(On) mechanical energy balance in the Baltic Sea

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Baltic Sea is big. Do we need to care about man-made interferences?

In 1940s nobody cared. See for example **dumped chemical munitions**.

Now there is **deep understanding on sustainable development** approaches, including pollution abatement, environmental protection, biodiversity conservation.

Some people think that **extraction of marine wind energy** and other **mechanical interference does not have significant feedback** to the physical system, but **scientists illustrate increasing concern.**

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Background for mechanical energy interference

(1) Ship-induced mixing. In confined areas with intense shipping, added mixing may be considerable. Such an area can be Öresund.

(2) Waves and coastal erosion due to high-speed ships. The problem has been actual in Tallinn Bay.

(3) Altering cross-sections and sill depths by construction. The problem arises in many places due to construction of bridges, tunnels, artificial islands, laying pipelines.

(4) Oceanographic effects of wind farms. There could be changes in the local wave and current regime. There are also likely changes in the wind field on larger scales that may have feedback on currents (change of wind stress), mixing (change of current shear generating turbulence), and ecosystem health.

Policy background

The Marine Strategy Framework Directive has acknowledged that permanent alteration of hydrographical conditions must not adversely affect marine ecosystems.

Basic terms

Kinetic energy
$$KE = \frac{\rho_0}{2} \iiint (u^2 + v^2)\ dz dy dx$$

Potential energy
$$PE = \iiint \rho g z\ dz dy dx$$

Using Boussinesq' approximation $\rho = \rho_0 + \rho'(x,\ y,\ z,\ t)$ with $|\rho'| \ll \rho_0,$

In the ideal case there is mechanical energy conservation
(like pendulum without friction)
$$\frac{d}{dt}(\,PE + KE\,) = 0.$$

Energy cascade takes place from larger to smaller scales, until turbulent dissipation.

Example:

Mesoscale eddies are generated by **baroclinic instability.** Eddies take their **energy from large-scale potential energy, apparent due to sloping density surfaces.**

Ocean: from polar to tropical **Baltic: from straits to large rivers**

Potential energy formulations

APE Available potential energy

Lorenz, 1955

APE is determined in reference to the minimum potential energy state where all **isopycnals are adiabatically converted parallel to isobars**.

In Boussinesq approximation APE of baroclinic (wave) motions depends on isopycnal vertical excursions ξ and strength of stratification N.

$$\mathrm{APE} = \frac{1}{2}\rho_0 \overline{N^2 \xi^2}$$

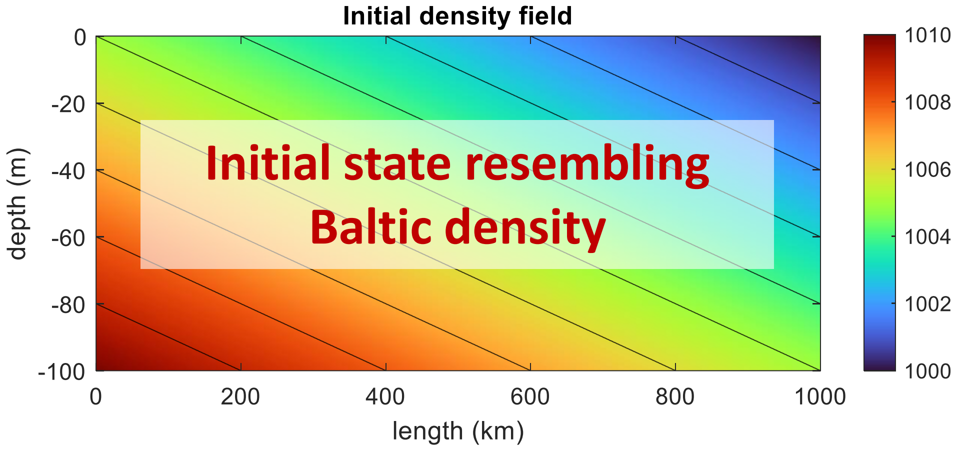
(in baroclinic waves)

PEA Potential energy anomaly

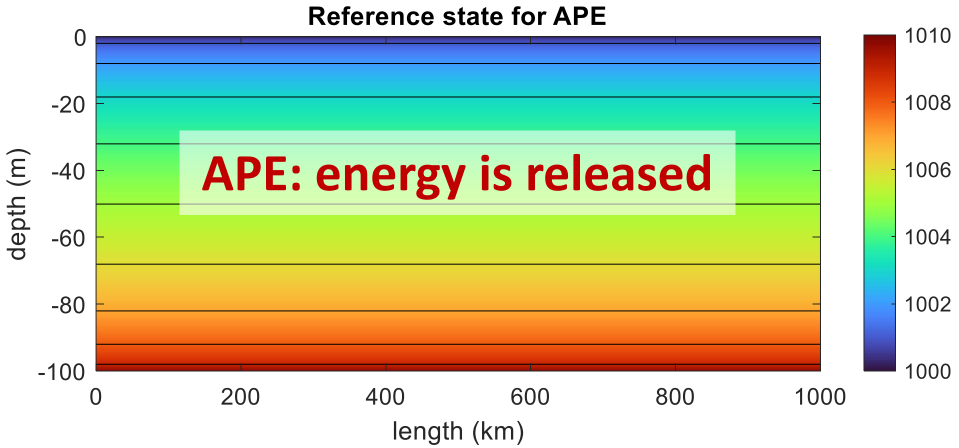
Simpson and Bowers, 1981

$$\mathrm{PEA} = \frac{g}{H}\int_{-H}^{0} \left(\bar{\rho} - \rho\right) z \, dz \qquad \bar{\rho} = \frac{1}{H}\int_{-H}^{0} \rho \, dz$$

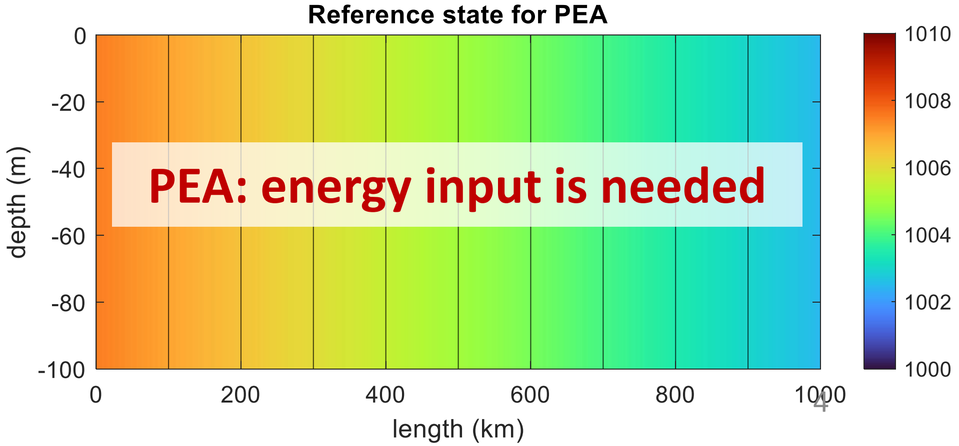
Energy input is needed to reach reference **vertically mixed-through state**. Remaining horizontal density gradients are not considered.



Initial state resembling Baltic density



APE: energy is released

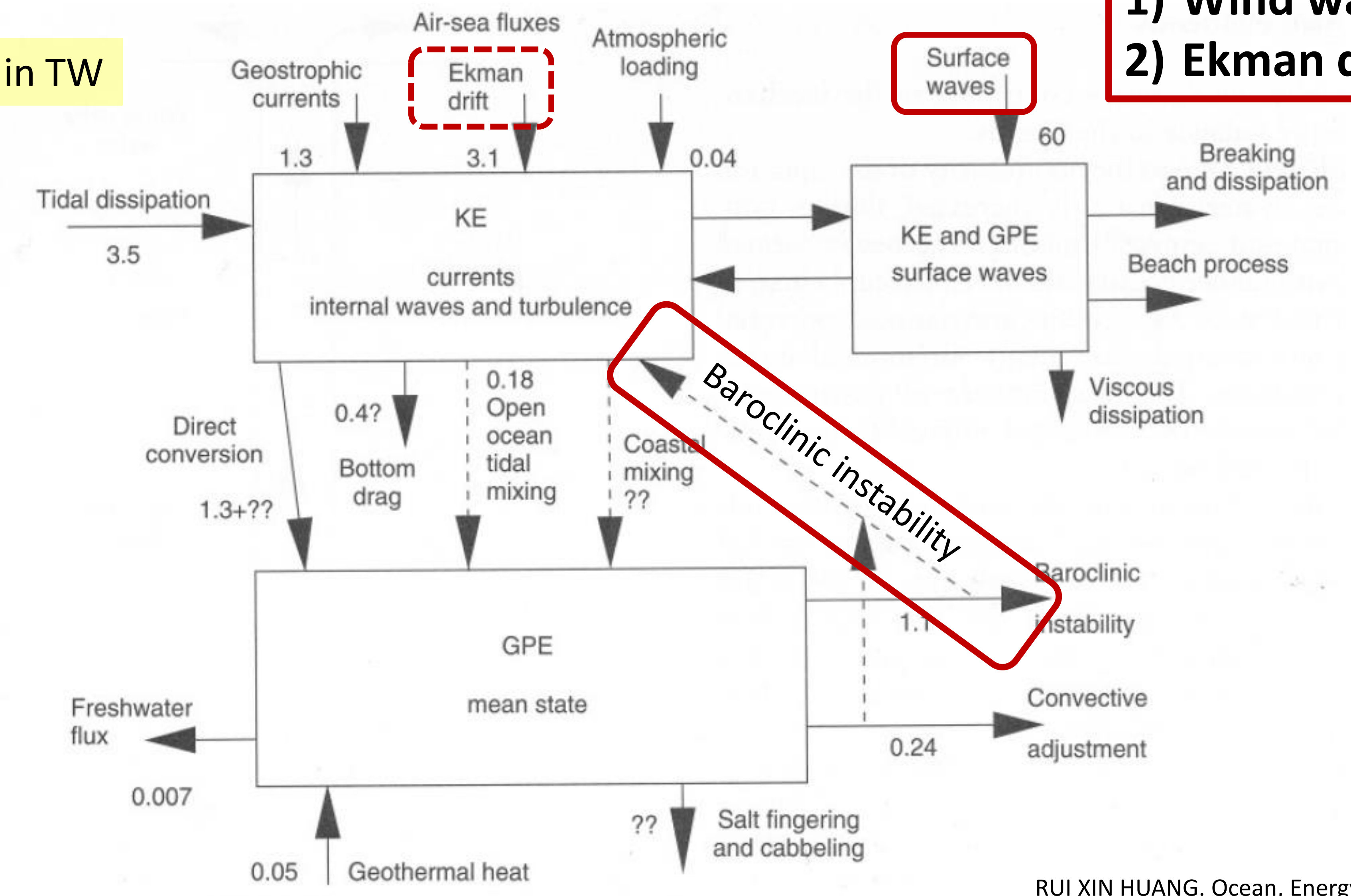


PEA: energy input is needed

Mechanical energy balance concept for the world ocean

Energy flows in TW

Largest energy input:
1) **Wind waves**
2) **Ekman drift**



Baroclinic instability

RUI XIN HUANG. Ocean, Energy Flows in. Encyclopedia of Energy, Volume 4. 2004 Elsevier Inc.

Estuarine dynamics

Potential energy anomaly (**PEA**)

$$\phi = \frac{1}{D}\int_{-H}^{\eta} gz(\bar{\rho} - \rho)\,\mathrm{d}z = -\frac{1}{D}\int_{-H}^{\eta} gz\tilde{\rho}\,\mathrm{d}z$$

$$\bar{\rho} = \frac{1}{D}\int_{-H}^{\eta} \rho\,\mathrm{d}z,$$

$$\begin{aligned}\partial_t\phi = & \underbrace{-\nabla_h(\bar{\boldsymbol{u}}\phi)}_{(A)} + \underbrace{\frac{g}{D}\nabla_h\bar{\rho}\cdot\int_{-H}^{\eta} z\,\tilde{\boldsymbol{u}}\,\mathrm{d}z}_{(B)} \\ & \underbrace{-\frac{g}{D}\int_{-H}^{\eta}\left(\eta-\frac{D}{2}-z\right)\tilde{\boldsymbol{u}}\cdot\nabla_h\tilde{\rho}\,\mathrm{d}z}_{(C)} \\ & \underbrace{-\frac{g}{D}\int_{-H}^{\eta}\left(\eta-\frac{D}{2}-z\right)\tilde{w}\partial_z\tilde{\rho}\,\mathrm{d}z}_{(D)} + \underbrace{\frac{\rho_0}{D}\int_{-H}^{\eta} P_b\,\mathrm{d}z}_{(E)} \underbrace{-\frac{\rho_0}{2}(P_b^s + P_b^b)}_{(F)} \\ & \underbrace{+\frac{g}{D}\int_{-H}^{\eta}\left(\eta-\frac{D}{2}-z\right)Q\mathrm{d}z}_{(G)} \\ & \underbrace{+\frac{g}{D}\int_{-H}^{\eta}\left(\eta-\frac{D}{2}-z\right)\nabla_h(K_h\nabla_h\rho)\mathrm{d}z}_{}, \qquad (14)\end{aligned}$$

- **Mixing** driven by wind and buoyant convection increases PEA and **reduces stratification.**
- **Lateral saline and freshwater flows** cause **straining**; they either **enhance** (estuarine flows) **or weaken** (counter-estuarine flows) the stratification.

A: advection by mean horizontal velocity
B: depth-mean **straining**
C: non-mean **straining**
D: vertical advection
E: **vertical mixing of density**
F: **surface and bottom buoyancy fluxes**
G: inner sinks or sources of potential density
H: divergence of horizontal turbulent transport

Burchard, H. and Hofmeister, R., 2008. A dynamic equation for the potential energy anomaly for analysing mixing and stratification in estuaries and coastal seas. *Estuarine, Coastal and Shelf Science*, *77*(4), pp.679-687.

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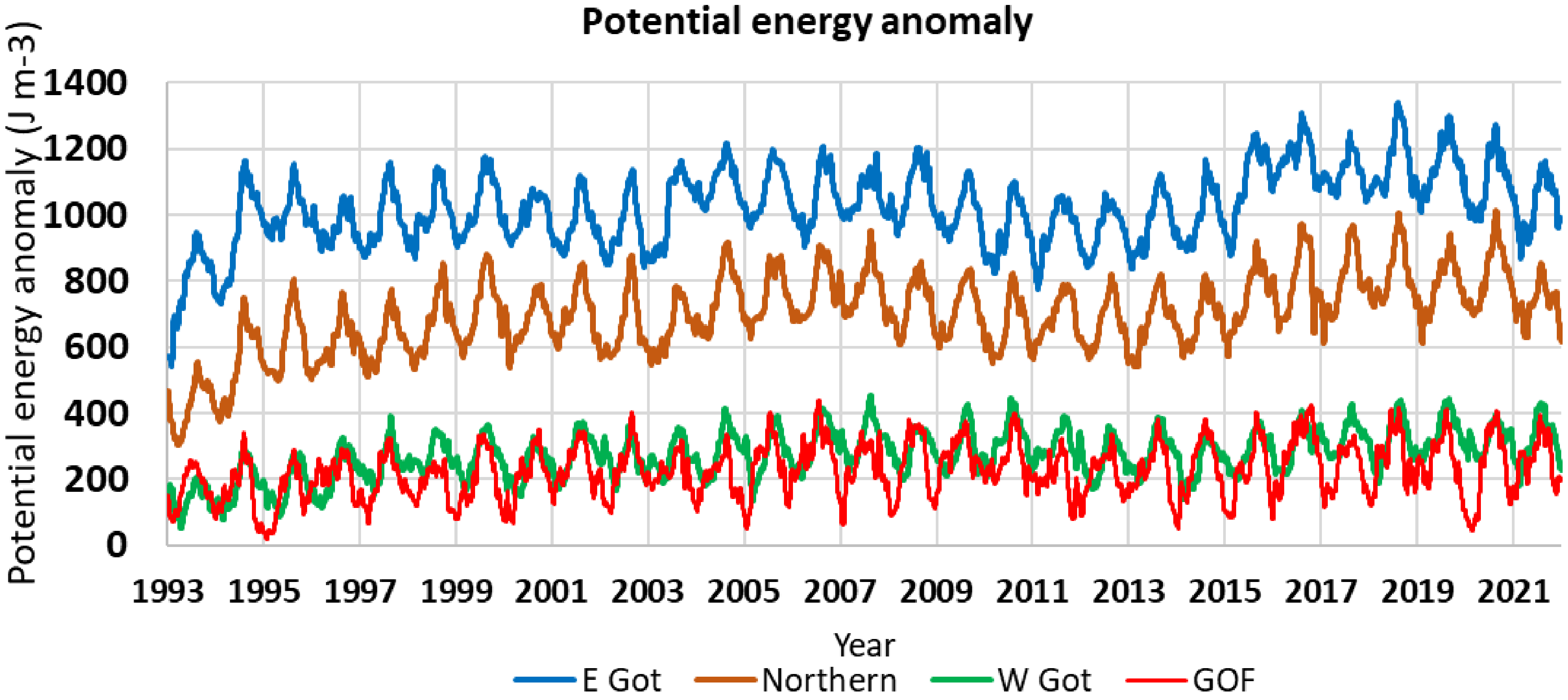
Time series of potential energy anomaly



- Significant **seasonal cycle on the background of long-term variations**. In winter, stratification is weaker and less energy is needed to reach well-mixed state.
- In some areas like the Gulf of Finland, PEA levels have been **occasionally reduced to enable complete mixing during the winter.**

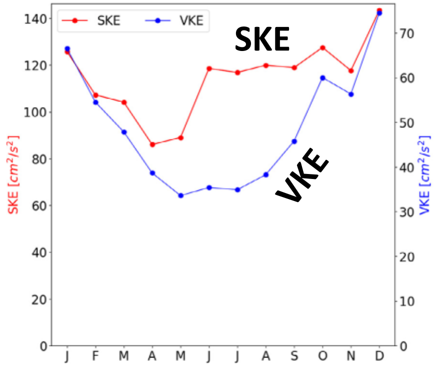
Gotland Deep (E Got), Northern Deep (Northern), Western Gotland Basin (W Got) and the Gulf of Finland near Tallinn (GOF). Data from Copernicus Marine reanalysis.

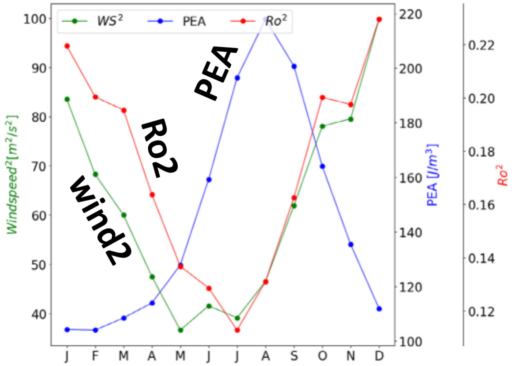
Energy and vorticity of sub-mesoscale dynamics

Close relationship between the wind speed and the kinetic energy at the surface and the vertically averaged kinetic energy in the sea.

Lagged correlation between the kinetic energy at the surface and the eddy field.

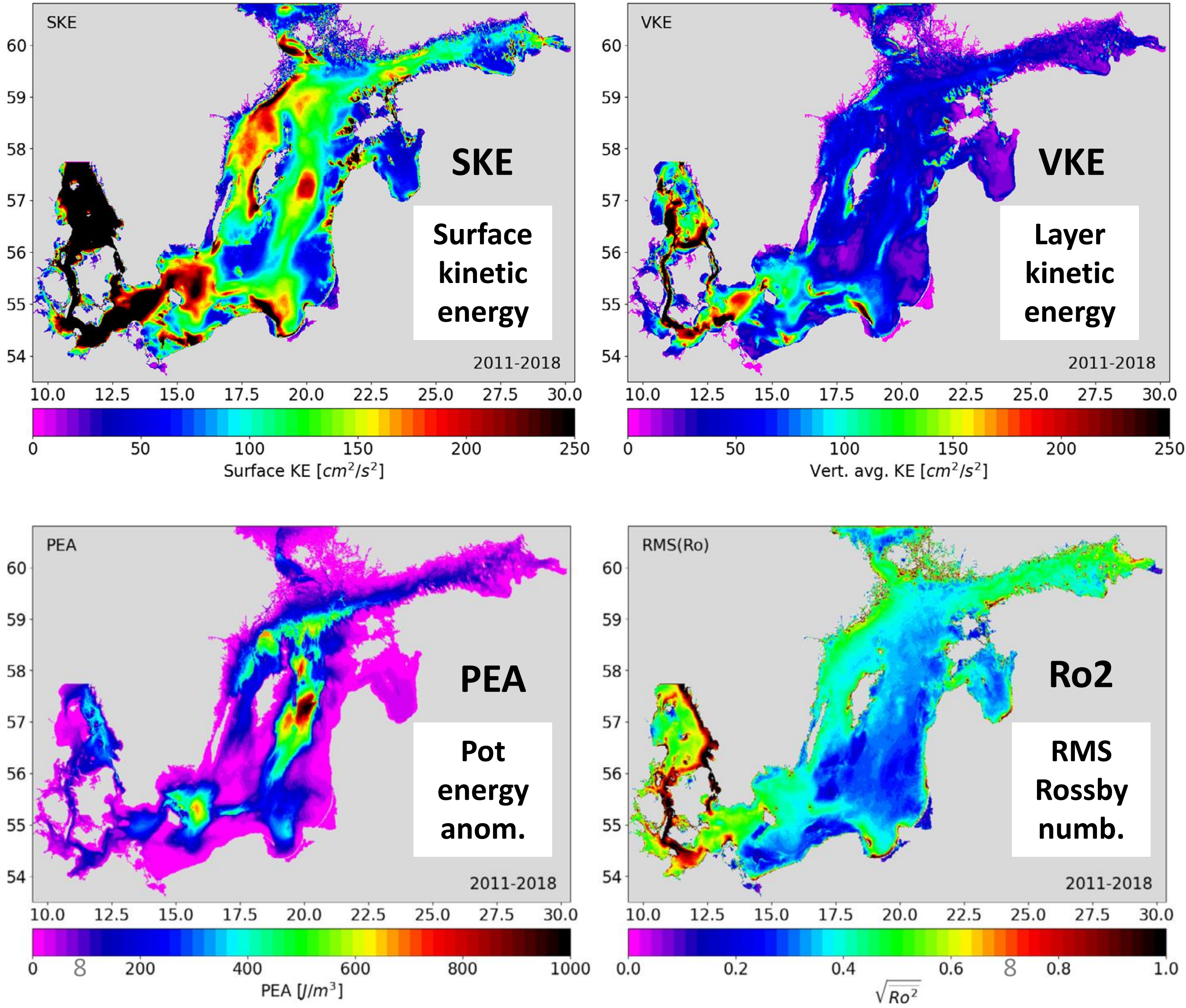
Annual course: PEA max in summer, SKE, wind2 and Ro2 in winter





Väli, G., Meier, H.M., Liblik, T., Radtke, H., Klingbeil, K., Gräwe, U. and Lips, U., 2023. Submesoscale processes in the surface layer of the central Baltic Sea: A high-resolution modelling study. *Oceanologia*.

GETM 250 m 2011 - 2018


SKE

Surface kinetic energy

VKE

Layer kinetic energy

PEA

Pot energy anom.

Ro2

RMS Rossby numb.

Turbulent energy and mixing

k-ε model

$$\frac{\partial k}{\partial t} - \frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial z}\right) = P + G - c_m\varepsilon,$$

$$\frac{\partial \varepsilon}{\partial t} - \frac{\partial}{\partial z}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) = c_{\varepsilon 1}\frac{\varepsilon}{k}\left(P + c_{\varepsilon 3}G\right) - c_{\varepsilon 2}c_m\frac{\varepsilon^2}{k},$$

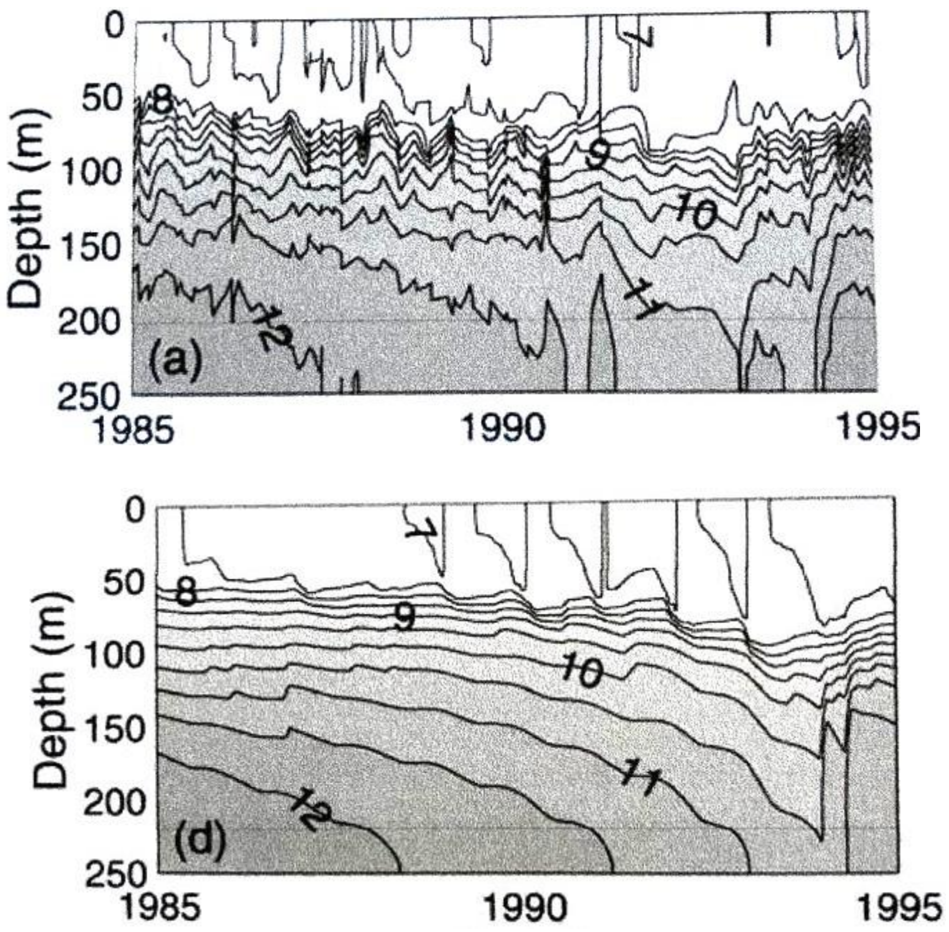
with

$$P = \nu_t\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right], \qquad G = -\frac{\nu_t}{\sigma_t}N^2,$$

$$\nu_t = c_\mu\frac{k^2}{\varepsilon}.$$

Additional deepwater mixing due to breaking of internal waves

$$\boxed{\nu = \nu_t + \sigma_t \min\left(\frac{\alpha}{N},\ \nu_{0,\max}\right)}$$



Observed salinities from the central Baltic Sea (above) and calculated salinities (below) by adding Langmuir circulation and internal wave energy (Axell, 2002).

Discussion and conclusions (1)

- The **main force behind mechanical energy in the Baltic Sea is the wind**. Surface layers are agitated by the wind stress and downward mixing of momentum. **Saline and freshwater flows** contribute to the **potential energy**.
- Mixing effects of wind can be calculated by multiplying the wind stress to the ocean surface drift velocity (Axell, 2002), resulting approximately in the **energy flux proportional to the wind speed cubed**.
- **Further studies of the mechanical, potential, and turbulent kinetic cycles are needed**. The effects of Baltic Sea stratification due to human-induced changes in the wind field need to be investigated.

Discussion and conclusions (2)

- Suppose the **energy flux from the wind is reduced** with a decrease in energy to the internal wave energy. In that case, we may expect a stronger vertical stratification that will influence the **marine environment differently**, for example, by lowering the oxygen concentration. Extensive use of offshore wind farms in the Baltic Sea may have environmental impacts, as was reported by Daewel et al. (2022) for the North Sea.
- Akhtar et al. (2022) have shown that the **presence of wind farms reduces the 10 m wind speed by approximately 7%** within a wake behind the farm structures during stably stratified atmospheric conditions. This causes changes to stratification, but it is still uncertain how important these changes are to the ecosystems. For the Baltic Sea, this issue remains to be investigated.