BAROCLINIC TIDES

Theoretical Modeling and Observational Evidence

Internal waves are water motions originating from density variations within the water body in which they propagate. When an oceanic tidal wave that is primarily active on the water surface impinges on the ocean shelf or passes a region with a seamount, this wave is modified by the topographic disruption. It is split into a less energetic surface wave and other internal modes with different wavelengths and propagation speeds. This cascading process, from the barotropic tides to the baroclinic components, eventually leads to the transformation of tidal energy into turbulence and heat. This is an important process for the dynamics of the lower ocean.

BAROCLINIC TIDES demonstrates how analytical and numerical methods can be used to study the generation and evolution of baroclinic tides and, by comparison with experiments and observational data, shows how internal waves can be distinguished and interpreted. Particular attention is paid to the investigation of strongly nonlinear solitary internal waves, which are generated by internal tidal waves at the final stage of their evolution. This book is intended for researchers and graduate students of physical oceanography, geophysical fluid dynamics, and hydroacoustics.

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To our parents

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Preface

The scientific literature on baroclinic tides in the ocean is as abundant as is the general mathematical theory of internal gravity waves. The majority of research papers on this topic written since the late 1970s deal mainly with the attempts to provide a theoretical description of the vast number of experimental data obtained on the dynamics of baroclinic tides. Various analytical and semianalytical models were developed for the case of infinitesimal waves when the external tidal forcing is negligible. However, observations show that strong nonlinear baroclinic tides are the more common phenomena; they demand not only theoretical but also numerical methods to describe the wave processes adequately.

The idea of the book is to present the theoretical basis of baroclinic tides at all stages of their genesis and evolution (generation, transformation, dissipation), and to give, by comparison with experiments, advice and help regarding the theoretical interpretation and prognosis of baroclinic tides. Such an exhaustive and complete theoretical review does not exist at present, nor is there a scientific book which describes this phenomenon multilaterally. So we are intending to fill this gap.

A second reason for writing a book on this topic is to gather in one place our experience, which extends over more than 20 years, in investigating internal waves in general and baroclinic tides in particular. This includes the development of different linear and nonlinear mathematical models of internal tidal motions and the application of these to concrete oceanic situations. In so doing, we will report not only on our own research, but also on many other publications on the studied topic and subject them to a careful analysis. It is impossible to mention thousands of papers published on baroclinic tides, so our list of references is not exhaustive. We apologize to those colleagues whose references are not quoted.

This book is the outgrowth of our common research activity on the internal dynamics of the ocean and of lakes, in particular as exhibited by waves; this subject has been studied separately by Kolumban Hutter since the mid 1970s in Lakes Zurich, Lugano, and Constance, and by Vasiliy Vlasenko and Nataliya Stashchuk in the World Ocean since 1980. A lucky break brought us together in 1999 to work on research projects funded by the Deutsche Forschungsgemeinschaft on the propagation of waves in stratified rotating basins. Some topics in the present book are the direct result of our joint investigations. The research cooperation was so constructive and our achievements were so fruitful that after three years of collaboration we decided to summarize our work in a book. Vasiliy Vlasenko and Nataliya Stashchuk, who were the active researchers and less occupied by administrative duties, took on the burden of designing the first skeleton of the book's outline; they also were the sole writers of the first drafts of all the chapters. The role of Kolumban Hutter was to act as *advocatus diaboli* and to read, criticize and revise the various versions of the individual chapters. This process went back and forth at least three, more likely five, times. During approximately two years of writing, we learned to appreciate one another, and we now present a book that is a joint effort in which the first two authors carried the heavier burden than the third, but which all three of us agree with. We hope the product is fairly free from misconceptions and professional errors. However, we must ask the reader to bear with our English wording, a mixture of what two Ukrainians and a Swiss with their school English have tried to do. If the English is good, it is due to the copy-editorial staff of Cambridge University Press.

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Work on this book was started at the Darmstadt University of Technology (Germany) with financial support from the Deutsche Forschungsgemeinschaft, and was continued at a later stage at Plymouth University (UK), although many of the scientific results were obtained in collaboration with colleagues from the Marine Hydrophysical Institute of the National Academy of Science of the Ukraine (Sevastopol). The authors express their gratitude to the co-authors of joint publications, whose valuable contributions made this book possible. Vlasenko and Stashchuk feel deeply indebted to Professor Leonid Cherkesov, who was their first teacher in wave theory. They profited not only from the generous sharing of his ideas and wisdom, but also from his friendship, support, and encouragement.

In the course of the preparation for the book we visited each other, and the hospitality of Plymouth University and Darmstadt University of Technology is gratefully acknowleged. Special thanks are due to the Head of the School of Earth, Ocean and Environmental Sciences, Professor David Huntley, who generously helped and encouraged our efforts.

Most figures included in this book have previously been published by the authors in various scientific journals. We are grateful to copyright holders for granting their permission to reproduce their figures in the text: the American Meteorological Society (Figures 1.1, 1.7, 5.9, 5.10, 5.12–5.19, and 5.27–5.34); Brill Academic Publishers (Figures 3.10, 4.10, 4.11, and 6.18–6.22); Elsevier (Figures 2.22, 4.9, 4.14, 4.15, 4.21, 6.1–6.10, and 7.1–7.14); the European Geophysical Union (Figures 5.20–5.26 and 5.35–5.46); MAIK “Nauka/Interperiodica” (Figures 4.1–4.5, 4.7, 4.8, 4.16–4.18, 5.2, and 6.23–6.26); Nauka (Figures 2.6, 2.7, 3.1–3.3, 4.12, 4.15, 5.5, 5.6, and 6.14–6.17); and Transworld Research Network (Figures 2.3, 2.4, 2.6, 2.7, 2.21, 4.19, and 4.20).

We also acknowledge the work of three anonymous reviewers who took the time to read the manuscript and who have made many fruitful comments on the improvement of the book's contents. Finally, we thank the staff of Cambridge University Press for their fruitful cooperation and attention to detail through the various stages of the publishing process.

Symbols

$A^{\mathrm{H}}, A^{\mathrm{V}}$	coefficients of horizontal and vertical turbulent viscosity
$A(x, t)$	profile of internal wave used in a weakly nonlinear theory
a_j	amplitude of stream function of jth mode generated in zone III
a_ξ	amplitude of vertical isopycnal displacement of solitary internal wave
$a_\xi^{(j)} = \dfrac{a_j k_j}{\sigma}$	amplitude of isopycnal displacement of jth mode generated in zone III
a_m^{inc}	amplitude of stream function of incoming mth mode in zone I
b_j	amplitude of stream function of jth mode generated in zone I
$b_\xi^{(j)} = \dfrac{b_j k_j}{\sigma}$	amplitude of isopycnal displacement of jth mode generated in zone I
c_1, c_2, c_3	coefficients of the model pycnocline
c_{p}	phase speed
c_{g}	group speed
$f = 2\Omega_{\mathrm{E}} \sin\varphi$	Coriolis parameter
g	acceleration due to gravity
$\mathcal{G}$	Green function

H	depth of ocean
H_0	average depth of ocean
$H_{\max}$	height of bottom obstacle
H_1, $H_2(x)$, H_3	water depth in zones I, II, and III, respectively
H_{p}, ΔH_{p}	depth and width of the model pycnocline
h_+, h_-	thickness of upper and lower layers in two-layer model
$h = z_1(-H)$	water depth in (x, z_1) variables
$h_0 = z_1(-H_0)$	average depth of a basin in (x, z_1) variables
$h_1 = z_1(-H_1)$, $h_2(x) = z_1(-H_2(x))$, $h_3 = z_1(-H_3)$	water depth in zones I, II, III in (x, z_1) variables
$h_{\max}$	height of bottom obstacle in (x, z_1) variables
$\mathscr{X} = x + z_1$	characteristic line
$J(a, b) = a_x b_z - a_z b_x$	Jacobian operator
K^{H}, K^{V}	coefficients of horizontal and vertical turbulent diffusivity
k_{1j}, k_{3j}	wave number of jth baroclinic mode in areas I and III, respectively
l	half-width of bottom obstacle
$\mathscr{Z} = x - z_1$	characteristic line
$M = \dfrac{g}{\rho_0}\dfrac{\partial\rho}{\partial x}$	horizontal analog of buoyancy frequency
m	number of incident baroclinic mode
$N = \left(-\dfrac{g}{\rho_0}\dfrac{\partial\rho_0}{\partial z}\right)^{1/2}$	buoyancy frequency
N_0	value of buoyancy frequency for monotonic stratification
N_p	maximum value of buoyancy frequency
P	pressure
P_{a}	atmospheric pressure
$\tilde{P}$	wave disturbance of pressure
$q_j(z_1)$	eigenfunction of jth baroclinic mode

$\mathrm{Ri} = N^2/u_z^2$	Richardson number
$\mathcal{R}$	Riemann function
S	salinity
T	temperature
T	tidal period
$T_0 = \lambda/c_\mathrm{p}$	time scale for solitary internal waves
t_0	reference time
t_b	instant of wave breaking
U_0	amplitude of barotropic tidal velocity
u	component of velocity vector **v** in x-direction
u_+, u_-	velocities of upper and lower layer, respectively, in x-direction in two-layer model
v	component of velocity vector **v** in y-direction
v_+, v_-	velocities of upper and lower layer, respectively, in y-direction in two-layer model
w	component of velocity vector **v** in z-direction
$z_1 = \int_0^z \frac{ds}{\alpha(s)}$	z_1-transformation
$z_2 = \frac{\int_0^z N(s)\,ds}{\int_0^{-H(x)} N(s)\,ds}$	z_2-transformation
$\alpha, \alpha_+, \alpha_-$	slopes of characteristic lines
β	coefficient of dispersion
$\gamma = dH/dx$	bottom inclination
$\gamma_0 = dh/dx$	bottom inclination in $(x_1 z_1)$ variables
$\varepsilon = a_\xi/H$	nondimensional wave amplitude
$\varepsilon_0 = h_{\max}/h_0$	nondimensional height of bottom obstacle
ε_1	parameter of nonlinearity
$\theta = x - c_\mathrm{p}t$	variable in coordinate system moving with speed c_p

λ	wavelength
$\mu = (H/\lambda)^2$	parameter of dispersion
ξ	vertical isopycnal displacement
ξ_+, ξ_-	vertical displacements of free surface and interface, respectively (two-layer model)
ρ	density
$\rho_0(z)$	density in hydrostatic equilibrium
$\tilde{\rho}(x, z, t)$	wave disturbance of density
$\bar{\rho}_0 = \text{const.}$	reference density
ρ_+, ρ_-	densities of upper and lower layers, respectively (two-layer model)
σ	wave frequency
$\sigma_t = \rho - 1000$	conventional density
φ	latitude
φ_c	critical latitude
ψ, Ψ	stream function
ω	vorticity
Ω_E	angular rotation rate of Earth

Abbreviations

ADCP	acoustic Doppler current profiler
ADIM	alternative direction implicit method
BBL	bottom boundary layer
BSPF	Barents Sea Polar Front
BVP	boundary value problem
CFL	Courant Friedrich Levi
CTD	conductivity, temperature, depth (profiler)
ERS-1, ERS-2	European Remote-Sensing Satellite
GW	gigawatt
JASIN experiment	Joint Air–Sea Interaction Experiment
JUSREX-92	Joint United States–Russian Experiment
K–dV	Korteweg–de Vries
eK–dV	extended Korteweg–de Vries
ODE	ordinary differential equation
POM	Princeton Oceanographic Model
R/V	research vessel
SAR	synthetic aperture radar
SIW	solitary internal wave
TOPEX	Topography Experiment
TOPEX/Poseidon	Joint US–French orbital mission, launched in 1992 to track changes in sea-level height with radar altimeters
TW	terawatt
WKB	Wentzel, Kramers, Brillouin