Physical Oceanography of the Baltic Sea

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Preface

The Baltic Sea is a small intra-continental sea located in northeast Europe. It is a young basin, unveiled from beneath the Fennoscandian ice sheet at the end of the Weichselian glaciation 9,000–13,500 years ago. The area has been inhabited from the time of the retreating ice sheet, and presently there are altogether 85 million people living in the 14 countries of the drainage basin of the Baltic Sea. This sea has always been an important shipping route, a source for fishery, and an area of recreation. During the last one hundred years, however, human influence on the Baltic Sea has been harmful. Pollutants have been dumped into the basin and strong nutrient loading has led to severe eutrophication, and consequently the state of the Baltic Sea has become drastically worse. Research and protection strategies need to be further developed, as the Baltic Sea is maybe the most polluted sea in the world.

Scientific research of the Baltic Sea commenced in the 1800s. The main motivation was then, in addition to basic science, the knowledge required by fishery, shipping, and coastal conditions. One specific scientific and practical question was land upheaval in the region.

International science collaboration was intensive from the early stages on, leading to joint research programs and conference series. The role of the Baltic Sea countries was important in the foundation of the International Council for the Exploration of the Sea (ICES) in 1902 in Copenhagen. The strategic role of the Baltic Sea was important throughout the 20th century as told in the history of the World Wars. Due to efforts to take better care of these waters the Baltic Sea Protection Agreement was signed in 1974, and as a consequence the Helsinki Commission (HELCOM) was founded. This agreement was renewed in 2000 and deemed valid for the time being. The state of the Baltic Sea has, however, continued weakening, and as a response to this a number of actions have been undertaken and programmes have been initiated to "Save Our Sea" (the slogan adopted by people from the area).

Physics forms the fundamental basis for understanding the behavior of the Baltic Sea system. It is interesting to note that several classical findings in physical

oceanography are due to the Baltic Sea research community. At the early stages of physical oceanography, Martin Knudsen worked in Copenhagen and developed his water and salt exchange laws for semi-enclosed basins. Torsten Gustafsson and Börje Kullenberg observed inertial oscillations in the Central Baltic Sea in the 1930s. Research on marine optics began in the 1930s, with Nils Jerlov becoming a worldwide leading scientist in the field. Since the Baltic Sea is a freezing basin with a dense coastal population, sea ice research began here early on. Erkki Palosuo made pioneering investigations about the structure and morphology of drift ice from the 1940s to the 1960s. More recently in climatological research, long oceanographic time-series (temperature, sea-level elevation, salinity, ice cover) from the Baltic Sea have provided very important information about the conditions in North Europe during the last 300 years.

There are a few general books about the geology, biology, chemistry, and physics of the Baltic Sea. The best-known examples are *Meereskunde der Ostsee* (1974), edited by L. Magaard and G. Rheinheimer; *The Baltic Sea* (1981), edited by A. Voipio; and *A System Analysis of the Baltic Sea* (2001), edited by F. Wulff, L. Rahm, and P. Larsson. Such books contain excellent reviews of various Baltic Sea research topics but they do not provide a general view or a systematic presentation of Baltic Sea physical oceanography starting from the basics. Two major handbooks *Baltiyskoe more: Gidrometeorologicheskie usloviya* [The Baltic Sea: Hydrometeorological Conditions] (1992), edited by F. S. Terzieva, V. A. Rožkova, and A. I. Smirnov, and *State and Evolution of the Baltic Sea, 1952–2005* (2008), edited by R. Feistel, G. Nausch, and N. Wasmund, have been published.

In consequence, a comprehensive textbook of the physics of the Baltic Sea has long been needed. The present authors have given a course on this topic in the University of Helsinki since 1995 and prepared an undergraduate textbook (in Finnish) *Itämeren fysiikka, tila ja tulevaisuus* [Physics, State and Future of the Baltic Sea] in 2006 with Harri Kuosa, a professor in marine ecology of the Baltic Sea. After this the present book—*Physical Oceanography of the Baltic Sea*—has been prepared with a focus on physics and targeted at the research community and as a course textbook for Ph.D. students. In addition, it is anticipated that the book would be very useful to environmental monitoring units, marine engineers, and decision-makers, who work both to exploit and protect the Baltic Sea, and to people who have a deep interest in learning about the Baltic Sea.

The book presents—as it is titled—a complete physical oceanography of the Baltic Sea including the physics of sea ice. Oceanography is presented from the basics, so that researchers coming from other fields such as physics, environmental science, or geography can use the book as a handbook or self-study material. This is also of great use for general oceanographers since the Baltic Sea is a brackish water or low-salinity basin, and because of that it has its own oceanographic characteristics. The leading principle is to present the physics of the Baltic Sea based on theoretical and observational material. Models are also presented as tools for analysis and practical applications. The introduction (Chapter 1) gives a general picture of the Baltic Sea. Chapter 2 presents the geological history and geography of the region. Chapters 3–6 present classical physical oceanography: hydrography; water, salt, and

heat budgets; circulation; and waves, respectively. Chapter 7 treats the ice of the Baltic Sea, from its fine-scale structure to seasonal characteristics, and discusses the role of ice in the general oceanography of this sea. Chapter 8 is devoted to coastal processes. Chapter 9 introduces the interface between physical oceanography and environmental problems. Chapter 10, the closing chapter, discusses the future of the Baltic Sea and its research and poses the questions: What will be the role of physical oceanography in the future? and What will be the impact of the expected environmental and climate change on the Baltic Sea? There then follow two appendices entitled ''Useful constants and formulas'' and ''Study problems''. The book ends with an index, preceded by a list of references. There is no separate chapter for numerical modeling, as different models with their applications and main results are discussed in model sections in the appropriate chapters.

As our research progressed, we learned about the Baltic Sea from a large number of colleagues. Especially, we want to thank our teachers: former Director General of the Finnish Institute of Marine Research Pentti Mälkki, Professor Erkki Palosuo, and D.Sc. Rein Tamsalu. Estonian Academician Tarmo Soomere and Dr. Andreas Lehmann are greatly acknowledged for their careful review of the manuscript.

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Matti Leppäranta and Kai Myrberg
Helsinki, August 10, 2008

Figures

Tables

Abbreviations and acronyms

AVHRR	Advanced Very High Resolution Radiometer
BACC	Baltex Assessment of Climate Change
BALTEX	Baltic Sea Experiment
BASIS	Baltic Air–Sea–Ice Study
BASYS	Baltic Sea System Study
BED	Baltic Environmental Database
BEERS	Baltic Experiment for ERS-1
BEPERS	Bothnian Experiment in Preparation for ERS-1
BMB	Baltic Marine Biologists
BMG	Baltic Marine Geologists
BMP	Baltic Monitoring Program
BOOS	Baltic Operational Oceanographic System
BOSEX	Baltic Open Sea Experiment
BP	Before present
BSH	*Bundesamt für Seeschifffahrt und Hydrographie* [Federal Maritime and Hydrographic Agency, Germany]
BSHcmod	Model code developed at *Bundesamt für Seeschifffahrt und Hydrographie* (BSH)
BSI	Baltic Sea Index
BSSC	Baltic Sea Science Congress
CBO	Conference of Baltic Oceanographers
CDOM	Colored dissolved organic matter
COHERENS	Coupled Hydrodynamical Ecological Model for Regional Shelf Seas
CTD	Conductivity–Temperature–Depth
DAS	Data Assimilation System
DHI	Danish Hydraulic Institute
DIAMIX	DIApycnal MIXing

DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
DMI	Danish Meteorological Institute
DR	Drogden Sill
DS	Darss Sill
ECMWF	European Centre for Medium-range Weather Forecasting
EDIOS	European Directory of the Ocean-observing System
ERS-1	European Remote Sensing Satellite-1
ESA	European Space Agency
EU	European Union
FIMR	Finnish Institute of Marine Research
FinEst	Finnish–Estonian model
FMI	Finnish Meteorological Institute
FRESCO	Finnish–Russian–Estonian Cooperation
GCM	General circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GMES	Global Monitoring of Environment and Security of the European Area
GMT	Greenwich Mean Time
GOOS	Global Ocean Observing System
GPS	Global Positioning System
HBV	*Hydrologiska Byråns Vattenbalansmodell* [Water balance model of the Hydrological Office, SMHI, Sweden]
HELCOM	Helsinki Commission
HIRLAM	High Resolution Limited Area Model
HIROMB	High Resolution Operational Model for the Baltic Sea
I/B	Icebreaker
IBY	International Baltic Year
ICES	International Council for the Exploration of the Sea
IOW	*Leibniz-Institut für Ostseeforschung Warnemünde* [Leibniz Institute for Baltic Sea Research, Germany]
IPCC	International Panel on Climate Change
MBI	Major Baltic Inflow
MERIS	Medium Resolution Imaging Spectrometer Instrument
MODIS	Moderate Resolution Imaging Spectroradiometer
MOM	Modular Ocean Model
NAO	North Atlantic Oscillation
NATO	North Atlantic Treaty Organization
NOAA	National Oceanographic and Atmospheric Administration
NOAMOD	Northeastern Atlantic 2D Model
OAAS	Oleg Andrejev–Alexander Sokolov
OAS	Optically active substance
OCCAM	Ocean Circulation Climate Advanced Modeling
PAR	Photosynthetically active radiation
PCB	Polychlorinated biphenyl

PEX-86	Baltic Sea Patchiness Experiment
POM	Princeton Ocean Model
PSU	Practical salinity unit
R/V	Research vessel
S/S	Steam ship
SAR	Synthetic Aperture Radar
SCOR	Scientific Committee on Oceanic Research
SEGUE	Searching efficient protection strategies for the eutrophied Gulf of Finland: the integrated use of experimental and modeling tools
SMHI	Swedish Meteorological and Hydrological Institute
SOOP	The ship of opportunity
SPBIO	St. Petersburg Institute of Oceanology
SYKE	Finnish Environment Institute
TS	Temperature–Salinity
UNESCO	United Nations Educational, Scientific and Cultural Organization
WAM	Wave Prediction Model
WAMDI	Wave Model Development and Implementation
WMO	World Meteorological Organization

Symbols

A	Surface area; ice compactness
A_H, A_v	Eddy diffusion coefficient, horizontal and vertical
c	Wave phase speed
c_g	Group speed of waves
c_p	Specific heat at constant pressure
C_D, C_H, C_E	Turbulent exchange coefficients for momentum, heat, and moisture
D	Ekman depth
E	Evaporation; stability
f	Coriolis parameter
F	Freshwater budget
g	Acceleration due to gravity on Earth's surface
h	Ice thickness
H	Sea depth
i	$\sqrt{-1}$
K	Bulk modulus of seawater; Eddy diffusion coefficient
$\boldsymbol{K}$	Wave vector
L	Latent heat of freezing
L_E	Latent heat of evaporation
N	Cloudiness; Brunt–Väisälä frequency
p	Pressure
P	Precipitation
q	Specific humidity; complex velocity vector
Q	Power (rate of change of energy)
Q_b	Heat flux from sea bottom
Q_c	Sensible heat flux
Q_e	Latent heat flux
Q_{La}	Atmospheric thermal radiation

Q_{Lo}	Outgoing thermal radiation
Q_n	Net heat flux
Q_P	Heat flux from precipitation
Q_R	Radiation balance
Q_s	Incoming solar radiation
Q_{sc}	Solar constant
Q_r	Outgoing solar radiation
r	Sun–Earth distance
R	Relative humidity; Rossby radius of deformation
S	Salinity; spectral density of surface waves
t	Time
T	Temperature (°C); timescale
$\underline{T}$	Temperature (K)
T_f	Freezing point temperature
T_m	Temperature of maximum density
$\boldsymbol{u}$	Three-dimensional velocity
u	East velocity component
u^*	Friction velocity
$\boldsymbol{U}$	Horizontal velocity
v	North velocity component
V_i	Inflow into Baltic Sea at the mouth
V_o	Outflow into Baltic Sea at the mouth
V_r	River discharge into the Baltic Sea
w	Vertical velocity
x	East coordinate
y	North coordinate
z	Vertical coordinate
z_0	Surface roughness
Z	Zenith angle
α	Albedo; temperature expansion coefficient of seawater
β	Salinity coefficient for density of seawater
ε	Emissivity
γ	Fraction of visible light in solar radiation
Γ	Adiabatic temperature gradient
κ	von Kármán constant; light attenuation coefficient
λ	Wavelength
ω	Frequency
$\boldsymbol{\Omega}$	Angular velocity of the Earth
ρ	Density of water
ρ_a	Density of air
σ	Stefan–Boltzmann constant
τ	Reynolds stress
τ_a	Wind stress
θ	Potential temperature
ξ	Sea-level elevation

Subscripts

a	Air
a	Ice; inflow
H	Horizontal
o	Surface; outflow
V	Vertical