

# Contents

Preface xiii

Guided Tour xviii

## Chapter 1

### The History of Oceanography 1

- 1.1 The Early Times 3
- 1.2 The Middle Ages 5
- 1.3 Voyages of Discovery 6
- 1.4 The Beginnings of Earth Science 7
- 1.5 The Importance of Charts and Navigational Information 8
- Box: Marine Archaeology** 10
- 1.6 Ocean Science Begins 12
- 1.7 The *Challenger* Expedition 13
- 1.8 Oceanography as Science 13
- Field Notes: Planning and Executing a Successful Oceanographic Expedition** 15
- 1.9 Oceanography in the Twentieth Century 19
- 1.10 The Recent Past, the Present, and the Future of Oceanography 22
- Summary* 24

## Chapter 2

### The Water Planet 26

- 2.1 Beginnings 27
  - Origin of the Universe 27
  - Origin of Our Solar System 29
- Box: Origin of the Oceans** 30
  - Extraterrestrial Oceans 30
  - Early Planet Earth 32
- 2.2 Age and Time 33
  - Age of Earth 33
  - Geologic Time 34
  - Natural Time Periods 34
- 2.3 Shape of Earth 36
- 2.4 Location Systems 37
  - Latitude and Longitude 37
  - Charts and Maps 39
  - Measuring Latitude 40
  - Longitude and Time 40
- 2.5 Modern Navigational Techniques 41

## 2.6 Earth: The Water Planet 42

- Water on Earth's Surface 42
- Hydrologic Cycle 43
- Reservoirs and Residence Time 44
- Distribution of Land and Water 45
- Oceans 45
- Hypsographic Curve 47
- Summary* 48

## Chapter 3

### Plate Tectonics 50

- 3.1 Earth's Interior 51
  - Investigating Earth's Structure 51
  - Internal Layers 54
- 3.2 Lithosphere and Asthenosphere 55
  - The Layers 55
  - Isostasy 55
- 3.3 Movement of the Continents 56
  - History of a Theory: Continental Drift 56
  - Evidence for a New Theory: Seafloor Spreading 57
  - Evidence for Crustal Motion 59
  - Polar Wandering Curves 64
- 3.4 Plate Tectonics 65
  - Plates and Their Boundaries 65
  - Divergent Boundaries 67
  - Transform Boundaries 69
  - Convergent Boundaries 71
  - Continental Margins 73
- 3.5 Motion of the Plates 74
  - Mechanisms of Motion 74
  - Rates of Motion 74
  - Hot Spots 74
- Field Notes: New Approaches to Exploring the Oceans** 76
- 3.6 History of the Continents 79
  - The Breakup of Pangaea 79
  - Before Pangaea 80
  - Terranes 82
- 3.7 Exploring Divergent Boundaries 83
  - Project FAMOUS 83
  - Seafloor Spreading and Hydrothermal Vents 83
  - Hydrothermal Vent Communities 85
- Box: Recovery of Black Smokers** 86
  - Summary* 88



## Chapter 4

### The Sea Floor and Its Sediments 90

4.1 Measuring the Depths 91

**Box: Bathymetrics** 93

4.2 Bathymetry of the Sea Floor 94

Continental Margin 94

Ocean Basin Floor 100

Ridges, Rises, and Trenches 101

4.3 Sediments 103

Particle Size 103

**Field Notes: Giant Hawaiian Landslides** 104

Location 107

Rates of Deposit 107

Source and Chemistry 107

Patterns of Deposit on the Sea Floor 112

Formation of Rock 114

Sampling Methods 114

Sediments as Historical Records 117

4.4 Seabed Resources 117

Sand and Gravel 117

Phosphorite 118

Sulfur 118

Coal 118

Oil and Gas 118

Gas Hydrates 119

Manganese Nodules 120

Sulfide Mineral Deposits 120

Laws and Treaties 120

*Summary* 121

## Chapter 5

### The Physical Properties of Water 124

5.1 The Water Molecule 125

5.2 Temperature and Heat 126

5.3 Changes of State 127

5.4 Specific Heat 129

5.5 Cohesion, Surface Tension, and Viscosity 129

5.6 Density 130

The Effect of Pressure 130

The Effect of Temperature 130

The Effect of Salt 131

5.7 Dissolving Ability 132

5.8 Transmission of Energy 132

Heat 132

Light 134

5.9 Ice and Fog 140

Sea Ice 140

**Box: Acoustic Thermometry of Ocean Climate** 140

Icebergs 141

Fog 145

*Summary* 145

## Chapter 6

### The Chemistry of Seawater 148

6.1 Salts 149

Units of Concentration 149

Ocean Salinities 149

Dissolved Salts 150

Sources of Salt 151

Regulating the Salt Balance 153

Residence Time 154

Constant Proportions 154

Determining Salinity 154

6.2 Gases 155

Distribution with Depth 155

The Carbon Dioxide Cycle 156

The Oxygen Balance 157

Measuring the Gases 157

**Box: Messages in Polar Ice** 158

6.3 The pH of Seawater 160

6.4 Other Substances 161

Nutrients 161

Organics 161

6.5 Practical Considerations: Salt and Water 162

Chemical Resources 162

Desalination 162

*Summary* 164

## Chapter 7

### The Structure and Motion of the Atmosphere 167

7.1 Heating and Cooling Earth's Surface 168

Distribution of Solar Radiation 168

Heat Budget 168

Annual Cycles of Solar Radiation 170

Specific Heat and Heat Capacity 171

7.2 The Atmosphere 172

Structure of the Atmosphere 172

Composition of Air 173

Atmospheric Pressure 173

7.3 Greenhouse Gases 174

Carbon Dioxide and Greenhouse Effect 174

The Ozone Problem 176

7.4 The Role of Sulfur Compounds 178

7.5 The Atmosphere in Motion 178

Winds on a Nonrotating Earth 178

The Effects of Rotation 179

Wind Bands 181

7.6 Modifying the Wind Bands 183

Seasonal Changes 183

The Monsoon Effect 185

The Topographic Effect 186

Jet Streams 187

7.7 Hurricanes 188

- 7.8 El Niño–Southern Oscillation 189  
**Field Notes:** *The Oceans and Climate Change* 192
- 7.9 Practical Considerations: Storm Tides and Storm Surges 194  
*Summary* 198

## Chapter 8

### Circulation and Ocean Structure 200

- 8.1 Density Structure 201  
 Surface Processes 201  
 Changes with Depth 202  
 Density-Driven Circulation 203
- 8.2 Upwelling and Downwelling 204
- 8.3 The Layered Oceans 204  
 The Atlantic Ocean 204  
 The Pacific Ocean 205  
 The Indian Ocean 205  
 Comparing the Major Oceans 205  
 The Arctic Ocean 206
- Box:** *Arctic Ocean Studies* 207  
 Bordering Seas 209  
 Internal Mixing 210
- 8.4 Measurement Techniques 210
- 8.5 Practical Considerations: Ocean Thermal Energy Conversion 212
- Box:** *Ocean Gliders* 213  
*Summary* 215

## Chapter 9

### The Surface Currents 218

- 9.1 Surface Currents 219  
 The Ekman Spiral and Ekman Transport 219  
 Ocean Gyres 219  
 Geostrophic Flow 220
- 9.2 Wind-Driven Ocean Currents 221  
 Pacific Ocean Currents 221  
 Atlantic Ocean Currents 221  
 Indian Ocean Currents 222  
 Arctic Ocean Currents 222
- 9.3 Current Flow 223  
 Current Speed 223  
 Current Volume Transport 223  
 Western Intensification 223
- 9.4 Eddies 224
- 9.5 Convergence and Divergence 226  
 Langmuir Cells 226  
 Permanent Zones 226  
 Seasonal Zones 226
- 9.6 Changing Circulation Patterns 228  
 Global Currents 228  
 North Pacific Oscillations 230

**Box:** *Ocean Drifters* 231

- North Atlantic Oscillations 233
- 9.7 Measuring the Currents 234
- 9.8 Practical Considerations: Energy from the Currents 236  
*Summary* 237

## Chapter 10

### The Waves 239

- 10.1 How a Wave Begins 240
- 10.2 Anatomy of a Wave 241
- 10.3 Wave Motion 241
- 10.4 Wave Speed 242
- 10.5 Deep-Water Waves 242  
 Storm Centers 243  
 Dispersion 243  
 Group Speed 244  
 Wave Interaction 244
- 10.6 Wave Height 244  
 Episodic Waves 245  
 Wave Energy 246  
 Wave Steepness 246  
 Universal Sea State Code 247
- 10.7 Shallow-Water Waves 247  
 Refraction 248  
 Reflection 248  
 Diffraction 249  
 Navigation from Wave Direction 249
- 10.8 The Surf Zone 251  
 Breakers 251  
 Water Transport 252  
 Energy Release 252
- 10.9 Tsunami 253
- Field Notes:** *Modeling the December 26, 2004, Sumatra Tsunami* 256
- 10.10 Internal Waves 259
- 10.11 Standing Waves 261
- 10.12 Practical Considerations: Energy from Waves 263  
*Summary* 264

### Going to Sea 266

## Chapter 11

### The Tides 270

- 11.1 Tide Patterns 271
- 11.2 Tide Levels 271
- 11.3 Tidal Currents 272
- 11.4 Equilibrium Tidal Theory 272  
 The Moon Tide 274  
 The Tidal Day 274  
 The Tide Wave 274

The Sun Tide	275
Spring Tides and Neap Tides	275
Declinational Tides	276
Elliptical Orbits	276
11.5 Dynamic Tidal Analysis	276
The Tide Wave	277
Progressive Wave Tides	278
Standing Wave Tides	279
Tide Waves in Narrow Basins	280
11.6 Tidal Bores	280
11.7 Predicting Tides and Tidal Currents	282
Tide Tables	282
Tidal Current Tables	282
<b>Box: Measuring Tides from Space</b>	283
11.8 Practical Considerations: Energy from Tides	284
Summary	286

## Chapter 12

### Coasts, Beaches, and Estuaries 288

12.1 Major Zones	289
12.2 Types of Coasts	291
Primary Coasts	291
Secondary Coasts	293
12.3 Anatomy of a Beach	296
12.4 Beach Dynamics	297
Natural Processes	299
Coastal Circulation	300
12.5 Beach Types	301
12.6 Modifying Beaches	302
Coastal Structures	303
The Santa Barbara Story	304
The History of Ediz Hook	304
12.7 Estuaries	306
Types of Estuaries	306
<b>Box: National Marine Sanctuaries</b>	308
Circulation Patterns	310
<b>Box: Rising Sea Level</b>	311
Temperate-Zone Estuaries	311
12.8 High Evaporation Rates	311
12.9 Flushing Time	313
12.10 Practical Considerations: Case Histories	313
The Development of San Francisco Bay	313
The Situation in Chesapeake Bay	315
Summary	316

## Chapter 13

### Environmental Issues and Concerns 319

13.1 Water and Sediment Quality	320
Solid Waste Dumping	320
Sewage Effluent	321
Toxicants	322

13.2 Gulf of Mexico Dead Zone	324
13.3 Plastic Trash	326
13.4 Ocean Waste Management Proposals	328
13.5 Oil Spills	328
13.6 Marine Wetlands	332
<b>Box: Spartina: Valuable and Productive or Invasive and Destructive?</b>	334
13.7 Biological Invaders	334
<b>Field Notes: Ecological Nowcasting of Sea Nettles in Chesapeake Bay</b>	336
13.8 Overfishing and Incidental Catch	339
13.9 Afterthoughts	341
Summary	341

## Chapter 14

### The Living Ocean 343

14.1 Environmental Zones	344
14.2 Considerations of Size	344
14.3 Groups of Organisms	345
14.4 Facts of Ocean Life	348
Light	348
Carbon	350
Inorganic Nutrients	350
Oxygen	351
Salinity	352
Buoyancy	352
Temperature	353
Pressure	354
Circulation	354
14.5 Bottom Environments	354
14.6 Close Associations	355
Symbioses	355
<b>Box: Biodiversity in the Oceans</b>	356
14.7 Practical Considerations: Human Impacts of Marine Environments	356
Summary	357

## Chapter 15

### Production and Life 359

15.1 Primary Production	360
Gross and Net	360
Measuring Primary Productivity	361
15.2 Nutrient Cycles	363
15.3 Phytoplankton Biomass	363
15.4 Controls on Primary Production and Biomass	366
Global Primary Productivity	367
15.5 Food Webs and the Biological Pump	369
15.6 Practical Considerations: Ocean Fertilization	372
<b>Box: CalCOFI—Fifty Years of Coastal Ocean Data</b>	373
Summary	374

## Chapter 16

### The Plankton: Drifters of the Sea 377

- 16.1 Kinds of Plankton 378
- 16.2 Phytoplankton 378
- Field Notes:** *Discovery of the Role of Picoplankton* 384
- 16.3 Zooplankton 386
- 16.4 Bacterioplankton 393
- Box: Extremophiles** 394
- 16.5 Viruses 395
- 16.6 Sampling the Plankton 395
- 16.7 Practical Considerations: Marine Toxins 396
- Harmful Algal Blooms 396
- Paralytic Shellfish Poisoning (PSP) 397
- Neurotoxic Shellfish Poisoning (NSP) 398
- Diarrhetic Shellfish Poisoning (DSP) 398
- Ciguatera Fish Poisoning 398
- Amnesiac Shellfish Poisoning (ASP) 398
- Pfiesteria 399
- Cholera 399
- Summary* 399

## Chapter 17

### The Nekton: Free Swimmers of the Sea 401

- 17.1 Mammals 402
  - Whales 402
  - Whaling 405
  - Dolphins and Porpoises 407
  - Seals and Sea Lions 407
  - Box: Whale Falls** 409
    - Sea Otters 411
    - Walrus 411
    - Sea Cows 411
    - Polar Bears 412
    - Marine Mammal Protection Act 413
    - Communication 413
- 17.2 Marine Birds 414
- 17.3 Marine Reptiles 416
  - Sea Snakes 416
  - Sea Turtles 416
- 17.4 Squid 418
- 17.5 Fish 418
  - Sharks and Rays 419
  - Commercial Species of Bony Fish 420
  - Deep-Sea Species of Bony Fish 420

- 17.6 Practical Considerations: Commercial Fisheries 422
  - Anchovies 424
  - Tuna 425
  - Salmon 425
  - Atlantic Cod 426
  - Sharks 427
  - Fish Farming 427
  - Summary* 429

## Chapter 18

### The Benthos: Dwellers of the Sea Floor 431

- 18.1 Algae and Plants 432
  - General Characteristics of Benthic Algae 432
  - Kinds of Seaweeds 433
  - Marine Plant Communities 433
- 18.2 Animals 434
  - Animals of the Rocky Shore 435
  - Tide Pools 440
  - Animals of the Soft Substrates 440
  - Animals of the Deep-Sea Floor 443
  - Fouling and Boring Organisms 444
- 18.3 High-Energy Environments 444
- 18.4 Coral Reefs 445
  - Tropical Corals 445
  - Tropical Coral Reefs 445
- Field Notes:** *Biofouling* 446
  - Coral Bleaching 449
  - Predation and Disease 452
  - Human Activities 453
  - Deep-Water Corals 453
- 18.5 Deep-Ocean Chemosynthetic Communities 453
  - Hot Vents 453
  - Cold Seeps 454
- 18.6 Sampling the Benthos 454
  - Box: Deep-Sea Ice Worms** 455
- 18.7 Practical Considerations: Harvesting the Benthos 456
  - The Animals 456
  - The Algae 457
  - Biomedical Products 458
- Box: Genetic Manipulation of Fish and Shellfish** 459
  - Summary* 460
- Appendix A Scientific (or Exponential) Notation 461
- Appendix B SI Units 463
- Appendix C Equations and Quantitative Relationships 467
- Glossary 471
- Credits 483
- Index 487