INTERNATIONAL GEOPHYSICS SERIES . VOLUME 30

Atmosphere-Ocean Dynamics

Adrian E. Gill

16 2) 26 93 INSTITUT FÜR METEOROLOGIE U. KLIMATOLOGIE UNIVERSITÄT HANNOVER HERRENHÄUSER STR. 2 · 3000 HANNOVER 21

Atmosphere-Ocean Dynamics

ADRIAN E. GILL

Department of Applied Mathematics and Theoretical Physics University of Cambridge Cambridge, England



ACADEMIC PRESS

A Subsidiary of Harcourt Brace Jovanovich, Publishers

Paris San Diego San Francisco São Paulo Sydney Tokyo Toronto

Contents

хi

Acknow	vledgments		XV
Chapt	er One How the Ocean-Atmosphere System Is Driven		
1.1	Introduction		1
1.2	The Amount of Energy Received by the Earth		2
1.3	Radiative Equilibrium Models		7
1.4	The Greenhouse Effect		8
1.5	Effects of Convection		10
1.6	Effects of Horizontal Gradients		13
1.7	Variability in Radiative Driving of the Earth		15
Chapt	er Two Transfer of Properties between Atmosphere and Ocean		
2.1	Introduction		19
2.2	Contrasts in Properties of Ocean and Atmosphere		20
2.3	Momentum Transfer between Air and Sea, and the Atmosphere's Angular		
	Momentum Balance		22
2.4	Dependence of Exchange Rates on Air-Sea Velocity, Temperature,		
	and Humidity Differences		26
2.5	The Hydrological Cycle		31
2.6	The Heat Balance of the Ocean		33
2.7	Surface Density Changes and the Thermohaline Circulation of the Ocean		36
			*/

Preface

Chapter Three Properties of a Flu
--

3.1	The Equation of State	39
3.2	Thermodynamic Variables	41
3.3	Values of Thermodynamic Quantities for the Ocean and Atmosphere	43
3.4	Phase Changes	44
3.5	Balance of Forces in a Fluid at Rest	45
3.6	Static Stability	50
3.7	Quantities Associated with Stability	51
3.8	Stability of a Saturated Atmosphere	55
3.9	Graphical Representation of Vertical Soundings	58
Chapt	ter Four Equations Satisfied by a Moving Fluid	
4.1	Properties of a Material Element	63
4.2	Mass Conservation Equation	64
4.3 4.4	Balance for a Scalar Quantity like Salinity The Internal Energy (or Heat) Equation	66 70
4.5	The Equation of Motion	70 72
4.6	Mechanical Energy Equation	76
4.7	Total Energy Equation	79
4.8	Bernoulli's Equation	82
4.9	Systematic Effects of Diffusion	83
4.10	Summary List of the Governing Equations	84
4.11	Boundary Conditions	85
4.12	A Coordinate System for Planetary Scale Motions	91
Chapt	ter Five Adjustment under Gravity in a Nonrotating System	
5.1	Introduction: Adjustment to Equilibrium	95
5.2	Perturbations from the Rest State for a Homogenous Inviscid Fluid	99
5.3	Surface Gravity Waves	101
5.4	Dispersion	104
5.5	Short-Wave and Long-Wave Approximations	106
5.6	Shallow-Water Equations Derived Using the Hydrostatic Approximation	107
5.7	Energetics of Shallow-Water Motion	111
5.8	Seiches and Tides in Channels and Gulfs	112
Chapt	ter Six Adjustment under Gravity of a Density-Stratified Fluid	
6.1	Introduction	117
6.2	The Case of Two Superposed Fluids of Different Density	119
6.3	The Baroclinic Mode and the Rigid Lid Approximation	127
6.4	Adjustments within a Continuously Stratified Incompressible Fluid	128
6.5	Internal Gravity Waves	131
6.6	Dispersion Effects	134

Conten	ts	vii
6.7	Energetics of Internal Waves	139
6.8	Internal Waves Generated at a Horizontal Boundary	142
6.9	Effects on Boundary-Generated Waves of Variations of Buoyancy Frequency	
	with Height	146
6.10	Free Waves in the Presence of Boundaries	153
6.11	Waves of Large Horizontal Scale: Normal Modes	159
6.12	An Example of Adjustment to Equilibrium in a Stratified Fluid	162
6.13	Resolution into Normal Modes for the Ocean	167
6.14	Adjustment to Equilibrium in a Stratified Compressible Fluid	169
6.15	Examples of Adjustment in a Compressible Atmosphere	175
6.16 6.17	Weak Dispersion of a Pulse Isobaric Coordinates	177
6.18		180
0.16	The Vertically Integrated Perturbation Energy Equation in Isobaric Coordinates	186
Chant	ter Seven Effects of Rotation	
Спарі	el Severi Ellects di Rotation	
7.1	Introduction	189
7.2	The Rossby Adjustment Problem	191
7.3	The Transients	196
7.4	Applicability to the Rotating Earth	204
7.5	The Rossby Radius of Deformation	205
7.6	The Geostrophic Balance	208
7.7	Relative Geostrophic Currents: The Thermal Wind	215
7.8	Available Potential Energy	219
7.9	Circulation and Vorticity	226
7.10	Conservation of Potential Vorticity for a Shallow Homogeneous Layer	231
7.11 7.12	Circulation in a Stratified Fluid and Ertel's Potential Vorticity Perturbation Forms of the Vorticity Equations in a Uniformly Rotating Fluid	237
7.12	Initialization of Fields for Numerical Prediction Schemes	241 243
Chapt	er Eight Gravity Waves in a Rotating Fluid	
8.1	Introduction	247
8.2	Effect of Rotation on Surface Gravity Waves: Poincaré Waves	249
8.3	Dispersion Properties and Energetics of Poincaré Waves	254
8.4	Vertically Propagating Internal Waves in a Rotating Fluid	256
8.5	Polarization Relations	262
8.6	Energetics	266
8.7	Waves Generated at a Horizontal Boundary	268
8.8	Mountain Waves	274
8.9	Effects of Variation of Properties with Height	283
8.10 8.11	Finite-Amplitude Topographic Effects Discipative Effects in the Union Atmosphere	292
8.11	Dissipative Effects in the Upper Atmosphere The Liouville-Green or WKBJ Approximation	294
8.13	Wave Interactions	297 302
8.14	The Internal Wave Spectrum in the Ocean	302
8.15	Wave Transport and Effects on the Mean Flow	309
8.16	Quasi-geostrophic Flow (f Plane): The Isallobaric Wind	311

111			

Contents

Chapt	er Nine Forced Motion	
9.1	Introduction	317
9.2	Forcing Due to Surface Stress: Ekman Transport	319
9.3	Wind-Generated Inertial Oscillations in the Ocean Mixed Layer	322
9.4	Ekman Pumping	326
9.5	Bottom Friction: Velocity Structure of the Boundary Layer	328
9.6	The Laminar Ekman Layer	331
9.7	The Nocturnal Jet	332
9.8	Tide-Producing Forces	334
9.9	Effect of Atmospheric Pressure Variations and Wind on Barotropic Motion	337
0.10	in the Sea: The Forced Shallow-Water Equation	342
9.10 9.11	Baroclinic Response of the Ocean to Wind Forcing: Use of Normal Modes Response of the Ocean to a Moving Storm or Hurricane	346
	Spin-Down by Bottom Friction	353
9.12 9.13	Buoyancy Forcing	356
	Response to Stationary Forcing: A Barotropic Example	360
	A Forced Baroclinic Vortex	362
	Equilibration through Dissipative Effects	367
Chapt	er Ten Effects of Side Boundaries	
10.1	Introduction	371
10.2	Effects of Rotation on Seiches and Tides in Narrow Channels and Gulfs	373
10.3	Poincaré Waves in a Uniform Channel of Arbitrary Width	376
10.4	Kelvin Waves	378
10.5	The Full Set of Modes for an Infinite Channel of Uniform Width	380
10.6	End Effects: Seiches and Tides in a Gulf That Is Not Narrow	382
10.7	Adjustment to Equilibrium in a Channel	385
10.8	Tides	391
10.9	Storm Surges on an Open Coastline: The Local Solution	394 398
10.10	Surges Moving along the Coast: Forced Kelvin Waves	403
10.11 10.12	Coastal Upwelling Continental Shelf Waves	408
10.12	Coastally Trapped Waves	415
10.13	Eastern Boundary Currents	421
Chapt	er Eleven The Tropics	
11.1	Introduction	429
11.2	Effects of Earth's Curvature: Shallow-Water Equations on the Sphere	431
11.3	Potential Vorticity for a Shallow Homogeneous Layer	433
11.4	The Equatorial Beta Plane	434
11.5	The Equatorial Kelvin Wave	436
11.6	Other Equatorially Trapped Waves	438
11.7	The Equatorial Waveguide: Gravity Waves	440
11.8	Planetary Waves and Quasi-geostrophic Motion	444
11.9	Baroclinic Motion near the Equator	449
11.10	Vertically Propagating Equatorial Waves	450
11.11	Adjustment under Gravity near the Equator	454

Conten	ts	ix
11.12	Transient Forced Motion	458
11.13		465
11.14		466
11.15	The Tropical Circulation of the Atmosphere	472
11.16	Tropical Ocean Currents	482
Chapt	er Twelve Mid-latitudes	
12.1	Introduction	493
12.2	The Mid-latitude Beta Plane	494
12.3	Planetary Waves	500
12.4	Spin-Up of the Ocean by an Applied Wind Stress	507
12.5	Steady Ocean Circulation	512
12.6	Western Boundary Currents	516
12.7	Vertical Propagation of Planetary Waves in a Medium at Rest	523
12.8	Nonlinear Quasi-geostrophic Flow in Three Dimensions	527
12.9	Small Disturbances on a Zonal Flow Varying with Latitude and Height	532
12.10	Deductions about Vertical Motion from the Quasi-geostrophic Equations	543
Chapt	er Thirteen Instabilities, Fronts, and the General Circulation	
13.1	Introduction	549
13.2	Free Waves in the Presence of a Horizontal Temperature Gradient	550
13.3	Baroclinic Instability: The Eady Problem	556
13.4	Baroclinic Instability: The Charney Problem	560
13.5	Necessary Conditions for Instability	563
13.6	Barotropic Instability	565
13.7	Eddies in the Ocean	568
13.8	Fronts The Life Cycle of a Paraelinia Disturbance	571 578
13.9 13.10	The Life Cycle of a Baroclinic Disturbance General Circulation of the Atmosphere	582
Apper	ndix One Units and Their SI Equivalents	595
Арреі	ndix Two Useful Values	597
Арреі	ndix Three Properties of Seawater	
A3.1	The Equation of State	599
A3.2	Other Quantities Related to Density	600
A3.3	Expansion Coefficients	601
A3.4	Specific Heat	601
A3.5	Potential Temperature	602
A3.6	Speed of Sound	602
A3.7	Freezing Point of Seawater	602

Index

-				
Co	n	to	n	to

645

Appendix roal Troperties of Moist Air	Appendix Four	Properties	of	Moist	Air
---------------------------------------	---------------	-------------------	----	-------	-----

Appendix Four Froperties of Moist Air	
 A4.1 Methods of Specifying Moisture Content A4.2 Saturation Vapor Pressure A4.3 Further Quantities Related to Moisture Content A4.4 Latent Heats A4.5 Lapse Rates 	605 606 606 607 607
Appendix Five A List of Atlases and Data Sources	609
References	613