Baltic Ocean Dynamics
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Contents

Scales of motion
Flows in deep channels and straits
Eddies, fronts, upwelling etc
Waves and their effects
Important scales

<table>
<thead>
<tr>
<th></th>
<th>Ocean</th>
<th>Baltic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth $H$</td>
<td>5 km</td>
<td>100 m</td>
</tr>
<tr>
<td>Stratification, depth-mean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Väisälä frequency $N$</td>
<td>0.003 s$^{-1}$</td>
<td>0.015 s$^{-1}$</td>
</tr>
<tr>
<td>Rossby deformation radius $R_d = NH/\pi f$</td>
<td>50 km</td>
<td>5 km</td>
</tr>
</tbody>
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Example how basic knowledge is useful: inertial oscillations

- Theory developed in 1800s rotations of water particles with frequency of Coriolis parameter; in our latitude period about 14 h, circle 2-3 km

- First observations in the sea made in the Baltic by Gustafson and Kullenberg (1936)

- „Consumed“ formerly mainly by PhysOcean, as generators of mixing (e.g. Krauss, 1981, erosion of thermocline)

- Now important for „right“ advection-mixing balances in ecosystem, sediment dynamics, ice dynamics etc models
We learned from the scales:

- Baltic $R_d$ about 10 times smaller than in the ocean
- several ocean-type features present in the Baltic

Next:
Flows in deep channels and straits
Water exchange and mixing in connected rotational basins

Volume transport over rotating sill
(Whitehead et al., 1974)

\[ Q = \frac{g' h^2}{2f} \]

where \( g' = g \frac{\rho_2 - \rho_1}{\rho_2} \)

rotational control, if

\[ W > R_d = \frac{c}{f} = \frac{\sqrt{gh}}{f} \]

- wind transport in Ekman layer \( \Rightarrow \) compensation flow below
- vertical transport due to continuity
  \[ w_i(z,t) = \frac{1}{A_i} \int_{z}^{H_i} (q_i - q_i') \, dz \]
  has to be balanced by halocline erosion
- mixing in the halocline is mainly due to internal waves,
  \[ k_i^\nu = \frac{\alpha}{N_i} \]
Flow dynamics in the channels: north from Kriegers Flak

**Down-channel speed and density**

**Vertical buoyancy flux**

**Rotational sub-critical gravity current**

Frictional effects (Ekman number $\approx 1$):
- transverse Ekman circulation and interfacial jet
- downward bending of isopycnals on the right-hand slope
  - asymmetric density pattern
- strong entrainment on the right-hand slope

Flow dynamics in the channels: Stolpe / Słupsk

Sub-critical eddy-producing gravity current in a wide channel, including friction effects

Current maps at 60 m

Topography and transects

Variety of cross-channel density patterns (pinching and downward bending of isopycnals) is caused by meandering of the gravity current and mesoscale eddies – mostly above-halocline cyclones and intrahalocline anticyclones.
Flow dynamics in the channels: Northern Kvark Strait (1)

Two channels between the Bothnian Sea and the Bothnian Bay

Flow dynamics in the channels: Northern Kvark Strait (2)

Along-channel currents (positive north) (a) and with first EOF mode subtracted (b)

Intermittency of flow regimes
1. barotropically blocked regime
   - 45% of time
2. two-layer regime
3. continuously stratified regime
   - 55% of time, mainly hydraulically controlled (Fr ≈ 1)

Flow dynamics in the western Gulf of Finland

Persistent strong SW winds create during the winter
- anti-estuarine transport
- stratification collapse
- oxygenation of bottom layers

By ceasing the SW winds, stratification and hypoxia are rapidly restored

Liblik et al (2013)
We learned from the flows in deep channels and straits:

- high variability of flow patterns and dynamical regimes
- flow control by rotational hydraulics, but also by eddies and fronts

Next:
Eddies, fronts, upwelling etc
Examples of eddy manifestations in remote sensing

11 July 2005

MODIS Terra quasi true color image at 250m resolution using bands 1 (red), 4 (green), and 3 (blue).

Kahru & Elmgren (2014)

17 July 2009

optical image from radiometer ETM+ Landsat-7


RI from ASAR Envisat
Spiral eddies from SAR images

Normalized number of eddies per 6 x 6 mile grid cell 2009 - 2011

- Spiral eddies 5-8 km mainly cyclonic
- Thousands of eddy detections within a year
- „Black eddies“ - visualized due to surfactant films
- „White eddies“ – visualized due to wave/current interactions

Karimova (2012), Karimova and Gade (2016)
Mesoscale variability: observations from PEX-86

14 ships working 2 weeks in a 20 x 40 mile box

Phytoplankton spring bloom started in the cores of mesoscale eddies
Eddies generated during upwelling relaxation

POM model with 0.125 miles grid step, used for summer 2006

Identified features
1 – cyclonic vorticity thread at upwelling front
2 – submesoscale spot of high cyclonic vorticity
3 – long-living mesoscale cyclonic eddy
4 – spiral submesoscale cyclonic eddy

Väli et al (2017), J Mar Sys
Long-living mesoscale eddy in the Gulf of Finland

Eddy background is variable, still contrasts in eddy core are distinct over about 1 month. Diameter about 10 km, travel distance about 80 km over 33 days = translation speed 2-3 cm/s.

- Transects of temperature and salinity over 1 month: Väli et al (2017)
- Decrease of contrast eddy core – periphery:
  - Sea level: Start -4.7 cm, End -2.2 cm
  - SST: Start -4.1 °C, End -1.0 °C

Graphs showing vorticity, sea level, and SST transects over the 1 month period.
We learned from eddies and fronts:

- variety of eddy types: short-living (< few days) spiral and T-like submesoscale eddies, long-living (> few weeks) mesoscale eddies
- eddies are important for momentum and mass transfer
- knowledge about eddies still fragmentary, good detection methods not yet ready

Next:
Waves and their effects
Effects of waves on ocean dynamics

Standard ocean modelling approach prescribes wind and wave effects as a function of wind only.

Specific wave effects on ocean dynamics include:
- Stokes-Coriolis drift in non-linear waves
- wave-dependent momentum flux: surface roughness and drag coefficient for wind stress, release of momentum to ocean by breaking waves
- wave-dependent mixing: induced by breaking waves

Alari et al (2016)
Effect of waves on temperature during upwelling forcing by wind only and forcing by wind and waves.
Turbulence generation by surface waves (Stokes drift)

Stokes production of turbulent kinetic energy in the mixed layer is of the same order of magnitude as the shear production and must therefore be included in mixed layer models.

Presently most of the models count only the shear production (friction velocity) due to wind speed, not the effects of waves.


**TKE dissipation rate (in W kg\(^{-1}\))**
- a) observed
- b) modeled with wave breaking and Stokes drift
- c) modeled with wind dependence only

Microstructure observations in the Bornholm Basin
Wave products for the Baltic Sea

The spatial resolution and coverage of altimetry and SAR wave products

- Low-resolution altimetry wave products/algorithms and open ocean SAR wave mode products not good in the Baltic:
  - a number of islands and staggered coast line
  - limited fetch resulting in relatively small and short waves

- Sentinel-1 SAR data could be basis for much more detailed „dedicated Baltic“ wave information than altimetry products.
SAR wave product accuracy

- SAR based wave fields as accurate as from altimetry, but SAR coverage is better.
- The value of high-res wave field information retrieved from SAR imagery in the Baltic Sea and in the German Bight has been demonstrated:
  - Rikka, Pleskachevsky, Uiboupin, Jacobsen (2017) IGARSS Proceedings, „Sea state parameters in highly variable environmentof Baltic Sea fro m satellite radar images“

High-res SAR based wave fields need to be assimilated into forecast models.

Credit: Rivo Uiboupin and Sander Rikka
Spatial details of SAR wave products in the coastal area

Credit: Rivo Uiboupin, Sander Rikka and Victor Alari
We learned from wave effects:

- waves are important for currents, mixing, TS patterns
- wave models already quite good, still observations needed, e.g. for data assimilation
- wave products from SAR seem to have high value

Baltic ocean dynamics and remote sensing:

a number of new RS products would be highly valuable, for
- better understanding of complex natural processes
- improving quality and reliability of ocean forecasts