



Surface wave impacts on turbulent roughness length parameterization

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ABSTRACT

The interactions between sea surface waves and ocean circulation are often represented using simplified parameterizations that rely on open-ocean calibrations whilst using local wind conditions. More refined estimates of these interactions and their impact on hydrodynamics can be achieved by using explicit forcing from a wave model. This transition from implicit to explicit wave-dependence requires revisiting existing turbulence scheme parameterizations, particularly in coastal waters where the scale of wave-ocean interactions differs from the open ocean and wave growth is often limited by fetch or wind duration. In this study, we optimize the roughness length parameterization in the generic length-scale (GLS) turbulence scheme, using regional wave data from the Baltic and North Seas, and assess the impacts on thermal stratification. The recalibrated parameterization reduces the roughness length under high winds, better representing the regional limitations for wave-growth, and leads to an improved representation of sea surface temperature (SST). We find recalibration particularly important for moderating the impacts of explicit wave-modified ocean-side stress, which is conceptually different from the bulk stress, and leads to large discrepancies with the default parameterization, especially under active wave-growth. Although thermocline depth representation is improved in wave-forced experiments, the definition may still lead to overly enhanced mixing under fetch-limited conditions. The regional limitations are best captured by scaling roughness length with significant wave height, but existing formulations should take account of the energetically distinct wind-sea and swell regimes. In wave-forced setups, this can be achieved by replacing wave-height-based flux estimates with wave-model-computed turbulent kinetic energy (TKE).

1. Introduction

Surface waves modulate the roughness of the sea surface, modifying boundary layer processes and mixing both in the ocean-surface boundary layer (OSBL) and in the marine-atmospheric boundary layer. By redistributing momentum and energy within the atmosphere-ocean interface, surface waves are critical in the regulation of large-scale air-sea-climate interactions (Qiao et al., 2016; Babanin, 2023).

The strength and characteristics of wind-wave impacts depend on multiple factors, including wind forcing, ocean currents, sea surface height, and underlying bathymetry. In coastal waters, the impacts are particularly pronounced and are often observed as upwelling and downwelling events (Wu et al., 2019), mixed layer deepening induced by storms (Bruciaferri et al., 2021), and amplified sea surface height (SSH) variations (Arns et al., 2017; Leijala et al., 2018). As waves shoal and steepen over sloping bathymetry, breaking becomes more common,

thereby enhancing vertical mixing and turbulent kinetic energy (TKE) dissipation (Huang and Qiao, 2010). The impacts of wave-driven mixing and transport are further shaped by vertical stratification, which modulates the oceanic response to mechanical forcing and the rate at which energy is dissipated (du Plessis et al., 2026).

1.1. Modeling wave impacts on OSBL

Historically, computational cost has placed a limit on attempts to explicitly resolve the surface wave field in models that describe boundary layer processes. Instead, stand-alone models with simplified parameterizations have been used to represent the impacts of surface waves. The early models represented surface waves as constants (Charnock, 1955), but later these formulations were replaced by semi-empirical and implicit correlations (Craig and Banner, 1994; Taylor and Yelland,

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2001). Recently, advances in computational capacity have enabled a more detailed investigation of the boundary layer dynamics using explicit wave information.

As wind-forced surface waves grow, the momentum flux from wind is absorbed into the young wave field. Waves mature when the local wind dies or changes direction. Growing wind-seas (low wave-ages) are characterized by steep waves and frequent wave-breaking that leads to enhanced TKE injection and mixing in the OSBL. In these cases, the wave-modified ocean-side stress can be greater than the local wind stress (Huang and Qiao, 2021). In contrast, under swell conditions (high wave-age), the non-breaking waves outpacing the local wind can transfer momentum to the atmosphere. Zhao et al. (2022) found that the non-breaking waves can still have an important contribution to OSBL mixing.

Crucially, the wave-modified ocean-side stress is a balance between concurrent momentum uptake and release across the wave spectrum. Stand-alone hydrodynamic models typically neglect these processes, deriving ocean-side stress directly from wind stress without accounting for wave modifications. Long-term simulations highlight the significance of this discrepancy. Based on a 30-year global forecast, Wu et al. (2022) reported a mean relative difference of 6% between wind and wave stress magnitudes, with extremes exceeding 9% and the largest differences observed near the coast. Waves can also cause directional offsets, and Qiao et al. (2021) found that this misalignment increases with wave-age and with swell dominance. These differences have been found to be linked to thermal biases (Breivik et al., 2015; Alari et al., 2016; Wu et al., 2019), as well as to SSH prediction errors (Staneva et al., 2021; Grayek et al., 2023) in stand-alone hydrodynamic models. Moreover, Breivik et al. (2015) found that wave-modified ocean-side stress and energy fluxes can have a greater effect on upper-ocean hydrodynamics than Stokes-Coriolis forcing that impacts the structure of the surface Ekman layer and Wu et al. (2019) found the relative contribution larger than that of explicit TKE flux released in wave-breaking.

The ocean-side stress defines water-side friction velocity, a key parameter in modeling turbulent mixing. In the generic length-scale (GLS) turbulence scheme (Umlauf and Burchard, 2003), it commonly impacts the roughness length associated with mixing length scale, wave-enhanced TKE flux and dissipation following the (Craig and Banner, 1994) parameterization (CB94) (e.g. Refray et al., 2015; Madec and NEMO System Team, 2019). As detailed by Toba et al. (2001), the definition of roughness is in no way univocal, and several parameterizations exist. At the same time, as Craig and Banner (1994) have noted, the CB94 model is sensitive to the definition of the roughness length.

Although theoretical definitions and observational constraints exist for TKE dissipation and roughness (see also Gemmrich and Farmer, 1999; Agrawal et al., 1992), most ocean models rely on local-wind-based Charnock type parameterizations that are typically tuned to reproduce surface temperatures and stratification without explicit wave information. In practice, the related free parameters may compensate for biases in near-surface mixing and heat fluxes that arise when the underlying formulations do not fully represent the locally varying wave conditions.

1.2. Representing regional wave conditions

The extent of wave impacts on OSBL dynamics is highly dependent on the regional limitations for wave-growth, namely wind duration and fetch. Law Chune and Aouf (2018) noted that open-sea parameterizations describing steady wave regimes may not work for fetch-limited areas or for regions with transient wind — both common in coastal seas. Additionally, shallow depths can challenge open ocean formulations; whilst wave-breaking-induced mixing rarely reaches the thermocline in the open ocean (Babanin, 2023), shallow water mixing can extend all the way to the sea-floor.

Wu et al. (2022) noted that whilst the CB94 wave-breaking parameterization performs well with mature waves, it may misrepresent growing and decaying sea states, where wave-breaking intensity and energy transfer vary dynamically, with implications for both stand-alone and coupled models. In general, the wave-breaking parameterization can be optimized either by modifying the existing free parameters or by integrating explicit wave information. In addition to the explicit wave parameters described in the previous section, wave-ocean interactions have been studied using explicit wave model computed significant wave height as a proxy for the turbulence model's roughness length to replace the implicit wind-speed based formulation.

Despite advances in wave-ocean coupling, a significant fraction of operational forecasting systems still rely on stand-alone ocean model approaches that lack the explicit information about wave spectra needed to resolve wave-driven modifications to surface roughness. As noted by Fragkou et al. (2023), coupling models originally designed to operate independently can lead to new uncertainties in calibration, and further tuning may be needed to preserve physical consistency and avoid double-counting. This is evident in the process of introducing explicit wave forcing into ocean models calibrated to implicitly account for waves.

In the Baltic and North Seas, wave information has been integrated to Copernicus Marine Service ocean forecasts to different extents. In the North West Shelf product (EU Copernicus Marine Service Product, 2025a), wave-modified ocean-side stress, Stokes-Coriolis force and wave height based roughness are included. In the Baltic Sea (EU Copernicus Marine Service Product, 2024b), only Stokes-Coriolis forcing is included in the Nemo Nordic (Nord et al., 2021) based forecast. Kärnä et al. (2021) demonstrated that this setup produces a cold bias in the surface layer during summer and concluded that this was likely related to the estimation of vertical mixing. Moreover, Westerlund and Tuomi (2016) found (using an earlier version of the model, described by Hordoir et al., 2019) that the vertical temperature structure in the Baltic and North Sea Nemo Nordic model was sensitive to the choice of turbulence scheme (including CB94) and suggested that calibrating the wave-breaking parameterization for regional conditions could improve the representation of thermal dynamics.

1.3. Aims of this study

We study how the representation of turbulent roughness length influences the performance of a hydrodynamic model in thermally stratified conditions. Focusing on how the GLS turbulence model's wave-related parameterizations reflect regional wave conditions, we recalibrate the roughness length parameterization for the Baltic and North Sea region, where wave-growth is often fetch-limited. The impacts of regional calibration are considered with stand-alone NEMO together with explicit wave forcing from WAVEWATCH III, focusing on the development of seasonal thermal stratification in the Baltic Sea. The impacts are compared to those of roughness from explicit wave height, wave-modified ocean-side stress, and Stokes-Coriolis force.

This paper is structured as follows: Section 2 describes models, data and regional characteristics. We then cover roughness length theory and recalibrate the TKE roughness length parameterization for fetch-limited regions (Section 3), and outline the experimental design and describe the model configurations (Section 4). Section 5 presents the differences between the roughness parameterizations and their impacts on thermal dynamics. We discuss integrating regional wave information into turbulence models in Section 6 and conclude the study in Section 7.

2. Models and data

We investigate surface wave impacts on vertical mixing and thermal stratification using a wave-forced ocean model for the semi-enclosed, coastal Baltic and North Seas. We present the component models in the respective subsections (Sections 2.1.1 and 2.1.2), followed by regional conditions (Section 2.2) and datasets used for model validation (Section 2.3). Details of the experiments will be covered later (Section 4).

2.1. Models

2.1.1. Surface waves – WAVEWATCH III

We employ the WAVEWATCH III® (WW3) model (Tolman, 1991, 1992) to compute the surface wave spectrum and the derived quantities relevant to OSBL momentum and energy budgets. WW3 is a third-generation wave model that solves the action balance equation

$$\partial_t N + \partial_x(c_x N) + \partial_y(c_y N) + \partial_\sigma(c_\sigma N) + \partial_\theta(c_\theta N) = \frac{S}{\sigma} \quad (1)$$

where $N = N(x, y, \sigma, \theta)$ is the action density of the energy spectrum, c represents the wave energy propagation speed, x, y are Cartesian dimensions, σ is intrinsic frequency and θ is the direction of propagation. Partial derivatives are denoted as $\partial_n = \frac{\partial}{\partial n}$. With ST4 physics (Ardhuin et al., 2010), the source terms for the wind input parameterization S_{in} are adapted from Janssen (1991), for non-linear wave-wave interactions S_{nl} from Hasselmann et al. (1985), and for dissipation and wave-breaking S_{ds} from Ardhuin et al. (2010). The ice transmissions for wave propagation are considered by simple ice-blocking (Tolman, 2003).

2.1.2. Hydrodynamics – NEMO

We use the NEMO 3D ocean circulation model that solves prognostic variables, including SSH, currents, temperature, and salinity. Our configuration employs the ocean dynamics and thermodynamics packages, and the sea ice engine (SI3), described in detail by Madec and NEMO System Team (2019). Vertical mixing is computed using the generic length-scale (GLS) turbulence closure scheme, a 2 1/2 equation model solving the prognostic equations of TKE k and length-scale ψ , from which dissipation rate ϵ and intrinsic length l are derived (Umlauf and Burchard, 2003, 2005).

The transport equations of TKE and the generic statistical field variable $\psi = \tilde{\psi}(k, \epsilon)$ are written in the general form as

$$\begin{aligned} \partial_t k + u_i \partial_{x_i} k &= D_k + P + G - \epsilon \\ \partial_t \psi + u_i \partial_{x_i} \psi &= D_\psi + \frac{\psi}{k} (C_{\psi 1} P + C_{\psi 3} G - C_{\psi 2} \epsilon) \end{aligned}$$

where D_k, D_ψ are turbulent and viscous transport terms for the variables, P turbulence production by mean shear, G turbulence production by buoyancy, $C_{\psi n}$ are constants determined by the selected closure type. The TKE and length-scale are related by diagnostic equation

$$\psi = C_{0\mu}^p k^m l^n$$

enabling solving ϵ for different pairs of k, ψ , as $C_{0\mu}^p, p, m, n$ are constants. For $k - \epsilon$ model used in our work, the length-scale and dissipation rate are equal $\psi = \epsilon$ and the intrinsic length $l \sim k^{3/2} \epsilon^{-1}$. For the sake of clarity, we refer to Umlauf and Burchard (2005), Refray et al. (2015) and Madec and NEMO System Team (2019) for the full forms of the GLS equations. In our experiments, the surface and bottom boundary conditions are calculated using the Neumann boundary conditions, and Canuto A definition (Canuto et al., 2001) is used for the stability function.

Wave-breaking enhances turbulence near the ocean surface (Terray et al., 1996), and this injection of TKE enhances vertical mixing. The TKE flux ϕ_{oc} is often parameterized as a function of the water-side friction velocity w_* and roughness length z_0 , following the CB94 parameterization that enhances turbulence compared to wall-layer formulations. In this case, explicit shear production is not included, as the surface TKE is controlled by momentum input through wave-breaking (Reffray et al., 2015). The roughness length can be computed based on 1) a standard Charnock parameterization based on local wind, analogous to air-side definitions, 2) parameterized significant wave height H_s with a wave-age-dependent, modified Charnock formulation, or 3) by assuming linear scaling with the wave model significant wave height H_s (independent of friction velocity). We focus on definitions 2 (wave-age formulation, available in stand-alone models) and 3 (significant wave height formulation).

2.2. Model domain: The Baltic and North Seas

We examine the representation of regional wave conditions in the semi-enclosed Baltic and North Seas, where the respective mean depths are 54 and 90 m (including the Norwegian trench). The Baltic Sea is characterized by seasonal thermal stratification and winter ice cover, a permanent halocline and sill-bounded estuarine circulation resulting in residence time of ca. 40 years (Döös et al., 2004). In the North Sea, dynamical differences are more pronounced due to tidal currents and strong flows through the English Channel and along the British Isles as well as shallow regions mixed throughout the year. Due to the immediate dynamical differences between the basins, we focus on analyzing the impacts of surface wave formulations on seasonally developing thermal stratification in the Baltic Sea within the year 2021. As detailed by Hordoir et al. (2019), the North Sea is crucial in the setup, which is why we discuss the validity of the parameterizations in the turbulence model in the context of both regions.

In both regions, seasonal variations in wave conditions are related to variability in atmospheric forcing. The mean values of significant wave height H_s are typically highest during winter, except for the sub-basins with seasonal ice cover, where the highest values are reached during autumn (Tuomi et al., 2011). Spring and summer have a considerably milder wave climate. The highest mean values of H_s in the Baltic Sea are seen in the Baltic Proper, up to 1.75 m (Björkqvist et al., 2018), whereas in the North Sea values vary from 1.5 to 2.5 m, being higher in the northern part (Breivik et al., 2021).

Higher waves are observed more frequently in the North Sea, where the 99th percentile of H_s reaches 7 m in the northern part (Breivik et al., 2021). In the Baltic Sea, the same quantity reaches only 4 m (Björkqvist et al., 2018). Maximum wave heights are reached with the combination of high winds and long fetches. The measured record for H_s in the Baltic Sea is 8.2 m, observed by the Northern Baltic Proper wave buoy (Björkqvist et al., 2017) (location shown in Fig. 1). Even with the highest waves, the wave periods (and wavelengths) are generally lower in both seas compared to the open ocean, and thus the relative steepness of waves (ratio of wave height to wave length $H_s \lambda^{-1}$) is higher. Björkqvist et al. (2017) analyzed the maximum values of wave parameters during storms, finding values for the mean inverse wave steepness in the range 25–30.

In the North Sea, long-period NW swell entering from the Norwegian Sea is common. Additionally, northerly and easterly winds can result in regionally generated swell. The Danish Straits function as a low-pass filter limiting the swell propagation to the Baltic Sea leaving the region wind-wave dominated. Due to the small size of the Baltic Sea, wave growth is typically fetch-limited under high winds and storms, duration-limited with low winds, and the narrowness of the gulfs further limits wave growth (Petersson, 2004). The Baltic Sea swell is frequently caused by the crossing wind, and Björkqvist et al. (2021) found that the relative contribution of the swell to total energy of the wave field is considerably smaller than in the open ocean. Notably, a large part of the total energy of the wave field is contained in the growing wind-sea.

2.3. Model validation

We assess the model performance on capturing thermal stratification over the year 2021 with SST measurements from the northern Baltic Proper, Bothnian Sea and Bothnian Bay wave buoys and vertical temperature profiles from FMI Argo float (Siirä et al., 2019) missions 6903703, 6903710 and 6903707 (EU Copernicus Marine Service Product, 2024a), locations shown in Fig. 1. Argo measurements from dates with salinity sensor issues were excluded from the analysis, namely 5 September 2021 of the Bothnian Sea (6903710), and 7 September 2021 and 22 November 2021 of the northern Baltic Proper (6903703) data. The wave model validation with in-situ wave buoy and satellite measurements is presented in Appendix A. Statistical methods

used in model validation are described in [Appendix B](#). As the focus is on seasonal thermal stratification, we are primarily interested in the ice-free season. For the northern Baltic Proper and most of the Bothnian Sea, ice-free conditions lasted for the whole year, whereas

in the Bothnian Bay the last remaining ice melted on 20 May 2021. Temperature measurements are analyzed only for ice-free conditions. More information on the 2020–2021 ice winter can be found in [Finnish Meteorological Institute \(2021\)](#).

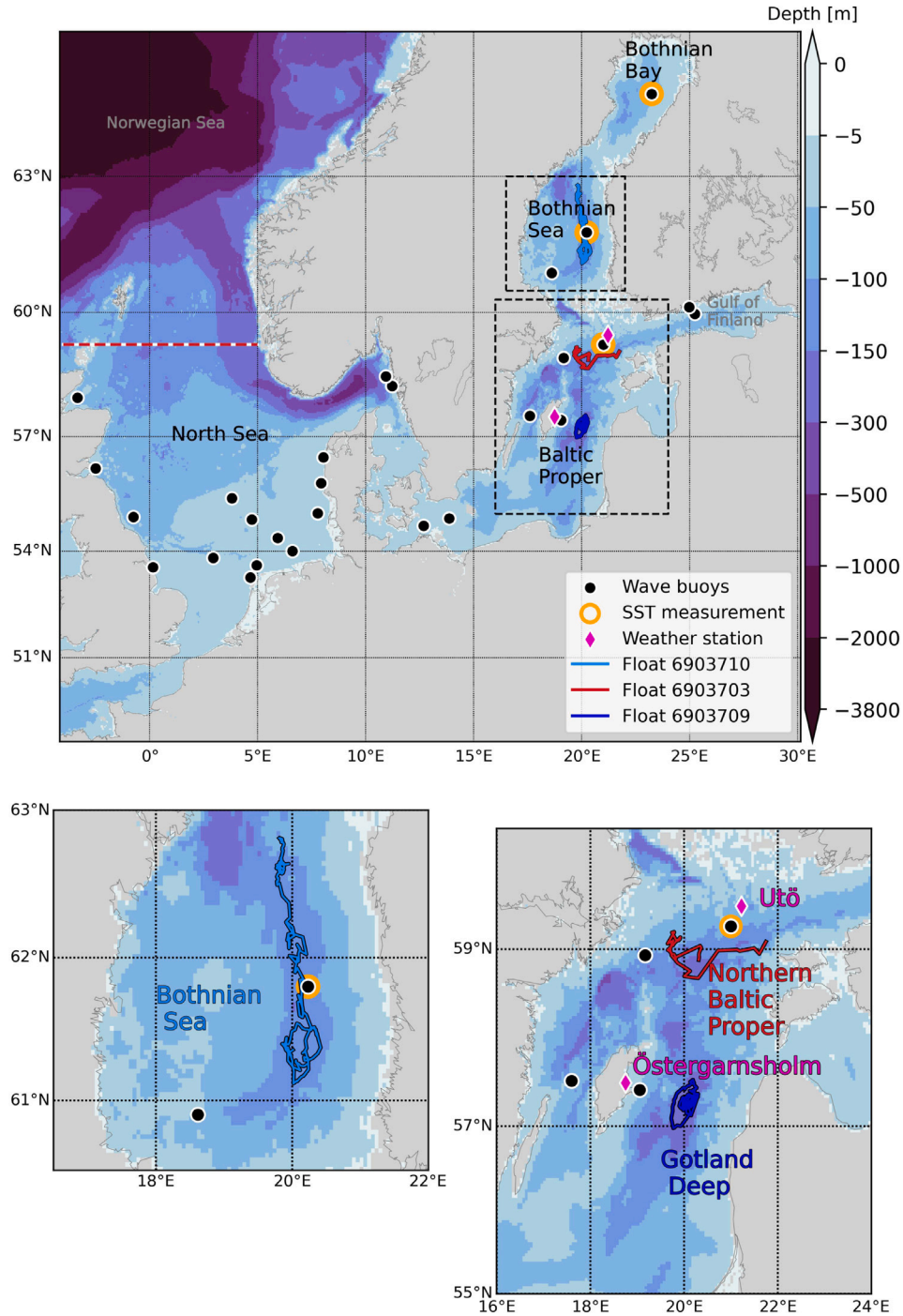


Fig. 1. Bathymetry of the model domain. Wave buoys, SST measurement sites, and marine-atmospheric stations used in analysis are marked with scatters. Argo float trajectories are marked with solid lines. The Nemo Nordic domain's NW boundary is marked with dashed red line, wave model has been run for the whole area.

3. Theory and regional recalibration

We focus on different definitions of the roughness length $z_{0,\text{TKE}}$ within the GLS scheme (see Section 2.1.2) and their descriptions of regional wave conditions. Here, we introduce the theory for approximating roughness length as a function of wave height (Section 3.1.1) and ocean-side stress (Section 3.1.2). Building on this, we recalibrate the existing roughness length parameterization for fetch-limited regions (Section 3.2).

3.1. Theory

The sea surface roughness parameter z_0 describes the scale of momentum and energy exchange at the atmosphere-ocean interface. Grant and Madsen (1979) showed that surface waves increase roughness length under steady currents, as was also discussed by Donelan (1990) and Smith et al. (1992). Whilst Janssen (1991) found that young wind-seas produce greater roughness than swell, Terray et al. (1996) found that the roughness length increases proportional to significant wave height H_s as waves grow.

Although all roughness length formulations represent the impacts of surface waves, different definitions exist to serve different purposes. The air-side roughness $z_{0,a}$ and water-side roughness $z_{0,w}$ influence momentum input, whereas turbulent roughness length $z_{0,\text{TKE}}$ specifically affects vertical mixing in turbulence schemes. Whereas aerodynamic roughness typically ranges from millimeters to centimeters (Charnock, 1955), hydrodynamic roughness $z_{0,w}$ represents physical roughness of the sea surface (up to meters, discussed by e.g. Drennan et al., 2005; Terray et al., 1996, 2000), and TKE roughness length $z_{0,\text{TKE}}$ is an effective scale representing the depth of wave-enhanced turbulence near the surface (Craig and Banner, 1994; Umlauf and Burchard, 2003).

3.1.1. TKE roughness length in hydrodynamic models

Terray et al. (1996) proposed that sea surface roughness could be estimated directly from significant wave height H_s as

$$z_{0,w} = \gamma H_s, \quad (2)$$

where $\gamma \in (0.85, 1.6)$ is a dimensionless constant (based on literature review). Mellor and Blumberg (2004) demonstrated that this can be combined with the empirical results of Donelan et al. (1993) to express significant wave height as a function of wave-age $c_p u_*^{-1}$ (phase speed c_p and air-side friction velocity u_*) and water-side friction velocity w_*

$$H_s = \frac{665}{0.85g} \left[\frac{c_p}{u_*} \right]^{1.5} w_*^2. \quad (3)$$

Building on this, Raschle et al. (2008) presented a semi-empirical parameterization for wave-age based on significant wind-sea wave heights from open ocean locations in the Atlantic. They introduced thresholds for wave-age $[c_p u_*^{-1}]_{\text{ref}} = 30$ and friction velocity $u_{*,\text{ref}} = 0.3 \text{ ms}^{-1}$ to account for wave-growth dependency on fetch and wind duration

$$\frac{c_p}{u_*} = \frac{c_p}{u_*} (u_*) = \left[\frac{c_p}{u_*} \right]_{\text{ref}} \tanh \left(\frac{2u_{*,\text{ref}}}{u_*} \right). \quad (4)$$

Eqs. (2)–(4) result in the roughness length implementation used in NEMO GLS

$$z_{0,\text{TKE}} = \max \left[\gamma \cdot \frac{665}{0.85g} \left(\left[\frac{c_p}{u_*} \right]_{\text{ref}} \tanh \left(\frac{2u_{*,\text{ref}}}{u_*} \right) \right)^{1.5}, z_{0,\text{bg}} \right], \quad (5)$$

where $z_{0,\text{bg}} = 0.02$ represents the background value for surface roughness (Ardhuin et al., 2010; Refray et al., 2015). Crucially, Eq. (5) represents turbulent roughness length as a function of local friction velocity.

3.1.2. Ocean-side stress definition

The water-side friction velocity w_* is computed based on ocean-side stress $w_* = \sqrt{\tau_{oc} \rho_w^{-1}}$. In hydrodynamic models, ocean-side stress is typically equal to wind stress,

$$\tau_{oc} = \tau_a, \quad (6)$$

which reduces the ratio of ocean-side to air-side friction velocities to the ratio of the densities,

$$r = \frac{w_*}{u_*} = \sqrt{\frac{\rho_a}{\rho_w}} \approx \frac{1}{28}. \quad (7)$$

enabling the approximation $u_* = 28w_*$ (see Eq. (5)). Following the NCAR bulk formula (Large and Yeager, 2009), the wind stress is computed as

$$\tau_a = \rho_a C_d |U_{10}|^2, \quad (8)$$

where ρ_a is the density of air, C_d is the neutral drag coefficient (based on air-side surface roughness $z_{0,a}$) and U_{10} is wind speed at 10 m.

Wave models compute ocean-side stress τ_{oc} based on momentum input from wind and modifications due to growth and breaking of surface waves,

$$\tau_{oc} = \tau_a - \tau_w, \quad (9)$$

where τ_a is the incoming momentum flux from the atmosphere under neutral stability (based on air-side friction velocity u_*), and the wave-dependent term τ_w is computed as

$$\tau_w = \rho_w g \int \frac{dk}{c_p} S. \quad (10)$$

Here, ρ_w is the density of seawater, g gravitational acceleration, c_p peak phase speed, and S the sum of energy source terms (see Eq. (1)). In this case, shear stress continuity is dependent on sea state, and friction velocities may not be linearly proportionate ($u_* \neq 28w_*$).

We have identified certain ambiguities in both the derivation and implementation of Eq. (5) that are detailed in Appendix C. Even if multiple alternative functional forms for roughness length exist (Toba et al., 2001), our focus is on demonstrating the impacts of wave-dependent roughness length definitions on mixing using commonly used approaches. Therefore, we take the implemented constants as given in Eq. (5), and only consider the impacts of changing the thresholds $(u_{*,\text{ref}}, [c_p u_*^{-1}]_{\text{ref}})$.

3.2. Calibrating roughness parameterization for regional conditions

The thresholds for wave-age $[c_p u_*^{-1}]_{\text{ref}}$ and critical friction velocity $u_{*,\text{ref}}$ in Eq. (4) describe the wave-age dependency on wind speed corresponding to characteristic values above which wave-growth is typically limited by either fetch or wind duration. We expect that the coastal ocean wave data differ from the open ocean data (original calibration), which implies different dependencies between the local wind, wave height, and the corresponding roughness length. To ensure realistic estimates for vertical mixing, the values of $[c_p u_*^{-1}]_{\text{ref}}$ and $u_{*,\text{ref}}$ should be selected so that the relation between wave-age and air-side friction velocity corresponds to regional conditions.

We compute optimal values for the wave-age and friction velocity thresholds $[c_p u_*^{-1}]_{\text{ref}}$ and $u_{*,\text{ref}}$ in the Baltic and North Seas based on WW3 data (validation of wave model output shown in Appendix A). For this, we compute the wave-age $c_p u_*^{-1}$ based on air-side friction velocity u_* and peak phase speed c_p (derived from peak period T_p and depth z following the dispersion relation $\omega^2 = gk \tanh(kz)$, where ω is angular frequency, g gravitational acceleration and k wavenumber) for the buoy locations shown in Fig. 1 over the year 2021. We find the optimal threshold values by considering the RMSE (see Appendix B) of parameterized wave-age and WW3 wave-age estimates in the friction velocity – wave-age threshold $(u_{*,\text{ref}}, [c_p u_*^{-1}]_{\text{ref}})$ space (Fig. 2(a)).

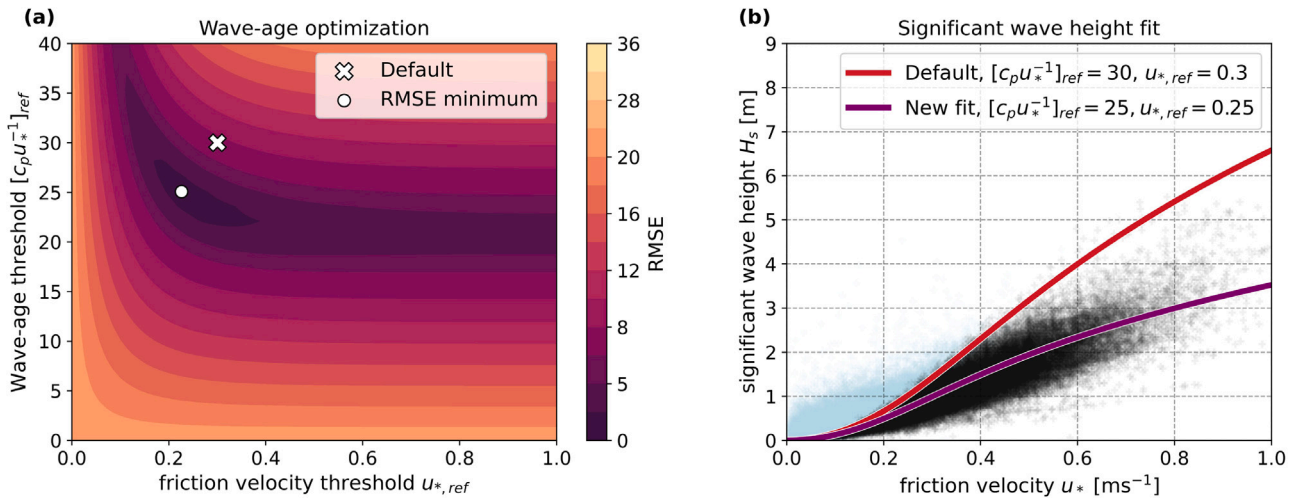


Fig. 2. Wave-age optimizations for the Baltic and North Sea wave buoys in friction velocity – wave-age space (a). Comparison of parameterized and modeled significant wave heights as a function of air-side friction velocity (b). Default parameterization is shown with red and regionally optimized shown with purple line. Black scatter markers represent wind-sea and light blue markers represent swell.

The RMSE minimum is located at $\text{RMSE}_{\min}(u_{*,\text{ref}}, [c_p u_*^{-1}]_{\text{ref}}) = (0.25, 25)$. The wave-age limit $[c_p u_*^{-1}]_{\text{ref}} = 25$ corresponds to the WW3 limit for fully-developed waves. With the regional wave-informed thresholds, Eq. (4) can be written as

$$\frac{c_p}{u_*}(u_*) = 25 \tanh\left(\frac{2 \cdot 0.25}{u_*}\right). \quad (11)$$

The considered fits are shown in Fig. 2(b) together with wave model output and the default fit.

4. Experiments

We assess the impacts of the turbulence model's roughness definition under fetch-limited conditions in the ocean model with implicit and explicit wave parameterizations. Details of the experiments are provided in Section 4.1 and the forced model configuration is described in Section 4.2.

4.1. Examining impacts of regional wave information

We examine the impacts of roughness length definitions through seven ocean model experiments, designed to separate the effects of i) roughness length method ii) ocean-side stress definition and iii) Stokes-Coriolis force. Details of the experiments and modified parameters are provided in Table 1.

In the first group of experiments, roughness length is computed using the stress-dependent implicit formulation of Eq. (5). We consider two specifications of wave-age and friction velocity thresholds:

1. Default thresholds, based on open ocean wave model output, given by Rascle et al. (2008).
2. Optimized thresholds, based on regional wave data, given in Eq. (11).

Each of these is considered with two definitions of ocean-side stress:

1. Wind stress τ_{oc}^{MEMO} , computed by the ocean model (see Eq. (6)).

2. Wave-modified ocean-side stress τ_{oc}^{WW3} , computed by the wave model (see Eq. (9)).

In addition to the implicit formulations described above, we consider one experiment with explicit significant wave height H_s based roughness length, computed following Eq. (2).

We perform three experiments with wind stress (CTRL) to separate the impacts of regionally optimized thresholds (CTRL_MOD) and Stokes-Coriolis force (STCOR). We emphasize that in these experiments, the roughness length definition remains the same in CTRL and STCOR. We run four experiments with wave-modified ocean-side stress. In these, the relative impacts of stress definition (TAUOC), Stokes-Coriolis force (TAUST), regionally optimized thresholds (TAUST_MOD) and explicit H_s based roughness (TAUST_Hs) are considered. In this case, the roughness definition remains the same in TAUOC and TAUST, but differs among all other experiments. A flow diagram of the experiments is presented in Fig. 3.

4.2. Experiment design

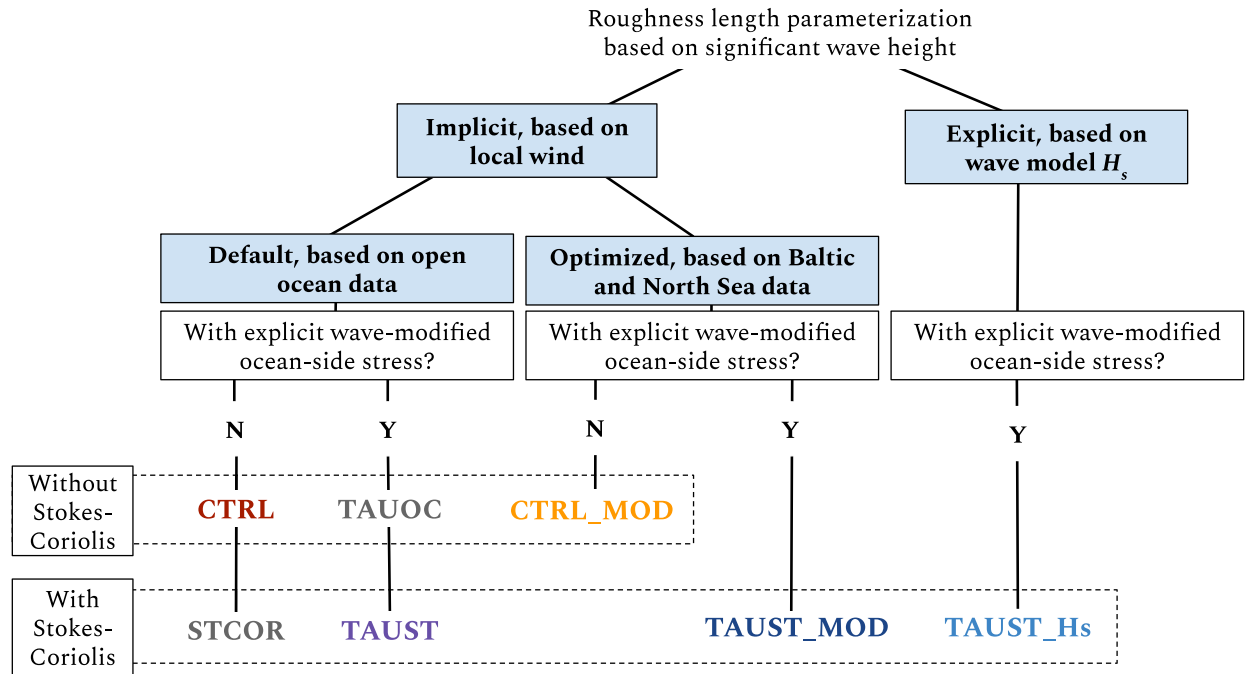
We analyze the thermal dynamics in the previously described experiments (see Table 1) during the year 2021. This period is sufficient to consider development of the seasonal thermocline in the spring, strong summertime stratification, deepening of the thermocline towards the autumn and the thermocline-free state during the winter. The hydrodynamic model is restarted from an existing state and a three-month spin-up (October to December 2020) is used to adjust to the modified momentum flux in the wave-forced experiments. The cold start used in WW3 simulations is sufficient, as waves propagate across the domain within days. The direct impacts of explicit wave forcing develop on timescales from days to weeks.

For hydrodynamics, we use the Nemo Nordic (Hordoir et al., 2019; Kärrnä et al., 2021) configuration, which covers both the North Sea and the Baltic Sea with a horizontal resolution of 1 NM. Detailed validation and description of the configuration has been presented by Kärrnä et al. (2021). For surface waves, our WW3 configuration uses a 2 NM horizontal resolution for the North Sea, with a nested 1 NM grid

Table 1

Description of experiments and considered model parameters. Experiments are grouped based on the ocean-side stress definition used.

Experiment		Wave forcing		Sea surface roughness definition	
		Stokes drift, Stokes-Coriolis force	Wave-modified stress	Implicitly from τ_{oc}	From wave model H_s
Wind stress ($\tau_a = \tau_{oc}$)					
CTRL	Control, default roughness	N	N	Y, default fit, $\tau_{oc} = \tau_a$.	N
CTRL_MOD	Control, optimized roughness	N	N	Y, with optimized parameterization, $\tau_{oc} = \tau_a$.	N
STCOR	Stokes-Coriolis, default roughness	Y	N	Y, as CTRL.	N
Wave-modified stress ($\tau_a \neq \tau_{oc}$)					
TAUOC	Wave-modified stress, default roughness	N	Y	Y, as CTRL but $\tau_{oc} = \tau_a - \tau_w$.	N
TAUST	Wave-modified stress, Stokes-Coriolis force, default roughness	Y	Y	Y, as TAUOC.	N
TAUST_MOD	As TAUST but optimized roughness	Y	Y	Y, with optimized parameterization.	N
TAUST_Hs	As TAUST, but explicit H_s roughness	Y	Y	N	Y

**Fig. 3.** Flow diagram demonstrating how roughness length is defined in different experiments, and how experiments integrate the ocean-side stress and Stokes-Coriolis force. CTRL and CTRL_MOD experiments are run without explicit wave information.

for the Baltic Sea. The boundary conditions for the North West Shelf are taken from ERA5 (Hersbach et al., 2023). Both WW3 and NEMO models are forced by the same atmospheric fields from MetCoOp-HARMONIE (Müller et al., 2017; Bengtsson et al., 2017). A subset of WW3 parameters is used to force NEMO. The parameters exchanged in the forced model system are characterized in Fig. 4. Further details of the configurations are given in Table 2.

In the CTRL and CTRL_MOD experiments, explicit wave information is not provided to NEMO, whereas in all other experiments forcing from WW3 is read in hourly. For the NEMO model, hourly forcings are applied for atmospheric pressure, air temperature, 10 m wind speed components, and humidity. The WW3 model is forced with the same wind speed components. Wave-ice interactions are not explicitly considered, as such experiments would require a fully coupled model. However, to ensure self-consistency and minimize the errors of external ice forcing, ice concentrations from the CTRL experiment are used

to force WW3. In WW3, ice has been considered using simple ice blocking (Tolman, 2003).

From WW3, we extract Stokes drift components ($u_{s,x}, u_{s,y}$), wave-modified ocean-side stress components ($\tau_{oc,x}, \tau_{oc,y}$), significant wave height H_s , peak period T_p and mean wave period $T_{0\ m,-1}$ as input to NEMO. The Stokes-Coriolis term in NEMO momentum equations is computed following the existing parameterization (Breivik et al., 2016; Wu et al., 2019). The wave-modified ocean-side stress (τ_{oc}^{WW3}) calculated by WW3 is applied in NEMO as a surface boundary condition that overrides the wind stress based definition (τ_{oc}^{NEMO}). In the GLS scheme, it influences the roughness length definition (see Section 2.1.2). As NEMO distinguishes between the air-side roughness parameter used in the bulk formula (see Eq. (8)) and the roughness length in GLS, the changes in roughness length definition do not affect the momentum input at the surface.

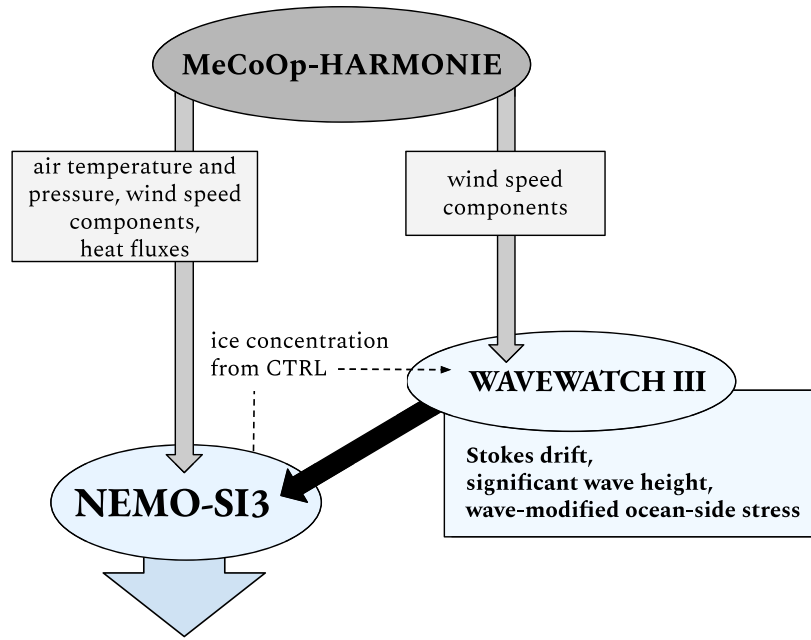


Fig. 4. A schematic figure of relevant explicit fields exchanged between the ocean, wave and atmospheric models in the forced ocean model experiments. Both wave and ocean models use the same wind forcing and a subset of wave parameters is used to force the ocean model.

Table 2

Details of the models and setups used in the experiments.

Model	NEMO-SI3	WAVEWATCH III
Model version	4.0	7.14
Restart	2 October 2020	Cold start from 1 October 2020
Horizontal grid	1 NM	2 NM North Sea, 1 NM Baltic Sea
Vertical grid	56 layers, focused at surface	N/A
Spectral resolution	N/A	35 frequencies, 36 directions
$\rho_{\max}$	N/A	1.55 (Ardhuin et al., 2010)
Energy source terms	N/A	ST4 (Ardhuin et al., 2010)
Turbulence closure	GLS $k - \epsilon$	N/A
Time step	90s	60s
Atmospheric forcing	MetCoOp-HARMONIE (Müller et al., 2017; Bengtsson et al., 2017)	MetCoOp-HARMONIE (Müller et al., 2017; Bengtsson et al., 2017)
Boundary forcing	NWS PHY (EU Copernicus Marine Service Product, 2025a)	ERA5 (Hersbach et al., 2023)
River forcing	EHYPE (Arheimer et al., 2012)	N/A
Ice	SI3	Exact ice concentrations from NEMO with simple ice blocking (Tolman, 2003)

For the roughness to significant wave height ratio, we use $\gamma = 1.3$ in all experiments (see Equation (2)), which has been adopted in global models (Couvelard et al., 2020; Law Chune and Aouf, 2018) as well as in regional Baltic Sea (Hordoir et al., 2019; Kärrnä et al., 2021) and North Sea applications (Bruciaferri et al., 2021; Partridge et al., 2026). We focus on comparing the roughness length definitions and therefore keep the CB94 parameterization unchanged with a default value $\alpha_{CB} = 100$. It is important to note that via these parameterizations, the wave effects are implicitly included even in experiments with ocean-side stress equaling wind stress — both with the default (open ocean) and recalibrated (regional) definitions.

5. Results

We analyze the impacts of roughness length definitions on thermal stratification during the year 2021. The differences between the definitions and the resulting impacts on turbulence parameters are covered in Section 5.1. The impacts on thermal dynamics are covered in Section 5.2, focusing on the ice-free season from June to November.

5.1. Differences in TKE roughness length definitions

Differences in TKE roughness length definition arise from 1) different definitions of ocean-side stress, 2) different values for wave-growth thresholds, and 3) the difference between implicit (wave-age) and explicit (H_s based) definitions. Here, we cover the differences in ocean-side stress (Section 5.1.1) and the joint impacts with the roughness definition on the turbulence parameters (Section 5.1.2).

5.1.1. Stress difference dependent on sea state

Wind stress (in CTRL, CTRL.MOD and STCOR, see Eq. (6)), or alternatively the wave-modified ocean-side stress (all other experiments, see Eq. (9)), defines the momentum input at the surface. To assess the differences between these two stress definitions across the domain, we consider the 25th and 75th percentiles of the difference $\Delta\tau = \tau_{oc}^{WW3} - \tau_{oc}^{NEMO}$ over the four seasons (DJF, MAM, JJA, SON), together with the seasonally averaged magnitude of wind stress $|\tau_a| = |\tau_{oc}^{NEMO}|$, shown in Fig. 5.

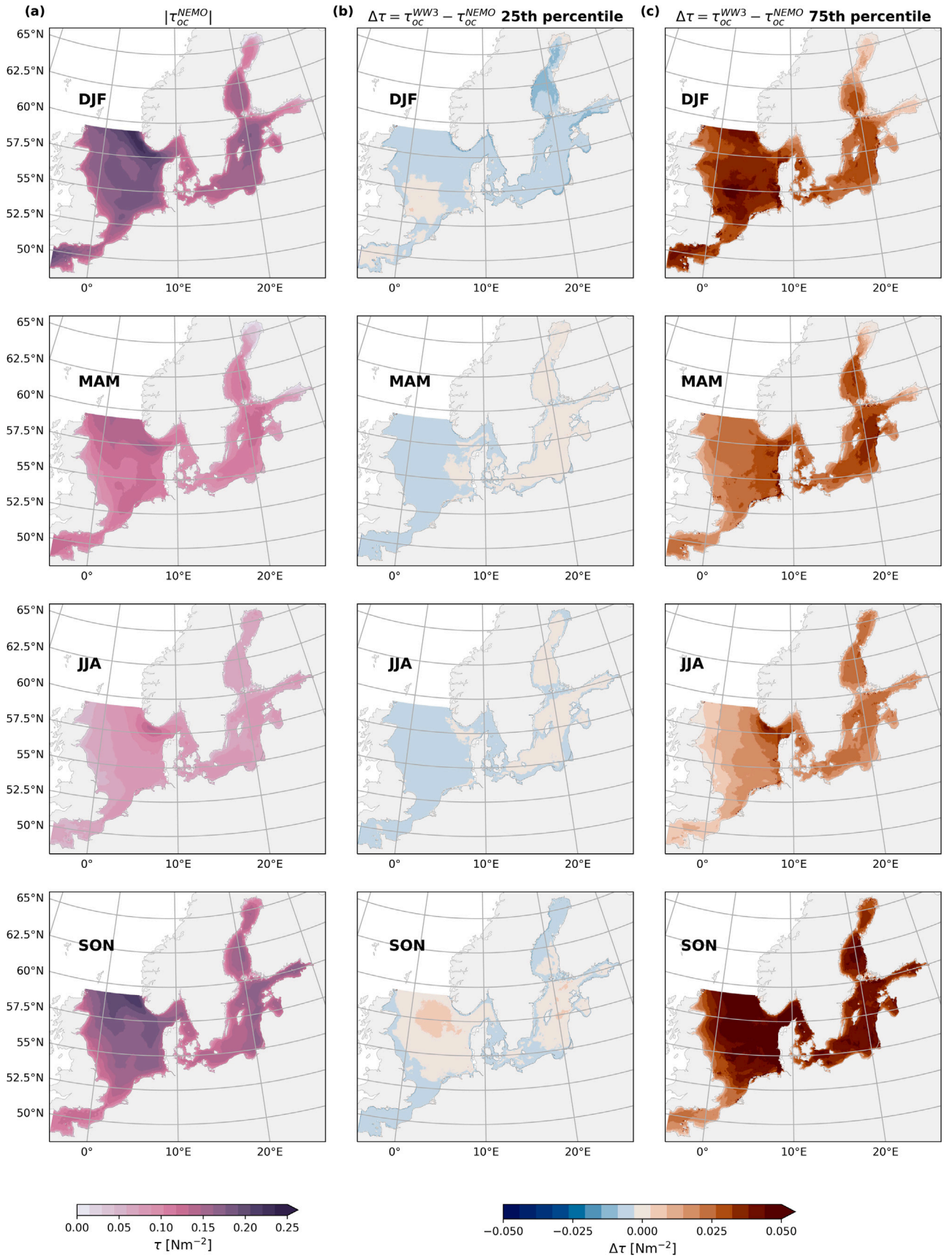


Fig. 5. Ocean-side stress based on bulk formula (wind stress) τ_{oc}^{NEMO} (a) plotted side-by-side with 25th (b) and 75th (c) percentiles of wave-modified and wind stress differences $\Delta\tau = \tau_{oc}^{WW3} - \tau_{oc}^{NEMO}$. Positive differences correspond to wave-modified stress exceeding the wind stress. Each row corresponds to seasons (DJF, MAM, JJA, SON), and all presented fields are seasonal means.

The seasonality of wind forcing is evident in the stress differences, as the strongest impacts are obtained during DJF and SON, whereas MAM shows more moderate impacts and JJA shows the smallest differences (see Fig. 5). The differences are mostly positive throughout the entire model domain, with the 25th percentile being closer to zero across the seasons compared to the 75th percentile.

To assess the dependence on sea state, we compare the stress differences $\Delta\tau$ to modeled wave properties (see Fig. 6) at the Northern Baltic Proper wave buoy site (see Fig. 1). The highest density of points is found in the regime with small stress differences $\Delta\tau < 0.03 \text{ Nm}^{-2}$ combined with low wave heights $H_s < 1 \text{ m}$ (Fig. 6(a)). Conversely, above $H_s = 1 \text{ m}$ the wave-modified stress (from WW3) is mainly higher than the NEMO bulk estimates, and the largest differences are obtained for the highest H_s values.

In order to separate the growing wind sea from mature waves, we compare the stress differences to wave-age and wave steepness, shown in Fig. 6(b). Whereas negative and near-zero stress differences are seen across the steepness–wave-age space, the strong positive differences with wave-modified stress exceeding NEMO bulk stress, occur systematically in growing wind-sea conditions with steep (moderate to high steepness) and young waves (low wave-age).

5.1.2. Turbulence parameters sensitive to roughness length

The differences in ocean-side stress affect roughness length estimation (see Sections 3.2 and 2.1.2), which in turn impacts the modeled TKE, dissipation rate and mixing length. We demonstrate the differences in the roughness definitions with following experiments: wind-stress with default roughness (CTRL), wind-stress with regional roughness (CTRL_MOD), wave-modified ocean-side stress with default roughness (TAUST) and wave-modified ocean-side stress with explicit regional roughness (TAUST_Hs).

Differences in TKE and dissipation rate in selected experiments (CTRL, CTRL_MOD, TAUST, TAUST_Hs) are considered for the Northern Baltic Proper wave buoy site (Fig. 7). All experiments capture the

expected seasonal cycle: suppressed turbulence during strong summer stratification, enhanced turbulence during autumn thermocline deepening (see also Fig. 5). However, systematic differences arise from stress and roughness parameterizations, and these impacts extend beyond seasonal variability.

In wind stress experiments, regionally calibrated roughness (CTRL_MOD) lowers TKE throughout the surface layer compared to CTRL, whilst TKE in the uppermost layer remains unchanged (see Section 2.1.2). Introducing wave-modified ocean-side stress with default roughness (TAUST) increases TKE (also in the uppermost layer) and deepens the injection throughout the year, as a result of enhanced momentum flux. In terms of the remaining experiments, the roughness definitions are the same in CTRL and STCOR, as well as in TAUOC and TAUST. The differences seen between the default and regional roughness definitions with wave-modified ocean-side stress (TAUST and TAUST_MOD) are comparable to those presented between the wind stress experiments (CTRL and CTRL_MOD). When wave-modified ocean-side stress is combined with explicit H_s based roughness estimates (TAUST_Hs), TKE injection is clearly reduced compared to TAUST, bringing the results closer to CTRL. TAUST_Hs still shows elevated TKE in the uppermost 10 m, and occasional deeper injection events, but also periods of reduced TKE injection.

Wave-informed roughness with wind stress (CTRL_MOD) redistributes dissipation rate enhancing it in the near-surface layer and reducing below 10 m. Adding wave-modified ocean-side stress with default roughness (TAUST) produces a steady increase in dissipation rate across the surface layer (due to enhanced stress forcing), but maintains a structure similar to CTRL. Wave-informed roughness with wave-modified ocean-side stress (TAUST_Hs) enhances near-surface dissipation similar to CTRL_MOD but does not give the same sharp decline in dissipation rate below 10 m. Crucially, TAUST_Hs shows clear spatial and temporal differences compared to all other experiments with implicit formulations.

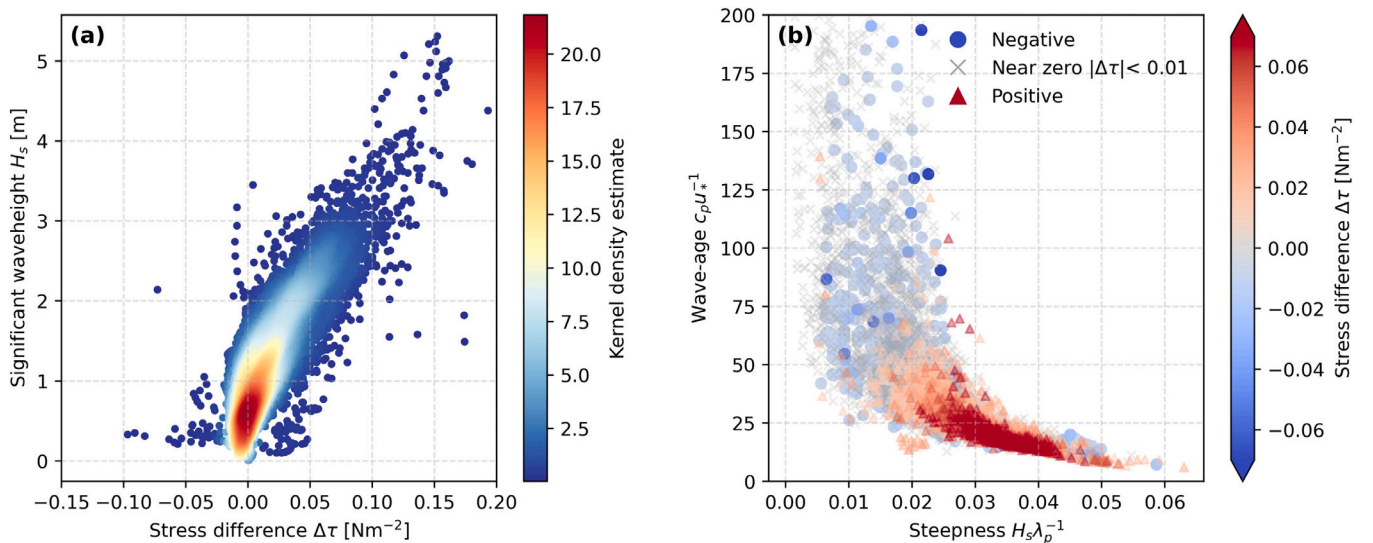


Fig. 6. Northern Baltic Proper significant wave height H_s plotted against the difference in wave-modified stress and wind stress $\Delta\tau = \tau^{\text{WW3}} - \tau^{\text{NEMO}}$ shown in panel (a) with kernel density estimation (Pedregosa et al., 2011). The corresponding stress differences in steepness–wave-age space ($H_s \lambda_p^{-1}, c_p u_*^{-1}$) are shown in panel (b).

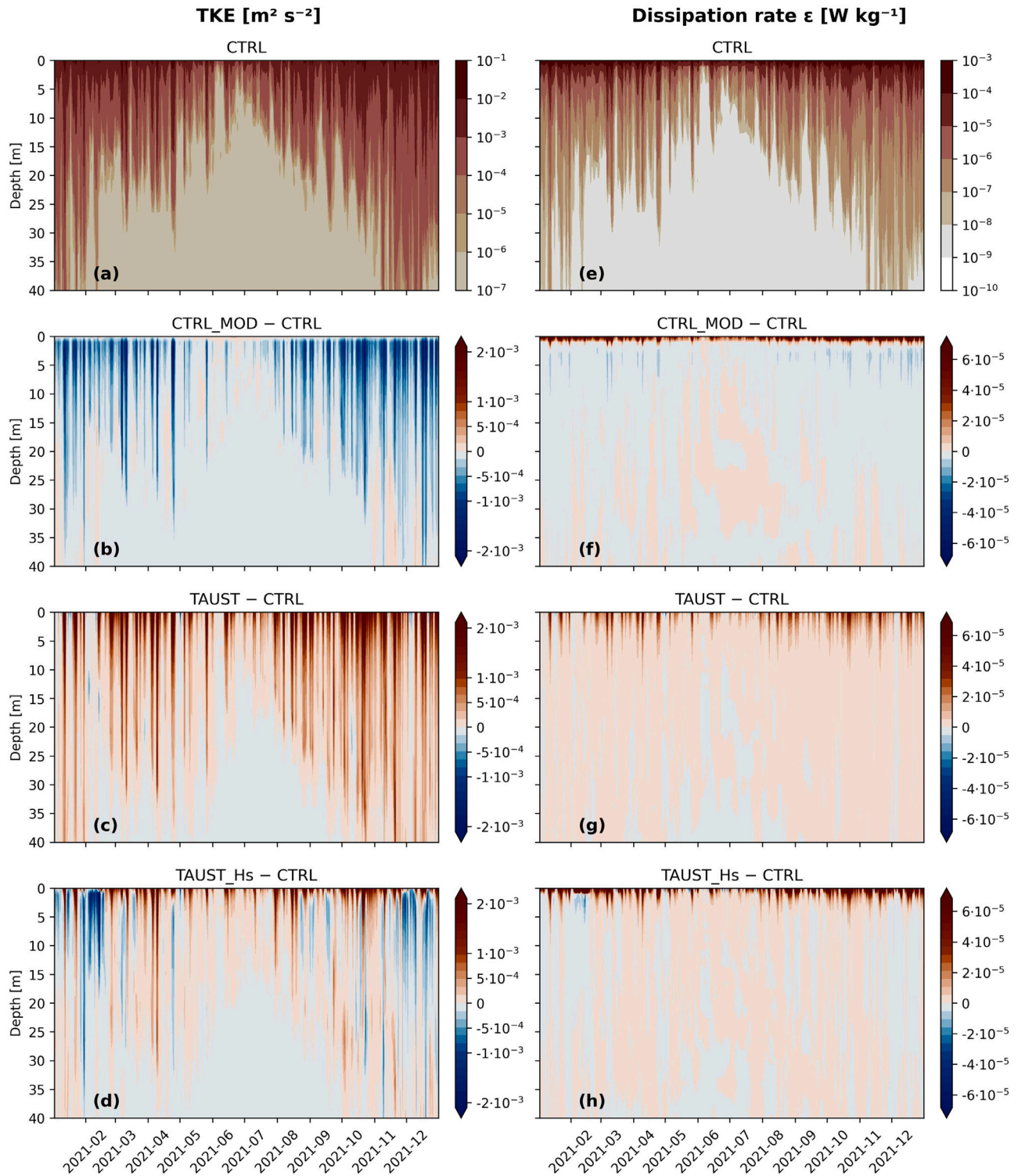


Fig. 7. Differences in TKE (a–d) and dissipation rate (e–h) between different roughness length definitions in CTRL, CTRL_MOD, TAUST and TAUST_Hs experiments over the year 2021 at the Northern Baltic Proper site.

5.2. Thermal response to wave-dependent TKE roughness definitions

We now assess the impacts on thermal dynamics including statistical metrics of modeled SST (Section 5.2.1), model performance during an anomalously high temperature event (Section 5.2.2) and impacts on thermal stratification (Section 5.2.3 and 5.2.4).

5.2.1. Impacts on SST

The impacts on SST in the Bothnian Bay, Bothnian Sea and Northern Baltic Proper are assessed for all experiments (see Fig. 1 for locations). Model SST is taken from the uppermost 1 m layer, while buoy SST is measured between 0–0.3 m. The values for RMSE, BIAS, and correlation coefficient R (see Appendix B) are presented in Table 3. Data coverage spans May–December for the Bothnian Bay (ice-free season), and the entire year for the Bothnian Sea and Northern Baltic Proper.

Regionally calibrated roughness with wind stress (CTRL_MOD) reduces SST bias in the Bothnian Sea and Northern Baltic Proper compared to CTRL. The regional thresholds lead to higher SST at all stations, but in the Bothnian Bay this leads to increased positive bias. Despite the increase in bias in the Bothnian Bay, the RMSE is reduced. As seen in the experiments using wind stress, the regional roughness (in CTRL_MOD) increases the SST at all stations. This impact is up to 0.1 °C in the Bothnian Sea and the Northern Baltic Proper, but 0.35–0.6 °C in the Bothnian Bay. The correlation with observations is generally high, but appears highest for CTRL_MOD across experiments.

Applying wave-modified ocean-side stress with default roughness (TAUST) increases negative bias and variability of SST in all stations. We find that both wave-informed roughness definitions (TAUST_MOD and TAUST_Hs) mitigate this bias and yield results closer to CTRL. In addition, regional wave dependent roughness definitions lead to reduced RMSE compared to default thresholds.

The impacts of Stokes-Coriolis force are an order of magnitude smaller than those from ocean-side stress and roughness length definitions. The differences between CTRL and Stokes-Coriolis force (STCOR) experiments are small across stations, as are those between wave-forced experiments with default roughness (TAUOC and TAUST). Although there are slight differences between wave-forced runs with regional roughness definitions (TAUST_MOD and TAUST_Hs), both act in the same direction relative to TAUST. Therefore, we choose to focus on the differences between CTRL, CTRL_MOD, TAUST, TAUST_MOD and TAUST_Hs, and mention other experiments where relevant.

The temporal differences in the selected experiments are demonstrated for the Northern Baltic Proper station in Fig. 8 (location shown

in Fig. 1). We consider the SST and anomaly time series together with average SST deviation from observations in different temperature ranges. Introducing regional roughness with wind stress (CTRL_MOD) reduces deviation by 0.5 °C between 4–8 °C (compared to CTRL). The largest impacts are seen between 18–24 °C during the strongly stratified summer period (June–July). In the same temperature regime, wave-modified stress with default roughness (TAUST) leads to excessive mixing and an increase in cold bias that is up to 1.75 °C below CTRL and over 2 °C below observations. The SST estimates with wave-modified stress and regional roughness (TAUST_MOD and TAUST_Hs) are broadly consistent with CTRL, but show increased variability.

5.2.2. Capturing a high SST anomaly

SST differences become more pronounced following an anomalously warm event in June (see Fig. 8). Between 5–12 June 2021, a marine heatwave occurred in the Gulf of Bothnia and the Baltic Proper (identified relative to the 1993–2020 SST climatology from the Baltic Sea Reanalysis EU Copernicus Marine Service Product, 2025b). We analyze the Northern Baltic Proper SST simulated with different roughness length definitions (Fig. 9) close to the event. All experiments capture the warming signal consistently, but notable differences emerge in the heatwave dissipation phase (between 12 June 2021 04:30–13 June 2021 06:30 UTC).

Warming of the sea surface during the heatwave event was driven by high-pressure conditions persisting for 10 days prior to 12 June (Fig. 9(a)). The dissipation phase is characterized by two rapid drops in atmospheric pressure during 13 June and 15 June, with moderate to strong winds first to SE, and then turning NE, with magnitudes up to 13 ms⁻¹ (Fig. 9(b)). The warming signal, as well as the drop in temperatures, can also be seen in air temperature observations of Utö and Östergarnsholm marine-atmospheric stations (see Figs. 1 and 9(a)).

The estimated roughness lengths respond directly to changes in wind speed (magnitude) (Fig. 9(b), (c)). Steep SST cooling during the dissipation phase is characterized by three spikes in roughness length. Wave-modified stress with default roughness (TAUST) exhibits the highest roughness lengths (up to 5 m) leading to the lowest SST values (Fig. 9(d)). The experiment with wind stress and optimized roughness (CTRL_MOD) reproduces the dissipation phase temperatures accurately, with roughness lengths up to 2.5 m, and remains closest to SST observations throughout the summer after the event. The roughness peaks of CTRL (up to 3.9 m) exceed those obtained with wave-modified stress and regional roughness definitions (approximately 3.2 m), despite showing more moderate cooling.

Table 3

SST buoy observations against model output in the seasonally thermally stratified Baltic Sea stations: the Bothnian Bay, Bothnian Sea and Northern Baltic Proper stations are shown together with number of observations, RMSE, BIAS and correlation coefficient R for all experiments.

	Bothnian Bay (N=4061)			Bothnian Sea (N=8427)			Northern Baltic (N = 8476)		
	RMSE [°C]	BIAS [°C]	R	RMSE [°C]	BIAS [°C]	R	RMSE [°C]	BIAS [°C]	R
<i>Wind stress, default roughness</i>									
CTRL	1.64	0.03	0.97	0.72	−0.48	0.99	0.96	−0.52	0.99
STCOR	1.67	0.06	0.97	0.75	−0.48	0.99	0.89	−0.50	0.99
<i>Wind-stress, regional roughness</i>									
CTRL_MOD	1.25	0.38	0.98	0.87	−0.42	0.99	0.79	−0.40	0.99
<i>Wave-modified stress, default roughness</i>									
TAUOC	4.45	−0.54	0.96	1.73	−0.70	0.98	1.80	−0.59	0.98
TAUST	4.64	−0.54	0.96	1.80	−0.69	0.98	1.76	−0.56	0.98
<i>Wave-modified stress, regional roughness</i>									
TAUST_MOD	2.08	−0.05	0.96	1.15	−0.60	0.99	1.30	−0.49	0.99
TAUST_Hs	1.77	0.11	0.96	1.19	−0.63	0.99	1.32	−0.49	0.99

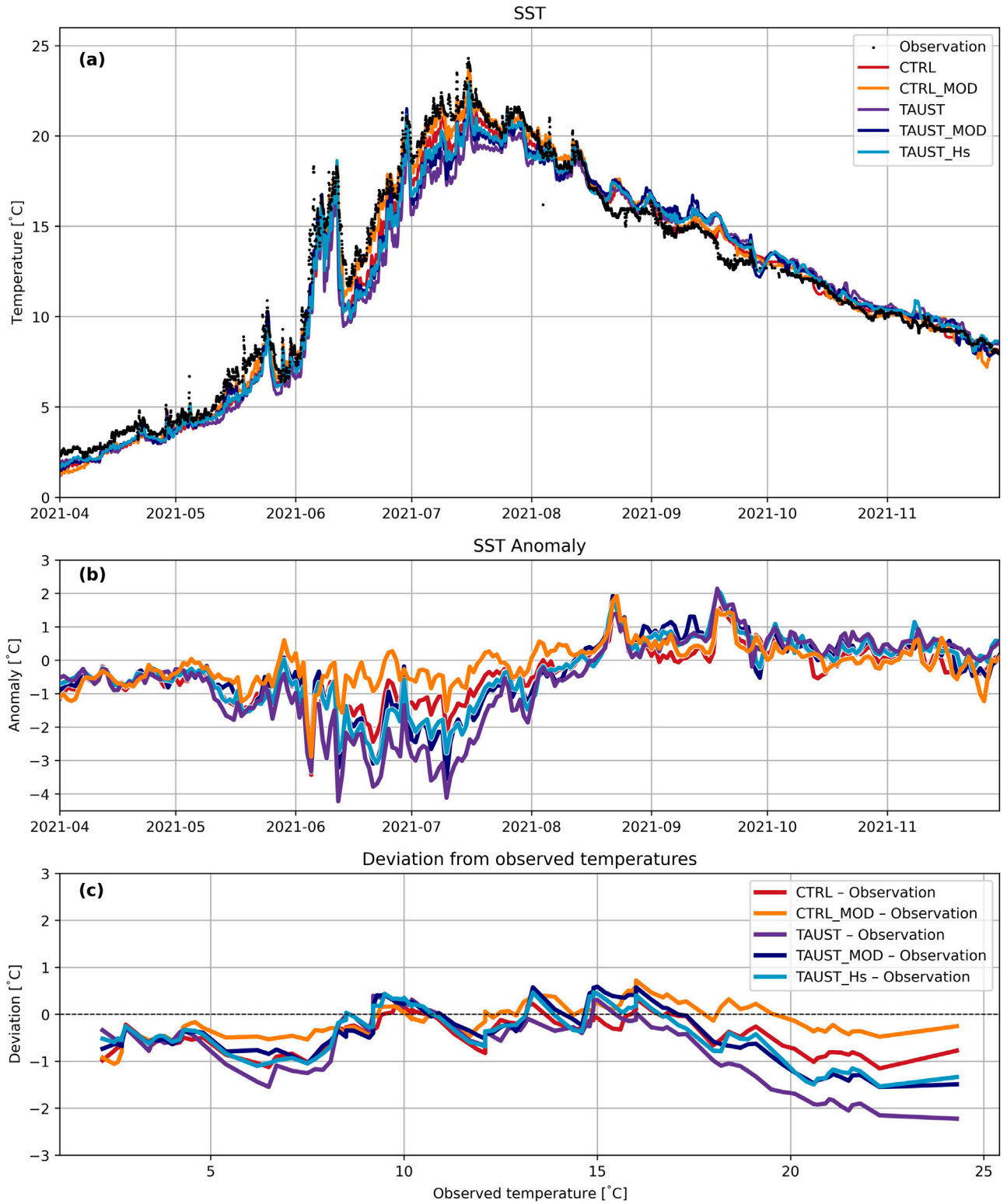


Fig. 8. Northern Baltic Proper wave buoy measured SST compared to modeled SST (a), temperature anomaly $T_{\text{mod}} - T_{\text{obs}}$ showing negative values where modeled temperatures are lower than observed (b), and average deviations with respect to observed temperatures (c).

Differences in roughness length (Fig. 9(c)) between explicit (TAUST_Hs) and implicit definitions (all other experiments) arise when the winds weaken (Fig. 9(b)). Although the wind-speed-based definitions show a steep decrease with decreasing wind magnitude, the explicit H_s based definition shows a slower decrease as surface waves

gradually decay. This difference is most evident after 15 June, when all wind speed based definitions decrease from $z_{0,\text{TKE}} = 1.5$ m to 0.5 m within the day, whilst the H_s based roughness $z_{0,\text{TKE}}$ shows a slower decrease and reaches the same level nearly two days later.

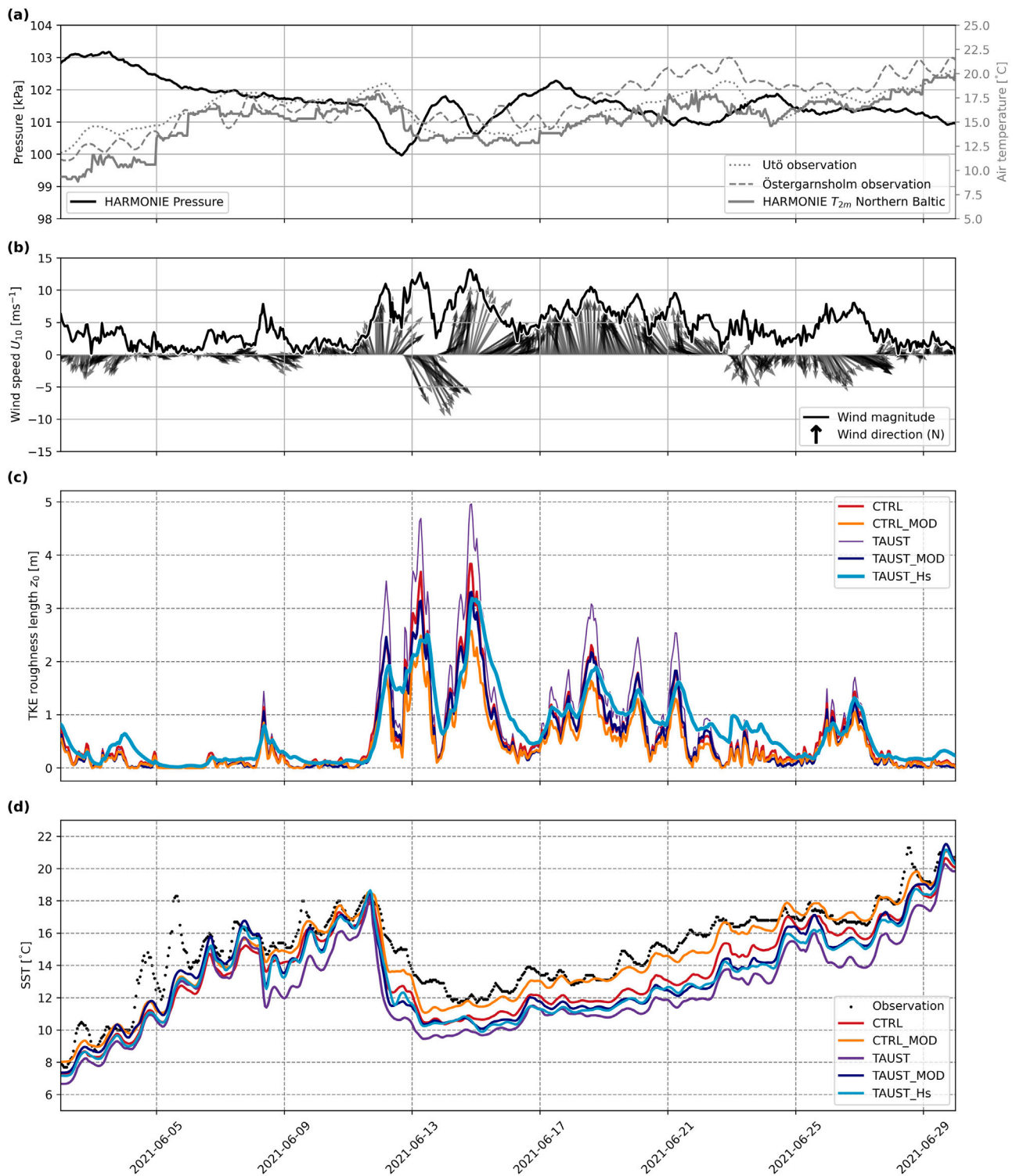


Fig. 9. Northern Baltic Proper conditions during June 2021 marine heatwave related to large SST differences between experiments. The panels show atmospheric pressure and temperature forcing together with Utö and Östergarnsholm air temperature observations (a), wind speed magnitude and directions (b), turbulent roughness lengths under different definitions (c) and the resulting SST time series (d).

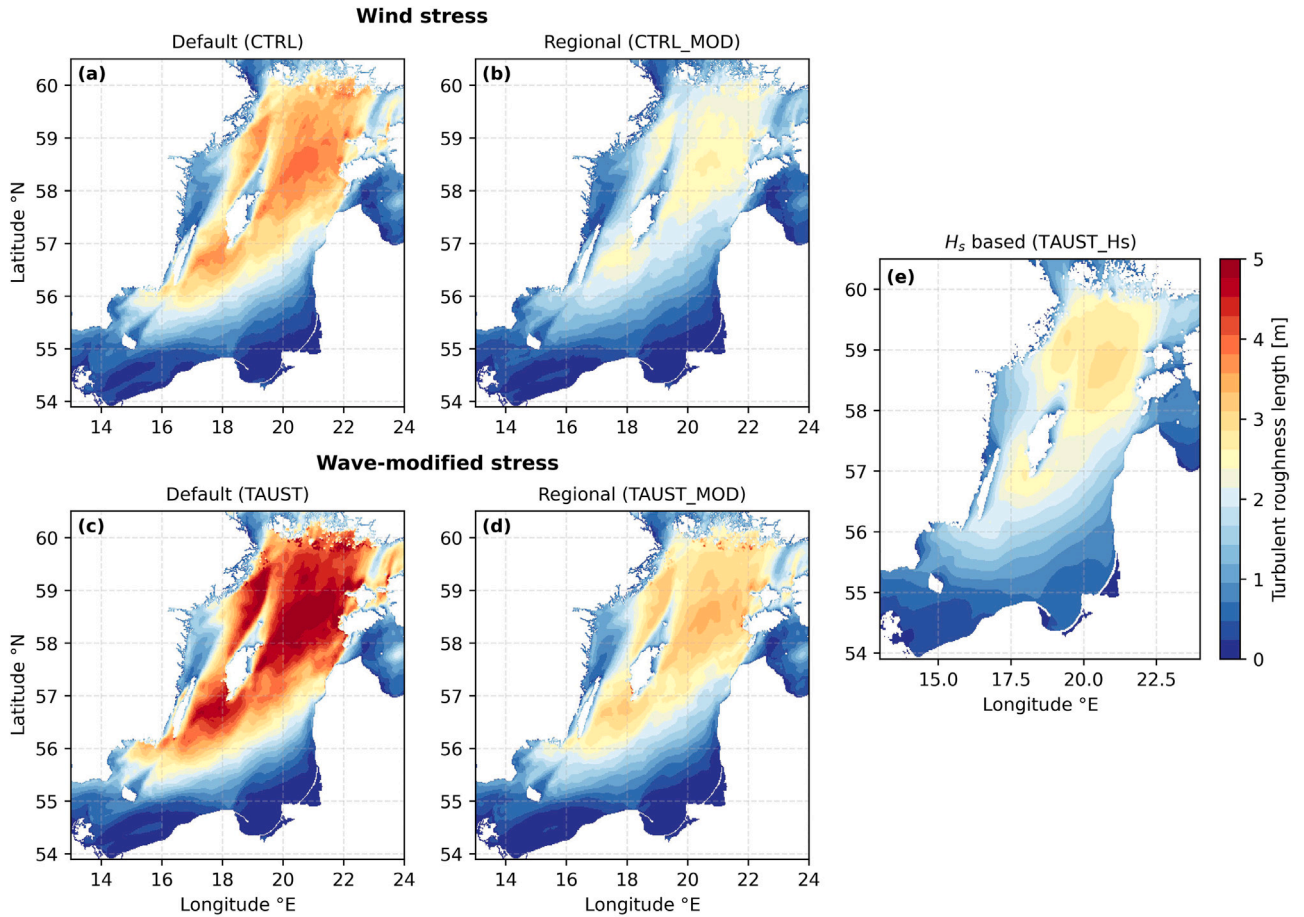


Fig. 10. Turbulent roughness length definitions in experiments CTRL, CTRL_MOD, TAUST, TAUST_MOD and TAUST_Hs on 12 June 2021 at 20:00 UTC to compare wind stress (a–b), wave-modified ocean-side stress (c–d) and explicit H_s based (e) experiments. The values are overall largest in TAUST experiment, and lowest in TAUST_Hs and CTRL_MOD.

In addition to temporal evolution and magnitudes, spatial extents differ between definitions. Implicit parameterizations (Fig. 10(a)–(d)) result in large regions with near-zero values when the wind dies out. These are commonly non-zero with the explicit H_s based definition (Fig. 10(e)), which also results in an overall smoother roughness field compared to more varying stress-dependent definitions. Additionally, wind based parameterizations result in higher and more localized extremes. For example on 12 June 2021 at 20:00 UTC, localized high values of roughness length can be seen near the Archipelago Sea, southern tips of Öland and Gotland islands in the implicit experiments, whereas H_s dependent roughness produces low values in these regions (see Fig. 10). Overall, the roughness length fields computed with regionally optimized thresholds are closer to the H_s based definition, both in the wind and wave-modified stress experiments.

5.2.3. Thermocline depth sensitive to roughness length

Differences observed during the heatwave dissipation phase (Section 5.2.2) highlight the role of regional, wave-dependent roughness length, in heat propagation. Similar mechanisms are evident along the northern Baltic Proper Argo float's path (Fig. 1). On 10 May 2021 (Fig. 11(a)), all experiments agree closely, with differences within 1 °C across the water column. We see most of these differences up to 60 m deep, whereas the maximum depth of the observations is 80 m. Wind stress with regional roughness (CTRL_MOD) results in the highest thermocline depth estimates, between 60–70 m, whilst all experiments converge between 70–80 m.

By 14 June 2021 (Fig. 11(b)), the seasonal thermocline has formed and the heatwave dissipated. The surface layer temperatures drop below 15 °C, but the previously obtained differences between experiments persist (see Fig. 8). Crucially, none of the experiments are able to capture the shape of the thermocline, as observations show a deeper OSBL. Wind stress with regional roughness (CTRL_MOD) matches the observed SST the best, but shows the shallowest mixed layer, deviating from observations between 10–25 m. Wave-modified stress with default roughness (TAUST) exhibits again the coolest surface layer temperatures (up to –3 °C from observed), but is aligned with observations below 25 m. The regional wave-informed experiments (TAUST_Hs and TAUST_MOD) agree within the uppermost 15 m, with less than 1 °C differences compared to CTRL, but deviate from each other between 15–65 m. This highlights the differences arising from the implicit and explicit wave height definitions.

At the same time (Fig. 11(b)), CTRL underestimates temperatures in the uppermost 20 m, but remains close to observations between 25–40 m. The largest differences between CTRL and observed temperatures can be seen in the inverse thermocline below 40 m. In addition to CTRL, the same is seen in the wind stress experiment with regional roughness (CTRL_MOD) but also in the wave-modified ocean-side stress experiment with explicit roughness (TAUST_Hs), whereas the implicit roughness definitions with wave-modified stress match observations more closely.

By 2 August 2021 (Fig. 11(c)), SST differences diminish and all experiments capture the thermocline shape despite differences in the

temperature values. Both wind stress experiments remain warmest and closest to observations in the uppermost 10 m, whereas the wave-modified stress experiments produce deeper mixing.

On 21 September 2021 (Fig. 11(d)), surface layer has cooled up to 30 m in all experiments. Notable differences occur in the thermocline depth between the simulations using the wave-modified stress and wind

stress. Although the differences between the surface layer temperatures remain small, we find SST warmer in wave-modified ocean-side stress experiments. The same can be seen on 29 November (Fig. 11(e)), as the wave-modified stress experiments align with observations down to 55 m, whilst both wind stress experiments place the thermocline too shallow (a difference of approximately 15 m).

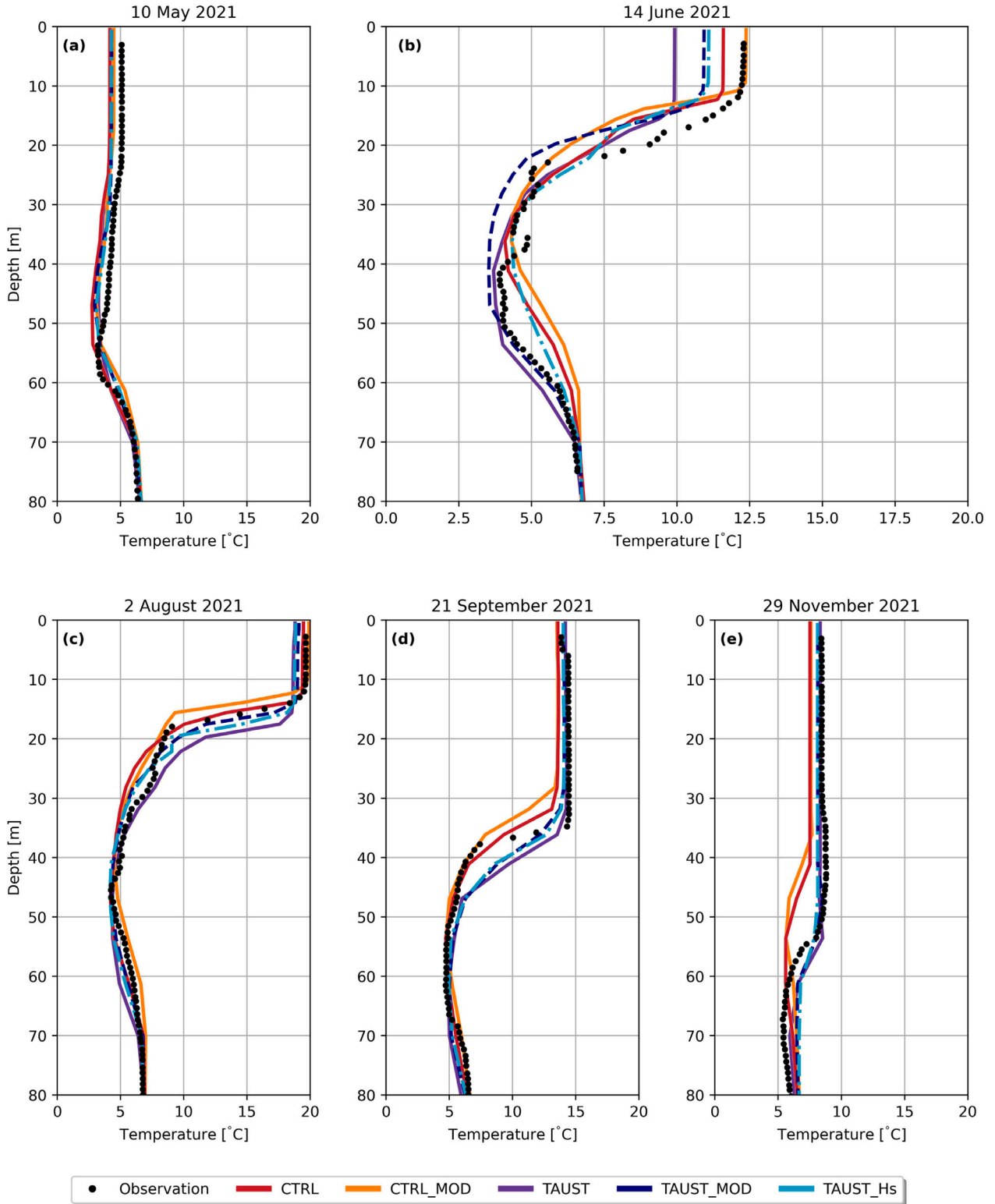


Fig. 11. Northern Baltic Proper float temperature profiles against modeled temperatures for selected dates demonstrating the seasonal development of thermocline and differences arising from the wave-dependent parameterizations.

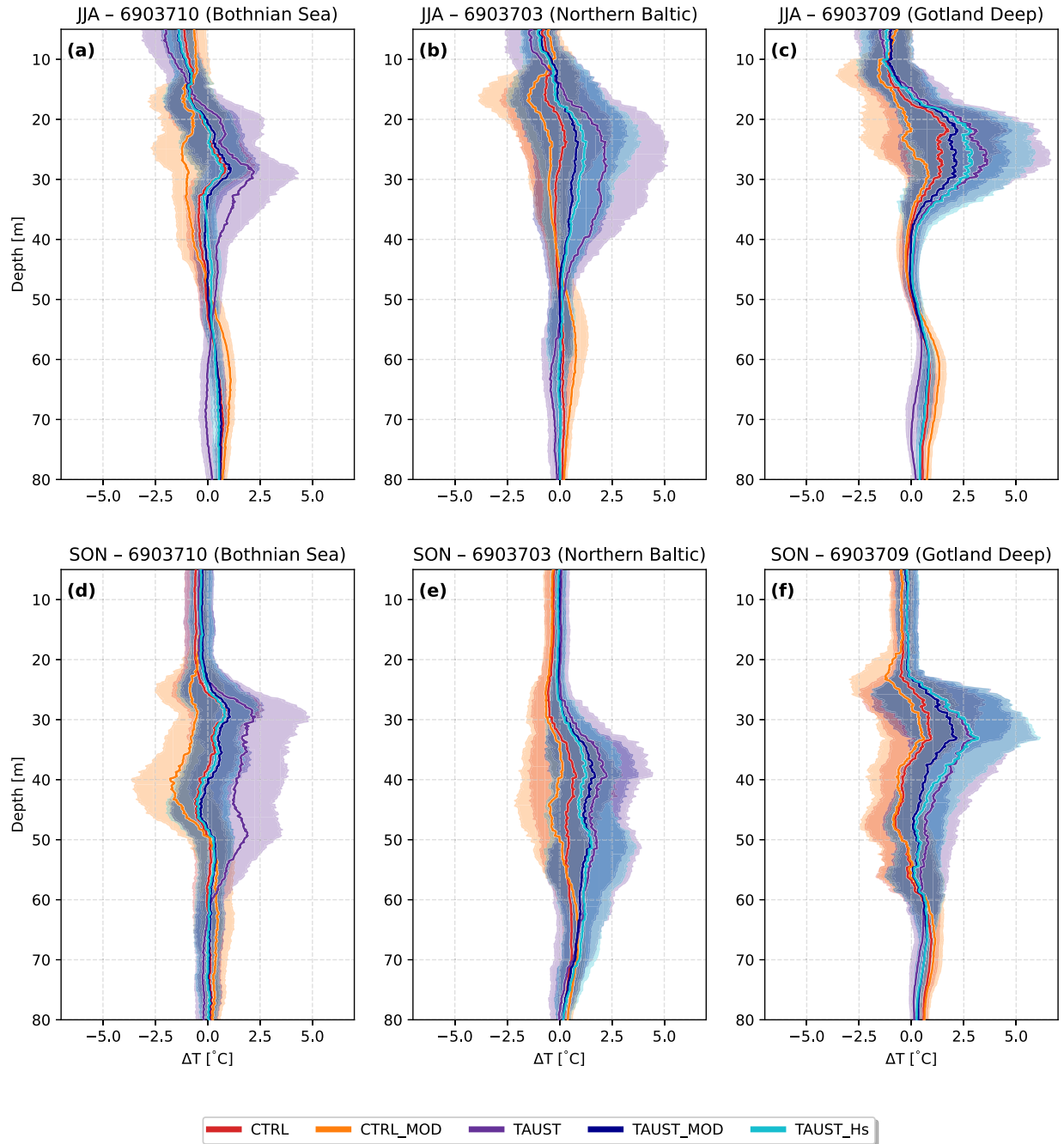


Fig. 12. Temperature anomalies between the experiments and observations from three float missions, shading represents standard deviation. Figures (a)–(c) contain anomalies during JJA for Bothnian Sea, Northern Baltic Proper and Gotland Deep respectively, whereas Figures (d)–(e) contain the anomalies during SON. Negative values represent situations where observations are higher than modeled temperatures.

5.2.4. Seasonal temperature anomalies across basins

Thermal response to roughness length definition is consistent across the basins and impacts seasonal stratification, as seen via comparison with three Argo missions: Bothnian Sea, northern Baltic Proper, and Gotland Deep, trajectories shown in Fig. 1. We compute seasonal means and standard deviations of temperature anomalies for summer (JJA: June–August) and autumn (SON: September–November). We interpolate the model points to the observation depths and compute vertically interpolated ranges for the standard deviations. Fig. 12 demonstrates the impacts of roughness length on OSBL with increased variability following thermal stratification: variability increases in JJA between 15–40 m, whereas in SON variability is enhanced between 25–60 m corresponding to the seasonal thermocline depths.

During JJA, surface layer temperatures above 15 m differ by up to 2 °C. The wind stress experiment with regional roughness (CTRL_MOD) experiment is the warmest, whilst the wave-forced experiment with default roughness (TAUST) is coolest, consistent with previous results (see Figs. 8 and 11). Wave-informed roughness definitions (TAUST_MOD and TAUST_Hs) reduce variability compared to wave-forced run with default roughness (TAUST) and take the results closer to CTRL, despite retaining a slight negative bias. The wind stress experiment with regional roughness (CTRL_MOD) minimizes near-surface temperature anomalies, but shows an increased negative bias at 15–45 m, where the wave-forced model with default roughness (TAUST) exhibits the largest positive anomaly. Below 50 m, CTRL_MOD remains warmest and TAUST coolest, while all other experiments converge.

The same pattern is seen in SON, when the surface waters have cooled down and the mixed layer has deepened. In this case, the uppermost 20 m become more homogeneous compared to JJA, and the direct impacts of different roughness length definitions are more pronounced deeper down in the water column. Although the magnitude of anomalies varies by basin between different experiments, the direction of impacts (positive or negative) and relative ranking of experiments remain coherent. Some basin-dependent differences can be seen. In the Bothnian Sea, the combination of wave-modified stress and wave-informed roughness (TAUST_MOD and TAUST_Hs) produces vertical temperature distributions comparable to CTRL. In the northern Baltic Proper we see an increased positive anomaly in response to wave-modified stress. In the Gotland Deep during SON, the mean temperature anomaly of wave-forced model with explicit roughness (TAUST_Hs) remains close to wave-forced with default roughness (TAUST) between depths 20–40 m, differing from the results for the Bothnian Sea and Northern Baltic Proper, where the regional roughness runs (TAUST_Hs and TAUST_MOD) are closer to each other.

6. Discussion

Optimizing the roughness length parameterization using regional wave information substantially reduces the estimates under moderate and high wind conditions compared to the default parameterization used in the GLS turbulent closure scheme within NEMO (Section 3.2). Although this adjustment does not alter the simulated momentum input via ocean-side stress (Section 2.1.2), it does play a critical role in how TKE and dissipation are distributed in the water column, impacting the thermal dynamics during the stratified season with both implicit and explicit wave parameterizations.

Incorporation of regional wave information is important for the turbulent roughness length definition and helps in capturing a high SST anomaly in the northern Baltic Sea. We find that wind stress with default roughness definition (CTRL) together with the CB94 wave-breaking parameterization provides a reasonable baseline for thermal dynamics, but tends to underestimate summertime SST and produces an overly shallow thermocline in the autumn (Fig. 11). The regional roughness length improves the SST estimates in the ocean model with wind stress (CTRL_MOD), but features the smallest values for roughness length (Fig. 10) indicating weaker mixing and is linked to a shallow thermocline which further exaggerates the shallow bias in the autumn OSBL (Fig. 12).

We find the differences between wind stress and wave-modified ocean-side stress more pronounced under active wave-growth (Fig. 6). The wave-modified stress forcing from wave model introduces the enhanced momentum flux from steep, young waves – a process that is entirely ignored by the wind stress formulation. As the existing GLS scheme implicitly accounts for wave-breaking impacts via the CB94, the parameterization has been designed to compensate for the lacking wave processes. Therefore, introducing the conceptually different wave-modified stress does not directly improve the modeled hydrodynamics with existing formulations. This effect appears more pronounced in thermally stratified conditions, as incorporating wave-modified ocean-side stress (TAUST) shifts the thermocline too deep when using the default roughness length definition with CB94.

The elevated TKE and dissipation rate in TAUST runs (Fig. 7) promote excessive mixing, which redistributes heat to deeper layers and contributes to the observed cold SST bias and deeper thermocline during the summer (Fig. 11). However, combining wave-modified ocean-side stress with wave-informed roughness length (TAUST_Hs and TAUST_MOD) reduces negative SST biases and produces thermocline depths comparable to CTRL. We find that the regional, wave-informed roughness definitions consistently reduce the temperature deviation from observations and improve the deep-layer temperature representation compared to the default roughness definition with wave-modified stress (Fig. 12).

In the following subsections, we discuss the results in the context of modeling hydrodynamics without explicit wave information available (Section 6.1) and introducing explicit wave information to ocean model configurations (Section 6.2), and conclude the study with directions for future research (Section 6.3).

6.1. Representing regional wave conditions implicitly

Regional optimization of turbulent roughness length thresholds is a feasible approach for calibrating ocean models to match regional wave characteristics when explicit wave information is not integrated into the model system. We found that the default parameterization in GLS has a tendency to overestimate mixing in fetch-limited regions, particularly under moderate and high winds, resulting in deeper TKE injection and lower estimates of near-surface dissipation. Our findings of the Baltic Sea and North Sea threshold values are supported by literature, as lower thresholds correspond to stronger limitations in wave-growth due to fetch or wind duration compared to the open ocean (see Section 2.2).

The regionally optimized fit helped capture anomalous SST during a marine heatwave, reducing the temperature bias even after the dissipation phase. This was a direct consequence of shorter mixing length estimates under moderate winds (see Fig. 9) resulting in enhanced dissipation in the near-surface layer and reduced TKE injection, as the momentum input and TKE in the uppermost layer remain the same (see Fig. 7 and Section 2.1.2). However, the regional formulation did not prove superior during autumn stratification in terms of overall model performance resulting in a too shallow mixed layer. Our findings complement the results of Westerlund and Tuomi (2016), who linked CB94 to an improved deepening of the autumn thermocline but also to a spring-summer cold temperature bias in the Baltic Sea. Crucially, our regional thresholds modify the input to CB94.

We found that the magnitude of impacts from changing the roughness length definition alone can be comparable to those of wave-modified stress. This provides complementary information to the results of Alari et al. (2016), who found that most of the large scale differences in Baltic Sea temperatures were induced by wave-modified ocean-side stress (in a forced setup). Our results indicate that differences of similar magnitude may arise from the roughness length formulation, even without explicit wave information.

However, we contend that optimizing the wave-age and friction velocity thresholds alone does not provide a comprehensive solution for tuning the ocean model to account for regional wave impacts. Rather, the regional roughness length optimization should be combined with adjustments to mechanical mixing response (the Galperin limit), TKE injection (the CB94 coefficient) and stratification strength (the roughness scaling factor γ , see Eq. (2)). We acknowledge that the impacts of adjusting γ are (to some extent) comparable to those achieved through threshold optimization (see Eq. (5)). In addition to this, derivation of the constants in the formulation appears to include a different value for γ than commonly used in the models, see details in Appendix C.

As the underlying approximations and assumptions are not readily apparent to users of the model, revising the parameterization (including the constants in Eq. (5)) could facilitate more effective model calibration. Although regionally tuned roughness length formulations can improve model performance under specific conditions, their usefulness remains limited by the absence of dynamical wave fields. This becomes evident in situations where waves cause mixing independently of the local wind (see Fig. 9). However, when explicit wave information is incorporated into a previously calibrated model configuration using implicit representations of surface waves, the boundary layer definitions must be redefined to ensure that the modeled fluxes remain physically consistent.

6.2. Explicit wave information in ocean models

We found that replacing wind stress with wave-modified ocean-side stress substantially altered surface fluxes, increasing momentum input under young waves and amplifying SST and stratification biases (Figs. 8 and 11). Wave-informed roughness length became essential to maintain consistency in the flux definitions linked with CB94 wave-breaking. Both the optimized wind-based fit and the significant wave height H_s scaled approach reduced the aforementioned biases, but additional tuning appears necessary to approach the performance of the calibrated model with wind stress (CTRL). Here, we discuss wave-modified stress (Section 6.2.1), and TKE injection and dissipation (Section 6.2.2) under explicit wave forcing.

6.2.1. Wave-modified ocean-side stress

We found that the wave-modified ocean-side stress produced higher values compared to the bulk formula, with the highest differences corresponding to young wind-sea and higher H_s (Fig. 5). Wu et al. (2022) demonstrated that wind stress based definitions underestimate the flux of TKE at mid- and high latitudes, as well as near the coast. In our study, wave-modified ocean-side stress results in enhanced momentum input and TKE to an extent that requires adapting the existing dissipation formulations. Whereas a large fraction of existing studies demonstrate wave-modified stress values mainly close to wind-stress (Wu et al., 2024), our results appear comparable to the findings of Huang and Qiao (2021) showing the momentum flux to ocean higher compared to wind input under wind-wave breaking and low swell.

The separation of wave and ocean model computed wind stresses is crucial to compare our results to existing studies. For instance, Qiao et al. (2021) and Wu et al. (2022) compute the normalized momentum flux $\tilde{\tau} = \tau_{oc}/\tau_a$ based on air-side stress from the wave model $\tau_a = \tau_a^{WW3}$. As our interest is on the momentum formulation entering the turbulence model, we use the ocean model wind stress as a baseline $\tau_a = \tau_a^{NEMO}$ (see Section 5.1.1). As a result, the definitions are fundamentally different and the wave-age dependencies are therefore not comparable. Importantly, wave-age enters the wave model wind stress definition via the growth rate parameter β in computation of wind input S_{in} (Janssen, 1991; Ardhuin et al., 2010) but is ignored in the bulk formulation used in ocean model. Therefore, the pronounced differences for the growing wind sea seen in Fig. 6(b) are largely methodological.

Regarding wind stress, the WW3 formulation is based on friction velocity $\tau_a^{WW3} = \rho_a u_*^2$ under neutral stability. In NEMO, the bulk transfer coefficients used with NCAR formulation (Eq. (8)) are stability corrected using (Monin and Obukhov, 1954) similarity theory (Madec and NEMO System Team, 2019). This correction leads to lower stress estimates in stable air-sea conditions compared to neutral stability estimates, with more pronounced impacts when the air is warmer than the sea (Large and Yeager, 2009; Kara et al., 2005). In the Baltic Sea, this is highly relevant during the spring (Svensson et al., 2016). Bonino et al. (2022) demonstrated that NCAR parameterization leads to higher wind stress under low winds compared to ECMWF bulk formulation, but produces lower estimates as the winds grow. This could lead to the GLS turbulence model with NCAR being calibrated to compensate for lower momentum input under moderate and high winds, whereas the needs for recalibration are likely different with ECMWF formulation. The wave model stability correction of Abdalla and Bidlot (2002) (based on SST) is available for the ST4 package and should be considered in future studies.

When replacing the existing momentum input definition with wave-modified ocean-side stress, impacts are also dependent on the wave model source-term package selected (see Eq. (10)). Specifically, differences may arise between wave breaking, dissipation, and swell attenuation, modulated by wind input and by effective fetch definitions (Pettersson, 2004). For instance, Christakos et al. (2021) found the wind input stronger for narrow fetch geometries in ST6, compared to other source term packages, and the effect was not counteracted

by dissipation. Moreover, Valiente et al. (2021) found the differences between ST4 and ST6 source terms packages larger under young, fast-growing waves and short fetches in the North Sea. As the dissipation term is empirically calibrated and depends on the selected parameterization, a detailed assessment of the source term balance would require sensitivity analysis beyond the scope of our study.

6.2.2. TKE injection and dissipation

In the GLS turbulence scheme, both TKE injection and dissipation are sensitive to the prescribed roughness length. In the current implementation in NEMO, roughness length controls the mixing length scale and magnitude of the CB94 TKE flux. Thereby, biases in roughness length definitions directly impact the balance between mechanical mixing, stratification, and seasonal development of the thermocline — factors which are especially important to represent correctly in the Baltic Sea whilst maintaining the permanent halocline.

Despite the reductions in thermal biases achieved through regional tuning, both of the considered roughness definitions (wind-based and wave height based) have limitations, as neither fully represents the sea state that controls TKE injection. Roughness length defined solely from wind speed neglects wind-direction variability and fetch. It also ignores phase lags between wind and waves, which in the Baltic can reach up to 10 h during high-swell events (Björkqvist et al., 2021). Under strong winds in short and narrow fetch conditions, the resulting wave height can be substantially lower than what the implicit wind-based parameterization would predict — despite the regional optimization. This behavior is already evident in the Baltic Proper with along-the-basin winds (Fig. 10), and we expect it to become even more pronounced when moderate or strong winds blow from land towards the sea, in the narrow Gulf of Finland and in the Danish Straits. In these situations, regional limitations of wave growth and the mixing lengths relevant for TKE injection can only be captured with explicit H_s instead of a local wind formulation.

However, the explicit significant wave height H_s based roughness does not distinguish between wind-sea and swell. The present GLS implementation therefore collapses the physically different wave regimes into a single scalar. Because the CB94 definition has been formulated for an active wind-sea (Craig and Banner, 1994), we expect this to lead to an overestimated TKE injection and dissipation in swell-dominated situations. In the wind-wave-dominated Baltic Sea, total H_s remains a reasonable approximation (see Section 2.2), but in the North Sea the frequent NW swell would require separating the wind-sea and swell contributions to roughness length when used for estimating wave-breaking released TKE and dissipation. This may contribute to the temperature biases discussed by Partridge et al. (2026).

Alari et al. (2016) and Breivik et al. (2015) have discussed that CB94 parameterization often produces enhanced vertical mixing and TKE injection in coastal regions. As several studies have done, the CB94 parameterization should therefore be replaced by TKE flux ϕ_{oc} from the wave model. This decouples the TKE dissipation from wave height (implicit and explicit) and avoids the need for additional tuning to compensate for the use of wave-modified ocean-side stress (Section 6.2.1). Although Alari et al. (2016) tested using explicit, wave model derived CB94 coefficient in GLS, such explicit modifications have not been introduced into the official NEMO GLS implementation (up to v5). Based on the aforementioned differences between wind-sea and swell, we find this crucial for ocean model setups that include explicit wave forcing.

In the absence of a GLS turbulence scheme representing different wave regimes, the regional threshold optimization presented in our study may provide a remedy to tuning forced and coupled wave-ocean setups. Nevertheless, it should be noted that tuning the single thresholds for the Baltic Sea may degrade North Sea simulations (and vice versa), which can via the NW swell representation influence the dynamics of water exchange in the Danish Straits. This underlines the need for more refined definitions of the contribution of the waves to turbulent mixing in the dynamically different but closely interacting Baltic and North Seas.

6.3. Implications and future directions

Our results highlight that regional, wave-modified differences in turbulent roughness length definitions are critical for representing turbulent mixing in hydrodynamic models. Although explicit wave forcing is available, existing turbulence formulations need to be reviewed. Future work should separate wind-sea and swell contributions to mixing length, TKE input and dissipation rate. When explicit significant wave height H_s is used as roughness length, traditional CB94-based TKE release should be replaced with flux estimates derived from a wave model. This distinction may be minor in wind-wave-dominated regions, but becomes essential in regions with frequent high-swell conditions.

The calculation of the roughness length from the friction velocity includes several approximations (detailed in [Appendix C](#)) that seem to make the formulation theoretically inconsistent with the wave-modified ocean-side stress. Therefore, we find it worthwhile to consider using wave model computed roughness directly ([Law Chune and Aouf, 2018](#)) instead of tuning the existing formulation to the wave-modified ocean-side stress. Additionally, adapting the existing wave-age formulation to use the wave-age from wave model or examining wave steepness based definitions ([Taylor and Yelland, 2001](#)) appear feasible options. As surface roughness is also dependent on Langmuir circulation ([Craig and Banner, 1994](#)), currently unresolved in NEMO GLS, the Langmuir parameterization for $k-\epsilon$ presented by [Axell \(2002\)](#) should be revisited.

In our study, both wave and ocean models were forced with the same atmospheric forcing, and selected wave parameters were subsequently used to force the ocean model. Although this approach ensures consistency between the model components, it is important to note that uncertainties in atmospheric forcing propagate into both the wave and ocean simulations. Additionally, calibration of both models is implicitly tied to this forcing. The one-way exchanges considered in our study provide a controlled framework for considering the role of roughness parameterization on thermal stratification, but this setup does not enable considering wave-ice interactions. We used the ice conditions from CTRL simulation in WW3 simulations to limit uncertainties arising from different ice conditions between the models. However, enabling two-way interaction between the models would be far more preferable and enable considering interactions during the winter ([Li et al., 2025](#)). Moreover, simple ice-blocking ([Tolman, 2003](#)) should be replaced in future studies with the ice source terms that are relevant for Stokes drift ([Kumar et al., 2020](#)). Two-way exchange between the component models would also enable simulations of oceanic surface current impacts on waves ([Kanarik et al., 2021](#)), and SST based stability correction in the wave model. Ultimately, a fully coupled model with wave, ocean, and atmospheric components would improve the representation of swell contributions to wind ([Kahma et al., 2016](#); [Wu et al., 2020](#)), and provide surface roughness and SST to the atmospheric model.

Although our analysis focused on temperature evolution during the thermally stratified and ice-free season within a single year, long-term implications on salinity are also likely and should be assessed in future studies. In particular, the differences between the CTRL and TAUST_Hs experiments identified here call for an assessment of how wave-modified stress and regional roughness modify the circulation patterns, transport over sills and Major Baltic Inflows through the Danish Straits. Although the current setup adequately resolves seasonal thermal stratification and mixing patterns, investigating the effects of wave forcing on eddy dynamics would require a finer resolution (eddy-permitting 0.5 km), particularly in the Gulf of Finland ([Vankevich et al. \(2016\)](#), [Westerlund et al. \(2019\)](#)). The sensitivity of mixing length scale demonstrated in this study further implies differences in current fields that are crucial for sea level predictions, drift forecasting, and the fate of harmful substances ([Bruciaferri et al., 2021](#)). Stand-alone ocean and wave forcings have already been applied in Baltic Sea drift studies ([Pärt et al., 2023](#)). Building on this, future work should compare drift trajectories obtained from wave-forced ocean currents to those produced by ocean models that represent wave impacts implicitly, in order to quantify the sensitivity of drift predictions to wave-modified stress, roughness length, and turbulent mixing.

7. Conclusions

We examined the thermal response to wave-dependent turbulent roughness length definitions, with an emphasis on fetch-limited characteristics of the Baltic and North Seas. We found that the GLS turbulence scheme in NEMO is sensitive to the roughness length definition and has an important role in estimating SST and thermocline depths. Although the hydrodynamic models often neglect explicit wave impacts, wave growth and breaking are implicitly represented via the GLS roughness length and CB94 parameterizations. Consequently, the roughness length formulation must be recalibrated when explicit wave-modified stress is introduced, to ensure consistent surface flux definitions. Moreover, because the default roughness formulation has been tuned for open ocean conditions, regional calibration appears crucial when modeling fetch-limited regions, even without explicit wave forcing.

In fetch-limited conditions, the regionally calibrated parameterization produced lower roughness estimates under moderate and high winds compared to the default formulation, reducing the mixing length and enhancing dissipation near the surface. These impacts were most pronounced in thermally stratified conditions in the Baltic Sea, where wave-informed optimization improved the SST representation – particularly during warm anomalies – but did not fully capture the seasonal thermocline deepening associated with wind-driven entrainment. In wave-forced experiments, the recalibration moderated the model's sensitivity to explicit wave-modified ocean-side stress, yielding mixed layer depths comparable to those obtained with wind stress formulation calibrated for the default roughness definition, yet further enhancing near-surface dissipation. This was evident with both implicit roughness length definition and explicit wave height based roughness estimates.

While regional recalibration of roughness length provides an immediate and practical solution for hydrodynamic models in fetch-limited and wind-sea-dominated regions, the availability of explicit wave information calls for more refined approaches within the NEMO GLS scheme. The existing implicit roughness formulation tends to overestimate mixing lengths in sheltered regions where wave growth is strongly limited by fetch. At the same time, the available explicit wave height definition does not distinguish between wind-sea and swell. When combined with the TKE dissipation profiles of [Craig and Banner \(1994\)](#), the use of total significant wave height obscures the energetically distinct wave regimes, which may lead to an overestimated TKE flux under swell conditions. Although significant wave height largely corresponds to wind-sea wave height in the Baltic Sea, accurately capturing the North Sea dynamics and refining the water exchange estimates in the Danish Straits would likely benefit from definitions that prevent swell from artificially enhancing turbulent mixing. For this reason, the roughness-sensitive CB94 parameterization should be replaced with an explicit, wave-informed formulation in GLS when a wave model is available.

CRedit authorship contribution statement

Veera Haapaniemi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Laura Tuomi:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Jan-Victor Björkqvist:** Writing – review & editing, Methodology, Conceptualization. **Andrew Twelves:** Writing – review & editing, Visualization, Methodology. **Jens Murawski:** Writing – review & editing, Conceptualization. **Hedi Kanarik:** Writing – review & editing, Validation, Methodology. **Saeed Falahat:** Writing – review & editing, Methodology. **Antti Westerlund:** Writing – review & editing. **Aleksi Nummelin:** Writing – review & editing, Methodology.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Wave model validation

The WW3 model was validated against wave buoy and satellite altimeter measurements for the significant wave height H_s for the year 2021 (Fig. A.1). The validation was done separately for the North Sea ($\text{lon} < 9^\circ \text{E}$) produced with 2 NM horizontal resolution and the Baltic Sea ($\text{lon} > 9^\circ \text{E}$), produced with 1 NM resolution.

Wave buoy measurements were retrieved from the Copernicus Marine Service (EU Copernicus Marine Service Product, 2024c) for locations shown in Fig. 1. Satellite observations were retrieved from 8 different satellite altimeters active in the area during the year 2021, also available in Copernicus Marine Service (EU Copernicus Marine Service Product, 2023). These included SARAL/AltiKa, Cryosat2, CFOSAT, HaiYang-2B, Jason-3, Sentinel-3 A, Sentinel-3B and Sentinel-6 A satellites.

Validation shows the used WW3 setup agrees well with the observations with BIAS ranging between 0.05 and 0.13 m, RMSE between 0.25 and 0.4 m and R between 0.9 and 0.96. WW3 underestimates waves with $H_s > 4$ m at the buoy locations, more notably in the North Sea (Fig. A.1(a), (c)), where the wave model has a coarser resolution and most of the buoy locations considered were close to the coast (see Fig. 1). Comparison to satellite altimeters in the Baltic Sea (Fig. A.1(d)) shows a large number of modeled $H_s = 0$ m with measured waves up to 5 m, that were caused by errors at the ice edge modeled by the CTRL run of NEMO (see e.g. Tuomi et al., 2019).

Appendix B. Statistical methods

To assess the model performance, we compute the following statistical measures: bias, root-mean-square-error (RMSE) and the correlation coefficient R. Bias quantifies the mean difference between model m and observation o values

$$\text{BIAS} = \bar{m} - \bar{o}.$$

RMSE measures the overall deviation between modeled and observed values

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (m_i - o_i)^2},$$

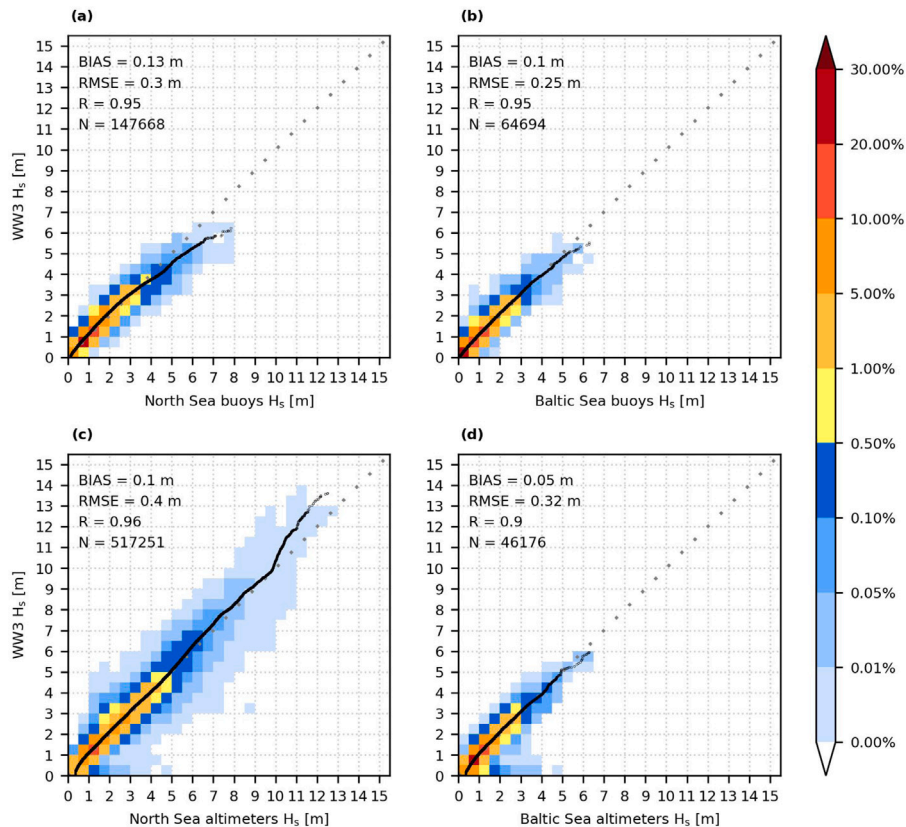


Fig. A.1. Scatter plots comparing modeled significant wave height H_s against wave buoy observations (a, b) and satellite altimeter measurements (c, d) at North Sea (a, c) and Baltic Sea (b, d) for the period of 1 January to 31 December 2021. Wave buoy locations are shown in Fig. 1.

where N is the number of points. The correlation coefficient R characterized the linear association between modeled and observed anomalies

$$R = \frac{1}{\sigma_o \sigma_m} \frac{1}{N} \sum_{i=1}^N (m_i - \bar{m})(o_i - \bar{o}),$$

where standard deviations (σ_x) are computed

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2.$$

Appendix C. Roughness length parameterizations

Roughness length to wave height ratio

As far as we understand, the ratio $\gamma = z_0/H_s$ has been assumed to have a fixed value ($\gamma = 0.85$) in the derivation of Eq. (5). This assumption is then built into the NEMO GLS implementation, where the ratio γ is used as a tunable parameter.

Based on Mellor and Blumberg (2004) (Equations 6a-b), roughness length can be written as

$$z_{0,w} = \frac{665}{g} \left(\frac{c_p}{u_*} \right)^{1.5} u_*^2, \quad (C.1)$$

where water-side friction velocity is computed from air-side friction velocity using the ratio of densities, which is also included in deriving the dimensionless constant $C = 665$. Comparing this to Eq. (5), it is evident, that the implemented function is obtained by using Mellor and Blumberg (2004) Equation 5b, i.e. $z_0 = 0.85 H_s$, originating from Terray et al. (2000). Although (Raschle et al., 2008) aimed to limit to values of wave height when formulating the wave-growth-dependent roughness length parameterization, Eq. (5) appears to include two different roughness lengths.

Namely, in the NEMO GLS implementation (see Eq. (5)) we can identify

$$z_{0,\text{TKE}} = \gamma_{\text{TKE}} \frac{1}{\gamma_w} z_{0,w}, \quad (C.2)$$

where $\gamma_w = 0.85$ (Terray et al., 2000). Which effectively separates the water-side roughness length and turbulent roughness length scaling parameters. Out of the different roughness definitions discussed in Section 3.2, the explicit definition based on wave model significant wave height H_s corresponds to $z_{0,w}$ whereas the implicit definitions correspond to $z_{0,\text{TKE}}$.

Whilst the ratio $\gamma_{\text{TKE}}/\gamma_w$ effectively functions as a free tuning parameter in the implementation, this is not currently visible to model users. As a result, retuning the individual scaling factor γ_{TKE} easily breaks the theoretical balance. For the stand-alone model case, the roughness length definition could then be written as

$$z_{0,\text{TKE}} = \frac{C}{g} \frac{w_*^2}{u_*} \left(\left[\frac{c_p}{u_*} \right]_{\text{ref}} \tanh \left(\frac{2u_{*,\text{ref}}}{u_*} \right) \right)^{1.5}, \quad (C.3)$$

where C is a dimensionless constant and the corresponding estimate for significant wave height would be based on Mellor and Blumberg (2004) and Raschle et al. (2008) written as

$$H_s = \frac{1}{\gamma} \frac{C}{g} \left(\left[\frac{c_p}{u_*} \right]_{\text{ref}} \tanh \left(\frac{2u_{*,\text{ref}}}{u_*} \right) \right)^{1.5} u_*^2. \quad (C.4)$$

It is worth to note that the argument follows the power law u_*^{-1} , differing from the U^{-2} dependent Sverdrup-Munk-Bretschneider growth curves traditionally used to more wave field dependency on fetch together with the hyperbolic tangent parameterizations (see e.g. Kahma and Calkoen, 1992; Holthuijsen, 2007).

If explicit wave-modified ocean-side stress is integrated into the model system, it is worth noticing that the shear stress continuity changes impacting also the implementation of these equations. This is covered in the following section.

Shear stress continuity

In the derivation of Eq. (5), the air-side stress is computed based on ocean-side stress module as $u_* = 28w_*$, which includes the assumption that ocean-side stress is equal to wind stress. This is no longer the case, when the wave-modified ocean-side stress is applied as $u_* \neq 28w_*$ (see Eq. (10)). For this reason, we have used the wind stress to compute the parameterized wave-age in all experiments (see Eq. (4)), ensuring consistency with the threshold optimization. In the wave-modified ocean-side stress experiments, the new stress definition is only included in the water-side friction velocity coefficient (u_*^2) term, not in the parameterized wave-age term. Notably, this does not impact the experiment TAUST_Hs, where the ocean-side stress definition does not impact the roughness length (see Eq. (2)). Moreover, as far as we could follow, the derivation of dimensionless constant C in Eq. (C.1) includes the assumption of ocean-side stress equaling wind stress, meaning that the definition is inherently inconsistent with wave-modified stress and should be replaced with a theoretically sound and more easily tunable formulation when explicit wave information is taken into account.

Data availability

Data will be made available on request.

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