Oceanic Internal Tides: Observations, Analysis and Modeling

Eugene G. Morozov

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A Global View

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Preface

This book presents the author's study of the properties of internal tides. The experimental data that were used in this research were collected during experiments aimed at studying other physical processes in the ocean, for example the general circulation or mesoscale eddies. To date, special experiments designed to study internal tides have been very rare. Since the horizontal size of mesoscale eddies and internal tide wavelengths have almost the same length, it was possible to interpret the data in light of the phenomena related to internal tides. In the experiments aimed at studying mesoscale eddies, additional instruments were sometimes set on the moorings and additional moorings were deployed with the goal of better understanding of the internal tides.

This book is the result of 50 years of scientific research carried out by the author since 1967. Internal waves are investigated across a wide range of frequencies with special emphasis on internal tides. The research is based on the statistical analysis of temperature and velocity measurements in different regions of the World Ocean. Systematic studies of internal waves presented in Krauss (1966), Miropolsky (2001), Vlasenko et al. (2005), Gerkema and Zimmerman (2008) are generally related to theoretical studies. A summary of the experimental studies is presented in Roberts (1975), Morozov (1985), Konyaev and Sabinin (1992). This book focuses mainly on the experimental studies of internal waves. It is a progressive study of the research presented by Morozov (1985). The data of measurements in the ocean are interpreted in light of the modern concepts and models of oceanic internal waves.

Surface waves are familiar to everybody. Waves similar to surface waves can appear at the density interface between fluids of different density or over the continuous stratification of fluid. If a perturbation displaces the water particles from the state of equilibrium, oscillations will appear under the influence of the buoyancy forces and forces returning the particles to the equilibrium. Since the water particles are interconnected, spatial oscillations will develop, which are known as gravity waves. The density differences within the fluid are smaller than at the surface between water and air; hence, the returning forces are weaker, and the wave periods are longer than the periods of surface waves. In oceanic conditions, the amplitudes of waves can be as large as several tens or even hundreds of meters as reported in early publications (Bockel 1962; Perry and Schimke 1965; Niiler 1968; Osborne and Burch 1980).

The measurements show that internal gravity waves are found everywhere in the ocean where positive density stratification of water exists. Upon the discovery that this phenomenon is global, studies of oceanic internal waves became one of the leading research fields of oceanography in the second half of the twentieth century. Internal waves play an important role in all dynamical processes in the ocean, especially in the energy transfer from the surface to the ocean interior and in the mixing of water layers. Internal waves exist everywhere in the ocean; they are the main mechanism by which wind energy is transferred from the ocean surface to the depths. In addition to the important influence of internal waves on ocean dynamics as a whole, they are important in the practical sense for underwater navigation, marine biology, sedimentation, acoustics, and optics of the ocean.

Cold dense water masses are formed in the polar regions of the Earth and descend to the deep layers in all oceans. The Sun warms only the upper ocean layer. Since the density distribution is generally stationary in the ocean, which is significantly different from two-layer stratification, we can conclude that the existing stratification is a result of the long mixing processes.

Munk and Wunsch (1998) discussed the problem of mixing in the ocean and the formation of the existing stratification. According to their estimates, the flow of Antarctic Bottom Water formed over the continental slope of Antarctica is approximately equal to 25–30 Sv. Approximately one-third of this amount of water flows to the north. Without internal mixing, a layer of warm water would be located in the upper part of the ocean, and cold waters would fill the entire depths of the ocean. According to the estimates of Munk and Wunsch, such a structure could be formed in approximately 3000 years. However, mixing induces an upward buoyancy water flow, and the cold waters mix with the overlying layers. The current estimates of vertical diffusivity in the abyssal depths of the ocean are 10^{-5} m^2/s. This is not sufficient to perform the necessary mixing. Hence, "hot points" of mixing exist, in which the vertical diffusivity is much greater, and intense mixing occurs exactly at these points. Such regions are characterized by sharp changes in the bottom topography: submarine ridges, continental slopes, seamounts, and abyssal channels and fractures.

Mixing in the ocean is generally determined by the energy transferred from wind and tides. The role of internal tides in the vertical and horizontal exchange dominates over that of other types of internal waves. In the theoretical paper by Müller (1976), internal wave packets are compared with gas molecules. A quantitative estimate of the role of internal waves in the transport of energy, momentum, and mass, the influence of internal waves on the mixing processes in the ocean, and the study of the generation, propagation, instability, and breaking of internal waves are among the main problems of modern physics of the ocean. The understanding of internal wave dynamics is important for the study of circulation in the ocean and its thermohaline structure.

Density stratification is a necessary condition for the existence of internal waves. Internal waves occupy a wide frequency band from the Brunt–Väisälä frequency to the inertial frequency. Tidal oscillations and partly turbulent pulsations also belong to this frequency range. The problem of the physical mechanism of perturbations of physical fields in the ocean can be solved jointly by experimental field measurements, theoretical studies, and numerical and laboratory modeling. Experimental research can verify the theoretical conclusions and put forward the questions that need theoretical interpretation.

The study of internal wave properties and their relation to the mean state of the ocean is key to understanding many processes in the ocean. The influence of the mean ocean state on the internal wave regime, revealing the mechanisms of the generation and breaking of internal waves, the influence of tide and wind on internal wave parameters, the investigation of the energy exchange between waves of different frequency ranges and between waves and mean motion are the most pressing problems of internal wave research.

In this book, we consider the characteristics of internal waves and determine their relation to the mean state of the ocean and other oceanic processes. The analysis is based on the application of statistical methods in the processing of large amounts of field data on temperature and currents measured on moorings in various regions of the ocean. The main focus was on the temperature measurements and the analysis of temperature fluctuations because these data reflect the vertical displacements of water caused by internal waves.

This book is the result of more than 50 years of research. Over these years, the oceanographers of the world have come to a better understanding of the important role of internal waves in ocean dynamics. Our knowledge of internal waves has increased rapidly. During this time period, the oceanographic concept has changed. New instruments for measuring in the ocean have been developed and applied in the research. The theory of ocean physics has also progressed.

The author would have been unable to accomplish such a vast amount of work including the development of the database, without the help of other scientists from the Shirshov Institute of Oceanology and colleagues from other oceanographic institutes around the world.

Moscow, Russia — Eugene G. Morozov

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Contents

About the Author

Eugene G. Morozov is the Head of the Laboratory of Hydrological Processes at the Shirshov Institute of Oceanology in Moscow, Russia. He has been working at this institute after graduating from the Moscow Institute of Physics and Technology in 1970. He never changed his place of work.

His research is focused on oceanic internal waves and large-scale circulation of the ocean. He is a field oceanographer and a specialist in the observations in the open ocean. He works on data acquisition, data processing, interpretations, and partly numerical modeling. Since 2002, he has been interested in the abyssal flows in the Atlantic Ocean and abyssal circulation, especially in the flows in deep fractures. Since 2008, he has been also working on the problems of arctic oceanography in cooperation with scientists from the University Centre in Svalbard. His interests lies in the interaction of the ocean water and glaciers descending to the fjords.

During his oceanographic career, he participated in 47 long oceanic cruises in all oceans of the globe and in 15 coastal expeditions. His field work is related to internal tides and currents in the ocean such as the Gulf Stream, Kuroshio and their rings, Antarctic Circumpolar Current, Falkland Current, California Current, equatorial countercurrents in the Indian and Atlantic oceans.

He was a Guest Scientist at Woods Hole Oceanographic Institution, USA; Universidad Complutense de Madrid, Spain; Royal Netherlands Institute of Sea Research; the University Centre in Svalbard, Norway; Universidad de Buenos Aires, Argentina; Universidad de Montevideo, Uruguay; Arizona State University, USA; Florida State University, USA; University of Victoria, Canada; and University of Cape Town, South Africa.

In 1999, he became a member of the Executive Committee of the International Association for the Physical Sciences of the Oceans (IAPSO). From 2011 to 2015, he was the President of this Association. He was also a member of the Executive Committee of the International Union of Geodesy and Geophysics (IUGG) and a member of the Executive Committee of the Scientific Committee on Oceanic Research (SCOR).

Abbreviations

AABW	Antarctic Bottom Water
ADCP	Acoustic Doppler current profiler
ADOX	Antarctic Deep Outflow Experiment
AVP	Absolute velocity profiler
AWI	Alfred Wegener Institute
BEST	Benguela Source and Transport Experiment
CMDAC	Current Meter Data Assembly Center
COARE	Coupled Ocean–Atmosphere Research Experiment
CONSLEX	Continental Slope Experiment
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity temperature depth profiler
DESOTO	DESOTO experiment in 1997 (near the De Soto Canyon)
DOMES	Deep Ocean Mining Environmental Study
EBC	Eastern Boundary Current Experiment
EPOCS	Equatorial Pacific Ocean Climate Studies
ESTOC	European Station for Time Series in the Ocean
FASINEX	Frontal Air-Sea Interaction Experiment
FOCI	Fisheries-Oceanography Coordinated Investigations
FZ	Fracture zone
GARP	Global Atmospheric Research Program
GARS	Gulf of Alaska Recirculation Study
GATE	GARP Atlantic Tropical Experiment
GM	Garrett–Munk model (Garrett and Munk 1972, 1975)
GMPO	Gulf of Mexico Physical Oceanography Program
GW	Gigawatts
HOME	Hawaii Ocean Mixing Experiment
IBCAO	International Bathymetric Chart of the Arctic Ocean
IWEX	Internal wave experiment
KERE	Kuroshio Extension Regional Experiment

LADCP	Lowered acoustic Doppler current profiler
LDE	Local dynamic experiment
LLWODP	Low Level Waste Ocean Dumping Program
MANOP	Manganese Nodule Program
MAPCOWS	Abyssal Boundary Current Studies in the Atlantic Ocean
MAPKIWI	Abyssal Boundary Current Studies in the Pacific Ocean
MAPSOON	Abyssal Boundary Current Studies in the Indian Ocean
MASAR	Mid-Atlantic Slope and Rise Experiment
MILDEX	Mixed Layer Dynamics Experiment
MODE	Mid-Ocean Dynamics Experiment
MORENA	Multidisciplinary Oceanographic Research in the Eastern Boundary of the North Atlantic project
MOVE	Meridional Overturning Variability Experiment
NASA	National Aeronautics and Space Administration
NEADS	North-East Atlantic Dynamic Study
NIO	National Institute of Oceanography, India
NIOZ	Netherlands Institute of Sea Research
NOAA	National Oceanic and Atmospheric Administration
NPBC	North Pacific boundary current experiment
OMEX	Ocean Margin Exchange Project
OPTOMA	Ocean Prediction Through Observations Modeling and Analysis
OTIS	Oregon State University (OSU) Tidal Inversion Software
PEQUOD	Pacific Equatorial Ocean Dynamics Experiment
PIRATA	Pilot Research Moored Array in the Tropical Atlantic changed to Prediction and Research Moored Array in the Tropical Atlantic
POLYMODE	Joint Russian Polygon and USA Mid-Ocean Dynamics Experiment
POM	Princeton Ocean Model
ROMS	Regional Ocean Modeling System
SAZ	Sub-Antarctic Zone Experiment
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEQUAL	Seasonal Equatorial Atlantic Experiment
SOGLOBEC	Southern Ocean experiment of the Global Ocean Ecosystems Dynamics
SWINDEX	Southwest Indian Ocean Experiment
SYNOP	Synoptic Ocean Prediction Experiment
TOGA	Tropical Ocean Global Atmosphere Experiment
TOPEX/POSEIDON	TOPography EXperiment and the Greek god of the ocean Poseidon
TW	Terawatts
WBUC	West Boundary Undercurrent experiment
WHOI	Woods Hole Oceanographic Institution
WOCE ACM	WOCE Atlantic current meter program

WOCE ICM	WOCE Indian Ocean current meter program
WOCE PCM	WOCE Pacific current meter program
WOCE SCM	WOCE Southern Ocean current meter program
WODB	World Ocean Database
XBT	Expandable bathythermographs

Abstract

This book is dedicated to the study of the structure and variability of internal tides and their geographical distribution in the ocean.

The work is mainly the result of the experimental analysis of oceanic measurements combined with numerical modeling, and it gives a comprehensive presentation of internal wave processes on the globe. In particular, it is based on the observations from moored buoys in many regions of the global ocean (Atlantic, Pacific, Indian, Arctic, and Southern) that have been carried out over 40 years within many oceanographic programs, including WOCE and CLIVAR, by many researchers from different countries. However, a significant part of the data was collected by the author who is a field oceanographer. These data were processed and interpreted within the concept of the modern knowledge of internal wave motion. The properties of internal waves are analyzed in relation to the bottom topography and mean state of the ocean in specific regions.

Internal waves play an important role in the formation of the existing stratification of seawater and are responsible for important processes of ocean dynamics, such as energy transfer and mixing. One of the most important ideas presented in this book is the strong generation of internal tides over submarine ridges. Energy fluxes from submarine ridges related to tidal internal waves exceed by many times the fluxes from continental slopes. Submarine ridges form an obstacle to the propagation of tidal currents that can cause the generation of large amplitude internal tides. The energy fluxes from these submarine ridges account for approximately one-fourth of the total energy dissipation of barotropic tides. Combined model simulations and moored measurements result in a map of the global distribution of internal tide amplitudes.