

Contents

Preface	xv	Questions and Exercises	31
To the Student	xv	References	32
To the Instructor	xv	<i>Suggested Reading in Scientific American</i>	32
What's New in this Edition?	xvi	Oceanography on the Web	33
The New Instructional Package	xvii		
Acknowledgments	xviii		
Environmental Issues in Oceanography	xix		
<hr/>			
Introduction	1	2	
What is Oceanography?	1	Plate Tectonics and the Ocean	
Earth's Oceans	2	Floor	34
Rational Use of Technology?	3		
<hr/>			
I			
Introduction to the Planet "Earth"	6		
Key Questions	7		
Feature: Diving into the Marine Environment	7		
Geography of the Oceans	7		
<i>The Four Principal Oceans, Plus One</i>	7	Evidence for Continental Drift	35
<i>The Seven Seas? Comparing the Oceans to the Continents</i>	10	<i>Fit of the Continents</i>	35
Explorations of the Oceans: Some Historical Notes		<i>Matching Sequences of Rocks and Mountain Chains</i>	36
About Oceanography	10	<i>Glacial Ages and Other Climate Evidence</i>	37
<i>Early History</i>	10	<i>Distribution of Organisms</i>	38
<i>The Middle Ages</i>	13	<i>Objections to the Continental Drift Model</i>	39
<i>The Age of Discovery in Europe</i>	13		
Box 1-1 How do Sailors Know Where They Are at Sea?		Evidence for Plate Tectonics	40
From Stick Charts to Satellites	14	<i>Earth's Magnetic Field and Paleomagnetism</i>	40
<i>The Beginning of Voyaging for Science</i>	17	<i>Sea Floor Spreading and Features of the Ocean Basins</i>	43
<i>History of Oceanography... To Be Continued</i>	17		
The Nature of Scientific Inquiry	17	Box 2-1 Do Sea Turtles (and Other Animals) Use Earth's Magnetic Field for Navigation?	44
<i>Observations</i>	18	<i>Other Evidence from the Ocean Basins</i>	45
<i>Hypothesis</i>	18	<i>The Acceptance of a Theory</i>	47
<i>Theory</i>	18	Earth Structure	47
<i>Theories and the Truth</i>	18	<i>Chemical Composition Versus Physical Properties</i>	47
Origins	19	<i>Near the Surface</i>	50
<i>Origin of the Solar System and Earth</i>	19	<i>Isostatic Adjustment</i>	50
<i>Origin of the Atmosphere and the Oceans</i>	21	Plate Boundaries	52
Life Begins in the Oceans	22	<i>Divergent Boundaries</i>	53
<i>The Importance of Oxygen to Life</i>	22	<i>Convergent Boundaries</i>	53
<i>Plants and Animals Evolve</i>	23	<i>Transform Boundaries</i>	59
Radiometric Dating and the Geologic Time Scale	25	Testing the Model: Some Applications	
<i>Students Sometimes Ask...</i>	26	of Plate Tectonics	60
Box 1-2 "Deep" Time	28	<i>Mantle Plumes and Hotspots</i>	60
Chapter in Review	31	<i>Seamounts and Tablemounts</i>	62
Key Terms	31	<i>Coral Reef Development</i>	63
		<i>Detecting Plate Motion with Satellites</i>	65
		<i>The Past: Paleoceanography</i>	65
		<i>The Future: Some Bold Predictions</i>	66
		<i>Students Sometimes Ask...</i>	67
		Chapter in Review	70
		Key Terms	70
		Questions and Exercises	71
		References	72
		<i>Suggested Reading in Scientific American</i>	73
		<i>Oceanography on the Web</i>	73

3**Marine Provinces** 74**Key Questions** 74**Feature: Experiments in Underwater Living** 74

Bathymetry 75

Bathymetric Techniques 75 *Provinces of the Ocean Floor* 77 *Features of Continental Margins* 77Box 3-1 *Sea Floor Mapping from Space* 80*Features of the Deep-Ocean Basin* 84Box 3-2 *A Grand "Break": Evidence for Turbidity**Currents* 86*Features of the Mid-Ocean Ridge* 87*Students Sometimes Ask...* 91

Chapter in Review 94

Key Terms 94

Questions and Exercises 95

References 95

Suggested Reading in Scientific American 95*Oceanography on the Web* 96**4****Marine Sediments** 97**Key Questions** 97**Feature: Collecting the Historical Record of the Deep-Ocean Floor** 97

Lithogenous Sediment 100

Origin 100 *Composition* 101 *Sediment Texture* 101 *Distribution* 103

Biogenous Sediment 105

Origin 105 *Composition* 106

Hydrogenous Sediment 110

Origin 110 *Composition and Distribution* 110Box 4-1 *Diatoms: The Most Important Things You Have (Probably) Never Heard Of* 111*Distribution* 112

Cosmogenous Sediment 114

Origin, Composition, and Distribution 114Box 4-2 *When a Sea Was Dry: Clues from the Mediterranean* 115

Distribution of Neritic and Pelagic Deposits: A Summary 116

Box 4-3 *When the Dinosaurs Died: The Cretaceous-Tertiary (K-T) Event* 117

Mixtures 118

Ocean Sediments as a Resource 120

Petroleum 120 *Gas Hydrates* 121 *Sand and**Gravel* 121 *Evaporative Salts* 122*Phosphorite (Phosphate Minerals)* 123*Manganese Nodules and Crusts* 123*Students Sometimes Ask...* 124

Chapter in Review 125

Key Terms 126

Questions and Exercise 127

References 128

Suggested Reading in Scientific American 129*Oceanography on the Web* 129**5****Water and Seawater** 130**Key Questions** 130**Feature: The HMS Challenger Expedition: Birth of Oceanography** 130

Atomic Structure 131

The Water Molecule 132

Geometry 132 *Polarity* 132 *Interconnections of Molecules* 133 *Water: The Universal Solvent* 133

Water's Thermal Properties 134

Heat, Temperature, and Changes of State 134*Water's Freezing and Boiling Points* 135 *Water's Heat Capacity* 135 *Water's Latent Heats* 136

Water Density 139

Seawater 140

Salinity 140 *Salinity Variations* 142Box 5-1 *How to Avoid Goiters* 143*Determining Salinity* 144

Dissolved Components Added and Removed from Seawater 144

Acidity and Alkalinity of Seawater 146

The pH Scale 146 *The Carbonate Buffering System* 146

Processes Affecting Seawater Salinity 147

Processes That Decrease Seawater Salinity 147*Processes That Increase Seawater Salinity* 148*The Hydrologic Cycle* 148

Surface and Depth Salinity Variation 148

Surface Salinity Variation 148 *Depth Salinity Variation* 149

Seawater Density 150

Pycnocline and Thermocline 152Box 5-2 *The Hot and Cold About OTEC Systems* 154

Comparing Pure Water and Seawater 155

Desalination 155

Distillation 155 *Membrane Processes* 156*Other Methods of Desalination* 157*Students Sometimes Ask...* 157

Chapter in Review 158

Key Terms 159

Questions and Exercises 160

References 160

Suggested Reading in Scientific American 161*Oceanography on the Web* 161

6**Air-Sea Interaction 162****Key Questions 162****Feature: RMS *Titanic*: Lost (1912) and Found (1985) 162**

Uneven Solar Heating on Earth 164

Distribution of Solar Energy 164 *Earth's Seasons* 164 *Oceanic Heat Flow* 165 *The Atmosphere: Physical Properties* 166
 An Example: A Non-Spinning Earth 168

The Coriolis Effect 168

Example 1: Perspectives and Frames of Reference on a Merry-Go-Round 169 *Example 2: A Tale of Two Missiles* 170 *Changes in the Coriolis Effect with Latitude* 171

Atmospheric Circulation Cells on a Spinning Earth 172

Circulation Cells 172 *Pressure* 172 *Wind Belts* 173 *Boundaries* 173 *Circulation Cells: Idealized or Real?* 173

Box 6-1 Why Christopher Columbus Never Set Foot on North America 174

The Oceans, Weather, and Climate 175

Winds 175 *Storms* 175 *Tropical Cyclones (Hurricanes)* 178 *Climate Patterns in the Oceans* 182

Box 6-2 The Storm of the Century: Galveston, Texas (1900) 184

The Atmosphere's Greenhouse Effect 185

Which Gases Contribute to the Greenhouse Effect? 186 *What Changes Will Occur as a Result of Increased Global Warming?* 186
 The IPCC and the Kyoto Protocol 189 *The Ocean's Role in Reducing the Greenhouse Effect* 189
 What Should We Do About the Increasing Greenhouse Gases? 190

Students Sometimes Ask... 190

Chapter in Review 191

Box 6-3 The ATOC Experiment: SOFAR so Good? 192

Key Terms 194

Questions and Exercises 194

References 195

Suggested Reading in Scientific American 195

Oceanography on the Web 196

7**Ocean Circulation 197****Key Questions 197****Feature: Benjamin Franklin: The World's Most Famous Physical Oceanographer 197**

Measuring Ocean Currents 198

Surface Currents 199

Equatorial Currents, Boundary Currents, and Gyres 200 *Ekman Spiral and Ekman Transport* 202Box 7-1 Running Shoes as Drift Meters: Just Do It 203
 Geostrophic Currents 205
 Western Intensification 205Box 7-2 The Voyage of the *Fram*: A 1000-Mile Journey Locked in Ice 206 *Equatorial Countercurrents* 207 *Ocean Currents and Climate* 208

Upwelling and Downwelling 209

Diverging Surface Water 209 *Converging Surface Water* 209 *Coastal Upwelling and Downwelling* 209 *Other Upwelling* 211

Surface Currents of the Oceans 211

Antarctic Circulation 211 *Atlantic Ocean Circulation* 213 *Pacific Ocean Circulation* 217
 Indian Ocean Circulation 223

Box 7-3 El Niño and the Incredible Shrinking Marine Iguanas of the Galápagos Islands 224

Deep Currents 225

Origin of Thermohaline Circulation 225 *Sources of Deep Water* 226 *Worldwide Deep-Water Circulation* 227

Students Sometimes Ask... 230

Chapter in Review 231

Key Terms 233

Questions and Exercises 233

References 233

Suggested Reading in Scientific American 234

Oceanography on the Web 235

8**Waves and Water Dynamics 236****Key Questions 236****Feature: The Biggest Wave in Recorded History: Lituya Bay, Alaska (1958) 236**

What Causes Waves? 238

How Waves Move 240

Wave Characteristics 240

Circular Orbital Motion 241 *Deep-Water Waves* 241 *Shallow Water Waves* 242
 Transitional Waves 243

Wind-Generated Waves 243

"Sea" 244 *Swell* 245 *Surf* 247

Box 8-1 Rogue Waves: Ships Beware! 249

Wave Refraction 251 *Wave Reflection* 252

Tsunami 253

Coastal Effects 254 *Historic Tsunami* 254
 Tsunami Warning System 256

Box 8-2 The Big Shake: A Tsunami from the Cascadia Subduction Zone Hits Japan 257

Power from Waves	259
<i>Students Sometimes Ask...</i>	259
Chapter in Review	261
Key Terms	262
Questions and Exercises	263
References	264
<i>Suggested Reading in Scientific American</i> 264	
Oceanography on the Web	264

9**Tides 265****Key Questions 265****Feature: A Brief History of Some Successful Tidal****Power Plants 265**

Generating Tides 266

<i>Tide-Generating Forces</i>	266
<i>Tidal Bulges: The Moon's Effect</i>	270
<i>Tidal Bulges: The Sun's Effect</i>	270
<i>Earth's Rotation</i>	270
<i>The Monthly Tidal Cycle</i>	271
<i>Other Factors</i>	273
<i>Idealized Tide Prediction</i>	274

Tides in the Ocean 274

<i>Tidal Patterns</i>	276
<i>An Example of Tidal Extremes: The Bay of Fundy</i>	277
<i>Coastal Tidal Currents</i>	277

Box 9-1 *Tidal Bores: Boring Waves these Are Not!* 278

<i>Some Considerations of Tidal Power</i>	280
-------------------------------------------	-----

Students Sometimes Ask... 282Box 9-2 *Grunions: Doing What Comes Naturally on the Beach* 282

Chapter in Review 285

Key Terms 286

Questions and Exercises 286

References 287

<i>Suggested Reading in Scientific American</i>	287
-------------------------------------------------	-----

Oceanography on the Web 287

10**The Coast: Beaches and Shoreline Processes 288****Key Questions 288****Feature: The Ultimate Protection: The National Flood Insurance Program (NFIP) 288**

The Coastal Region 289

<i>Beach Terminology</i>	289
<i>Beach Composition</i>	290
<i>Movement of Sand on the Beach</i>	290

Erosional- and Depositional-Type Shores 292

<i>Features of Erosional-Types Shores</i>	293
-------------------------------------------	-----

Box 10-1 *Warning: Rip Currents ... Do You Know What to Do?* 294

<i>Features of Depositional-Types Shores</i>	295
Emerging and Submerging Shorelines	300
<i>Tectonic and Isostatic Movements of Earth's Crust</i>	301
<i>Eustatic Changes in Sea Level</i>	302
<i>Sea Level and the Greenhouse Effect</i>	303

Characteristics of U.S. Coasts 304

<i>The Atlantic Coast</i>	304
<i>The Gulf Coast</i>	305

The Pacific Coast 305

Hard Stabilization 305

<i>Groins and Groin Fields</i>	307
<i>Jetties</i>	307
<i>Breakwaters</i>	308
<i>Seawalls</i>	309
<i>Alternatives to Hard Stabilization</i>	310

Students Sometimes Ask... 310Box 10-2 *The Move of the Century: Relocating the Cape Hatteras Lighthouse* 312

Chapter in Review 313

Key Terms 314

Questions and Exercises 314

References 315

<i>Suggested Reading in Scientific American</i>	315
-------------------------------------------------	-----

Oceanography on the Web 315

11**The Coastal Ocean 316****Key Questions 316****Feature: The Law of the Sea 316**

Coastal Waters 318

<i>Salinity</i>	318
<i>Temperature</i>	318
<i>Coastal Geostrophic Currents</i>	318

Estuaries 320

<i>Origin of Estuaries</i>	320
<i>Water Mixing in Estuaries</i>	321
<i>Estuaries and Human Activities</i>	322

Coastal Wetlands 323

<i>Serious Loss of Valuable Wetlands</i>	324
------------------------------------------	-----

Lagoons 326

<i>Laguna Madre</i>	326
---------------------	-----

A Case Study: The Mediterranean Sea 327

<i>Mediterranean Circulation</i>	327
----------------------------------	-----

Pollution in Coastal Waters 327

<i>What is Pollution</i>	327
<i>Petroleum</i>	329

Box 11-1 *The Exxon Valdez Oil Spill: Not the Worst Spill Ever* 330

<i>Sewage Sludge</i>	335
<i>DDT and PCBs</i>	336

<i>Mercury and Minamata Disease</i>	338
-------------------------------------	-----

<i>Non-Point-Source Pollution and Trash</i>	340
---------------------------------------------	-----

Students Sometimes Ask... 340Box 11-2 *From A to Z in Plastics: The Miracle Substance?* 342

Chapter in Review 344

Key Terms 345

Questions and Exercises 345

References 345

Suggested Reading in Scientific American 345
 Oceanography on the Web 345

12

The Marine Habitat 346

- Key Questions** 346
- Feature: Charles Darwin and the Voyage of HMS Beagle** 346
- Classification of Living Things 347
 - Classification of Marine Organisms 349
 - Plankton (Floaters)* 349 *Nekton (Swimmers)* 350 *Benthos (Bottom Dwellers)* 350
 - Distribution of Life in the Oceans 352
 - Why Are There So Few Marine Species?* 352
 - Adaptations of Organisms to the Marine Environment 352
 - Need for Physical Support* 353 *Water's Viscosity* 355 *Temperature* 356 *Salinity* 358
 - Dissolved Gases* 360 *Water's High Transparency* 361 *Pressure* 361
 - Divisions of the Marine Environment 363
 - Pelagic (Open Sea) Environment* 363
 - Box 12-1 A False Bottom: The Deep Scattering Layer (DSL)** 364
 - Benthic (Sea Bottom) Environment* 365
 - Students Sometimes Ask...* 367
 - Chapter in Review 369
 - Key Terms 369
 - Questions and Exercises 370
 - References 371
 - Suggested Reading in Scientific American* 371
 - Oceanography on the Web 371

13

Biological Productivity and Energy Transfer 372

- Key Questions** 372
- Feature: Baseline Studies in the California Current: The CalCOFI Program** 372
- Primary Productivity 373
 - Photosynthetic Productivity* 373 *Availability of Nutrients* 374 *Availability of Solar Radiation* 375 *Margins of the Oceans* 375
 - Light Transmission in Ocean Water* 376
 - Photosynthetic Marine Organisms 379
 - Seed-Bearing Plants (Spermatophyta)* 379
 - Macroscopic (Large) Algae* 380 *Microscopic (Small) Algae* 382
 - Regional Productivity 382
 - Productivity in Polar Oceans* 383
 - Box 13-1 Red Tides: Was Alfred Hitchcock's *The Birds* Based on Fact?** 384
 - Productivity in Tropical Oceans* 384
 - Box 13-2 *Pfiesteria*: A Morphing Peril to Fish and Humans** 386
 - Productivity in Temperate Oceans* 388
 - Energy Flow* 389
 - Energy Flow in Marine Ecosystems* 389
 - Symbiosis* 390
 - Biogeochemical Cycling 391
 - Trophic Levels and Biomass Pyramids 392
 - Trophic Levels* 392 *Transfer Efficiency* 393
 - Biomass Pyramid* 393
 - Ecosystems and Fisheries 394
 - Incidental Catch* 397 *Fisheries Management* 398
 - Students Sometimes Ask...* 398
 - Box 13-3 A Case Study in Fisheries Mismanagement: The Peruvian Anchoveta Fishery** 399
 - Chapter in Review 401
 - Key Terms 402
 - Questions and Exercises 403
 - References 404
 - Suggested Reading in Scientific American* 404
 - Oceanography on the Web 405

14

Animals of the Pelagic Environment 406

- Key Questions** 406
- Feature: Alexander Agassiz: Advancements in Ocean Sampling** 406
- Staying above the Ocean Floor 407
 - Gas Containers* 407 *Floating Organisms (Zooplankton)* 408 *Swimming Organisms (Nekton)* 412
 - Adaptations for Seeking Prey 415
 - Lungers versus Cruisers* 415 *Speed and Body Size* 416
 - Box 14-1 Some Myths (and Facts) About Sharks** 417
 - Cold-Blooded Versus Warm-Blooded* 418
 - Circulatory System Modifications* 418
 - Adaptations to Avoid Being Prey 418
 - Schooling* 418
 - Marine Mammals 420
 - Order Carnivora* 420 *Order Sirenia* 421
 - Order Cetacea* 422 *An Example of Migration: Gray Whales* 430
 - Box 14-2 Killer Whales: A Reputation Deserved?** 431
 - Students Sometimes Ask...* 432
 - Chapter in Review 434

Key Terms	435
Questions and Exercises	435
References	436
<i>Suggested Reading in Scientific American</i> 437	
Oceanography on the Web 437	

15

Animals of the Benthic Environment 438

Key Questions 438

Feature: The Great Debate on Life in the Deep Ocean: The Rosses and Edward Forbes 438

Rocky Shores	439
<i>Spray (Supralittoral) Zone</i> 439 <i>High Tide Zone</i> 440	
<i>Middle Tide Zone</i> 440 <i>Low Tide Zone</i> 441	
Sediment-Covered Shores	446
<i>The Sediment</i> 446 <i>Intertidal Zonation</i> 446	
<i>Life in the Sediment</i> 446 <i>Sandy Beaches</i> 447	
<i>Mud Flats</i> 449	
Shallow Offshore Ocean Floor	450
<i>Rocky Bottoms (Sublittoral)</i> 450 <i>Coral Reefs</i> 452	
Box 15-1	How White I Am: Coral Bleaching and Other Diseases
454	
<i>The Deep-Ocean Floor</i> 458 <i>The Physical Environment</i> 458 <i>Food Sources and Species Diversity</i> 459 <i>Deep-Sea Hydrothermal Vent Biocommunities</i> 459	
Box 15-2	How Long Would Your Remains Remain on the Sea Floor?
460	

Low Temperature Seep Biocommunities 464

Students Sometimes Ask... 466

Chapter in Review 468

Key Terms

Questions and Exercises

References

Suggested Reading in Scientific American 470

Oceanography on the Web 470

Afterword 471

Marine Sanctuaries and Marine Reserves 471

What Can I Do? 471

Appendices 473

I	Metric and English Units Compared	473
II	Geographic Locations	476
III	Latitude and Longitude on Earth	478
IV	A Chemical Background: Why Water Has 2 H's and 1 O	481
V	Careers in Oceanography	485

Glossary 489

Credits and Acknowledgments 510

Index 514