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Key Points:

- High-resolution turbulence observations in a coastal, strongly stratified region with extremely rough seafloor topography
- Acoustic turbulence imaging shows highly intermittent and localized mixing due to wake eddies and internal-wave breaking near obstacles
- Turbulent diffusivities and transport rates of salt increased by two orders of magnitude inside mixing hotspots near rough bathymetry

Supporting Information:

Supporting Information may be found in the online version of this article.

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Diapycnal Mixing Induced by Rough Small-Scale Bathymetry

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Abstract Diapycnal mixing impacts vertical transport rates of salt, heat, and other dissolved substances, essential for the overturning circulation and ecosystem functioning in marine systems. While most studies have focused on mixing induced by individual obstacles in tidal flows, we investigate the net effect of non-tidal flow over multiple small-scale (<1 km) bathymetric features penetrating a strongly-stratified density interface in a coastal region. We combine high-resolution broadband acoustic observations of turbulence microstructure with traditional shear microstructure profiling, to resolve the variability and intermittency of stratified turbulence related to the rough bathymetry. Scale analysis and acoustic imaging suggest that underlying mixing mechanisms are related to topographic wake eddies and breaking internal waves. Depth averaged dissipation rates ($1.1 \times 10^{-7} \text{ W kg}^{-1}$) and turbulent vertical diffusivities ($7 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$) in the halocline exceed reference values by two orders of magnitude. Our study emphasizes the importance of rough small-scale bathymetric features for the vertical transport of salt in coastal areas.

Plain Language Summary Mixing of water across density interfaces is important for ecosystems and the circulation between basins. However, mixing related to rough small-scale bathymetry is often not resolved in models and difficult to measure. In this study, we show high-resolution acoustic observations of intense vertical mixing across a strong density interface, that separates the saltier bottom water from the fresher surface water in the northern Baltic Sea. In the study region, steep underwater hills and ridges extend into the density interface. As water flows over the region, the hills and ridges cause the water to mix. Measured values of mixing and vertical salt fluxes in this region are up to two orders of magnitude higher than at a nearby reference station with smooth bathymetry. Our analysis suggests that the observed high mixing is mainly caused by eddies in the wake of obstacles and secondarily by breaking internal waves, which are waves within the water that occur on interfaces between layers with different properties. Understanding mixing mechanisms and estimating their contribution to the total mixing is needed to implement mixing into ocean models. This study highlights the importance of rough small-scale (<1 km) seafloor features for mixing and vertical transport of salt.

1. Introduction

Rough bathymetry is known to considerably increase vertical mixing in the deep ocean (Garabato et al., 2004; Kunze et al., 2006; Ledwell et al., 2000; Nikurashin & Legg, 2011; K. L. Polzin et al., 1997; Waterhouse et al., 2014), in fjords (Arneborg et al., 2017), and in lakes (Wüest & Lorke, 2003). Several mechanisms have been shown to result in enhanced mixing near rough bathymetry; internal-wave generation (Alford et al., 2011; Garrett & Kunze, 2007; MacKinnon et al., 2017; Nycander, 2005), hydraulic effects (Alford et al., 2013; Arneborg et al., 2017; Legg & Klymak, 2008), and the shedding of eddies in the wake of topographic obstacles (Caldeira et al., 2005; MacKinnon et al., 2019; Pawlak et al., 2003; Puthan et al., 2022; Warner & MacCready, 2009) are believed to be particularly relevant. However, field studies of these processes, typically based on in-situ profiling measurements, were generally unable to capture the extreme spatial heterogeneity and intermittency of turbulence near bathymetric features, and focused only on individual obstacles rather than the overall effect in regions with extremely rough bathymetry.

Here, we combine traditional in-situ turbulence microstructure profiling measurements with a new type of high-resolution broadband acoustic turbulence observations to investigate the effect of extremely rough bathymetry on energy dissipation and mixing. Our study area, a coastal region in the Southern Quark, northern Baltic Sea, is characterized by negligible tides and a large number of topographic features (hills and ridges) penetrating

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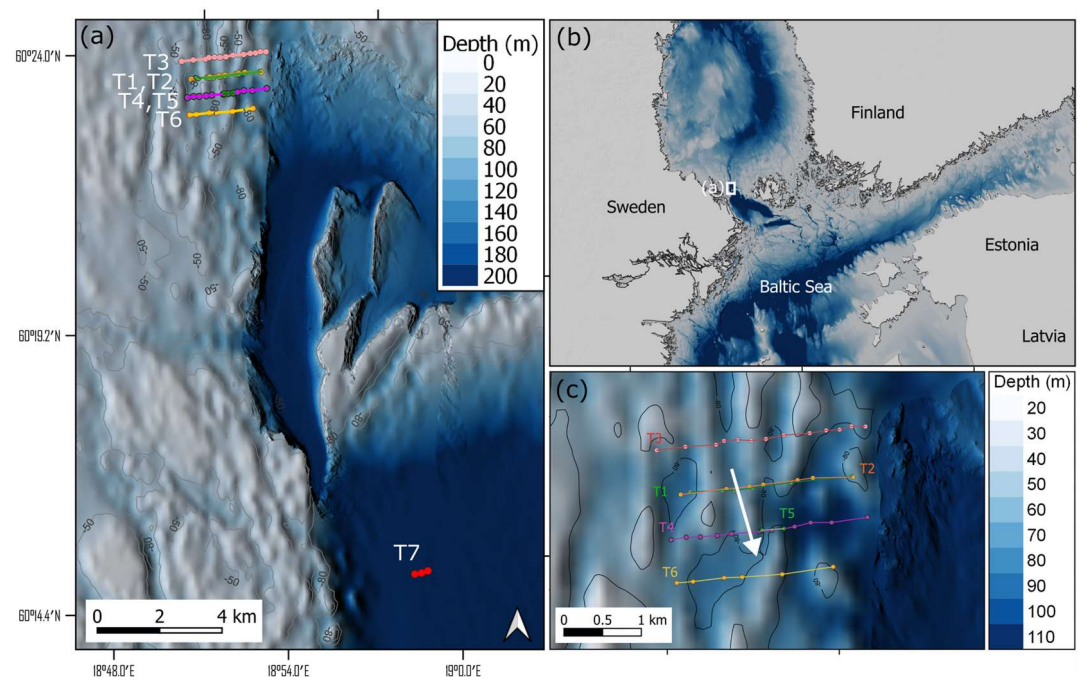


Figure 1. Bathymetry of the study area in the Åland Sea: (a) Overview map with MSS transects T1–T7 marked by colored lines (MSS casts 76–125, collected between 2 March 2020, 14:45 UTC and 3 March 2020, 17:10 UTC). (b) Overview map of northern Baltic Sea with study region in the Åland Sea shown in (a) marked by white rectangle; (c) main study region with transects T1–T6 enlarged. Each dot represents a MSS cast. White arrow marks average direction of currents during the time of the measurements T2–T6 based on ship Acoustic Doppler Current Profiler data (Figure S1 in Supporting Information S1). Background bathymetry data from EMODnet (EMODnet Bathymetry Consortium, 2020), detailed multibeam bathymetry data in (a) and (c) acquired by R/V *Electra* and granted public release by the Swedish Maritime Administration (release 17-03187).

into a strongly stratified density interface. Its bathymetry is known to be particularly rough with horizontal scales O_h (100 m) (Jakobsson et al., 2019) and previous studies showed its large potential for enhanced mixing (e.g., Nohr & Gustafsson, 2009). Our study points at the relevance of seafloor-ocean interactions in coastal regions with strongly corrugated bathymetry that lead to enhanced energy dissipation and vertical transport of salt. Vertical mixing of salt, the main stratifying agent in the Baltic Sea and in many other estuaries and coastal systems, forms an intrinsic part of the larger-scale overturning circulation and is essential for deep-water renewal and ecosystem functioning.

This study adds to the knowledge about processes that cause mixing below the wind-mixed layers in ocean basins. The underlying processes are important to determine in order to parametrize mixing in numerical models, as different mechanisms have fundamentally different parametrizations. Besides the potential to improve mixing parameterizations in numerical models, a better understanding of the underlying mechanisms may even lead to improved drag parameterizations and thereby more accurate currents and transports in the models, as has been shown to be the case for atmospheric models (Alexander et al., 2010).

2. Study Area and Methods

The study area in the Southern Quark is located between the Bothnian and Åland seas (Figure 1). It constitutes a major oceanographic bottleneck in which the bathymetry controls water exchange between two of the Baltic Sea's main basins (Elken & Matthäus, 2008). The particularly rough seafloor is due to the underlying bedrock geology, tectonic lineaments (Beckholmen & Tiren, 2009), and interaction between the seafloor and the Scandinavian Ice Sheet (Greenwood et al., 2017). Here, we use the gridded bathymetric model compiled by EMODnet at a grid-cell resolution of 1/16 arc min (ca. 115 m) (EMODnet Bathymetry Consortium, 2020) to assess the seafloor morphology. The version we use includes multibeam bathymetry in the Southern Quark acquired with Stockholm University's Research Vessel R/V *Electra* in 2017 (Jakobsson et al., 2019).

Oceanographic and acoustic data presented in this study were collected during a cruise with R/V *Electra* on 2–3 March 2020 on six transects in a region of particularly rough bathymetry. The height of 30 bathymetric features along the cruise track varies between 5 and 50 m (average ~ 20 m), their half-width between 30 and 500 m (average ~ 160 m), and their steepness between 0.05 and 0.5 (average ~ 0.16). As reference, we collected profiles in a deeper, smooth basin south-east of the study area (Figure 1). Oceanographic data were collected with a free-falling MSS-90L microstructure profiler (MSS) from Sea & Sun Technology (SST, Germany), equipped with two PNS06 airfoil shear probes for estimates of the dissipation rate of turbulent kinetic energy, a FP07 fast-response thermistor, precision CTD (Conductivity, Temperature, Depth) sensors, and an oxygen sensor. All sensors were sampled at 1,024 Hz and digitized at 16-bit resolution. The sinking velocity of the profiler was adjusted to about 0.7 m s^{-1} . In total, 50 MSS casts were collected, of which 47 casts are located in the study region and three casts at the reference station (Figures 1a and 1c). From the MSS profiles, conservative temperature Θ , absolute salinity S_A , and buoyancy frequency N were computed according to the international TEOS-10 standard for seawater (IOC, SCOR and IAPSO, 2010). The location of the transects and positioning of MSS casts was based on real-time acoustic observations.

Acoustic observations were conducted with a Simrad ES70-7C (45–90 kHz) split beam transducer (Kongsberg, Norway) in combination with a Simrad EK80 wideband transceiver, using a ping rate of 1 Hz and a pulse duration of 4.1 ms. The received signal was processed using pulse compression and compensated for spherical spreading and absorption. The system was calibrated in the study area during the measuring campaign with a 38.1-mm tungsten carbide sphere, as described in Demer et al. (2015). R/V *Electra's* Seapath 330+ RTK GPS unit and a MRU5+ motion sensor were used for accurate positioning and compensation of (wave-induced) heave in the acoustic observations. We show calibrated acoustic backscatter strength per volume (S_v) with units of dB re $1 \mu\text{Pa}$.

While the MSS profiler measures small-scale turbulent velocity fluctuations, the EK80 measures acoustic backscatter from density and sound speed fluctuations, caused by temperature and salinity fluctuations (e.g., Lavery et al., 2013). Therefore, acoustics only register turbulent structures in regions with existing background temperature and salinity gradients, where turbulent stirring induces temperature and salinity microstructure and thus increased acoustic backscatter (Muchowski et al., 2022). In contrast, MSS measurements show dissipation rates also in well-mixed parts of the water column. Thus, the acoustic observations indicate regions where mixing of different water masses occurs and where the diapycnal transport of salt and/or heat is increased. Additionally, the EK80 records strong biological scattering in this data set. Muchowski et al. (2022) showed that in areas where biological scattering does not dominate the signal, turbulent microstructure is the primary source of acoustic backscatter recorded with the R/V *Electra* EK80 system in this region and time of year. In this study, real-time acoustic observations enabled us to plan positions of the MSS measurements and to target local mixing hotspots.

Acoustic Doppler Current Profiler (ADCP) data were collected using *Electra's* hull-mounted 600 kHz Workhorse ADCP (Teledyne RDI, USA) (see Figure S1 in Supporting Information S1). This instrument provided reliable data down to 40–50 m water depth and therefore did not include most of the halocline region below approximately 50 m depth. ADCP data were used to align the acoustic EK80 observations with the in situ MSS measurements as well as to discuss the underlying mechanisms of the observed mixing.

To estimate turbulent mixing, the turbulent vertical diffusion coefficient k_z is calculated from the dissipation rate of turbulent kinetic energy ϵ , following the Osborn (1980) model:

$$k_z = \gamma \epsilon N^{-2}, \quad (1)$$

where N is the buoyancy frequency of the background stratification and γ the flux coefficient, here assumed to be equal to 0.2 (Gregg et al., 2018).

The vertical transport due to turbulent mixing, F_{zX} , of a tracer, X (e.g., salinity, heat, oxygen, nutrients) is calculated from Fick's law

$$F_{zX} = -k_z \cdot \frac{\partial X}{\partial z} \cdot \rho, \quad (2)$$

where z is defined positive upward and ρ is the in-situ water density.

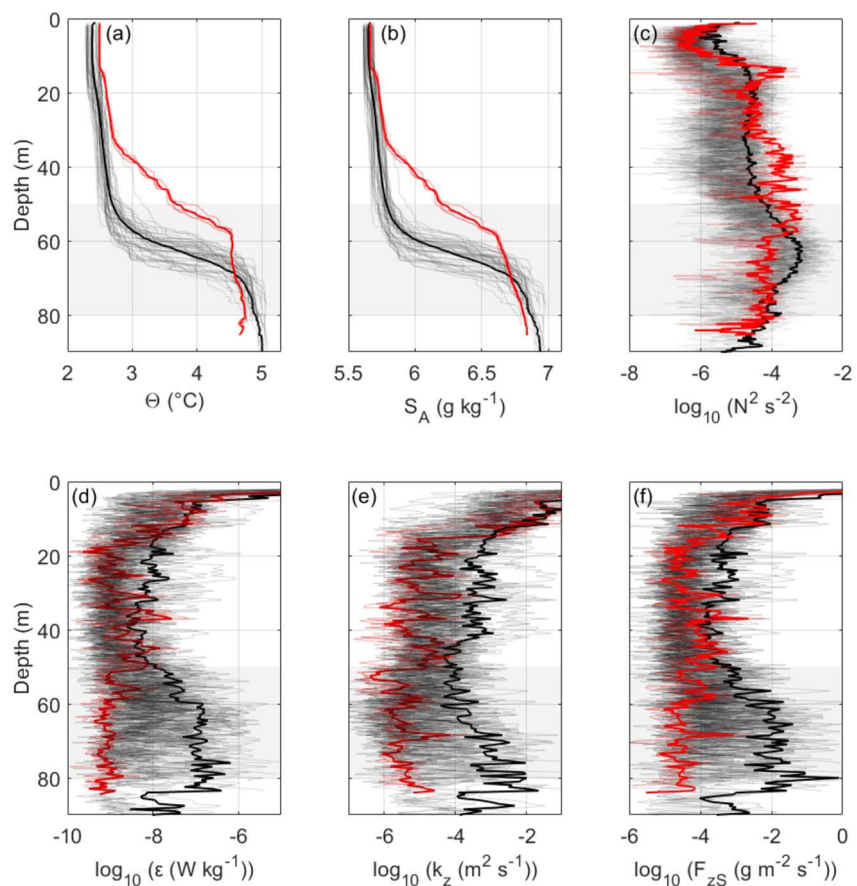


Figure 2. (a) Conservative temperature (Θ), (b) absolute salinity (S_A), (c) buoyancy frequency (N^2), (d) dissipation rate of turbulent kinetic energy (ϵ), (e) vertical turbulent diffusivity (k_z) and vertical salt flux (F_{zs}) from 47 MSS casts in the study region (black) and 3 MSS casts at the reference station (red) together with their arithmetic mean values (bold). Positions of MSS casts are shown on map in Figure 1 (MSS 76–125). Gray shaded patch marks the halocline in the study region.

3. Results and Discussion

3.1. Turbulence Observations and Impact

Microstructure (MSS) profiles of conservative temperature Θ , absolute salinity S_A , and buoyancy frequency N show that the stratification in the study area (transect T1–T7, Figure 1c) is characterized by a halocline between 50 and 80 m water depth. The halocline separates warmer and saltier deep water from a cooler and fresher surface layer (Figure 2). The entire water column is stably stratified with a buoyancy frequency that ranges from $N^2 = 10^{-6} \text{ s}^{-2}$ in the surface- and bottom layers to $N^2 = 10^{-3} \text{ s}^{-2}$ in the halocline. To isolate the effect of the corrugated topography in the study area, we compare our data to reference transect T7, south of the study region (Figure 1a, in red), where we expect a similar meteorological forcing but no significant topographic effects due to the larger water depth and the smooth seafloor. At this reference station, the halocline is shallower and broader but shows comparable maximum values for N^2 (Figure 2).

Average energy dissipation rates ϵ ($1.1 \times 10^{-7} \text{ W kg}^{-1}$) and vertical turbulent diffusivities k_z ($7 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$) are increased by two orders of magnitude in the halocline of the study region (Figures 2d–2f) compared to the reference station as well as other parts of the Baltic Sea.

The mean salinity flux F_{zs} ($0.01 \text{ kg m}^{-2} \text{ s}^{-1}$) through the halocline (50–80 m depth), calculated from Equation 2 and averaged over all MSS profiles in the study region, is one order of magnitude above the average in the Baltic Sea, including upwelling (Reissmann et al., 2009).

Vertical salt fluxes are an intrinsic part of the vertical overturning circulation of the Baltic Sea deep basins. The circulation of deep water in the Bothnian Sea (at around 60 m depth (Westerlund et al., 2022)) is directly impacted

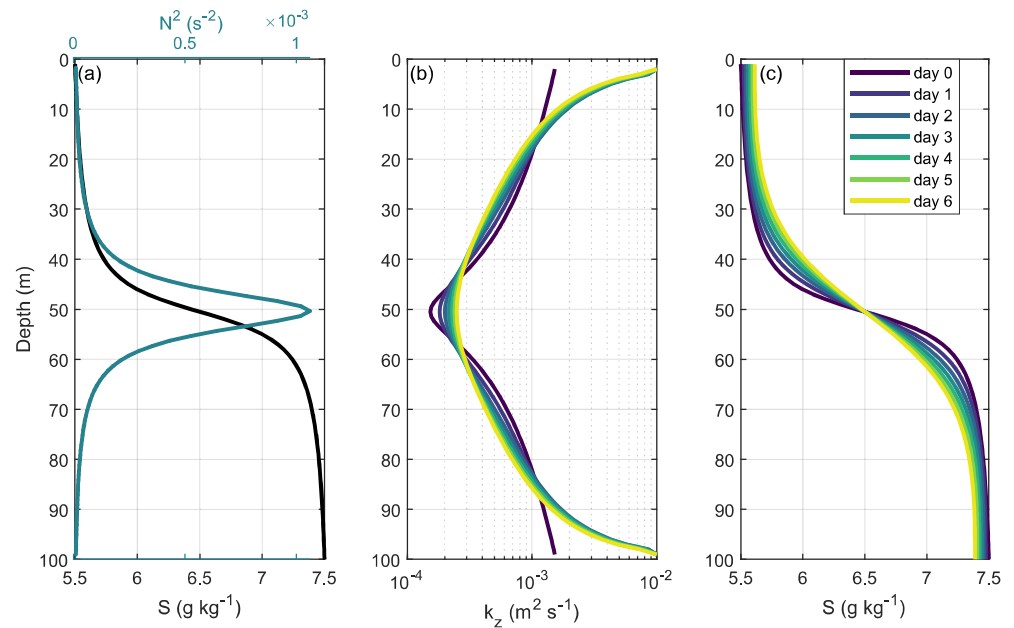


Figure 3. Diffusion model of the study region. (a) Initial salinity profile and corresponding buoyancy frequency, (b) initial turbulent vertical diffusivity profile (dark blue) and its development over time, (c) initial salinity profile (dark blue) and its development over time.

by mixing across the halocline (30–80 m depth) in our study region. Locally, vertical salt fluxes caused by diapycnal mixing lower the stratification and thereby the amount of energy needed for vertical transport and also directly ventilate the deep water by increasing vertical transport rates.

To investigate the impact of the observed mixing and vertical salt flux rates on the evolution of the halocline and the adjacent surface and deep-water layers, we numerically solved the one-dimensional diffusion equation with a vertically variable diffusivity, approximated as $k_z = \min(\alpha N^{-1}, k_{\max})$ (Stigebrandt, 1987, Equation 2.2), with $\alpha = 5 \times 10^{-6}$ and $k_{\max} = 10^{-2} \text{ m}^2 \text{ s}^{-1}$. With these parameters, the model reproduces the observed diffusivities in the halocline, and has the advantage, compared to a model with a prescribed (fixed) diffusivity profile, that the diffusivity dynamically adapts to the evolution of the halocline. The initial conditions are chosen to approximate the observed salinity profile by an inverse tangent function. Model results show (Figure 3) that the halocline width nearly doubles and that salinities in the layers above and below the halocline are modified by about 0.1 g kg^{-1} over a period of 5 days, which would correspond to a typical residence time for surface-layer waters in the study area (horizontal scale: 20 km) for typical current speeds of 0.05 m s^{-1} (see Figure S1 in Supporting Information S1). As the deep-water branch of the estuarine circulation in the area is predominantly northward, the observed mixing freshens the deep-water in the Bothnian Sea, adjacent to the north of the study region. Measured average deep-water salinities are about 7 g kg^{-1} south of the study region and about 6.5 g kg^{-1} to its north (Westerlund et al., 2022, stations F64 and F33). The observed mixing could therefore account for a substantial amount of the deep-water modification in the Åland Sea. Similarly, the predominantly southward flowing surface layer, that will eventually become surface water in the Northern Baltic Proper, is significantly enriched with salt due to the observed mixing.

3.2. Broadband Acoustic Observations

The unique advantage of acoustic observations compared to the traditional microstructure profiling described above lies in their spatial resolution, revealing the complex geometry and intermittency of mixing near topographic obstacles in a level of detail usually available only from turbulence-resolving numerical simulations (Puthan et al., 2022). Figure 4 shows that mixing in our study area occurs in confined regions, especially near hilltops that reach into the halocline and in detached mixing bands that are horizontally correlated on scales of 0.1–1 km. Overall, we see an excellent one-to-one correspondence between regions with enhanced acoustic

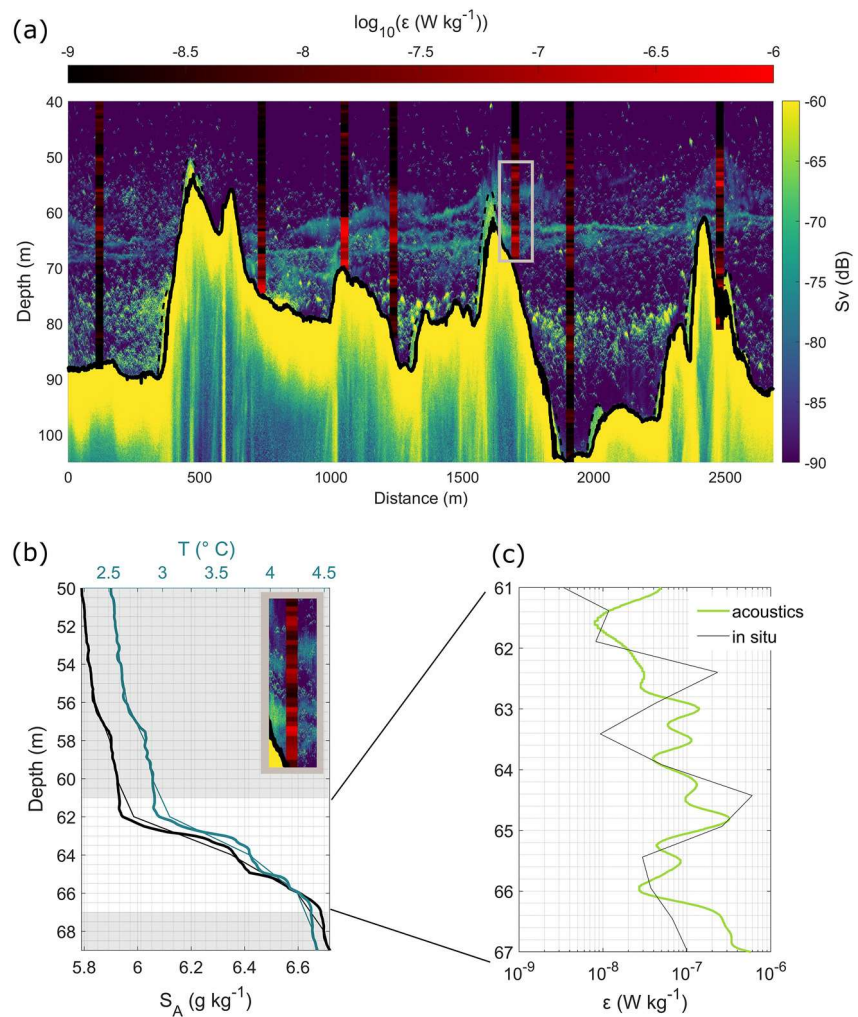


Figure 4. (a) EK80 echogram showing transect T2, sampled 3 March 2020, 09:08–10:00 UTC, with seafloor bathymetry marked in black, sidelobes marked by dashed black line. Vertical profiles show dissipation rates from MSS casts 82–88, color-coded in red. (b) Conservative temperature (turquoise) and absolute salinity (black) profile from MSS 86, (c) dissipation rate ϵ from MSS cast 86 (black) and inferred from acoustic backscatter (green) in combination with temperature and salinity profile shown in (b).

backscatter and enhanced energy dissipation from shear microstructure (Figure 4a), and in some cases also good quantitative agreements in the inferred dissipation rates (Figure 4c) in all six transects (not shown here).

Quantitative estimates of energy dissipation rates from acoustic observations in between microstructure profiles are complicated by the lack of commensurate observations of temperature and salinity stratification (extrapolations are highly inaccurate due to the strong spatial variability in this region). Additionally, the acoustic signal is often dominated by biological scattering, especially in the deeper layers below 70 m. We therefore avoid quantitative estimates and integration of dissipation rates based on acoustic backscatter. Nevertheless, the acoustic measurements provide a tool to visualize and map turbulent mixing at high resolution which cannot be achieved with traditional in-situ measuring techniques.

3.3. Mixing Mechanisms

Local mixing hotspots seen in Figure 4 are likely caused by a combination of mixing mechanisms related to the rough bathymetric features. To analyze the relevance of different potential mixing mechanisms, we define the most important bulk parameters characterizing the study area: $h = 20$ m as a typical vertical scale of the bathymetric features (average amplitude of the features from nearby bottom to top, as seen in Figure 4a),

$L_N = 30$ m as the thickness of the halocline (Figure 2b), $N = 0.015$ s⁻¹ for the average buoyancy frequency in the halocline (Figure 2c), $f = 1.26 \times 10^{-4}$ s⁻¹ for the Coriolis parameter, and $u = 0.05$ m s⁻¹ for typical velocities at the bottom of the ADCP range, that is, at the upper end of the halocline region (see Figure S1 in Supporting Information S1). The latter estimate is the most uncertain as the currents are fluctuating and measurements in the core of the halocline are lacking. Lateral scales of bathymetric features in this study are anisotropic, ranging from values of the order $d = 500$ m in the cross-ridge (west-east) direction to $d = 2,000$ m in the along-ridge (north-south) direction, respectively (Figure 1c).

Based on the above defined parameters, the non-dimensional topographic Froude number $Fr = u/(Nh)$, relating the square root of kinetic energy of the flow to the square root of the potential energy required to lift up a water parcel in the given stratification (Legg, 2021), can be estimated to approximately 0.17. The small Froude number suggests that much of the flow is blocked or, where possible, flows around the bathymetric features (Puthan et al., 2022) (unfortunately, our ship ADCP data only reach down to about 50 m water depth, which is in the same range as the upper end of the halocline). Near the hilltops, however, overflow could be possible. The Rossby number Ro , relating the inertial force of the flow to the strength of the Coriolis force on it, is $u/(fd) \approx 0.2 - 0.8$, where the smaller and larger values of Ro correspond to our along-ridge and cross-ridge estimates of d . These small to moderate values suggest that the flow is significantly affected by rotation. The intrinsic frequency of lee waves, $\omega = 2\pi u/d$, is about $(1.6 - 6.3) \times 10^{-4}$ s⁻¹ which is larger than f but much smaller than N , meaning that lee waves are possible but propagate with nearly horizontal phase lines. Possible mixing mechanisms are therefore breaking internal lee waves, non-linear hydraulic effects due to flow over bathymetric features, and lee vortices or topographic wake eddies due to flow around them. The horizontal anisotropy of the seafloor topography with bathymetric structures elongated in south-north direction lets us suspect different mixing mechanisms depending on the direction of the flow. For flow over the ridges in east-west direction, we expect a dominating two-dimensional flow leading to a hydraulic response and the formation of lee waves. For flow in south-north direction, we expect the dominating mixing mechanism to be topographic wake eddies. Our observations show similarities to model studies of wake eddies from Puthan et al. (2020, 2022), carried out at a topographic Froude number of 0.2 and 0.15, respectively but for a single hill and at a much larger Rossby number where rotation is less important. Puthan et al. (2022) pointed out that consistently higher dissipation rates are observed inside the thin hydraulic jet evolving at the apex of an obstacle for low Fr (see their Figure 7). The thin, banded structures of enhanced backscatter visible in both our EK80 and shear-microstructure measurements near the top of obstacles (Figure 4) could be interpreted as evidence for this process (again, our ship ADCP data do not reach down to this region).

These qualitative arguments can be substantiated with the help of shear microstructure measurements and theoretical energy dissipation estimates. Energy dissipation due to topographic wake eddies is suggested to scale as u^3/d (e.g., Puthan et al., 2022), yielding dissipation rates of $[0.6-2.5] \times 10^{-7}$ W kg⁻¹, in agreement with our observations ($\approx 1.1 \times 10^{-7}$ W kg⁻¹). As the scaling depends on the flow velocity cubed, uncertainties in u greatly impact its result. The integrated dissipation rate (based on the average dissipation rate $\bar{\epsilon}$ of all 47 MSS profiles) in the halocline of the study region is

$$D_i = \int_{z=50\text{ m}}^{z=80\text{ m}} \bar{\epsilon} \rho \, dz \approx 3.4 \text{ mW m}^{-2}. \quad (3)$$

Assuming that the dissipation rate scaling u^3/d is relevant for the halocline, the depth integrated dissipation (multiplied by the water density), corresponding to Equation 3, would scale as $\rho L_N u^3/d$, where L_N is the thickness of the halocline. With the parameters defined above, the resulting integrated dissipation rates are in the range $[1.3-5.2]$ mW m⁻², close to the observed value. Note that this parametrization for wake eddies is independent of stratification.

Integrated energy dissipation due to internal wave generation at topography in the ocean and the atmosphere is suggested to scale as $\rho N u^2 h^2/d$ in the linear limit (e.g., Arneborg et al., 2017; St. Laurent et al., 2002; Stigebrandt, 1976; Welch et al., 2001) and includes stratification. Using this scaling results in values of D_i in the range $[8-31]$ mW m⁻², that is, larger than the observed value (Equation 3). Previous studies of tidal stratified flow over steep topography (Arneborg et al., 2017; St. Laurent et al., 2002) have shown that 20%–30% of the energy flux calculated with this scaling is dissipated locally. This leads to estimates of D_i in the right order of magnitude as (Equation 3), with more comparable values for horizontal scales of 2,000 m. Studies of atmospheric

lee-waves also show a strong decrease in integrated energy conversion to lee waves relative to the linear limit for small Froude numbers (e.g., Welch et al., 2001) which means that the observed value can be in agreement with those results. There are, however, no clear signs of oblique bands that would be expected from breaking internal lee waves (e.g., Legg, 2021 and references therein; Jalali & Sarkar, 2017; Sarkar & Scotti, 2017). This suggests either that internal waves are not present or that they are horizontal due to the perpendicular transect relative to the northward flow.

4. Conclusions

The presented in-situ microstructure measurements of dynamic turbulent diapycnal mixing near steep small-scale bathymetric hills and ridges that reach into stratified flow have the potential to modify the deep water by about 0.1 g kg^{-1} . Our data suggest that the highly increased turbulent mixing and vertical salt flux rates in the Åland Sea are predominantly caused by topographic wake eddies and impact the larger-scale circulation between basins in the Baltic Sea.

Co-located acoustic observations of stratified mixing are consistent with shear-microstructure measurements but have much higher vertical and horizontal resolution. Thus, they provide insights into the complex anatomy of the mixing, including hotspots of mixing near the summits and crests of the particularly rough bathymetric features. The acoustic observations thereby enable us to map turbulent mixing at unprecedented resolution, which is helpful to identify turbulence hotspots and to determine locations for targeted in-situ microstructure measurements.

Measured dissipation rates ($1.1 \times 10^{-7} \text{ W kg}^{-1}$), vertical diffusivities ($7 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$), and salt flux rates ($0.1 \text{ g m}^{-2} \text{ s}^{-1}$) are 1–2 orders of magnitude larger than values directly observed in the halocline region away from topographic features in this and other studies, and also exceed average values determined from budgets for the Baltic Sea by the same factor (Reissmann et al., 2009). For comparison, Waterhouse et al. (2014) estimated globally averaged vertical diffusivities of $O(10^{-4}) \text{ m}^2 \text{ s}^{-1}$ below 1,000-m depth and $O(10^{-5}) \text{ m}^2 \text{ s}^{-1}$ above 1,000-m depth. More importantly, their analysis of existing data showed that observed energy dissipation rates were consistently smaller than the local energy inputs, suggesting that energy dissipation and mixing occur at locations not included in these data, for example, as these authors speculate, near topographic hotspots at the continental margins.

Topographic slopes in our study area vary between 0.05 and 0.5, which is in the range of typical slopes of approximately 0.04 in canyons and 0.2 on abyssal hills near the Mid-Atlantic Ridge (Mauritzen et al., 2002; K. Polzin, 2004), where highly increased mixing in the abyss has been observed (e.g., Ledwell et al., 2000; K. L. Polzin et al., 1997). Topographic slopes around seamounts range from 0.05 to 0.3 (Carter et al., 2006), congruent with those in our study region. Jalali and Sarkar (2017) and Puthan et al. (2022) modeled dissipation rates near seamounts with slopes of 0.5.

Data Availability Statement

Data are published and accessible for downloading on the Bolin Centre Database website: Julia C. Muchowski, Christian Stranne, Martin Jakobsson, Lars Arneborg, Lars Umlauf, Peter Holtermann (2023). Acoustic and in-situ observations of stratified turbulent mixing over rough bathymetry, Baltic Sea, March 2020. Data set version 1. Bolin Centre Database. <https://doi.org/10.17043/muchowski-2023-midwater-2020-1>.

References

- Alexander, M. J., Geller, M., McLandress, C., Polavarapu, S., Preusse, P., Sassi, F., et al. (2010). Recent developments in gravity-wave effects in climate models and the global distribution of gravity-wave momentum flux from observations and models. *Quarterly Journal of the Royal Meteorological Society*, 136(650), 1103–1124. <https://doi.org/10.1002/qj.637>
- Alford, M. H., Girtton, J. B., Voet, G., Carter, G. S., Mickett, J. B., & Klymak, J. M. (2013). Turbulent mixing and hydraulic control of abyssal water in the Samoan Passage. *Geophysical Research Letters*, 40(17), 4668–4674. <https://doi.org/10.1002/grl.50684>
- Alford, M. H., MacKinnon, J. A., Nash, J. D., Simmons, H., Pickering, A., Klymak, J. M., et al. (2011). Energy flux and dissipation in Luzon Strait: Two tales of two ridges. *Journal of Physical Oceanography*, 41(11), 2211–2222. <https://doi.org/10.1175/JPO-D-11-073.1>
- Arneborg, L., Jansson, P., Staalström, A., & Broström, G. (2017). Tidal energy loss, internal tide radiation, and local dissipation for two-layer tidal flow over a sill. *Journal of Physical Oceanography*, 47(7), 1521–1538. <https://doi.org/10.1175/JPO-D-16-0148.1>
- Beckholmen, M., & Tiren, S. A. (2009). The geological history of the Baltic Sea. A review of the literature and investigation tools. Retrieved from <https://www.osti.gov/etdweb/biblio/963502>

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- Caldeira, R. M. A., Marchesiello, P., Neelin, N. P., DiGiacomo, P. M., & McWilliams, J. C. (2005). Island wakes in the Southern California Bight. *Journal of Geophysical Research*, 110(C11), C11012. <https://doi.org/10.1029/2004JC002675>
- Carter, G. S., Gregg, M. C., & Merrifield, M. A. (2006). Flow and mixing around a small seamount on Kaena Ridge, Hawaii. *Journal of Physical Oceanography*, 36(6), 1036–1052. <https://doi.org/10.1175/JPO2924.1>
- Demer, D. A., Berger, L., Bernasconi, M., Bethke, E., Boswell, K., Chu, D., et al. (2015). *Calibration of acoustic instruments* [Report]. International Council for the Exploration of the Sea (ICES). <https://doi.org/10.25607/OBP-185>
- Elken, J., & Matthäus, W. (2008). Baltic Sea oceanography. In *Assessment of climate change for the Baltic Sea basin* (pp. 379–385).
- EMODnet Bathymetry Consortium. (2020). EMODnet Digital Bathymetry (DTM 2020) [Dataset]. EMODnet Bathymetry Consortium. <https://doi.org/10.12770/BB6A87DD-E579-4036-ABE1-E649CEA9881A>
- Garabato, A. C. N., Polzin, K. L., King, B. A., Heywood, K. J., & Visbeck, M. (2004). Widespread intense turbulent mixing in the Southern Ocean. *Science*, 303(5655), 210–213. <https://doi.org/10.1126/science.1090929>
- Garrett, C., & Kunze, E. (2007). Internal tide generation in the deep ocean. *Annual Review of Fluid Mechanics*, 39(1), 57–87. <https://doi.org/10.1146/annurev.fluid.39.050905.110227>
- Greenwood, S. L., Clason, C. C., Nyberg, J., Jakobsson, M., & Holmlund, P. (2017). The Bothnian Sea ice stream: Early Holocene retreat dynamics of the south-central Fennoscandian Ice Sheet. *Boreas*, 46(2), 346–362. <https://doi.org/10.1111/bor.12217>
- Gregg, M. C., D'Asaro, E. A., Riley, J. J., & Kunze, E. (2018). Mixing efficiency in the ocean. *Annual Review of Marine Science*, 10(1), 443–473. <https://doi.org/10.1146/annurev-marine-121916-063643>
- Jakobsson, M., Stranne, C., O'Regan, M., Greenwood, S. L., Gustafsson, B., Humborg, C., & Weidner, E. (2019). Bathymetric properties of the Baltic Sea. *Ocean Science*, 15(4), 905–924. <https://doi.org/10.5194/os-15-905-2019>
- Jalali, M., & Sarkar, S. (2017). Large eddy simulation of flow and turbulence at the steep topography of Luzon Strait. *Geophysical Research Letters*, 44(18), 9440–9448. <https://doi.org/10.1002/2017GL074119>
- Kunze, E., Firing, E., Hummon, J. M., Chereskin, T. K., & Thurnherr, A. M. (2006). Global abyssal mixing inferred from lowered ADCP shear and CTD strain profiles. *Journal of Physical Oceanography*, 36(8), 1553–1576. <https://doi.org/10.1175/JPO2926.1>
- Lavery, A. C., Geyer, W. R., & Scully, M. E. (2013). Broadband acoustic quantification of stratified turbulence. *The Journal of the Acoustical Society of America*, 134(1), 40–54. <https://doi.org/10.1121/1.4807780>
- Ledwell, J. R., Montgomery, E. T., Polzin, K. L., St. Laurent, L. C., Schmitt, R. W., & Toole, J. M. (2000). Evidence for enhanced mixing over rough topography in the abyssal ocean. *Nature*, 403(6766), 179–182. <https://doi.org/10.1038/35003164>
- Legg, S. (2021). Mixing by oceanic lee waves. *Annual Review of Fluid Mechanics*, 53(1), 173–201. <https://doi.org/10.1146/annurev-fluid-051220-043904>
- Legg, S., & Klymak, J. (2008). Internal hydraulic jumps and overturning generated by tidal flow over a tall steep ridge. *Journal of Physical Oceanography*, 38(9), 1949–1964. <https://doi.org/10.1175/2008JPO3777.1>
- MacKinnon, J. A., Alford, M. H., Voet, G., Zeiden, K. L., Shaun Johnston, T. M., Siegelman, M., et al. (2019). Eddy wake generation from broadband currents near Palau. *Journal of Geophysical Research: Oceans*, 124(7), 4891–4903. <https://doi.org/10.1029/2019JC014945>
- MacKinnon, J. A., Zhao, Z., Whalen, C. B., Waterhouse, A. F., Trossman, D. S., Sun, O. M., et al. (2017). Climate process team on internal wave-driven ocean mixing. *Bulletin of the American Meteorological Society*, 98(11), 2429–2454. <https://doi.org/10.1175/BAMS-D-16-0030.1>
- Mauritzen, C., Polzin, K. L., McCartney, M. S., Millard, R. C., & West-Mack, D. E. (2002). Evidence in hydrography and density fine structure for enhanced vertical mixing over the Mid-Atlantic Ridge in the western Atlantic. *Journal of Geophysical Research*, 107(C10), 3147. <https://doi.org/10.1029/2001JC001114>
- Muchowski, J., Umlauf, L., Arneborg, L., Holtermann, P., Weidner, E., Humborg, C., & Stranne, C. (2022). Potential and limitations of a commercial broadband echo sounder for remote observations of turbulent mixing. *Journal of Atmospheric and Oceanic Technology*, 39(12), 1985–2003. <https://doi.org/10.1175/jtech-d-21-0169.1>
- Nikurashin, M., & Legg, S. (2011). A mechanism for local dissipation of internal tides generated at rough topography. *Journal of Physical Oceanography*, 41(2), 378–395. <https://doi.org/10.1175/2010JPO4522.1>
- Nohr, C., & Gustafsson, B. G. (2009). Computation of energy for diapycnal mixing in the Baltic Sea due to internal wave drag acting on wind-driven barotropic currents. *Oceanologia*, 51(4), 461–494. <https://doi.org/10.5697/oc.51-4.461>
- Nycander, J. (2005). Generation of internal waves in the deep ocean by tides. *Journal of Geophysical Research*, 110(C10), C10028. <https://doi.org/10.1029/2004JC002487>
- Osborn, T. R. (1980). Estimates of the local rate of vertical diffusion from dissipation measurements. *Journal of Physical Oceanography*, 10(1), 83–89. [https://doi.org/10.1175/1520-0485\(1980\)010<0083:EOTLRO>2.0.CO;2](https://doi.org/10.1175/1520-0485(1980)010<0083:EOTLRO>2.0.CO;2)
- Pawlak, G., MacCready, P., Edwards, K. A., & McCabe, R. (2003). Observations on the evolution of tidal vorticity at a stratified deep water headland. *Geophysical Research Letters*, 30(24), 2234. <https://doi.org/10.1029/2003GL018092>
- Polzin, K. (2004). Idealized solutions for the energy balance of the finescale internal wave field. *Journal of Physical Oceanography*, 34(1), 231–246. [https://doi.org/10.1175/1520-0485\(2004\)034<0231:ISFTEB>2.0.CO;2](https://doi.org/10.1175/1520-0485(2004)034<0231:ISFTEB>2.0.CO;2)
- Polzin, K. L., Toole, J. M., Ledwell, J. R., & Schmitt, R. W. (1997). Spatial variability of turbulent mixing in the abyssal ocean. *Science*, 276(5309), 93–96. <https://doi.org/10.1126/science.276.5309.93>
- Puthan, P., Jalali, M., Ortiz-Tarin, J. L., Chongsiripinyo, K., Pawlak, G., & Sarkar, S. (2020). The wake of a three-dimensional underwater obstacle: Effect of bottom boundary conditions. *Ocean Modelling*, 149, 101611. <https://doi.org/10.1016/j.ocemod.2020.101611>
- Puthan, P., Pawlak, G., & Sarkar, S. (2022). Wake vortices and dissipation in a tidally modulated flow past a three-dimensional topography. *Journal of Geophysical Research: Oceans*, 127(8), e2022JC018470. <https://doi.org/10.1029/2022JC018470>
- Reissmann, J. H., Burchard, H., Feistel, R., Hagen, E., Lass, H. U., Mohrholz, V., et al. (2009). Vertical mixing in the Baltic Sea and consequences for eutrophication—A review. *Progress in Oceanography*, 82(1), 47–80. <https://doi.org/10.1016/j.pocean.2007.10.004>
- Sarkar, S., & Scotti, A. (2017). From topographic internal gravity waves to turbulence. *Annual Review of Fluid Mechanics*, 49(1), 195–220. <https://doi.org/10.1146/annurev-fluid-010816-060013>
- Stigebrandt, A. (1976). Vertical diffusion driven by internal waves in a sill fjord. *Journal of Physical Oceanography*, 6(4), 486–495. [https://doi.org/10.1175/1520-0485\(1976\)006<0486:VDDBIW>2.0.CO;2](https://doi.org/10.1175/1520-0485(1976)006<0486:VDDBIW>2.0.CO;2)
- Stigebrandt, A. (1987). A model for the vertical circulation of the Baltic deep water. *Journal of Physical Oceanography*, 17(10), 1772–1785. [https://doi.org/10.1175/1520-0485\(1987\)017<1772:AMFTVC>2.0.CO;2](https://doi.org/10.1175/1520-0485(1987)017<1772:AMFTVC>2.0.CO;2)
- St. Laurent, L. C., Simmons, H. L., & Jayne, S. R. (2002). Estimating tidally driven mixing in the deep ocean. *Geophysical Research Letters*, 29(23), 2106. <https://doi.org/10.1029/2002GL015633>
- Warner, S. J., & MacCready, P. (2009). Dissecting the pressure field in tidal flow past a headland: When is form drag “real”. *Journal of Physical Oceanography*, 39(11), 2971–2984. <https://doi.org/10.1175/2009JPO4173.1>

- Waterhouse, A. F., MacKinnon, J. A., Nash, J. D., Alford, M. H., Kunze, E., Simmons, H. L., et al. (2014). Global patterns of diapycnal mixing from measurements of the turbulent dissipation rate. *Journal of Physical Oceanography*, 44(7), 1854–1872. <https://doi.org/10.1175/JPO-D-13-0104.1>
- Welch, W. T., Smolarkiewicz, P., Rotunno, R., & Boville, B. A. (2001). The large-scale effects of flow over periodic mesoscale topography. *Journal of the Atmospheric Sciences*, 58(12), 1477–1492. [https://doi.org/10.1175/1520-0469\(2001\)058<1477:TLSEOF>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<1477:TLSEOF>2.0.CO;2)
- Westerlund, A., Miettunen, E., Tuomi, L., & Alenius, P. (2022). Refined estimates of water transport through the Åland Sea in the Baltic Sea. *Ocean Science*, 18(1), 89–108. <https://doi.org/10.5194/os-18-89-2022>
- Wüest, A., & Lorke, A. (2003). Small-scale hydrodynamics in lakes. *Annual Review of Fluid Mechanics*, 35(1), 373–412. <https://doi.org/10.1146/annurev.fluid.35.101101.161220>