Kolumban Hutter • Yongqi Wang Irina P. Chubarenko

Physics of Lakes

Volume 2: Lakes as Oscillators



18529 1866-8348 137819 978-3-642-19[15:4 DOI 10.1007/978-3-642-1

1107 Jackinst Johnen standurer in Annie-

The work is unject to converges AB dense are reserved, whether the whole or part of the material concerned, specifically the rights of transitions, audithing rense of illustration, maintened, the reproduction on materiality or any other way and starging to data here. Unplication of the path, and of parts shared is particulated only ander the providence of the Occurs Constellar Law of September 1995. 1965, in the correct version, and perturbation of the Occurs Constellar Law of September 1995. The unit of general descriptive starts (opticipation of the Occurs Constellar Law of September 1995). The unit of general descriptive starts (opticipation and starts), and the publication does the height, even in the startage of a specific another spectration of the the starts of the starts of the height, even in the startages of a specific attention and the starts are starting from the height, even in the startages of a specific starts on the starts are starting to the path of the start from and regulations and the starts are the general me.

D Springer

Contents

11	The F	Role of the Earth's Rotation: Fundamentals –					
	Dyna	mics	1				
	11.1	Estimations by Dimensional Reasoning	1				
		11.1.1 Tributary Affected Advection	2				
		11.1.2 Wind-Induced Circulation	3				
		11.1.3 Barotropic and Baroclinic Wave Dynamics	4				
	11.2	Rotation Influenced Shallow Water Waves	6				
	11.3	A Brief Classification of Rossby Waves	13				
	11.4	Plane Linear Waves in a Rotating Stratified Fluid	19				
		11.4.1 Waves in a Linearly Stratified Rotating					
		Unbounded Boussinesg Fluid	20				
		11.4.2 Waves in a Stably Stratified Shallow Layer					
		of a Boussinesg Fluid	28				
		11.4.3 The Two-Layer Model	39				
	11.5 Concluding Discussion						
	Refere	ences	48				
12	The I	Role of the Earth's Rotation: Oscillations					
	in Ser	ni-bounded and Bounded Basins of Constant Depth	49				
	12.1	Motivation	49				
	12.2	Kelvin Waves	50				
		12.2.1 Pseudo-Standing Kelvin Waves	55				
		12.2.2 Baroclinic Kelvin Waves	58				
	12.3	Inertial Waves	60				
	12.4	4 Poincaré Waves					
	12.5	5 Reflection from the End of a Channel Wall					
	12.6	Shallow Water Waves in a Rectangle of Constant Depth	73				
		12.6.1 Frequency Relation	77				
		12.6.2 Modal Structure	81				
		12.6.3 Additional Results	85				

1

	12.7	A 'Second-Class' of Inertial Wayes: 'Inertial Wayes Proper' 87						
		12.7.1 Governing Equations 88						
		12.7.2 Plane Inertial Sverdrup (Poincaré) Waves 01						
		12.7.3 Inertial Kelvin Waves						
		12.7.4 Inertial Poincaré Wayes in a Channel 04						
		12.7.5 Inertial Poincaré Channel Wayes Reflecting						
		from a Vertical Wall						
		12.7.6 Inertial Wayes in Rectangular Basin						
		of Constant Depth						
		12.7.7 Discussion						
	12.8	Concluding Discussion						
	12.9	Appendix: Solution Scheme of Proudman–Rao to Solve (12.1) 104						
	Refere	ences						
12	Dagin	Soulo Capatita Worses in Circular and Filitatian						
15	Conta	iners on the Bototing Forth						
	13.1	Metivation 115						
	13.1	Concentual Prerequisites						
	13.2	Circular Cylindrical Geometry						
	13.0	Three Lover Stratification Loka Kinneret Treated						
	13.4	as a Circular Cylinder of Constant Depth 122						
	13.5	as a Circular Cylinder of Constant Depth						
	13.5	Mathieu Functions						
	13.0	Filiptical Pasin: Normal Mode Analysis						
	13.7	Empirical Basin, Normal Mode Analysis						
	13.0	Discussion 151						
	15.9 Refere	Discussion						
	KCICIC	inces						
14	Barot	ropic and Baroclinic Basin-Scale Wave Dynamics						
	Affect	ed by the Rotation of the Earth155						
	14.1	Introduction155						
	14.2	Barotropic Basin-Wide Oscillations of Lake Michigan157						
	14.3	Internal Seiche Dynamics in Lake Geneva164						
		14.3.1 Introduction164						
		14.3.2 Lake Morphology and Data Handling165						
		14.3.3 Model Equations166						
		14.3.4 Modal Analysis for the TEDM168						
		14.3.5 Modal Analysis for the TCDM172						
		14.3.6 Internal Wave Dynamics Revealed						
		by Surface Level Data173						
	14.4	Transverse Internal Wave Motion in Lake Überlingen						
		14.4.1 Statement of the Problem						
		14.4.2 Observations During the						
		Bodensee-Experiment 1972179						
		14.4.3 Numerical Solution for the TVD Model						
		with Realistic Bottom Topography						

Contents

14.5	Lake Biwa
14.6	Concluding Discussion
Refere	ences

li

15	Higher	-Order Baroclinicity (I): Two Fluid Layers	107					
	with D	iffuse Interface – Three Fluid Layers with Sharp Interfaces.	197					
	15.1	Motivation and Review	197					
	A. Lab	oratory Experiments on Baroclinic Solitary Waves						
		in a Two-Layer Fluid System with Diffusive Interface	199					
	15.2	Experimental Set-Up and Wave Generation	199					
		15.2.1 The Wave Channel	199					
		15.2.2 Solitary Wave Generation and Measuring Technique	199					
		15.2.3 Error Estimation	202					
	15.3	The Experiments	202					
	10.0	15.3.1 Typical Experimental Data	203					
		15.3.2 Results	208					
	15.4	Analytical Models for the Evolution of Baroclinic Waves	212					
	15.4	15.4.1 Equations	212					
		15.4.2 Baroclinic modes for a two-layer system						
		vith diffuse interface	216					
		15.4.3 Pesults of the Numerical Modeling	219					
	D The	13.4.5 Results of the North Basin of the Lake of Lugano	224					
	B. Infee-Layer Woodel of the North Danity Structure of the North							
	15.5	Basin of Lake of Lugano						
	151	Linear Ways Dunamics of the Three Layer Model 229						
	15.0	Linear wave Dynamics of the Thee-Eaver Woder	233					
	15.7	Computational Results and Their Comparison with Tield Data	234					
		15.7.1 Mode 1	240					
		15.7.2 Mode 2	242					
		15.7.3 Mode 3	244					
		15.7.4 Modes 4 and 5	245					
	15.8	Model Sensitivity	245					
	15.9	Inferences	240					
	15.10	Summary						
	Refere	ences	248					
16	Highe	er-Order Baroclinicity (II): Interpretation of Lake						
	Data	with Rotating and Non-rotating Models	251					
	16.1	V2-Vertical Mode of the Internal Seiche in Lake Alpnach	252					
		16.1.1 Observations	253					
		16.1.2 Seiche Analysis	254					
	16.2	Internal Seiche Climate in Lake Banyoles, Catalonia (Spain)	258					
		16.2.1 Description of the Site	259					
		16.2.2 Methods of Computation and Data Analysis	260					
		16.2.3 Results	261					

lii

Con	iant	10
COII	len	LS.

Contents

 ۰.	٠	

	16.3	Internal Wave Weather in Stratified Lake Biwa	19	Topog	raphic V	Vaves in Enclosed Basins: Fundamentals
		16.3.1 Methodology and Overview of Field Results		and O	bservatio	ons
	16.4	Basin-Scale Wave Motion in Lake Constance		19.1	Review	of Early Work
		16.4.1 Morphology and Methodology		19.2	Some C	Observations and Proposed Interpretations
		16.4.2 Interpretation of the Observations			19.2.1	Lake Michigan
	16.5	Closing Remarks			19.2.2	Lake of Lugano (North Basin)
	Refere	ences			19.2.3	Other Lakes and Ocean Basins
				19.3	Barocli	nic Coupling: The Two-Layer Model
17	Barot	ropic Oscillations in Lake Onega: A Lake			19.3.1	Two-Layer-Equations
	of Con	mplex Geometry			19.3.2	Approximations
	17.1	Lake Morphology and First Interpretations			19.3.3	Scale Analysis
		of Water Level Measurements			19.3.4	Boundary Conditions
	17.2	Measured Water-Level Fluctuations and Water		19.4	Continu	uous Stratification
		Currents at Isolated Points			19.4.1	Modal Equations
	17.3	The Barotropic Eigenvalue Problem			19.4.2	Spectral Decomposition of the Baroclinic Fields
	17.4	Numerical Results and Their Comparison with Observations 298			19.4.3	Scale Analysis
	17.5	Concluding Remarks		19.5	Discus	sion
	17.6	Appendix: The Lanczos' Procedure in Solving		Refere	ences	
		Symmetric Eigenvalue Problems 309				
	Refere	ences	20	Topos	graphic H	Rossby Waves in Basins of Simple Geometry
		The Contract Contractory of the Contractory of the Providence	50	20.1	Motiva	tion
18	Obser	vation and Analysis of Internal Seiches		20.2	Topogi	aphic Wave Equation in Curvilinear
	in the	Southern Basin of Lake of Lugano			Orthog	onal Coordinate Systems
	18.1	Introductory Remarks, Lake Morphology			20.2.1	Preparation
	18.2	State of Stratification and Wind Forces: 15 August-15			20.2.2	Cylindrical Coordinates
		October 1984			20.2.3	Elliptical Coordinates
	18.3	Internal Seiche Response: Variation in Isotherm			20.2.4	Natural Coordinates
		Depth and Wind Stress			20.2.5	Cartesian-Coordinate Correspondence Principle
		18.3.1 Internal Oscillations 25 August–5 September 324		20.3	An Alı	manac of Analytical Solutions
		18.3.2 Internal Oscillations 7–30 September 326			20.3.1	Circular Basin with Parabolic Bottom
		18.3.3 Internal Seiche After 3 October			20.3.2	Circular Basin with a Power-Law Bottom Profile
		18.3.4 Harmonic Analysis			20.3.3	Elliptic Basin with Parabolic Bottom
	18.4	Model Predictions: The Two-Lavered			20.3.4	Elliptic Basin with Exponential Bottom
		Variable-Depth Model 333			20.3.5	Topographic Vorticity Waves in Infinite Domains
	18.5	Current Structure of the Internal Seiches 344			20.3.6	Elliptic Island in Infinite Space
	18.6	Closing Remarks		20.4	Applic	cation of Transformation Principles
		18.6.1 Observed Features Not Reproduced			20.4.1	Hyperbolically Curved Channels
		by the TVD-Model 348			20.4.2	Semi-Infinite Gulf and Patched-Up
		18.6.2 A Remark on the Generation of Topographic Wayes 349				Elongated Basins
		18.6.3 Barotropic–Baroclinic Coupling		20.5	Discus	ssion
		of the North- and South Basin 351		Refe	rences	
	Refere	ences		Refer	encosti	- 22.2.1 Houromener Lakes

and O	beorgations	
10.1	Daviou of Early	Work
19.1	Some Observat	ions and Proposed Interpretations
19.2	10.2.1 Laka	Aichigan
	19.2.1 Lake N	f Lugano (North Basin)
	19.2.2 Lake 0	Lakes and Ocean Basins
10.2	Parcolinia Cou	pling: The Two-I aver Model
19.5	10.2.1 Two I	aver-Equations
	19.3.1 Iwo-L	ximations
	19.3.2 Applo	Analysis
	19.3.5 Scale 1	ary Conditions
10.4	Continuous Str	atification
19.4	10.4.1 Model	Equations
	19.4.1 Widda	al Decomposition of the Baroclinic Fields
	19.4.2 Specu	Analysis
10.5	Disquesion	
19.5 Defen	Discussion	
Refere	ences	
Tanas	manhia Docchy	Wayas in Basins of Simple Geometry
10pog	Motivation	waves in basins of Shiple Geometry
20.1	Topographic V	Jove Equation in Curvilinear
20.2	Orthogonal Co	ordinate Systems
	20.2.1 Prepa	ration
	20.2.1 Fiepa	drical Coordinates
	20.2.2 Cyllin	incal Coordinates
	20.2.5 Empt	al Coordinates
	20.2.4 Natur	ai Coordinate Correspondence Principle 407
20.2	20.2.5 Cartes	f Analytical Solutions 407
20.3	An Almanac o	I Analytical Solutions
	20.3.1 Circu	lar Basin with a Power I aw Bottom Profile 411
	20.3.2 Circu	a Dasin with Parabolic Bottom 413
	20.3.3 Empt	ic Dasin with Exponential Bottom 417
	20.3.4 Empt	rearbie Verticity Wayes in Infinite Domains 425
	20.3.5 Topo	is Island in Infinite Space 432
20.4	20.3.6 Empl	Transformation Principles 434
20.4	Application of	realizably Curved Channels 434
	20.4.1 Hype	Infinite Culf and Databad Up
	20.4.2 Semi	Alter and Fached-Op
	Elong	aleu Dasilis
20.5	Discussion	
Refer	ences	

liv

21	Topog	graphic Waves in Basins with Complex Shapes						
	and C	Complex Bathymetries						
	21.1	Conceptual Review447						
	21.2	The Method of Weighted Residuals						
		21.2.1 The Method of Weighted Residuals Applied						
		to Topographic Waves448						
		21.2.2 Symmetrisation						
	21.3	Topographic Waves in Infinite Channels454						
		21.3.1 Basic Concept						
		21.3.2 Dispersion Relation						
		21.3.3 Channel Solutions						
	21.4	Topographic Waves in Rectangular Basins						
		21.4.1 Crude Lake Models						
		21.4.2 The Role of the Aspect Ratio						
		21.4.3 Lake Model with Non-constant Depth Along						
		Its Thalweg						
		21.4.4 Current Patterns						
	21.5	Curved Channels						
		21.5.1 The Method of Weighted Residuals						
		for Lakes with Curved Thalwegs						
		21.5.2 Dispersion Relation						
		21.5.3 TW-Wave Modes in Wedges of Annuli						
		with Smooth Bathymetry						
	21.6	Reflection of Topographic Waves						
		21.6.1 Reflection at a Vertical Wall						
		21.6.2 Reflection at a Gulf End with Continuous						
		Depth Lines But Discontinuous Slope Parameter						
		21.6.3 Reflection at a Channel End with Continuous						
		Depth Lines and Continuous Slope Parameter						
	21.7 Bay Modes and Resonances							
		21.7.1 The Boundary Value Problem for TWs						
		in a Semi-Infinite Gulf with Exponential Bathymetry513						
		21.7.2 The Flat Channel						
		21.7.3 Channel with Shelf Topography						
	21.8	Concluding Discussion						
	21.9	Appendix						
	Refere	ences						
22	A CL							
22	A Cla	SS of Chrystal-Type Equations						
	22.1	Mouvation						
	22.2	22.2.1 Homographic Labor						
		22.2.1 Homogeneous Lakes						
	22.2	22.2.2 IWo-Layer Channel Model						
	22.3	Extended Channel Models: Governing Equations						
	22.4	Method of Weighted Residuals						

				. 4		
-	e	 12	e	11	2.	
	۰.	м			э.	

22.5	Derivati	on of a Hierarchy of Channel Equations
haland	for Barc	stropic Motions in Lakes
	22.5.1	Mass Balance
	22.5.2	Momentum Balance
	22.5.3	Summary
22.6	Low-Or	der Channel Models for Curved Rotating
22.0	Elongat	ed Lakes
	22.6.1	Non-rotating Basins
	22.6.2	A First-Order Model Accounting for the
		Rotation of the Earth
22.7	Gravity	Wayes in Channels and Lakes of Rectangular
	Cross S	ection on the Rotating Earth
	22.7.1	Free Oscillations in a Non-rotating Rectangle
	22.7.2	Kelvin-Type Waves in an Infinitely Long
		Rectangular Straight Canal
	22.7.3	Wave Solutions of the Full First-Order
		System: Poincaré-Like Waves
	22.7.4	Reflection of Kelvin-Type Waves at a Barrier
		of a Half-Open Rectangular Canal and Free
		Oscillations in Rectangles
22.8	Ring-S	haped Basins with Constant Depth
	22.8.1	Solutions of the Two-Dimensional Tidal Equation600
	22.8.2	First-Order Channel Model603
22.9	Higher	Order Chrystal-Type Models Applied to Free
	Oscilla	tions in Natural Basins608
	22.9.1	The Nth Order Two-Point Boundary-Value
		Problem for Barotropic Forced or Free Oscillations608
	22.9.2	Integration Procedure612
	22.9.3	Barotropic Seiches of the Northern Basin
		of Lake of Lugano614
Appe	ndix 22.A	
Appe	ndix 22.E	3
Refe	rences	
Name Ind	lex	
Labo Ind		
Lake Ind	ex	
Subject I	ndov	
Subject I	IIUCA	

lv