research.

CONCLUSION

‘Prediction is very difficult, especially about the future’ – old Danish proverb.

The nature and trade-offs of future uses of the oceans will be influenced by both local and global values and markets, as well as climate change. Growing contributions by ocean-based industries look set to outperform the entire global economy.[4] Industries will require a social licence to operate, entailing consideration of the whole natural, economic and social environment in which an activity is undertaken. Considerations of sustainability also will shift towards more global assessments such that ocean uses and their environmental implications, carbon footprints, local employment and consumption, food safety and quality controls may all influence sustainability assessments locally. These pressures, in turn, will drive the growing need for research into how to integrate these many influences to provide comprehensive information for decision makers having to manage the multiple uses of our oceans and their resources.

FURTHER READING

Boschetti F, Fulton EA, Grigg NJ (2015) Citizens’ views of Australia’s future to 2050. *Sustainability* **7**, 222–247. doi:10.3390/su7010222

Hobday AJ, Bustamante RH, Farmery A, Fleming A, Frusher S, *et al.* (2014) Growth opportunities for marine fisheries and aquaculture industries in a changing climate. In: *Applied Studies in Climate Adaptation*. 1st edn. (Eds JP Palutikof, SL Boulter, J Barnett, D Rissik) pp. 139–155. John Wiley & Sons, Chichester, UK. doi:10.1002/9781118845028.ch16

Maxwell SM, Hazen EL, Lewison RL, Dunn DC, Bailey H, *et al.* (2015) Dynamic ocean management: defining and conceptualizing real-time management of the ocean. *Marine Policy* **58**, 42–50. doi:10.1016/j.marpol.2015.03.014

Poloczanska E, Babcock R, Butler A, Hobday A, Hoegh-Guldberg O, *et al.* (2007) Climate change and Australian marine life. *Oceanography and Marine Biology* **45**, 407–478.

CHAPTER 17.

Ocean changes to come

Richard Matear, Alistair Hobday and Matt Chamberlain

Key messages

- Oceans are key to the climate system's carbon, heat and freshwater cycles.
- Oceans are changing, and further physical, chemical and biological changes are projected for Australian waters this century.
- Ocean warming, acidification, deoxygenation and sea-level rise have important implications for marine ecosystems and the ocean services on which humans depend.
- Climate models are essential tools for exploring mitigation options and integrating climate predictions with human systems such as agriculture and fisheries.

INTRODUCTION

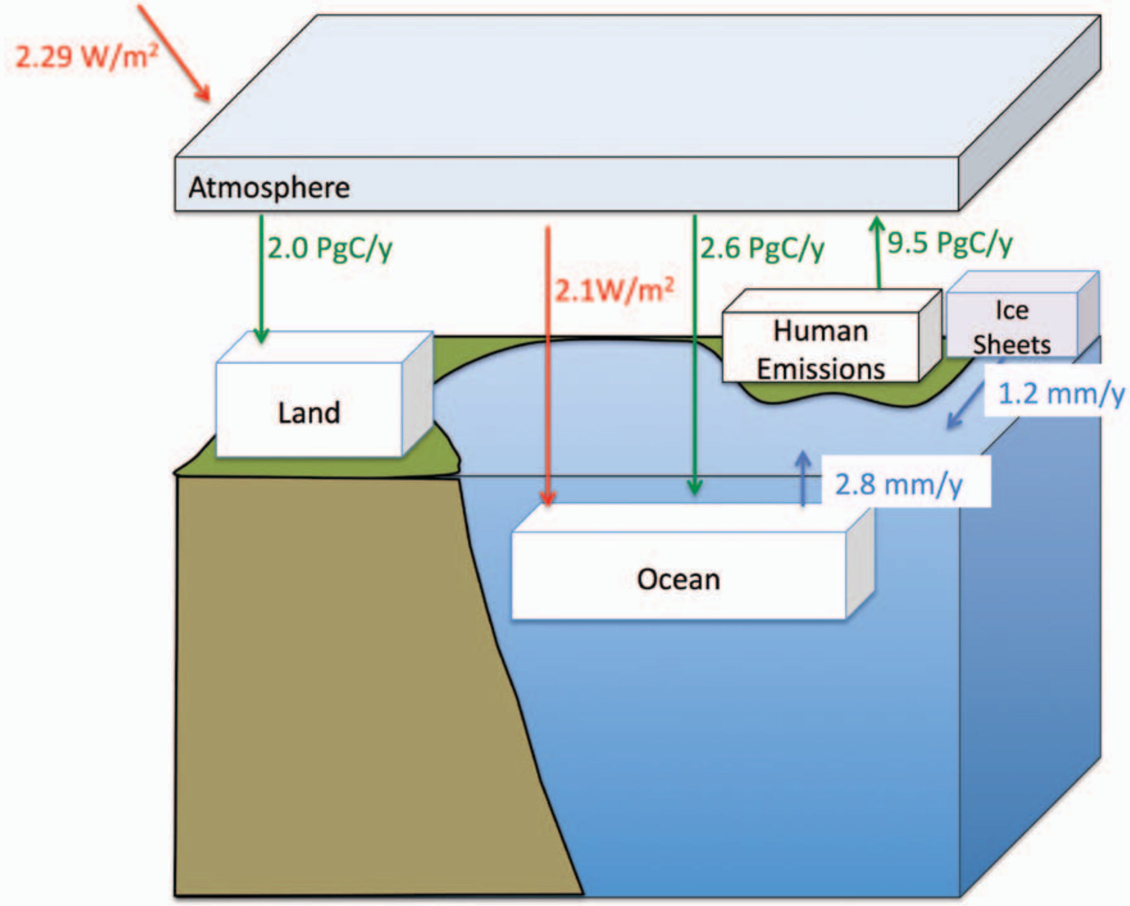
Oceans play key roles in the Earth's climate system through their storage and transport of heat, fresh water and carbon (Chapters 2, 5). The ocean carbon cycle has consequences for marine ecosystems by setting important ocean chemical conditions that link to productivity of marine plants that are at the bases of most marine ecosystems. Storage of heat and carbon in the oceans slows the rate of atmospheric warming from human emissions of greenhouse gases, mainly carbon dioxide (CO_2) (Chapter 5).

Significant climate-driven changes in ocean environments are projected over the next century. Climate change is the major known driver of global ocean change, with wide-reaching and long-lasting effects, though other changes, such as from pollution (Chapter 13) and fishing (Chapter 9) also will affect future ocean state. We discuss in this chapter some key climate-driven changes in the oceans projected by the end of this century.

HOW DO WE DO CLIMATE PROJECTIONS?

Climate models are based on physical principles of ocean, ice, atmosphere and land interactions and capture many important elements of the observed climate. These models bring together our understanding of atmospheric dynamics, weather forecasting, ocean dynamics and numerical ocean modelling. Climate models recently have been expanded into Earth system models by including carbon cycling on the land and in the oceans and their interactions with CO_2 in the atmosphere (Fig. 17.1).

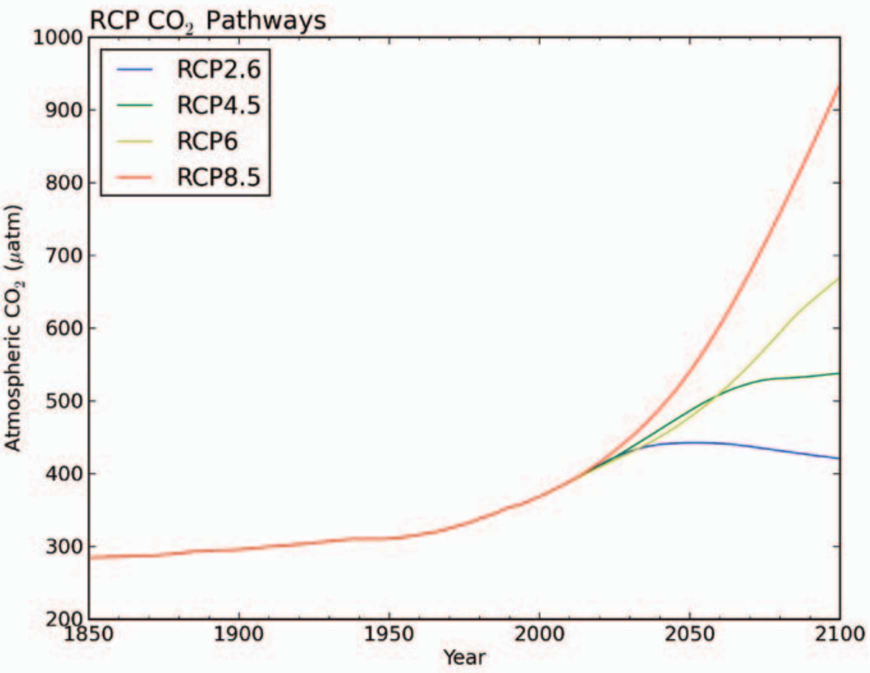
Existing climate models can reproduce the general features of global and annual average surface temperatures and changes known (from observations) to have occurred over the past 150 years, including warming in the second half of the 20th century and cooling immediately following large volcanic eruptions. Most simulations do not reproduce exactly observed reductions in the rate of global warming over the past 10 to 15 years, largely because of the challenges of modelling shorter-period climate variability. Importantly, however, reduced warming over recent years is consistent with observed increases in uptake of heat by the oceans, highlighting the oceans' ability to modulate global warming.



▲ ***Figure 17.1***: *Present change in the global heat (red) and carbon (green) cycles due to human activities. Blue arrows summarise sea-level rise and the contributions of ice sheets to sea-level rise (Source: Richard Matear, CSIRO).*

CLIMATE PROJECTIONS

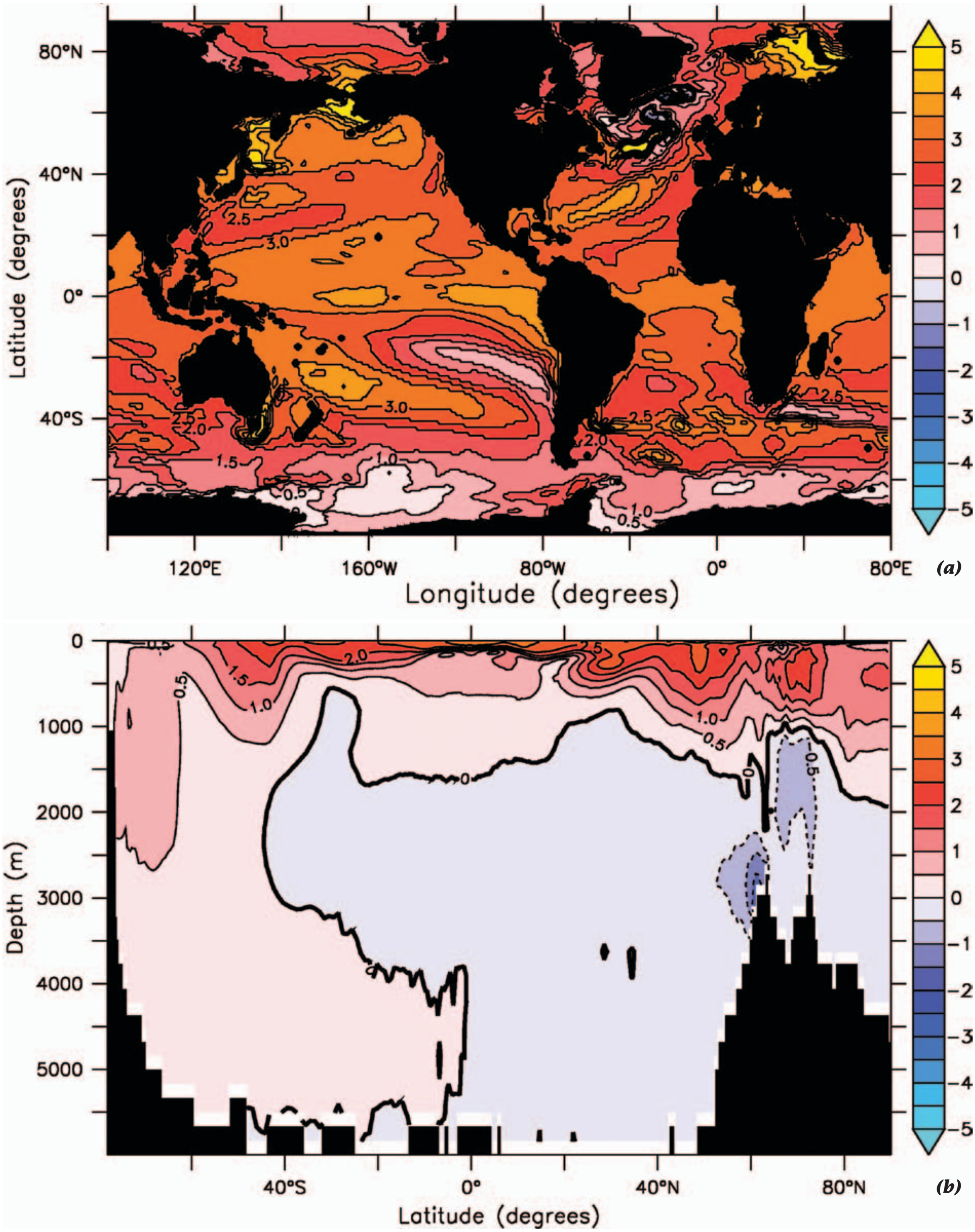
Climate projections must include human emissions of CO_2 to be realistic. A range of human emissions scenarios, termed representative concentration pathways (RCPs), has been developed that consider possible futures for use of carbon-based fuel sources[1] and other human-generated (anthropogenic) greenhouse gases (Fig. 17.2). The high scenario (RCP8.5) reflects a 'business-as-usual' case with little abatement of anthropogenic carbon emissions. The 'best-case' low scenario (RCP2.6) assumes substantial reductions in anthropogenic carbon emissions and rapid transition to non-carbon energy sources. Global warming is expected to be less than 2ºC by the end of the century under the 'best-case' scenario, consistent with the aim of the 'Paris Agreement' negotiated in December 2015. The situation is currently tracking above the 'worst case' scenario, making it very difficult to achieve the RCP2.6 trajectory.



▸ ***Figure 17.2**: Atmospheric carbon dioxide concentrations for some of the representative concentration pathways (RCPs) (Source: Richard Matear, CSIRO).*

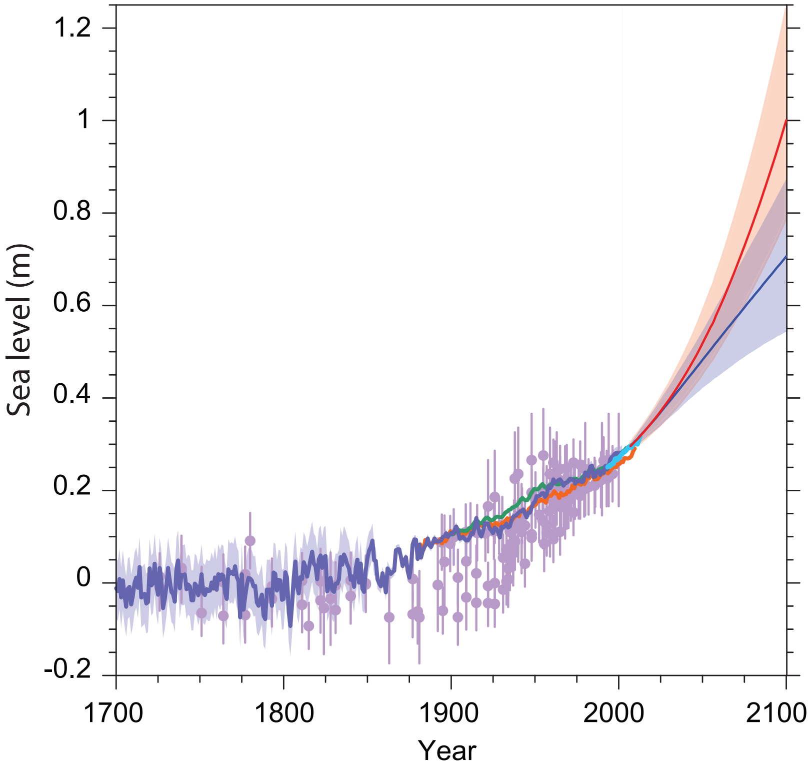
Warming

Oceans absorb ~90% of the additional heat in the Earth system as the planet's surface warms (Chapter 5). Global sea-surface temperature is projected to warm by ~2.7ºC by 2100 under the high-emission scenario. Greatest warming will occur in mid-latitude oceans, with oceans around Australia projected to warm by more than 3.5ºC (Fig. 17.3a). South-east Australia is projected to continue its pattern of particularly rapid warming. Global averaged sea-surface warming is projected to be 0.7ºC under the low-emission scenario but with a similar spatial pattern of warming. Ocean warming is not restricted to the surface. Ocean circulation transports warmer surface water into the deep ocean (Fig. 17.3b), ensuring that the entire ocean will change with global warming.



▲ ***Figure 17.3**: Changes in ocean temperature (ºC, yellow-red indicates warming, blue-purple indicates cooling) from the average in 1990–2010 to what is expected in 2080–2100 under the RCP8.5 high-emission scenario: **(a)** sea-surface changes and **(b)** an average profile from the surface to the bottom of the oceans (black), from Antarctica (left) to the Arctic (right) (Source: Richard Matear, CSIRO).*

The oceans expand as they warm (thermal expansion) causing sea level to rise. Warming of the atmosphere and oceans also causes shrinking of ice sheets and glaciers, with meltwater from land-based ice contributing to sea-level rise. Sea level will rise by 0.8–1.2 m by 2100 under the high-emissions scenario (Fig. 17.4). The long lead-times and slow rate of ocean processes, however, mean that sea levels will continue to increase long after we curtail greenhouse gas emissions.

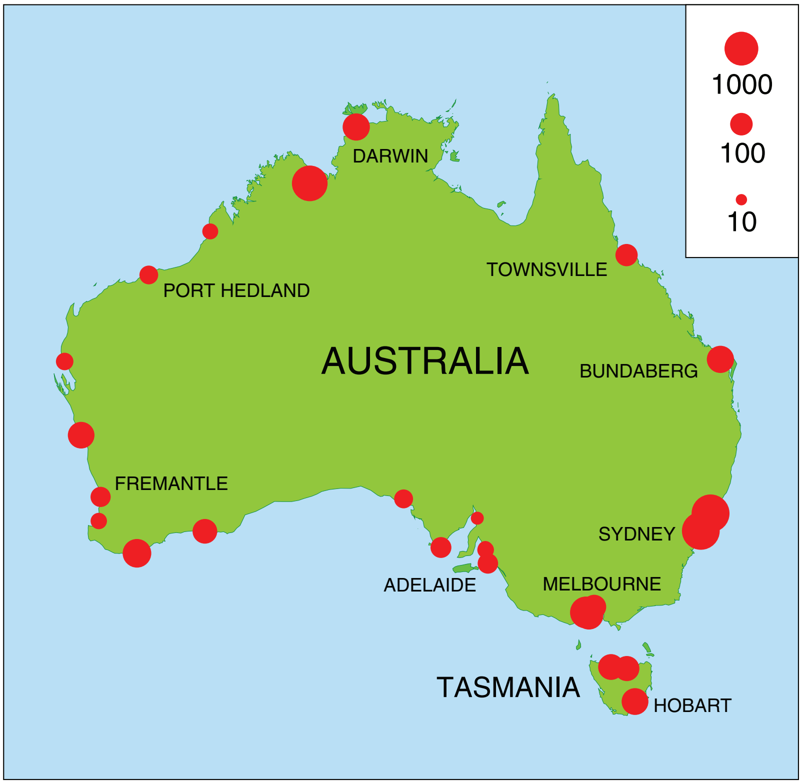


▸ ***Figure 17.4**: Observed and projected global mean sea-level change from 1700 to 2100. Historical estimates come from observations of past events, tide gauges and satellites. Projections are from global climate models and show likely rises for unmitigated emissions of greenhouse gases (RCP8.5, red lines and shading) and for significant reductions in emissions (RCP2.6, blue lines and shading) (Source:* IPCC Assessment Report 5, Working Group 1, *fig. 13.27).*

Changes in mean sea level also bring changes in sea-level extremes (e.g. king tides, storm surges). Coastal habitats and infrastructure that are now above sea-level extremes will become vulnerable to periodic inundation as sea level rises. Infrastructure in many parts of Australia that was built to withstand 1-in-100-year sea-level extremes will face increasing exposure to the sea as those events become more frequent and occur more often as the mean sea level rises[2] (Fig. 17.5).

Acidification

About 28% of anthropogenic CO_2 emissions since 1800 have been absorbed by the oceans. This carbon added to the oceans is affecting sea-water chemistry, making it more acidic and reducing the ability of animals to form calcium carbonate that is essential for shell growth.[3] Large areas of high latitude (polar) oceans are projected under the high-emission case to reach a state by 2100 that will prevent shell formation (Fig. 17.6a). Some regions, such as the surface Southern Ocean and deep water around Australia, will reach these corrosive conditions even with the low-emission case.

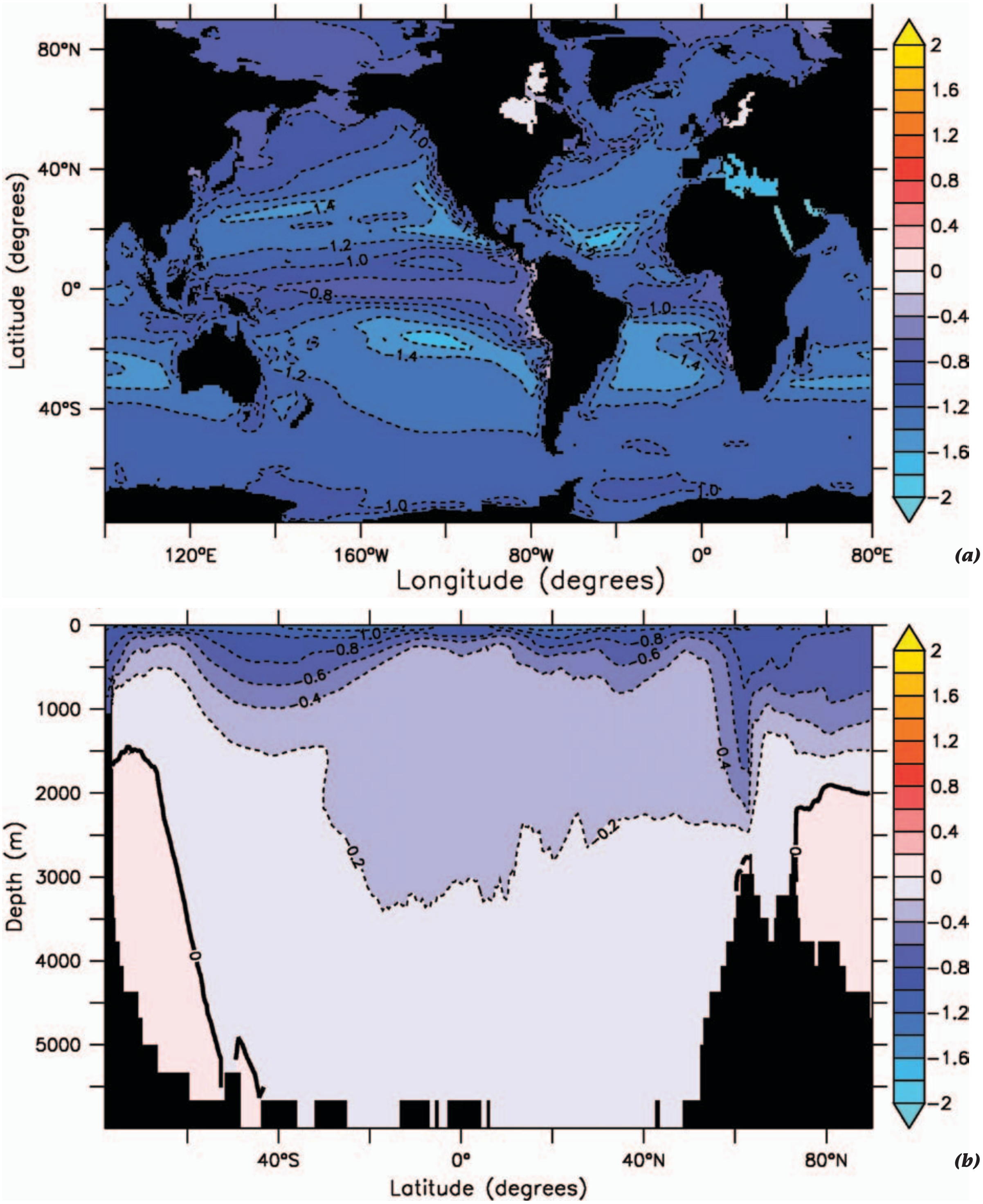


◂ ***Figure 17.5***: *Estimated increase in how often a given level of sea-level extreme will be experienced around Australia, with a 0.5 m increase in average sea level by 2100. The size of circles indicates how many times more often extreme events of given height will be experienced at each location (Source: John Hunter).*

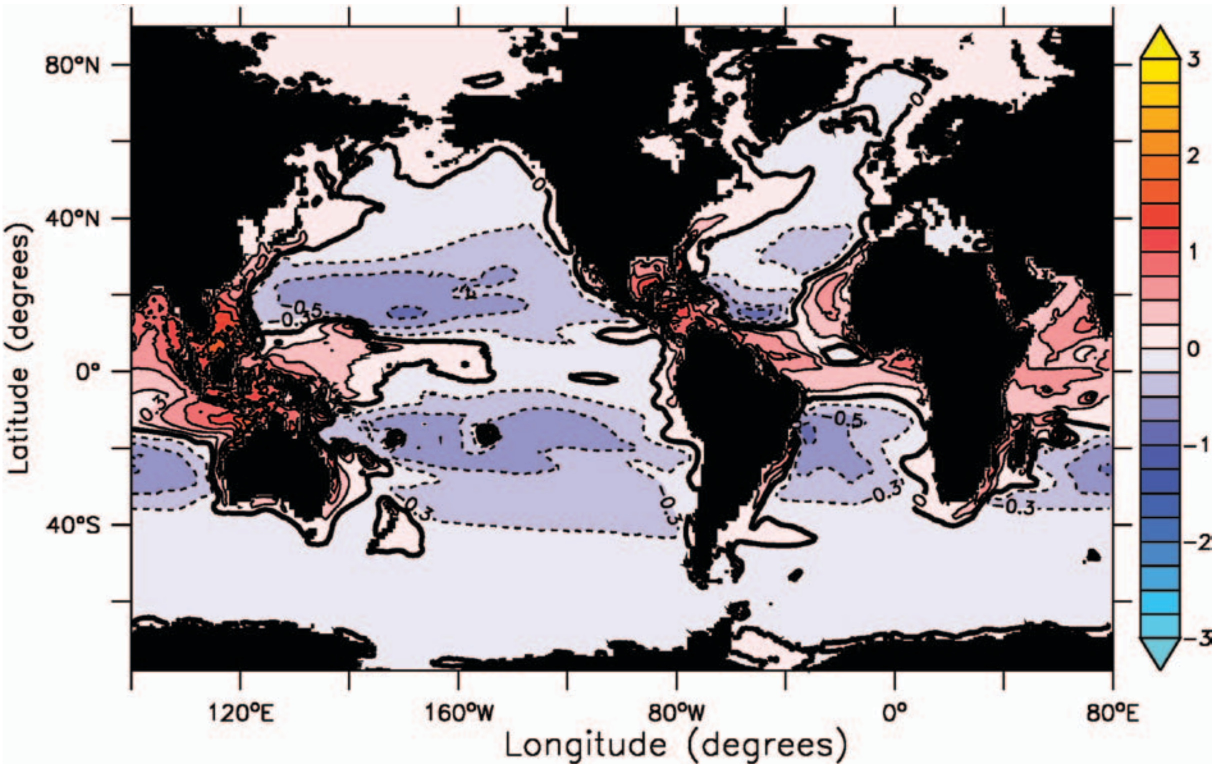
Anthropogenic CO_2 absorbed at the ocean surface also will be transported into the ocean interior. The entire ocean will experience ocean acidification in the long term (100s–1000s of years). The slow response of the ocean means ocean acidification will continue long after human carbon emissions have ceased, and return to a pre-industrial state will take tens of thousands of years.

Primary productivity

Microscopic marine plants (phytoplankton) are the main organisms that take light and ocean nutrients and convert them into living tissues that ultimately feed most ocean ecosystems. This process is called primary production. Ocean primary production is projected to decline as ocean warming and changing circulation reduce supply of nutrients to the upper oceans. Earth system simulations project a global average decline of primary production of around 8.6% in the high-emission case and 2% in the low-emission case. The pattern of changes in primary production generally shows the largest declines in the mid and low (tropical) latitudes, with slight increases elsewhere (Fig. 17.7). The pattern of change is uncertain, however, and recent studies suggest increases in primary production in the Tasman Sea and in the western Equatorial Pacific.[4] Response of ocean primary production to ocean warming and acidification is a crucial measure for projecting the future of marine ecosystems and productivity of fisheries but one that remains very uncertain.



▲ ***Figure 17.6***: *Projected change in aragonite saturation (one form of calcium carbonate required by marine animals, like corals) between the 1990–2010 average to that expected in 2080–2100 for the RCP8.5 scenario. Negative values (blue) mean aragonite is becoming more difficult for animals to produce aragonite-based skeletons or shells.* ***(a)*** *Ocean surface changes and* ***(b)*** *average profile from sea surface to sea floor (black) between Antarctica (left) and the Arctic (at right). Many corals will struggle to form their carbonate skeletons under the projected changes (Source: Richard Matear, CSIRO).*



▲ ***Figure 17.7**: Projected change in primary production (g C/m²/year, yellow-red indicates increased production, blue-purple indicates reduced production) from the average conditions in 1990–2010 to those expected in 2080–2100 for the RCP8.5 scenario (Source: Richard Matear, CSIRO).*

Deoxygenation

The level of dissolved oxygen in sea water significantly affects where marine plants and animals can live. Global climate models project a decrease of ~4% in the total amount of dissolved oxygen in oceans under the high-emission case. Oxygen levels are lowest at intermediate ocean depths (300–1000 m) and it is there where deoxygenation can affect marine animals most. Projections of future oxygen changes in these intermediate layers are complex, however, with both increasing and decreasing trends reflecting the balance of competing factors such as circulation, biological production, chemical changes and warming.

Ocean circulation

The large-scale ocean circulation (Chapter 2) also is projected to change as the oceans warm. Global ocean circulation between surface and deep waters is expected to slow, meaning declining rates of transport of heat and CO_2 into the deep oceans and less reliable nutrient supply to the surface. Projections vary locally and regionally. The East Australian Current, for example, will increase with global warming while the Leeuwin Current off Western Australia will decline.[5] These current changes could have important consequences for the connectivity and productivity of marine ecosystems around Australia.

ECOLOGICAL EFFECTS AND HUMAN USES

Australians rely on the oceans for food, recreation, tourism and transport (Chapter 6). Increases in wind speed and storm activity with changing climate may influence when and where people fish and alter risks associated with coastal shipping and recreation. Projected changes in the distribution of marine species show that offshore, large pelagic species, such as tuna and marlin, might move further south on both the east and west coasts of Australia.[6] There may be a need for new fisheries management approaches to ensure that only targeted species are captured as species distributions change. Other species might not move and changes in their growth rates and survival might reduce population sizes, with impacts on food webs and fisheries.

Habitats also will be affected by ocean warming and acidification. The Great Barrier Reef will likely change, with decreases in coral and coral-dependent species and increases in algae and herbivorous fish. Dugong and turtles are affected negatively during floods that decrease seagrass availability, while long-term changes in ocean productivity can affect breeding success of seabirds. Such events are likely to be more frequent and severe in future.

Human interventions, or adaptation responses, are being explored to help species and habitats adapt to projected ocean changes. For example, new predator controls and invasive species removal may be used. Introduction of warm-tolerant corals to the Great Barrier Reef is being tested in laboratories. Some adaptation options can seem dramatic but many species may decline, and even become extinct locally, without human interventions.

Humans also need to adapt to ocean changes. Fishers may need to seek new fishing grounds or target species previously unavailable or in low numbers. Aquaculture is an important source of seafood, but may be limited by suitable conditions such as water temperatures. Seafood consumers also may need to try new species, just as marine tourists will have to accept differences in oceans and holiday locations in future.

FUTURE CLIMATE APPLICATIONS

Future climate models will need to deliver shorter term climate predictions, from years to decades, to help Australian's respond to multi-year climate variability. These predictions will underpin new links between climate models and other human, economic and environmental models. Seasonal forecast models are providing information on ocean conditions and fish distributions for 2–4 months ahead.[7] Tuna fishers and managers, for example, have used seasonal ocean forecasts to decide where fishing operations should occur to improve economic efficiency and limit unwanted by-catch. Climate models are being combined with ecosystem models at longer timescales to investigate management approaches that could allow sustainable seafood harvest as oceans change.

Climate modelling also helps investigate options to mitigate impacts of global warming and ocean acidification. Deliberate manipulations of climate by geoengineering may be unpalatable to many but it is necessary to evaluate such options to enable informed choices of ways to tackle our CO_2 problem. Assessing the efficacy and consequences of geoengineering options, including exposing potential unforeseen consequences, is an important new application of Earth system models.

CONCLUSION

Observations show that physical, chemical and biological changes are occurring already in the oceans, with significant further changes projected by 2100. Ocean warming, acidification, deoxygenation and sea-level rise may have important consequences for the ocean services on which people depend. Fisheries and biodiversity will be affected by changes in ocean temperature, acidification, oxygen, ocean primary production and currents. Changes in ocean acidification and sea level will continue for millennia beyond the time our anthropogenic carbon emissions cease. Existing climate models provide essential tools to make Australia more resilient to climate variability, better integrate climate predictions with other human systems and assess potential mitigation options to reduce ocean changes.

FURTHER READING

IPCC (2013) Summary for policymakers. In: *Climate Change 2013: The Physical Science Basis*. (Eds TF Stocker, D Qin, GK Plattner, M Tignor, SK Allen, *et al.*) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

Raven JA, Caldeira K, Elderfield H, Hoegh-Guldberg O, Liss P, *et al.* (2005) *Ocean Acidification due to Increasing Atmospheric Carbon Dioxide*. Royal Society (Great Britain) Policy document 12/05. Clyvedon Press, Cardiff, <http://www.us-ocb.org/publications/Royal_Soc_OA.pdf>.

Shepherd J, Caldeira K, Cox P, Haigh J, Keith D, *et al.* (2009) *Geoengineering the Climate: Science, Governance and Uncertainty*. Royal Society Policy document 10/09. The Royal Society, London, UK, <https://royalsociety.org/policy/publications/2009/geoengineering-climate/>.

CHAPTER 18.

Future technologies

Bernadette Sloyan, Pascal Craw, Edward King, Craig Neill, Rudy Kloser and Levente Bodrossy

Key messages

- ✻ Miniaturisation is leading to automated, remote, real-time collection of measurements.
- ✻ Novel technologies and sensors are opening a window into the biology, physics and chemistry of the oceans with high spatial and temporal resolution.
- ✻ Concurrent collection of physical, chemical and biological measurements will become increasingly important in developing our understanding of ocean systems.
- ✻ Internet portals and visualisation tools will facilitate dissemination and fusion of multiple data sources and types, promoting interdisciplinary research and novel discoveries.

INTRODUCTION

Robotic platforms, low-power electronics and the possibility of small and capable sensors measuring a wide range of physical, chemical and biological variables will allow for significant enhancements of ocean observations. Measurements by novel sensors will lead to a more complete understanding of the health and productivity of the oceans. Advancements in genomics, satellite-based remote sensing and acoustic and visual observations of zooplankton and fish stocks will enable us to monitor the biology of the oceans with greater spatial and temporal resolution. Genomics methods enable the detection of organisms and the reconstruction of complex community structures based on their DNA found in tiny fragments of tissue in the environment. New miniature analysis systems are becoming available that allow analyses that once required a large laboratory of equipment to be done automatically in the field. Improvement of ocean modelling and associated ways of incorporating data streams into models will allow use of the full range of observations from new automatic sensors in near-real-time to provide increasingly sophisticated ocean information for an increasing range of applications.

NEW SENSOR TECHNOLOGIES

Ocean sensors need to have low power consumption, be compact and take stable and accurate measurements over long periods. Much progress has been made in the past 20 years in improving these properties for temperature and salinity sensors. A diverse range of optical sensors is now available to measure ambient light, reflected light and fluorescence, as well as dissolved oxygen, particulate carbon and organic matter in sea water. Novel, low-power, compact sensors for acidity and carbon dioxide will start to deliver high-resolution data on ocean acidification and carbonate chemistry. Novel nitrate sensors are being deployed on floats and moorings and will improve significantly our understanding of the marine nitrogen cycle. Automatic image analysis and pattern detection will allow routine identification of several types of plankton and other organisms. Sophisticated miniature genetic sensors, detecting biological diversity, will provide unprecedented insights to marine biodiversity and links with ocean chemistry and physics.

MINIATURISATION

Existing laboratory-based methods for physical, chemical and biological analysis of ocean water frequently rely on bulky, expensive and labour-intensive instruments that restrict use of our most powerful analytical tools to laboratory settings onshore or on well-equipped research vessels. Advances in the miniaturisation and automation of analytical devices are now offering the prospect of instruments capable of being deployed in the oceans, performing repeated analyses automatically and returning results via satellite. This model of analysis reduces the need for costly and time-consuming research voyages and increasingly will become standard practice for future research.

The Environmental Sample Processor (ESP), for example, developed by the Monterey Bay Aquarium Research Institute[1] is able to perform molecular analyses remotely from a mooring or as a drifting instrument to describe the bacterial communities found in the oceans. Future versions will be incorporated into autonomous underwater vehicles (AUVs) to increase the range over which analysis can be performed.

Miniaturisation will enable the measurement of nutrients, biodiversity and other variables – mostly those related to the biology of the oceans – in an automated, continuous, remote manner. It is possible to envisage a network of autonomous devices collecting data of greater diversity and at higher temporal and spatial resolution than would be feasible with vessel-based sampling.

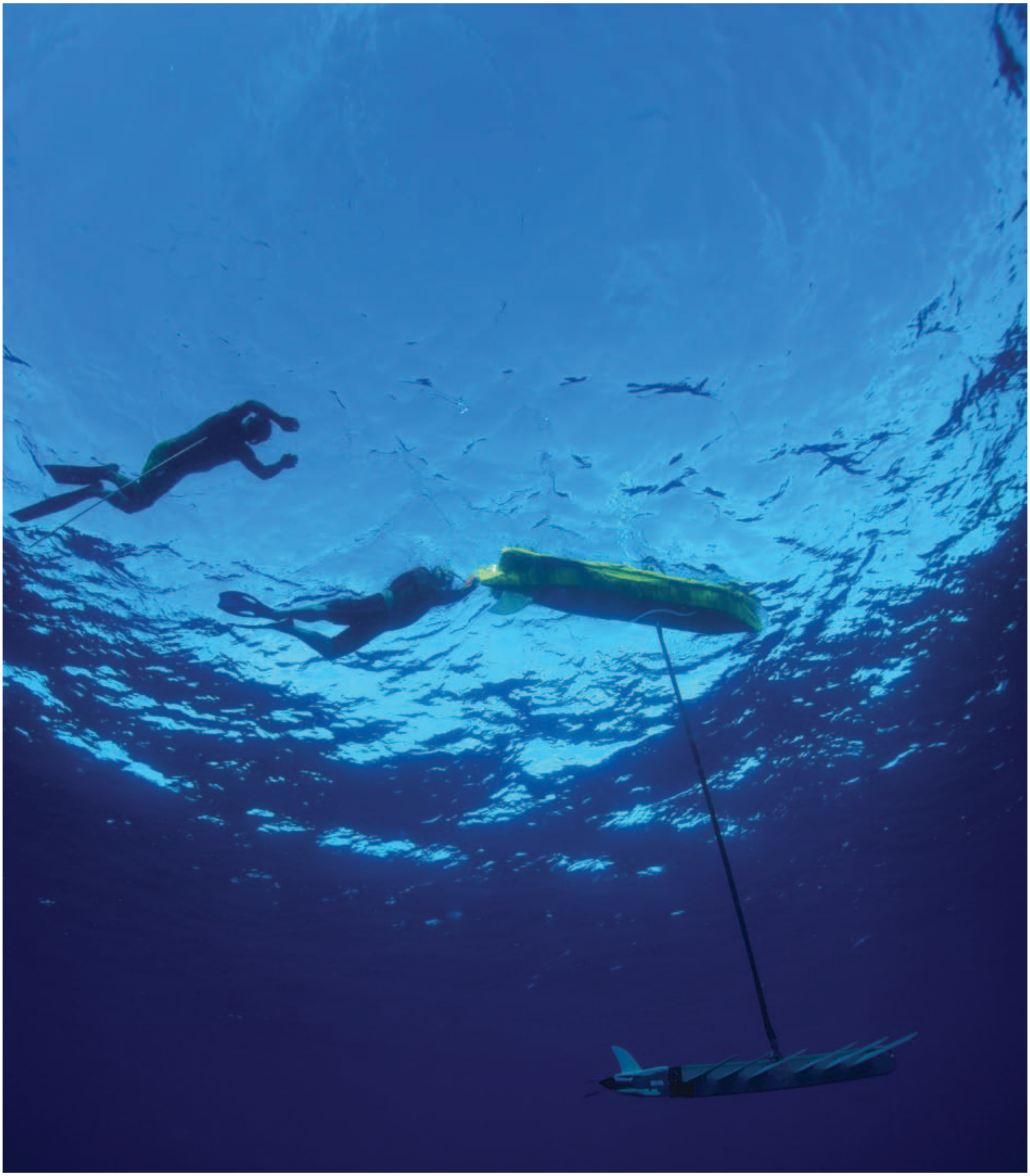
AUTONOMOUS SENSORS

Growth of autonomous ocean-observing platforms has been stimulated by demand for an increase in the variety of ocean variables recorded, data from remote and hostile environments, and continuous observations. Recent developments in robotic floats (Chapter 14), both in software and hardware, are extending the global range and ocean depth over which automatic observations are collected.[2] Novel use of miniature observing systems deployed on animals (e.g. seals) provides ocean observations in the high-latitude (polar) oceans.

Seals are gathering data via miniature observing systems from parts of the global oceans that are difficult to reach (Source: Clive R. McMahon, Sydney Institute of Marine Science).

Self-propelled ocean gliders capable of underwater navigation are used increasingly to observe ocean property changes routinely (e.g. http://www.ego-network.org). They can navigate the upper ocean (typically the upper 1000 m) and have battery endurance from several weeks up to almost a year, depending on profiling depth and sensors used. Many small AUVs are available with endurance of several hours, which are well suited for coastal and near-shore or ship applications. Other systems can sample to depths of 6000 m and have been used to make measurements of ocean processes near the deep seabed.

New near-surface platforms now being developed include large moored platforms with fast satellite communication and significant on-board power capable of supporting new multidisciplinary ocean observatories and complementing regional sea floor cabled installations. Other systems use surface wave energy to propel vehicles, such as the wave glider, and unmanned sailing vessels may become available in the near future.



The energy of ocean movements is harnessed to propel wave gliders (Source: Stephen Chin, CC2.0, https://www.flickr.com/photos/steveonjava/10438491113/).

A growing number of sea-floor automated observatories connected to land via cable will enable deployment of multi-disciplinary oceanographic sensor systems that take regular measurements over long periods with little need for maintenance. The relatively high investment cost of sea cables, however, will limit the number of installations for the foreseeable future.

MEASURING BIOLOGICAL DIVERSITY

Measuring biodiversity across the vastness of our oceans remains a major challenge. Recently developed genomics methods that enable description of complex microbial communities based on DNA extracted from small samples have become the most affordable approach to assess biological diversity from large numbers of samples. Many species can be detected from DNA in cells shed naturally into the environment without needing to sample individuals directly. Genomic analysis of planktonic animals collected in nets can complement direct microscopic observations and tiny planktonic plants and bacteria can be studied from samples as small as 2 L of water. Genomics is the first, and currently the only, method available to quantify bacteria and similarly tiny organisms in the ocean and has opened microbial oceanography as a new science frontier (see Box 18.1).

SATELLITES – MORE DATA, BETTER PROCESSING

The recent launchings of new-generation satellites with optical sensors capable of 500 m or finer resolution and other sensor technology advances will improve the spatial and temporal coverage of satellite observations of the ocean significantly. These innovations will enable routine exploration of more complex patterns (1–2 km resolution) in coastal areas not achievable by current technologies. Spatial resolution and frequency of observations will improve in the future, providing improved coverage through broken cloud cover and an ability to record ocean processes at sub-daily and, soon, sub-hourly timescales. These in turn will lead to better modelling and prediction accuracies.

ACOUSTICS AND OPTICAL OBSERVATION TECHNOLOGIES

Acoustic and optical sensors are ideal for sampling the behaviour, composition, biomass and distribution of marine organisms (millimetres to metres in length) at spatial scales of centimetres to kilometres and timescales of seconds to years. These observations are important to help build better ecosystem and fisheries models for sustainable management of our marine resources. A key knowledge gap is the poorly explored mesopelagic habitat (~200 m to 1000 m depth) with

Box 18.1: Microbial oceanography

Microbes (including bacteria and phytoplankton) constitute the majority of the marine biomass, carry out >50% of global photosynthesis and drive most of the biochemical cycles of the global oceans. We need high-resolution mapping of the marine microbial community to understand better how microbes contribute to ocean primary production and, thus, to whole marine ecosystems. The costs of sample collection and genomic analyses are the main constraints to this task.

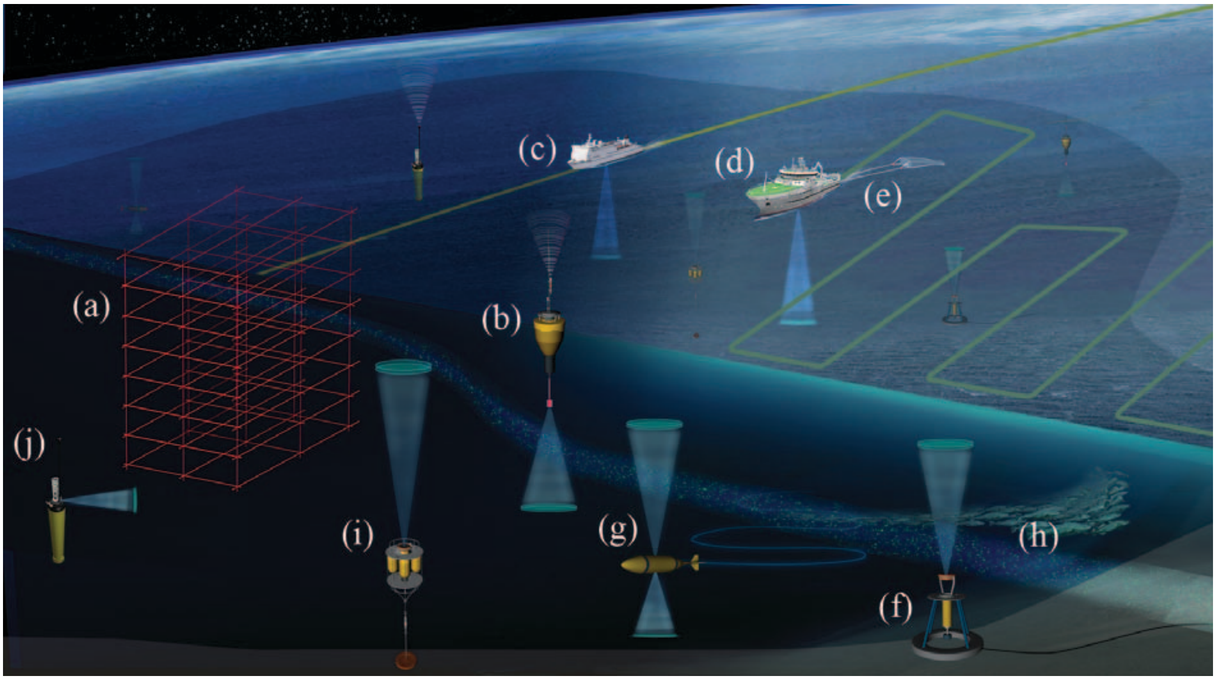
Australian Marine Microbial Biodiversity Initiative (AMMBI) – the first continental-scale marine microbial observatory

Two-litre water samples for genomics analyses are collected at the National Reference Stations[3] (NRSs) of Australia's Integrated Marine Observing System (IMOS) (Fig. 18.1) every month from every 10 m depth layer. DNA extracted from the samples is used to generate detailed community structures of bacteria and other diverse microscopic plants and animals around each NRS at the time of sampling. This nation-wide project will provide long-term observations of the marine microbial community around the Australian coastline. Regular observations of physical, chemical and other biological conditions at the same reference stations allows us to place the microbial observations in a detailed environmental setting.

◂ ***Figure 18.1***: *Locations (red dots) of Integrated Marine Observing System (IMOS) National Reference Stations around Australia's coast (Source: Australian Ocean Data Network, AODN, https://portal.aodn.org.au/, Google Earth).*

Long-term, high-resolution microbial observations, such as those from the AMMBI project, will help us understand how marine microbial communities work and to predict how they will react to large-scale environmental changes resulting from pollution, climate change, fishing, aquaculture and other human activities.

an estimated ~1–10 gigatonnes of fishes. New autonomous profiling probes are being developed with optical and acoustic sensors to count the fish, jellies, squids and crustaceans in this zone. Developments of low power, broadband and miniaturised sensors with high on-board processing capacity will see sensors used in a range of new platforms probing the full ocean depths (Fig. 18.2).



▲ ***Figure 18.2**: Conceptual diagram of an acoustic-based observation system coupled to ecosystem models to model ecosystem dynamics in the oceans: **(a)** model grid, **(b)** drifting buoy, **(c)** ship of opportunity with automatic sensor, **(d)** research vessel with **(e)** net sampling gear and various on-board sensors, **(f)** bottom mooring connected to shore by seabed cable, **(g)** autonomous underwater vehicle or glider, **(h)** pelagic organisms with concept of vertical movements indicated by shaded 'trail', **(i)** self-contained moored instruments, **(j)** drifting profiling float (such as Argo float) (Source: Handegard* et al. *2012[4]).*

CONCURRENT DATA, BIG DATA

The above advances will make observations on the physics, the chemistry and all levels of the biology of the oceans affordable at a significantly higher spatial and temporal resolution. Linking these different observations will increase their value exponentially, leading to high-resolution coupled oceanic observations. Concurrent observations will allow us to see the effects of the physical ocean on ocean chemistry, assess the influence of chemistry on microbiology and primary productivity, and link ecosystem processes to fish stocks and entire ecosystems. Global coupled observation and modelling efforts will enable us to unpick the complex dynamics of the oceans at finer scales than ever before.

CONCLUSION

The next decade will see a rapid increases in the volume, frequency, resolution and range of types of ocean observations. Autonomous sensors offer many advantages over vessel-based sampling that is becoming increasingly difficult to fund as labour and vessel costs increase. The use of fixed and drifting observation systems and long-range AUVs will provide a more evenly distributed ocean observing system, extending beyond regular voyage tracks and easy-to-reach oceanic regions. The novel platforms being developed will enable real-time or near-real-time data streams and linking together of multiple diverse observations. These changes will improve significantly our ability to understand and model the oceans' physical and biological impacts on Earth's climate and ecosystems and their interactions with human activities. Online data portals (making all data accessible) will enable researchers to identify interactions across different processes in near-real-time and interested members of the public to connect with ocean science.

FURTHER READING

Siedler G, Griffies S, Gould J, Church J (Eds) (2013) *Ocean Circulation and Climate: A 21st Century Perspective*. 2nd edn. Academic Press, Sydney.

CHAPTER 19.

Conclusion

Bruce Mapstone

Key messages

- Australia has a rich heritage of engagement with the oceans and good governance over them.
- Research has been central to the establishment, development and management of Australia's marine estate.
- Rapidly developing new technologies and expanding complexity of demands on oceans represent major challenges for research.
- Future oceans research will need to be more integrated across disciplines and accessible to an increasingly educated and interested community to deliver tangible benefits to governments, industries and communities.

Australians have a long and rich affinity for the oceans surrounding this island continent, extending over thousands of years of occupation by Indigenous Australians and expanding dramatically over the relatively short time since European arrival. The oceans represent many very special roles to different people, fulfilling cultural, social, recreational, commercial, operational, aesthetic and psychological functions. The majority of current Australians hold very positive, and somewhat protective, sentiments about our coasts and oceans. The Australian marine estate contributes billions of dollars to national, state and local economies and indirectly exercises some influence on almost every aspect of Australian life through the oceans' roles in weather and climate.

Australia's marine environment also has a high profile internationally. The Great Barrier Reef, Ningaloo and Australia's Antarctic Territory are recognised and formally valued internationally as iconic, unique and special places that should be protected from degradation. Australia has been a leader in oceans governance, despite the complexities of our federated system. We have provided leading examples, with declarations of marine protected areas intended to capture the diversity of marine habitats and species within Australian jurisdiction. Our fisheries are generally considered well managed, and we have moved towards ecosystem-based marine management earlier than most nations. Australian ecosystem-based management research expertise is highly sought-after internationally and Australian marine researchers across many disciplines are recognised leaders in their fields. Our marine environment and its resources, including fished stocks, are considered to be ‘in good shape’ and mostly relatively little-degraded from human uses, though great concern exists about the potential, but uncertain, effects of climate change on our marine ecosystems.

The well-being of the oceans around Australia in part is likely a result of good fortune related to relatively low human populations using the oceans and relatively low levels of use, or abuse, by people. This statement is not intended to denigrate the actions of successive governments, managers, researchers and communities in sound and progressive oceans governance that have regulated our oceans use, but simply to recognise the fortunate circumstances in which our marine estate exists. A key challenge is to consolidate our oceans governance to secure the good status of our oceans indefinitely.

The grand scale of our marine estate represents a major challenge for Australia. We have explored and documented only relatively little of the seabed and oceans in the marine estate; some estimate as little as 5%. We have relatively modest capacity to fund research and exploration over such a vast area compared with some other nations that have similarly large marine estates. The USA, Canada, France, Japan, China and others, for example, each have multiple dedicated long-range ocean research vessels whereas Australia has just one, complemented by a small number of shelf and coastal vessels and a multi-purpose ice breaker that supports Antarctic research. Research, however, is essential to informed, considered and safe decisions about our marine estate and how we use it to fulfil our national, international and inter-generational obligations. Collaboration both within Australia and internationally is one key strategy to live within national research means but be able to inform the decisions we need to make. The establishment of a national approach to funding and operating research infrastructure, including the Marine National Facility, the National Sea Simulator and the Integrated Marine Observing System, has been a great step towards nationally supported collaboration and one that hopefully will be expanded over coming decades.

Technology innovation also is key to Australian marine researchers filling the large gaps in our knowledge of our marine estate. Ocean observations historically have been slow, labour-intensive, time-consuming, very expensive and sparse. New technologies developed over just the past few decades can now provide orders of magnitude more observations of more detail, at finer resolution, with greater cover and greater frequency than we could have imagined 50 years ago. Automated observing devices in the oceans, satellite-based sensors, continuously recording instruments on ships and advanced chemical and genetic methods are, or have the potential to be, providing streams of data that document our marine estate in increasing detail, but will prove increasingly challenging to digest by conventional analytical methods. Developing the new methods that can process these diverse and abundant data routinely and efficiently will be an exciting and important area of future research.

Equally challenging will be our research capacity to fulfil community and policy expectations. Australians’ interests in the oceans mean that many marine issues attract great attention far beyond those immediately involved. There are popular expectations that our marine environment is, and will remain ‘healthy’ – expectations that increase pressure on policy makers to regulate marine activities very carefully. They also mean that researchers increasingly are asked to provide highly integrated information not only about the multi-dimensional features of the ocean but also incorporate analyses of the economic and social consequences of prospective decisions. This is a level of integration among disciplines that we sometimes have struggled to achieve to date but must become the ‘business as usual’ of the future.

The timeframes within which researchers are expected to provide analysis and advice also is shortening, in part as a result of the astounding growth in social media technologies and their influence in public discourse and, at times, decision making. Servicing such public and rapid demands, when appropriate, while retaining the rigour and quality of advice will prove challenging for researchers. An exciting area of research application is harnessing the new computing, communication and observing technologies to provide near-real-time access to information in forms accessible to non-scientists and able to be interrogated intuitively and interactively online.

There is a great deal to be excited about in the future face of marine research but it is also important to recognise that these innovations disguise a deep dependence on research hard work and due-diligence. Australia will continue to need research vessels, observing infrastructure, university research and training and well-resourced research agencies if it is to remain among the world’s best ocean stewards and to retain a leading role in our region. New technologies and better information delivery will be necessary but not sufficient for the research needed to tackle the grand challenges identified by Australia’s leading research agencies through the National Marine Science Committee. Investment in the people, their skills and infrastructure to make sense of the increasing amounts of observations arriving on our desks is essential if data are to be turned into information that can be consolidated into the knowledge needed to care for, and benefit from, our vast marine estate.

References

Chapter 1

1 Symonds P, Alcock M, French C (2009) Setting Australia's limits – understanding Australia's marine jurisdiction. *AusGeo* **93**, 1–8.

2 Australian Institute of Marine Science (2014) *The AIMS Index of Marine Industry*. Australian Institute of Marine Science, Townsville, <www.aims.gov.au/publications.html>.

3 Oceans Policy Science Advisory Group (2013) *Marine Nation 2025: Marine Science to Support Australia's Blue Economy*. Australian Government, Canberra.

4 National Marine Science Committee (Australia) (2015) *National Marine Science Plan 2015–2025: Driving the Development of Australia's Blue Economy.* National Marine Science Committee, Canberra, <http://www.marinescience.net.au/national-marine-science-plan/>.

Chapter 2

1 State of the Environment 2011 Committee (2011) *Australia State of the Environment 2011*. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. DSEWPaC, Canberra.

2 Sprintall J, Wijffels SE, Molcard R, Jaya I (2009) Direct estimates of the Indonesian Throughflow entering the Indian Ocean: 2004–2006. *Journal of Geophysical Research* **114**, C07001. doi:10.1029/2008JC005257

3 Feng M, Caputi N, Penn J, Slawinski D, de Lestang S, *et al.* (2011) Ocean circulation, Stokes drift and connectivity of western rock lobster population. *Canadian Journal of Fisheries and Aquatic Sciences* **68**, 1182–1196.

4 Feng M, McPhaden MJ, Xie S, Hafner J (2013) La Niña forces unprecedented Leeuwin Current warming in 2011. *Scientific Reports* **3**, 1277. doi:10.1038/srep01277

5 Rintoul SR (2000) Southern Ocean currents and climate. *Papers and Proceedings of the Royal Society of Tasmania* **133**, 41–50.

Chapter 3

1 O'Hara T, Rowden A, Bax N (2011) A Southern Hemisphere bathyal fauna is distributed in latitudinal bands. *Current Biology* **21**, 226–230.

2 Last PR, Lyne VD, Williams A, Davies CR, Butler AJ, Yearsley GK (2010) A hierarchical framework for classifying seabed biodiversity with application to planning and managing Australia's marine biological resources. *Biological Conservation* **143**, 1675–1686.

Chapter 5

1 Stephens GL, Li J, Wild M, Clayson CA, Loeb N, Kato S, *et al.* (2012) An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience* **5**, 691–696.

2 IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, *et al.* (Editors)]. Cambridge University Press, Cambridge, UK and New York, USA.

3 Lenton A, Tilbrook B, Matear RJ, Sasse TP, Nojiri Y (2016) Historical reconstruction of ocean acidification in the Australian region. *Biogeosciences* **13**, 1753–1765. doi:10.5194/bg-13-1753-2016

4 Le Quéré C, Moriarty R, Andrew RM, Peters GP, Ciais P, *et al.* (2015) Global carbon budget 2014. *Earth System Science Data* **7**, 47–85. doi:10.5194/essd-7-47-2015

5 Park GH, Wanninkhof R, Doney SC, Takahashi T, Lee K, *et al.* (2010) Variability of global net sea–air CO_2 fluxes over the last three decades using empirical relationships. *Tellus B* **62**, 352–368. doi:10.1111/j.1600-0889.2010.00498.x

6 Cai W, Borlace S, Lengaigne M, van Rensch P, Collins M, *et al.* (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change* **4**, 111–116.

7 Cai W, Wang G, Santoso A, McPhaden MJ, Wu L, *et al.* (2015) Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change* **5**, 132–137.

Chapter 6

1 Teh LCL, Sumaila UR (2013) Contribution of marine fisheries to worldwide employment. *Fish and Fisheries* **14**, 77–88.

2 FAO (2014) *The State of World Fisheries and Aquaculture: Opportunities and Challenges.* Food and Agricultural Organisation of the United Nations (FAO), Rome, Italy.

3 Wong PP (1998) Coastal tourism development in Southeast Asia: relevance and lessons for coastal zone management. *Ocean & Coastal Management* **38**, 89–109.

4 Deloitte Access Economics (2013) 'Economic contribution of the Great Barrier Reef'. Report to the Great Barrier Reef Marine Park Authority. Department of Environment, Canberra.

5 Stoeckl N, Farr M, Sakata H (2013) 'What do residents and tourists "value" most in the GBRWHA? Project 10-2 Interim report on residential and tourist data collection activities including descriptive data summaries'. Report to the National Environmental Research Program Reef and Rainforest Research Centre, Cairns.

6 Larson S, Stoeckl N, Farr M, Esparon M (2015) The role the Great Barrier Reef plays in resident wellbeing and implications for its management. *AMBIO* **44**, 166–77.

Chapter 7

1 Oceans Policy Science Advisory Group (2013) *Marine Nation 2025: Marine Science to Support Australia's Blue Economy*. Australian Institute of Marine Science, Townsville.

2 National Marine Science Committee (Australia) (2015) *National Marine Science Plan 2015–2025: Driving the Development of Australia's Blue Economy*. National Marine Science Committee, Canberra, <http://www.marinescience.net.au/national-marine-science-plan/>.

3 Deloitte Access Economics (2013) 'Economic contribution of the Great Barrier Reef. Report to the Great Barrier Reef

Marine Park Authority'. Department of Environment, Canberra.

4 FAO (2014) *The State of World Fisheries and Aquaculture: Opportunities and challenges*. Food and Agricultural Organisation of the United Nations, Rome, Italy.

5 Dyck A, Sumaila UR (2010) Economic impact of ocean fish populations in the global fishery. *Journal of Bioeconomics* **12**, 227–243.

6 Fenical W (2015) Marine pharmaceuticals: Past, present, and future. *Oceanography* **19**, 110–119.

7 Hoegh-Guldberg O (2015) *Reviving the Ocean Economy: the Case for Action – 2015*. World Wildlife Fund International, Geneva, Switzerland.

Chapter 8

1 Geoscience Australia <http://www.ga.gov.au/scientific-topics/marine/jurisdiction/maritime-boundary-definitions#heading-2>.

2 Geoscience Australia <www.ga.gov.au/ausgeonews/ausgeonews200903/limits.jsp>.

Chapter 9

1 FAO (2014) *The State of World Fisheries and Aquaculture: Opportunities and Challenges*. Food and Agricultural Organisation of the United Nations, Rome, Italy.

2 Pitcher TJ, Kalikoski D, Short K, Carkey D, Pramod G (2009) An evaluation of progress in implementing ecosystem-based management of fisheries in 33 countries. *Marine Policy* **33**, 223–232.

3 Pitcher TJ, Kalikoski D, Pramod G, Short K (2008) Not honouring the code. *Science* **457**, 658–659.

4 Henry GW, Lyle JM (2003) *The National Recreational and Indigenous Fishing Survey*. NSW Fisheries Final Report Series No. 48 for FRDC project 99/158. Fisheries Research and Development Corporation, Canberra.

5 Calogeras C, Carne R, Lui S, Schnierer S (2011) 'Shaping advice for Indigenous fishing and aquaculture RD&E within the national strategy including outcomes from the National Forum, 30–31 March 2011, Cairns'. Report for FRDC Project 2010/401. Fisheries Research and Development Corporation, Canberra.

6 Savage J, Hobsbawn P (2015) *Australian Fisheries and Aquaculture Statistics 2014*. Fisheries Research and Development Corporation project 2014/245. Australian Bureau of Agricultural and Resource Economics Sciences, Canberra.

7 Ruello NV (2011) 'A study of the composition, value and utilisation of imported seafood in Australia'. Final Report for FRDC Project 2010/222. Fisheries Research and Development Corporation, Canberra, <www.frdc.com.au/research/Documents/Final_reports/2010-222-DLD.pdf>.

8 Smith ADM, Smith DC, Knuckey I, Sainsbury K, Haddon M (2014) Implementing harvest strategies in Australia: 5 years on. *ICES Journal of Marine Science* **71**, 195–203.

9 Finn M, Flood M, Stobutzki I, Maloney L, Ward P, *et al.* (2015) *Status of key Australian*

fish stocks (SAFS) reports 2014 and beyond. Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

10 Ridge Partners (2015) '2014 Australian F&A sector overview. A report supporting the development of working together: the national fishing and aquaculture RD&E strategy'. Fisheries Research and Development Corporation, Canberra.

11 Vince J, Smith ADM, Sainsbury KJ, Cresswell I, Smith DC, Haward M (2015) Australia's oceans policy: past, present and future. *Marine Policy* **57**, 1–8.

12 Smith ADM, Fulton EA, Hobday AJ, Smith DC, Shoulder P (2007) Scientific tools to support practical implementation of ecosystem based fisheries management. ICES *Journal of Marine Science* **64**, 633–639.

13 Department of Agriculture and Water Resources, <http://www.agriculture.gov.au/fisheries/aquaculture/aquaculture-industry-in-australia>.

14 Spillman CM, Hobday AJ (2014) Dynamical seasonal ocean forecasts to aid salmon farm management in a climate hotspot. *Climate Risk Management* **1**, 25–38.

Chapter 10

1 ABS (2016) 2013–14 *Energy Account*. Australian Bureau of Statistics, Canberra, <http://www.abs.gov.au/ausstats/abs@.nsf/0/5E025753112D1A80CA2578800019C952?Opendocument>.

2 AIMS (2014) *The AIMS Index of Marine Industry*. Australian Institute for Marine Science, Townsville.

3 Geoscience Australia and BREE (2014) *Australian Energy Resource Assessment*. 2nd edn. Geoscience Australia, Canberra.

4 APPEA (2015) *Key Statistics 2015*. The Australian Petroleum Production and Exploration Association, Canberra.

5 Logan GA, Jones AT, Kennard JM, Ryan GJ, Rollet N (2010) Australian offshore natural hydrocarbon seepage studies, a review and re-evaluation. *Marine and Petroleum Geology* **27**, 26–45.

6 Hook S, Batley G, Holloway M, Irving P, Ross A (Eds) (2016) *Oil Spill Monitoring Handbook*. CSIRO Publishing, Melbourne.

7 Fowler AM, Macreadie PI, Jones DOB, Booth DJ (2014) A multi-criteria decision approach to decommissioning offshore oil and gas infrastructure. *Ocean and Coastal Management* **87**, 20–29.

8 Hemer MA, Zieger S, Durrant T, O'Grady J, Hoeke RK, *et al.* (2016) A revised assessment of Australia's national wave energy resource. *Renewable Energy*, <http://www.sciencedirect.com/science/article/pii/S0960148116307406>.

Chapter 11

1 Stocker L, Kenchington R, Kennedy D, Steven ADL (2012) Introduction to Australian coasts and human influences. In: *Sustainable Coastal Management and Climate Adaptation*. (Eds R Kenchington, L Stocker, D Wood) pp. 1–28. CSIRO Publishing, Melbourne.

2 Short AD, Woodroffe CD (2009) *The Coasts of Australia*. Cambridge University Press, Cambridge, UK.

3 Steven ADL (2012) Science for managing development across the catchment-coast continuum. *Australian Journal of Maritime & Ocean Affairs* **4**, 87–89.

4 SoE (2011) *State of the Environment 2011. Australia state of the environment 2011*. Independent Report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. Australian Government, Canberra.

5 National Marine Science Plan 2015–2025: Driving the development of Australia's blue economy, <http://www.marinescience.net.au/national-marine-science-plan/>.

6 Steven A, Johnson E, Apte S, Banks J, Bayliss P, *et al.* (2015) *Urban Coastal Environments*. Theme White Paper for the National Marine Science Plan. Australian Institute of Marine Science, Townsville, <http://frdc.com.au/environment/NMSC-WHITE/Pages>.

Chapter 13

1 Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, *et al.* (2015) Plastic waste inputs from land into the ocean. *Science* **347**, 768–771.

2 Derraik JGB (2002) The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin* **44**, 842–852.

3 Karim MS (2015) *Prevention of Pollution of the Marine Environment from Vessels*. Springer International Publishing, Berlin, Germany.

4 Coutts ADM, Moore KM, Hewitt CL (2003) Ships' sea-chests: an overlooked transfer mechanism for non-indigenous marine species? *Marine Pollution Bulletin* **46**, 1510–1513.

5 Hardesty BD, Lawson TJ, van der Velde T, Lansdell M, Perkins G, Wilcox C (2016) Estimating quantities and sources of marine debris at a continental scale. *Frontiers in Ecology and the Environment* **15**(1), 18–25.

6 UNEP (2014) *Valuing Plastic, The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry*. United Nations Environment Programme, Nairobi, Kenya.

Chapter 15

1 Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, *et al.* (2008) A global map of human impact on marine ecosystems. *Science* **319**, 948–952.

2 Sunday JM, Bates AE, Dulvy NK (2012) Thermal tolerance and the global distribution of animals. *Nature Climate Change* **2**, 686–690.

3 Jones G (2005) Is the management plan achieving its objectives? In: *Protected Area Management Principles and Practices*. 2nd edn. (Eds G Worboys, T De Lacy, M Lockwood) pp. 555–567. Oxford University Press, Oxford, UK.

4 Smith ADM, Fulton EA, Hobday AJ, Smith DC, Shoulder P (2007) Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science* **64**, 633–639.

5 Vince J, Smith ADM, Sainsbury KJ, Cresswell ID, Smith DC, Haward M (2015) Australia's

Oceans Policy: Past, present and future. *Marine Policy* **57**, 1–8.

6 Day JC, Dobbs K (2013) Effective governance of a large and complex cross-jurisdictional marine protected area: Australia's Great Barrier Reef. *Marine Policy* **41**, 14–24.

7 Great Barrier Reef Marine Park Authority (2014) *Great Barrier Reef Outlook Report 2014*. GBRMPA, Townsville.

8 Dunstan PK, Foster SD (2011) RAD biodiversity: prediction of rank abundance distributions from deep water benthic assemblages. *Ecography* **34**, 798–806.

9 Smith ADM, Sainsbury KJ, Stevens RA (1999) Implementing effective fisheries-management systems – management strategy evaluation and the Australian partnership approach. *ICES Journal of Marine Science* **56**, 967–979.

Chapter 16

1 Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, *et al.* (2011) The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**, 652–655.

2 Fulton EA, Smith ADM, Smith DC, Johnson P (2014) An integrated approach is needed for ecosystem based fisheries management: insights from ecosystem-level management strategy evaluation. *PLOS ONE* **9**, 1–16.

3 Plagányi EE, van Putten I, Hutton T, Deng RA, Dennis D, *et al.* (2013) Integrating Indigenous livelihood and lifestyle objectives in managing a natural resource. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 3639–3644.

4 OCED (2016) *The Ocean Economy in 2030*. OECD Publishing, Paris, France.

Chapter 17

1 Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, *et al.* (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* **109**, 213–241.

2 Church JA, Hunter JR, Mcinnes KL, White NJ (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine* **55**, 253–260.

3 Aze T, Barry J, Bellerby R, Brander L, Byrne M, *et al.* (2014) *An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity*. CBD Technical Series 75. Secretariat of the Convention on Biological Diversity, Montreal, Québec, Canada.

4 Matear RJ, Chamberlain MA, Sun C, Feng M (2015) Climate change projection for the western tropical Pacific Ocean using a high-resolution ocean model: implications for tuna fisheries. *Deep Sea Research Part II: Topical Studies in Oceanography* **113**, 22–46.

5 Sun C, Feng M, Matear R, Chamberlain M, Craig P, *et al.* (2012) Marine downscaling of a future climate scenario for Australian boundary currents. *Journal of Climate* **25**, 2947–2962.

6 Hobday AJ (2010) Ensemble analysis of the future distribution of large pelagic fishes off Australia. *Progress in Oceanography* **86**, 291–301.

7 Hobday AJ, Spillman CM, Eveson JP, Hartog JR (2016) Seasonal forecasting for

decision support in marine fisheries and aquaculture. *Fisheries Oceanography* **25**, 45–56.

Chapter 18

1 Scholin CA (2010) What are 'ecogenomic sensors?' A review and thoughts for the future. *Ocean Science* **6**, 51–60.

2 Wong APS, Riser SC (2011) Profiling float observations of the upper ocean under sea ice off the Wilkes Land Coast of Antarctica. *Journal of Physical Oceanography* **41**, 1102–1115.

3 Lynch TP, Morello EB, Evans K, Richardson AJ, Rochester W, *et al.* (2014) IMOS National Reference Stations: a continental-wide physical, chemical and biological coastal observing system. *PLOS ONE* **9**, e113652.

4 Handegard NO, du Buisson L, Brehmer P, Chalmers SJ, Roberts A, *et al.* (2012) Towards an acoustic-based coupled observation and modelling system for monitoring and predicting ecosystem dynamics of the open ocean. *Fish and Fisheries* **14**, 605–615.

This page intentionally left blank

Index

Aboriginal and Torres Strait Islander peoples, *see* Indigenous people
acidification, *see* ocean acidification
acoustic monitoring 44, 138, 139, 147, 183–5
adaptive management cycle 152
Agreement on the Conservation of Albatrosses and Petrels (ACAP) 6
agriculture
    climate 51, 57
    ecosystems (marine) 68
    El Niño–Southern Oscillation (ENSO) 56
    Great Barrier Reef 154
    greenhouse gases 53
    ocean pollution 134, 154
algae 28, 29, 30, 60, 74, 177
amphibious operations 120–1
animal health 60, 93, 94, 95, 132
Antarctica 10, 15, 22, 36, 41, 43, 59, 77, 89, 137, 140, 172, 175, 188
    ozone hole 57
    see also Australian Antarctic Territory
Antarctic Circumpolar Current (ACC) 15, 22
Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC) 3
Antarctic Treaty 6, 120
anthropogenic carbon dioxide emissions 171, 173, 174, 178
aquaculture 8, 26, 64, 70, 72–4, 87–95, 101, 109, 110, 128, 150, 153, 166, 177, 184
aquafeed 91
Arafura Sea 26, 40, 78
aragonite saturation 175
Arctic Ocean 172, 175
Argo floats 14, 119, 143, 144, 147, 163, 164
artificial reefs (rigs-to-reefs) 102
Ash Wednesday bushfires (1982) 57
Asia 57, 64, 65
Atlantic salmon 64, 90, 91, 92, 93, 94
Australia, Australian
    aquaculture 87–95
    blue economy 69–76
    climate change 10, 51–68
    coastal development 107–15
    coastline 9, 28–9, 137
    continental shelf 30
    deep ocean 30–5, 173
    energy resources 45–8, 97–105
    fisheries management 64, 87–95
    future directions 159–67, 179–86
    governance (marine) 77–86
    marine biodiversity 25–38
    marine employment 63, 65
    marine estate v, 2, 4–5, 13–95
    maritime jurisdiction 1, 2, 77–86
    ocean currents 13–24
    ocean geology 39–49
    ocean management 149–57
    oceanography 117–26, 137–48
    ocean pollution 52–61, 169–78
    tectonic plates 39–42
Australian Animal Health Laboratory (AAHL) 94
Australian Antarctic Territory 2, 3, 5, 26, 36, 108, 146, 187
Australian Border Force 83, 125
Australian Customs 120
Australian Defence Force 83, 120, 124, 125
    see also defence
Australian Fisheries Management Authority (AFMA) 90
Australian Government
    biodiversity 27, 37
    energy research 98
    marine management 81, 82, 110, 153
    marine research funding 3, 141, 146
Australian Institute of Marine Science (AIMS) 3, 98, 146

Australian Marine Microbial Diversity Initiative (AMMBI) 184
Australian Maritime Safety Authority (AMSA) 100, 130
Australian Ocean Data Network (AODN) 146
Australian Oceans Policy (AOP) 82, 85, 152, 153
Australian Renewable Energy Agency (ARENA) 104
automated observatories 163, 182, 183
autonomous
  gliders 143, 163, *see also* gliders main heading
  platforms 147, 161
  sensors 142–3, 180, 181, 185, 186, 188
  surface vessels (ASVs) 142, 143
  underwater vehicles (AUVs) 44, 100, 144–5, 147, 163, 180, 185

bacterial monitoring 180, 183, 184
ballast water 127, 128, 131, 134
barramundi 64, 91
Bass Strait 40, 103
bathymetric surveys 44, 139, 155
beaches
  cultural values 65–7
  habitat 23, 29, 108
  ocean forecasting 120–1
  pollution 134
bêche-de-mer 91
benthic habitats 30, 36, 101, 114
biodiversity
  management 82, 154
  marine 7–8, 25–38
  measurement 101, 155, 180, 183, 184
  social pressure 166
  threats 129, 150, 154, 178
biofouling 128, 131–2
biofuels 74
biological modelling 94, 101, 164–5, 180
biological productivity 2, 13, 14, 16–17, 20, 23–4, 26, 27, 113, 131, 155, 169, 174, 176–7, 179, 185
black abalone (aquaculture of) 91
blue carbon (coastal carbon) 68
'blue economy' 2, 69–76, 113, 166
Blue Mud Bay Case 2008 84
blue mussels (aquaculture of) 91
Bonney upwelling 17, 23
brittlestars 27, 33
Bureau of Meteorology (BoM) 2, 98, 104, 114, 118, 146

cable-based platforms 182, 183
cage rearing 80, 90, 93
calcium carbonate 30, 60, 173, 175
carbonate 60, 180
carbon cycle 10, 169, 170
carbon dioxide, CO_2
  air–sea exchange 10, 54, 55, 60, 61, 68, 170
  anthropogenic emissions 10, 53, 54, 55, 57, 68, 97, 169, 170, 171, 173, 174, 177, 178
  measurement 138, 180
  storage, sequestration 22, 46, 52, 53, 54–5, 60, 61, 68, 70, 74, 97, 104, 169, 170, 174, 176
  see also ocean acidification
carbon trading 75
catch (fisheries), *see* fisheries
Centaur, AHS 120, 121
Challenger, HMS 138
China, tourism from 71–2
chlorophyll 17, 120, 121, 123, 138, 160
Christmas Island 75, 133
citizen science 165
clean-up costs 134
climate, climate change 1–2, 6, 68, 70, 72, 85, 154, 166, 187–8
  biodiversity 37, 112, 154–5, 184, 186
  coasts, coastal communities 51, 108

- fisheries 94, 166
- marine research 166, 167
- oceans 10–11, 14, 18, 22, 43, 51–61, 68, 159
- projections 165, 169–78

coal
- energy 98, 103–4
- resources 39, 65, 111

coast, coastal
- climate change 51, 53, 56, 57, 59, 60, 68, 173, 177
- communities 1, 8, 9, 46, 51, 63, 65–8, 72, 107, 108, 134, 149, 150, 157, 165
- environmental impacts 110, 111, 113, 123, 128–9, 131, 132–3, 134, 177
- governance, management 78, 81–4, 110, 111, 112
- habitats 1, 9, 21, 26, 28–30, 36, 108, 109, 113, 154
- Indigenous peoples 67, 84
- infrastructure 14, 100
- monitoring 113, 140, 141, 145, 147, 181, 183, 184
- ocean currents 13, 15, 17–21, 23, 42, 56
- waters 2, 9, 59, 77, 78, 81, 82, 83, 108, 113
- zone development 9, 63, 65–6, 71–2, 74, 107–15, 134, 149, 150–1, 153–5, 157, 165 166

coastline length, Australia 108, 137

collaboration, marine research 3, 112, 165, 188

commercial
- aquaculture and fisheries 8, 23, 26, 33, 88–91, 94, 100, 110, 123, 162
- blue economy 69–76
- value 26, 39, 88, 90, 91, 103, 154

Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR) 6

Commonwealth Harvest Strategy Policy 89

Commonwealth Scientific and Industrial Research Organisation (CSIRO) 2–3, 19, 44, 48, 94, 98, 101, 104, 140, 141, 145, 146, 162, 163

community expectations 188

contaminants (oceans) 109, 128

contamination (chemical, oil) 130, 132, 134

continental shelf 18, 23, 30, 31, 37, 41–2, 78, 140

Convention for the Conservation of Southern Bluefin Tuna (CCSBT) 80

Convention on Biological Diversity 81

Convention on Migratory Species (CMS) 6, 81

Convention on Trade in Endangered Species of Wild Flora and Fauna (CITES) 80, 81

Convention on World Heritage 81

coral reefs 20, 26, 30, 32, 65, 82, 108, 112, 114, 145, 154, 155
- ocean acidification 60, 175
- reduction of 20, 21, 53, 177

Coral Sea 18, 26, 80

culture, cultural value 2, 8, 63, 67, 68, 69–70, 84, 88, 108, 111, 113, 150, 154, 166, 187

currents, *see* ocean currents

'dead zones' 128

decision support tools or systems 75, 93, 94, 114, 120, 149, 152, 153, 155, 162

decommissioning, oil and gas infrastructure 102

Deepwater Horizon oil spill 100, 123

defence 6, 13, 14, 117, 118, 163, 165, 166
- *see also* Australian Defence Force

deoxygenation 169, 176, 178

desalination 51, 75

dissolved oxygen 176, 180

DNA 179, 183, 184

dredging 43, 44, 47, 98, 109, 111

drug research 74

dugong 177

East Australian Current (EAC) 13, 14, 15, 16, 18–19, 23, 56, 176

Ecologically Sustainable Development (ESD) 81
economy, economic
  benefits 1, 7, 8, 9, 14, 20, 63, 65, 87, 94, 101, 107, 108, 112, 188, 150, 163
  blue economy 69–76, 113, 166
  coastal waters 101, 111, 187
  costs 127, 129, 130, 131, 134, 154, 157, 188
  fisheries and aquaculture 87–91, 163
  models 162, 165, 166, 177
  value (of marine activities) 2, 26, 65, 69, 70, 71, 73, 88, 90–1, 97, 98, 154, 157, 187
ecosystem-based fisheries management (EBFM) 87, 92, 94, 152
ecosystem-based management (EBM) 7, 81, 82, 87, 154, 187–8
ecosystems (marine)
  assessment, monitoring 101
  change, impacts 18, 24, 51, 93, 128, 157, 160, 166
  climate 51, 56, 61, 169, 176, 188
  health 7, 26, 67, 75, 111, 179, 188
  management 7, 81, 82, 87, 93, 110, 149, 151–7, 187–8
  models 101, 157, 162, 166, 177, 183, 185, 186
  ocean acidification 60, 61, 174–6
  primary production 28, 169, 174–6, 184
  risk 76, 110, 127
  services, value 23, 51, 68, 69, 70, 75, 101, 107, 113, 129, 169
  upwelling 17, 23
elephant seals, micro-sensors and 36, 145
El Niño Southern Oscillation (ENSO) 14, 20, 56, 57, 68
emissions (of greenhouse gases)
  anthropogenic, human generated 54, 58, 68, 104, 169, 171, 173, 174, 178
  reduction 68, 74, 97, 104, 171, 173
employment, marine industries 65, 71, 88, 1 13, 166, 167
energy
  carbon capture and storage 104–5
  climate (global energy balance) 52, 53, 56, 171
  fossil fuels 7, 45–6, 48, 97–8, 105
  infrastructure (and decommissioning) 102, 108
  regulation 99–100
  renewable 7, 74–5, 97, 103–5, 163, 166
  research 100–1, 105
environment, environmental
  agreements, Australia 80, 81, 82
  amenity, services 63, 65–8, 69–70, 72, 75, 108, 187
  biodiversity 25, 27, 29, 37, 38, 108, 156
  climate 10, 51, 53, 59, 60, 169, 177
  emergencies 100, 123
  energy production 7, 99–102, 104
  impacts, degradation 9, 11, 75, 81, 94, 97, 99–100, 104, 105, 111–13, 123, 127–35, 184, 188
  management 9, 11, 37, 69, 75, 81–5, 95, 99–100, 102, 110–12, 150–1, 153–4, 165, 188
  ocean currents 14, 24
  research 99–101, 113, 114, 162
  sustainability 8, 69, 92, 93–4, 107, 115, 167
Environmental Sample Processor (ESP) 180
Environmental Protection (Sea Dumping) Act 1981 129
Environment Protection and Biodiversity Conservation (EPBC) Act 1999 81, 93
equatorial oceans 15, 174
eReefs 114
estuary, estuaries 2, 5, 9, 42, 67, 89, 108, 110, 114
Europe 46, 64, 153

Exclusive Economic Zone (EEZ) 5, 77, 78, 81, 82, 83, 92, 101
exploration
  biodiversity 26, 163, 183, 188
  geological, marine basins 39, 40, 43–6, 48, 188
  minerals 40, 43, 46, 48, 75
  offshore oil and gas 7, 40, 75, 97–9, 100, 101, 105, 123, 162

FAO Code of Conduct for Responsible Fisheries 87
fish, fishes 30, 34, 53, 60, 64, 129, 145, 163, 164, 177, 184, 185
fisheries, fishing
  catch, catch limits 72, 87, 88–90, 110, 130
  climate 9, 94, 169, 174, 177, 178
  commercial 8, 84, 89, 111
  effects of (on environment) 8, 92, 109, 112, 128, 130
  employment 65
  food 6, 8, 30, 64, 72, 87–9, 92, 111, 150, 166, 177
  health 94, 111, 129, 130
  illegal, IUU 80, 83, 120
  Indigenous 8, 67, 84, 88, 89, 90, 165
  management, regulation 2, 75, 81, 85, 87, 92–3, 95, 110, 112, 150, 152, 154, 157, 165, 177, 187
  ocean currents 18, 20–1, 24
  ocean forecasts 118, 123, 159, 162–3
  pollution, waste 128, 129, 130–1
  recreational 8, 65–6, 67, 84, 88, 89, 111
  regional agreements 2, 78, 80, 81
  research 2–3, 87, 93–4, 100, 101, 113, 166
  sustainability, status of 81, 89–90, 92, 157, 166, 183
  value of 26, 65, 70, 72–3, 80, 87, 88–90, 154
  wild-harvest, wild-catch 64, 72–3, 87, 88, 89–90, 92–3, 166
Fisheries Administration Act 1991 81
fish stocks 8, 72, 163, 179, 185, 188
flesh-footed shearwaters 133
Flinders Current 18
fluorescence 138, 180
food chain, plastics and 132–3
food web 30, 36, 60, 149, 157, 177
forecasting, oceanographic 117–26
fossil fuel
  climate change 53, 54
  energy supply 7, 104
France 78, 83, 188
frontier offshore basins 40, 46

genetic sensors 163, 180
genomics 179, 183, 184
geoengineering 177–8
geological basins 39–42, 45–6, 71, 98–99, 104
  Bass Basin 40, 45
  Bight Basin 40
  Bonaparte Basin 40, 45
  Bowen/Surat Basin 45
  Browse Basin 40, 45
  Carnarvon Basin 40, 45, 46
  Eastern margin basins 40
  Eyre Sub-basin 40
  Gippsland Basin 45, 104
  Mentelle Basin 40
  Northern Margin Basins 40
  Otway Basin 40, 45
  Perth Basin 40, 42
  Recherche Sub-basin 40
  Roebuck Basin 40
  Sorell Basin 40
geological surveys 43
Geoscience Australia (GA) 2, 43, 98, 104, 146
geothermal vents 28
'ghost fishing' 130

glacier, glacial
  geology 43
  sea-level 51, 59, 61, 144, 173
Gladstone Harbour 110, 111
gliders 147, 164, 181, 182, 185
  see also autonomous, gliders
global warming 52, 53, 56, 57, 170, 171, 173, 176, 177
  see also climate change; sea-level rise
governance
  aquaculture 93
  Australia's marine estate 2, 77–86
  coastal ecosystems 110–12
  fisheries – wild catch 92–3
  future challenges 83, 166
  history 81
  Indigenous people 84
  international context 78–80
  jurisdictions 77–8
  marine environment 82, 152–4
  oceans 77–86, 187, 188
  surveillance 83
Great Australian Bight 30, 41, 101
Great Barrier Reef (GBR)
  biodiversity 30
  climate change 53, 177
  geology 44
  governance, management 81, 82, 93, 111, 114, 152, 154
  pollution 128, 177, 187
  use of, value 66, 67, 71–2, 187
greenhouse gases 18, 52, 53, 58, 59, 68, 104, 169, 171, 173
Greenland ice sheet 59

habitat
  change through global warming 20, 21, 37, 173, 177
  impacts on 113, 124, 134
  loss 25, 37, 104, 128
  types 25–38, 43, 108, 113, 155, 157, 183
Heard Island 39, 46, 83
heat storage and transport (oceans) 10, 14, 18, 22, 51–6, 61, 68, 169–71, 176
High Court of Australia 67, 81, 84
human activities
  carbon dioxide levels 54
  global warming 170, 171
  health 7, 67, 82, 127, 129, 130, 134
  marine biodiversity 37
  modelling 165
  oceans 63–8, 128
Huon Commonwealth Marine Reserve 82
hydrocarbon reserves 40, 42, 44, 48, 98–9

Ice Age 42
ice breaker 3, 188
ice sheets
  data, monitoring 140, 144
  sea level 51, 59, 61, 170
  shrinkage 59, 170, 173
illegal activities
  fishing 80, 83, 120
  migration 83
  waste discharge 129, 130–1
illness, contaminated water and 134
Indian Ocean 6, 13, 15, 18, 20, 22, 26, 56, 57, 78, 123, 124, 125
Indian Ocean Dipole (IOD) 56, 57
Indigenous people
  coastal culture 63, 67, 187
  fishing 8, 88, 89, 90, 94
  Great Barrier Reef 154
  marine governance 84, 110, 154, 165
  Traditional Owner groups 84
  see also Aboriginal and Torres Strait Islander peoples
Indigenous Protected Areas (IPAs) 84, 110
Indonesia 15, 78, 80
Indonesian Throughflow (ITF) 15, 18, 20
Indo-Pacific region 6

industry, marine-related
  blue economy 69–76, 167
  carbon capture and storage 104
  climate 53, 54, 55, 60
  coasts 9, 37, 109, 111
  development 74, 109, 110
  employment 65, 67
  fisheries and aquaculture 8, 87–95
  governance and management 78, 85, 99, 110, 112, 151
  mineral resources 40
  operational support 118, 120, 124, 162
  petroleum, oil and gas 48, 97–102, 162
  pollution 127, 128, 129, 131
  renewable energy 103–4
  research 7, 113, 166, 187
infrastructure developments, coastal 151
instrumentation 14, 119, 138–40, 143, 145
  future directions 180, 185, 188
integrated management 85, 93, 110, 127, 149–57, 165
Integrated Marine Observing System (IMOS) 3, 16, 19, 37, 121, 140, 141, 142, 146, 147, 163, 164, 184, 188
international agreements 6, 77
  Agreement on the Conservation of Albatrosses and Petrels (ACAP) 6
  Commission on the Conservation of Antarctic Marine Living Resources (CCAMLR) 6
  Convention for the Conservation of Southern Bluefin Tuna (CCSBT) 80
  Convention on Biological Diversity 81
  Convention on Migratory Species (CMS) 6
  Convention on Trade in Endangered Species of Wild Flora and Fauna (CITES) 80
  International Energy Agency 104
  International Ocean Discovery Program (IODP) 43
  International Whaling Commission 80
  Paris Agreement 2015 171
  United Nations Conference on Environment and Development (UNCED) 81
  United Nations Convention on the Law of the Sea (UNCLOS) 1, 78, 81, 124
  World Heritage Areas 81, 108, 111, 112, 128, 154
International Energy Agency 104
International Ocean Discovery Program (IODP) 43
International Whaling Commission 80
intertidal habitats 2, 28–30, 84
inundation 51, 59, 173
invasive species 37, 124, 131–2, 177
Investigator, RV 3, 37, 98, 101, 146, 163

Japan 46, 80, 188
jurisdiction, oceans governance 3, 5, 9, 11, 77–86, 92, 93, 95, 110, 187

Kerguelen Islands 78, 83
krill 23, 30, 36

land-based pollution, *see* pollution
land clearing 53, 110
La Niña 14, 20, 56, 57, 68
lanternfish 34, 35
lead–zinc deposits 48
Leeuwin Current 13, 14, 15, 16, 18, 20–1, 23, 56, 176
licences, aquaculture 93
liquefied natural gas (LNG) 45, 71, 98, 111
liquefied petroleum gas (LPG) 45
litter 128–30, 132–3, 134
long-term weather forecasts 10
Lord Howe Island 133
Lord Howe Rise 41, 46

McDonald Islands 46, 83
magnetometry 44

management
  adaptive management 152
  aquaculture 8, 93–4, 95
  biodiversity 25, 37
  bioregions 25, 27, 38
  biosecurity 131–3
  blue economy 69, 70, 72, 75–6
  climate change 177
  ecosystems, ecosystem-based 7, 70, 75, 81, 82, 87, 94, 110–12, 152, 187
  ecosystem services 70, 75
  fisheries 2, 8, 72, 75, 80, 81, 87, 90, 92–5, 152, 165, 177, 187
  future challenges 85, 94, 113, 177
  Gladstone Healthy Harbour Partnership 111
  Great Barrier Reef 114, 152, 154
  Indigenous governance 84
  integrated 11, 75, 85, 110, 127, 149–54, 157, 165
  marine jurisdictions 77–85, 92–3, 95, 110, 112, 153
  multiple-use 11, 69, 93, 108, 110, 111, 149–57
  Ningaloo Reef 112
  offshore oil and gas 82, 98–102
  pollution 131, 132, 134
  research and monitoring 93–4, 187
  resource allocation 11, 83, 84
  sustainability 108, 149, 183
  tools, support systems 114, 149, 153, 154, 155–7
mangroves 26, 28, 29, 67, 68, 75, 109, 134
mapping
  acoustic 138–9
  integrated management 154, 155, 165
  microbial 184
  seabed geology 43–4, 98
  seabed resources 98–9
Maria Island 141
mariculture 64
Marine Bioregional Plans (MBPs) 82
marine biota, Australia 26–37, 104
marine debris 125, 127, 129, 131, 132–3
marine estate, Australian
  benefits, value 1, 2, 8, 67, 70, 107, 187–9
  biodiversity 2, 7, 26, 28
  extent, size of 1, 2, 4–5, 26, 78–9, 137, 188
  geology, geomorphology 30, 39–41, 43–4, 98, 99
  governance, management 1, 2, 11, 77–85, 187–8
  Indigenous people 67, 84
  industries 71–3
  resources 2, 7–8, 11, 39, 46, 97–9
  sovereignty, security 6, 83
marine heatwave (Western Australia, 2011) 20, 21
Marine National Facility (MNF) 3, 37, 44, 98, 146, 163, 188
marine protected areas 7, 82, 108, 110, 153, 187
marine species
  distribution changes 9, 25, 37, 38, 177
  diversity 26
  invasive, pollution 124, 128
  richness map 156
marine tourism 7–8, 26, 60, 65–6, 70, 71–2, 101, 109, 112, 129, 134, 150, 154, 177
marron 91
mesopelagic habitat 183–4
Mesozoic 40, 41
MH370, search for 6, 124–5
micro-algae 74
microbial mapping 183, 184
micro-sensors 143, 145
mineral resources, offshore 2, 7, 39–40, 43, 46–8, 71, 75, 166
miniaturisation 145, 163, 179, 180, 181, 184

models, modelling
  climate 10, 56, 57, 58, 61, 169, 170, 173, 176, 177–8
  decision support 94, 111, 114, 155–6, 159–60, 162, 164–6, 177–8, 186
  ecosystems 101, 162, 164–5, 183, 185
  mineral deposits 48
  ocean forecasting 114, 117–20, 123, 124, 125, 138, 148, 160, 162, 164, 177, 179
  oil and gas, petroleum 100, 101
monitoring
  aquaculture and fisheries 93–4
  marine resources and environment 7, 25, 83, 152, 154, 159
  observation infrastructure and technology 37, 144, 146–7, 163, 179
  ocean dynamics 14, 123, 141, 159, 163
  oil and gas 100, 104
  safety and security 110, 120, 123
Montara oilrig 99, 100, 123
moorings 119, 140–1, 146–7, 164, 180, 185
municipal governments, coastal management and 110
mussels, invasive species of 124

National Computational Infrastructure facility 3, 119
National Marine Science Committee (NMSC) 6, 189
National Marine Science Plan 2015–25 6, 113
National Oceans Office (NOO) 153
National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) 82, 99–100, 102
National Plan for Maritime Environmental Emergencies 100
National Reference Stations (NRSs) (IMOS) 184
National Representative System of Marine Protected Areas (NRSMPA) 82, 153
National Sea Simulator 3, 188
native title 67, 84
natural gas resources 7, 39, 40, 45, 71, 98, 105, 111
Naturaliste Plateau 40
Navy, naval operations 6, 120–2
Neo-Proterozoic 40
New Caledonia 78
New South Wales 17, 30, 42, 71, 110
New Zealand 18, 74, 78, 80
Ningaloo Reef 30, 53, 112, 123, 187
North Atlantic Ocean 54
Northern Territory 48, 84, 104
North West Shelf 41, 43, 45, 98, 123
nutrients
  biodiversity 26, 30
  climate change 60, 174, 176
  measurement 138, 143, 180
  ocean currents 14, 15–17, 18, 114, 176
  pollution 74, 109–10
  upwelling 17, 18, 23

ocean acidification 10, 37, 51, 60, 61, 154, 169, 173–4, 177, 178, 180
OceanCurrent and Integrated Marine Observing System 19, 121, 142
ocean currents 2, 13–24, 25, 42, 43, 56, 118, 120–1, 123–4, 138, 140, 141–4, 160, 163, 176
ocean forecasting and modelling 6, 114, 117–20, 123, 124, 125, 138, 148, 160, 162, 164, 177, 179
oceanography 15–17, 75, 101, 117–26, 137–48
ocean overturning circulation 22
ocean pollution 127–35
Oceans Policy (Australian) 6, 81, 82, 85, 152, 153
ocean technology, future directions 179–89
ocean warming 18, 25, 37, 51, 53–4, 57, 59, 60, 61, 154, 169, 171–3, 174, 176, 177, 178
offshore basins 40, 71, 98, 99, 104
  see also geological basins
Offshore Constitutional Settlement (OCS) 78, 81, 85, 92, 110

offshore wind energy 74, 104
oil and gas
    environmental impacts 97, 99–102, 104, 105, 112, 123, 128, 134
    exploration 43–4, 46, 97, 98–9, 101, 105
    governance and management 77, 78, 81, 99–100, 102, 165, 166
    Ningaloo Reef 112
    ocean forecasts 118, 123, 159, 163, 166
    resources 7, 39, 40, 41, 45–6, 48, 97–8, 105
    value, benefits 65, 70, 71, 97
oil rigs, decommissioning 97, 100, 102, 105
oil spills 7, 97, 99, 100, 102, 105, 123, 128, 134
optical properties (coastal and ocean waters) 138, 143, 163, 180, 183, 184
overfishing 89–90
oxygen
    depletion 128, 169, 176, 178
    production 68, 70, 180
    sensors 138, 180
oyster farming 90–1, 93

Pacific Adventurer, MV 134
Pacific Ocean 2, 13, 15, 18, 22, 24, 26, 56, 57, 78, 124, 174
Palaeozoic 40
Papua New Guinea 2, 30, 46, 78
Paris Agreement 2015 171
passive autonomous devices 143
pelagic species 30, 101, 128, 177, 183, 185
persistent organic pollutants (POPs) 128
phytoplankton
    measurement 120, 138, 160, 180, 183
    ocean acidification 174
    production 17, 23, 30, 183
Pilbara Marine Conservation Partnership 112
pollution
    land-based 128–9, 132–3, 134, 150
    oceans 25, 37, 80, 124, 127–35, 150, 169, 184
port, ports 9, 43, 65, 72, 75, 108, 109, 111, 124, 150, 151, 154
primary production
    biodiversity 28, 30, 184
    climate change 174–6, 178

Queensland 42, 66, 82, 84, 111, 123, 134, 154

rainfall 10, 13, 56, 57
recreation, recreational
    benefits, value 7, 63, 65–8, 69, 70, 90, 134, 150, 177, 187
    fishing 8, 30, 65, 80, 84, 88, 89–90, 94, 111, 112, 154, 162
    management 110, 112, 150, 165
REDMAP 165
Reef 2050 Long-Term Sustainability Plan 154
regional marine planning, Regional Marine Plans (RMPs) 7, 39, 82, 153
RElocatable Coastal Model (RECOM) 114
remotely operated vehicles (ROVs) 44, 100
remote sensing 44, 141–2, 146, 148, 155, 179
renewable energy, marine 7, 74–5, 97, 98, 103–4, 105
representative concentration pathways (RCPs) 171, 172, 175, 176
research vessel(s) 3, 37, 43, 44, 98, 138, 139, 146, 163, 180, 185, 188, 189
Resource Assessment Commission (RAC) Coastal Zone Inquiry Report 81
robotic vehicles, robotic floats 14, 119, 142, 163, 179, 181
rock lobster fisheries 14, 20–1, 64, 84, 89, 100

salinity
    measurement 137–8, 141, 143, 144, 163, 180
    ocean properties 16, 29, 120
sand and gravel mining 46, 47

satellite
  data transmission 14, 140, 143, 144, 145, 180, 182
  remote sensing 98, 99, 114, 118–19, 141, 146, 147, 148, 155, 160, 161, 162, 163, 179, 183, 188
  sea level measurement 58, 59, 173
SCUBA diving 66, 67
seabed
  features, mapping 27, 30, 39, 98, 101, 102, 104, 112, 188
  images, photography 33, 36, 145
  jurisdiction 77–8
  mining 39
seabirds 28, 30, 74, 101, 129, 133–4, 177
sea-cage aquaculture 80, 90, 93
sea country 63, 67, 84, 110
sea-farming 150
seafloor geology 39–49, 104, 138, 139
seafood 30, 64, 72, 88–9, 95, 111, 166, 177
seagrass 26, 29, 68, 75, 177
sea-ice zone 143, 145
sea-level rise 9, 42, 51, 57–9, 61, 84, 169, 170, 173, 174, 178
seals, miniaturised equipment and 145, 181
seamounts 27, 33, 82
search and rescue 6, 13, 14, 24, 83, 117, 118, 120, 124–5, 131, 159
Seas and Submerged Lands Act 1973 78, 81
seasonal forecast models 177
sea-surface temperature
  climate 53, 56–7, 171–3
  extremes 20–1, 172
  maps 19, 23, 53, 121, 142, 160, 172
  measurement 138, 141, 160
  patterns 16
sea urchins 14, 29, 32, 33, 82
seaweeds 30, 64
sector-based management 70, 81, 85, 87, 93–4, 150–2, 165
security
  animal health (biosecurity) 94, 127, 131, 135
  Australian national 1, 6, 118
  economic 87
  energy 7, 104
  food 150, 166
  oceanography 120–2
sedimentary basins 39–42, 45–6, 98, 99
  see also geological basins
seismic surveys 44, 46, 98, 100
sensor technologies 44, 93–4, 114, 137, 139, 143–5, 147, 148, 179–81, 183–6
sequestration, carbon dioxide 46, 70, 75, 97, 104, 105
shell growth, reduction through ocean acidification 60, 173, 175
shipping 134, 150, 154, 165, 166
  coastal development 9, 109, 154
  data gathering 138–9
  invasive species 131
  management 150, 154, 165, 166
  oceanography 118, 124, 166
  pollution, associated waste 127, 129–31, 134, 177
  rights under native title 84
  value 9, 65, 70, 71, 150, 154
shipwreck searches, oceanography and 120, 121
social
  and economic values 93, 94, 101, 112, 113, 149–50, 154, 157, 166, 167, 188
  benefits 1, 2, 7, 68, 70, 72, 87, 88, 107–8, 111, 115, 118, 187
  costs of ocean pollution 134
  ecological feedbacks 162, 164
  effects of climate 51
  media technologies 189
solar radiation 52, 56
Solomon Islands 78
South Australia 17, 23, 80, 90, 93, 101

South Australian Research and Development Institute (SARDI) 101, 146
South Equatorial Current 15, 18
Southern Annular Mode (SAM) 57
southern bluefin tuna (SBT) 80, 90, 93
Southern Ocean 2, 13, 15, 22, 26, 39, 46, 54, 56, 57, 78, 83, 120, 124, 173
    overturning circulation 22
South Pacific gyre 18
sovereignty, marine estate and 6, 78, 120
spatial zoning 154, 163
sponges 29, 31, 32, 36, 155
stakeholders, and participatory management 93, 110, 163, 165
Starbug X 145, 163
states (Australian)
    fisheries management 92, 95
    jurisdiction and governance 3, 9, 77–8, 81–2, 85, 99–100, 110, 112
    marine research 2–3, 98, 113, 153
    surveillance 83
'Stow it don't throw it' campaign 130
submarine navigation and underwater acoustics 121–2
sub-seabed, sub-seafloor
    geology, structure 43, 44, 98–9
    resources 7, 45
subtidal habitats 28, 29, 30
surfing 66, 67
sustainable
    development 81
    fisheries and aquaculture 90, 92, 93, 157, 166, 177
    management 1, 14, 80, 81, 94, 108, 149, 157, 183
    resource use 8, 24, 107, 115, 154, 166, 167
Sverdrup (Sv) 18, 20, 22
Sydney 19, 75, 151, 174
Sydney Institute of Marine Science (SIMS) 146
Sydney-to-Hobart Yacht Race 120, 121
synthetic aperture radar (SAR) 44

Tasmania 14, 18, 27, 92, 93, 94, 137, 141, 143, 174
Tasman Sea 18, 26, 57, 174
tectonic plates 39, 40–2
    Eurasian Plate 41
    Pacific Plate 41
temperature
    atmospheric (and glacier melting) 59
    climate (Australian) 10, 13, 16, 26, 172, 178
    fishing 123, 177
    ocean 26, 28, 29, 30, 56, 155–6, 172
    sea-surface, *see* sea-surface temperature
    sensors, measurement 120, 137–9, 140, 141, 143, 144, 145, 180
    underwater navigation 121–2
Territorial Sea (governance of) 77, 78, 82
Timor-Leste (East Timor) 78
Timor Sea 18, 26, 78, 123
Torres Strait 78, 84
Torres Strait Islander peoples 84, 165
tourism, marine 7–8, 26, 60, 65–6, 70, 71–2, 101, 109, 112, 129, 134, 150, 154, 177
Traditional Owners 110, 151, 165
transport
    energy infrastructure 7, 100, 105, 123
    industries 2, 65, 69, 71, 150, 166, 177
    invasive species, marine pests 127, 128, 131–2
    ocean currents 13, 14, 20–2
    ocean heat (and climate) 52, 56, 61, 169, 171, 176
    oceanographic forecasts 124, 162
    pollution 127, 134
    sediment 39, 42, 114
tropical cyclones 51, 56, 108, 123
tsunami warnings 123

underwater acoustics 34, 44, 100, 121–2
underwater vehicles 44, 100, 143–5, 163, 180, 181, 185
United Kingdom (UK) 46, 47
United Nations Conference on Environment and Development (UNCED) 81
United Nations Convention on the Law of the Sea (UNCLOS) 1, 78, 81, 124
United States of America (USA) 46, 64, 153, 188
universities, marine research and 2–3
urbanisation, coastal zone and 75, 108, 109, 110, 113, 150

vents (geothermal, hydrothermal) 28, 39, 46
Victoria 17, 23, 103, 104
volcanic activity 41, 43, 46, 170

warm-tolerant corals 177
warm-water aquaculture 91
waste
    aquaculture 130
    disposal 130
    fisheries and shipping 130–1
    ocean dumping 128–9, 130, 135
    pollution 129, 130–1
water column 27, 30, 34, 44, 77, 98, 104, 114, 143, 160
water quality (coastal) 110, 114
water supply (from oceans) 68
    desalination 75
wave, waves
    effects 1, 28, 30, 42, 59, 108, 109
    energy 7, 74–5, 97, 103, 104, 143, 182
    monitoring, prediction 120–1, 122, 123, 124, 141
Western Australia 14, 17, 20, 21, 30, 103, 104, 109, 112, 123, 156, 176
whales 23, 30, 36, 66, 100, 145
wild-catch fisheries 64, 72–3, 87, 88, 89–90, 92–3, 166
wind
    energy 74, 104, 143
    forecasts 123, 124, 141
    ocean currents 15, 18, 20, 23, 24, 42, 56–7, 177
World Heritage Area (Great Barrier Reef) 108, 111, 112, 128, 154

yacht racing 120, 121
yellowtail kingfish 91, 93