A New Method for Thermocline and Halocline Depth Determination at Shallow Seas

MACIEJ JANECKI,[a] DAWID DYBOWSKI,[a] DANIEL RAK,[b] AND LIDIA DZIERZBICKA-GLOWACKA[a]

[a] *Ecohydrodynamics Laboratory, Physical Oceanography Department, Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland*
[b] *Observational Oceanography Laboratory, Physical Oceanography Department, Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland*

(Manuscript received 10 January 2022, in final form 26 May 2022)

ABSTRACT: This paper introduces a new method for finding the top of thermocline (TTD) and halocline (THD) depths that may become a powerful tool for applications in shallow marine basins around the world. The method calculates the moving average of the ocean vertical profile's short-scale spatial variability (standard deviation) and then processes it to determine the potential depth at which temperature or salinity rapidly changes. The method has been calibrated using an extensive set of data from the ecohydrodynamic model EcoFish. As a result of the calibration, the values of the input parameters that allowed the correct determination of TTD and THD were established. It was confirmed by the validation carried out on the in situ profiles collected by the research vessel S/Y *Oceania* during statutory cruises in the southern Baltic Sea. The "MovSTD" algorithm was then used to analyze the seasonal variability of the vertical structure of the waters in Gdańsk Deep for temperature and salinity. The thermocline deepening speed was also estimated in the region analyzed.

KEYWORDS: Ocean; Mixed layer; Thermocline; Ocean models

1. Introduction

The existence of a well-mixed surface layer where temperature, salinity, and density are almost homogeneous is a characteristic and almost universal feature of water bodies such as seas and oceans. Wind-driven interactions and heat flux exchange at the water–atmosphere boundary cause strong turbulent mixing processes within this layer.

The depth of this mixed layer shows high seasonal variability. It may be located close to the surface or be not present at all during the warm summer months. However, in winter, because of the deep convection stimulated by surface heat loss, the boundary of the mixed layer is observed at great depths. In selected ocean locations, it can reach 2000 m (Marshall and Schott 1999), while in shallow seas, an example of which is the Baltic Sea, it is observed at depths of tens of meters (Leppäranta and Myrberg 2009).

The correct determination of the mixed layer depth (MLD) is of key importance in oceanographic research. This knowledge is used in the development, parameterization improvements and validation of ocean general circulation models (OGCMs), which are used to simulate the physical and thermodynamic processes that occur in the ocean (Chen et al. 1994; Masson et al. 2002; Noh et al. 2002; Kara et al. 2003; Zhang and Zebiak 2002). Furthermore, since a significant proportion of biological activity occurs in the upper ocean (in the euphotic zone), the mixed layer is also important for work related to biological processes (Morel and André 1991; Longhurst 1995; Polovina et al. 1995).

The concept of a mixed layer is arbitrary and can be based on various parameters (e.g., temperature, density, salinity). The most commonly used criteria for defining a mixed layer are threshold methods, where MLD is the depth at which the temperature (or density) changes by a predetermined threshold value with respect to the one at a reference depth close to the surface. The choice of reference depth and threshold is usually arbitrary (de Boyer Montégut et al. 2004; Thomson and Fine 2003; Weller and Plueddemann 1996; Obata et al. 1996; Thompson 1976; Spall et al. 2000; Foltz et al. 2003; Rao et al. 1989); however, there are also studies in which it is based on a detailed analysis of thousands of profiles (Sprintall and Roemmich 1999), statistical analysis (Kara et al. 2000), water mass characteristics (Monterey and Levitus 1997), or other criteria (Schneider and Müller 1990). Gradient methods are also widely used, which, like threshold methods, are based on the assumption that there is a strong gradient at the base of the mixed layer and focus on finding its critical value (Lukas and Lindstrom 1991; Dong et al. 2008).

The limitation of these methods is their dependence on the reference depth and the threshold value. The consequence of the universal use of single parameterization for all profiles is overestimating (especially in those based on the temperature criterion) or underestimating the depth of the mixed layer. Due to the existence of salinity barrier layers, the density criterion was found to be better than the temperature one (Lukas and Lindstrom 1991); however, the availability of the density profiles is much lower than the temperature ones (Lorbacher et al. 2006). Due to these limitations, more complex methods of determining the MLD have developed. Examples can be the "curvature method" proposed by Lorbacher (Lorbacher et al. 2006), the "split and merge" (Thomson and Fine 2003), as well as a hybrid algorithm based on the

Supplemental information related to this paper is available at the Journals Online website: https://doi.org/10.1175/JPO-D-22-0008.s1.

Corresponding author: Maciej Janecki, mjanecki@iopan.pl

DOI: 10.1175/JPO-D-22-0008.1

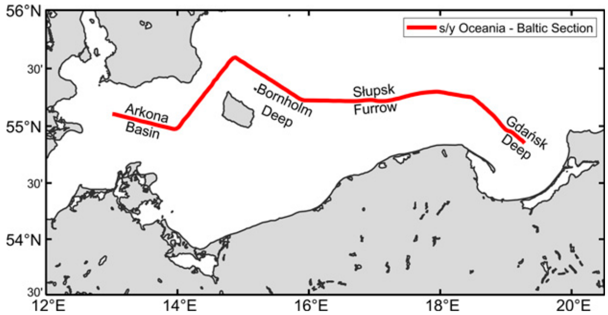

FIG. 1. S/Y *Oceania* section. Regular CTD measuring section of S/Y *Oceania*.

combined use of several methods to find the best MLD fit (Holte and Talley 2009).

The MLD determination methods presented above have been tested and applied on a number of water bodies (including the Global Ocean, Pacific Ocean, Atlantic Ocean, Indian Ocean), which all have a common feature of great depth. We could not find any papers with these methods dedicated and calibrated to semiclosed, shallow, and brackish seas such as the Baltic Sea. There are many factors that influence changes in water temperature in these types of seas, among others: diurnal variability (Karagali et al. 2012), strong winds, upwelling phenomenon, or freshwater inflow from rivers (Grelowska et al. 2018). These processes can impede the accurate and precise determination of TTD/THD.

The region of our particular interest is the Gulf of Gdańsk and Gdańsk Deep with a maximum depth of 118 m located in its northern part. It is related to the ongoing project "FindFish—Numerical Forecasting System for the Marine Environment of the Gulf of Gdańsk for Fisheries" (Dzierzbicka-Głowacka et al. 2018). Being aware of the applicability limitations of the existing methods and having the need to analyze the vertical structure of the waters of the Gulf of Gdańsk, we decided to develop our own method of determining the mixed layer depth and called it the "MovSTD" algorithm. We think that thanks to the methodology we used

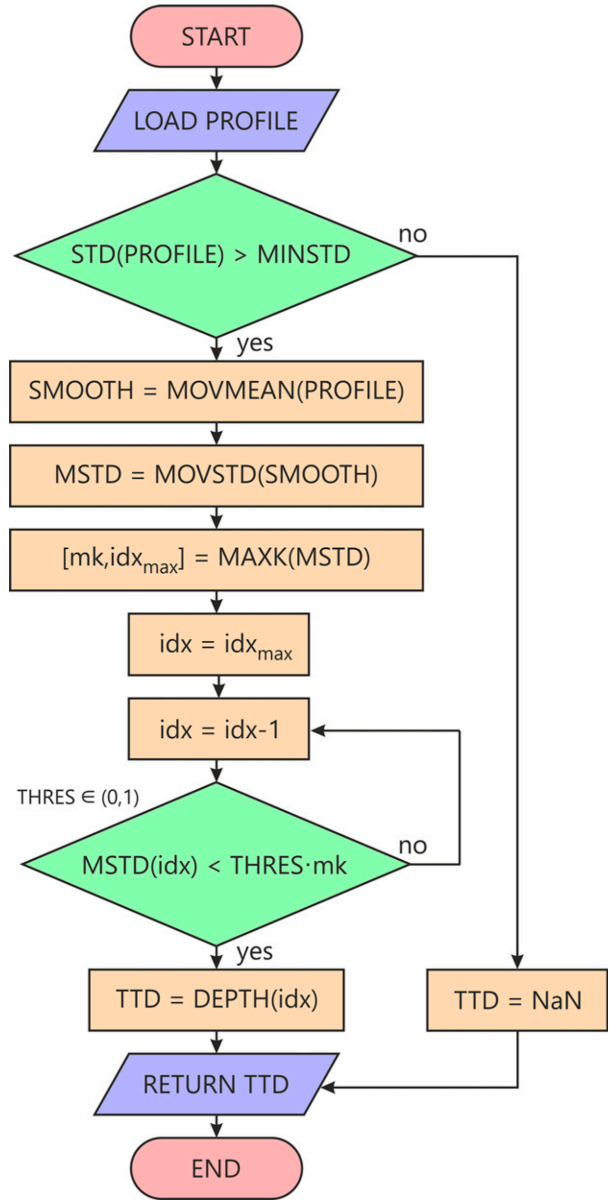

FIG. 3. The flow diagram of the MovSTD algorithm.

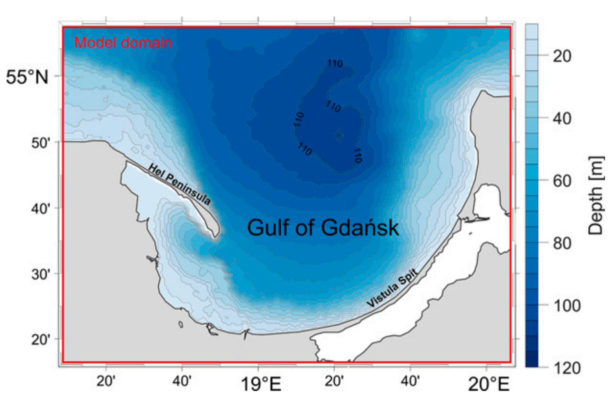

FIG. 2. Model domain. Topography of the EcoFish model domain with the analyzed 110-m isobath region emphasized.

and its low computational complexity, the MovSTD algorithm will fill the knowledge gap and become a powerful tool for applications in shallow marine basins around the world.

The MovSTD algorithm was calibrated and then validated against in situ profiles of temperature and salinity. After visually confirming that the method correctly determines the depth of the mixing layer, it was used to analyze the mechanism of thermocline and halocline formation in the Gdańsk Deep, using EcoFish model data from 1 January 2014 to 31 December 2020. Using the proposed method, we were able to analyze MLD in the waters of the Baltic Sea by determining the top of the thermocline (TTD) and halocline (THD) depths.

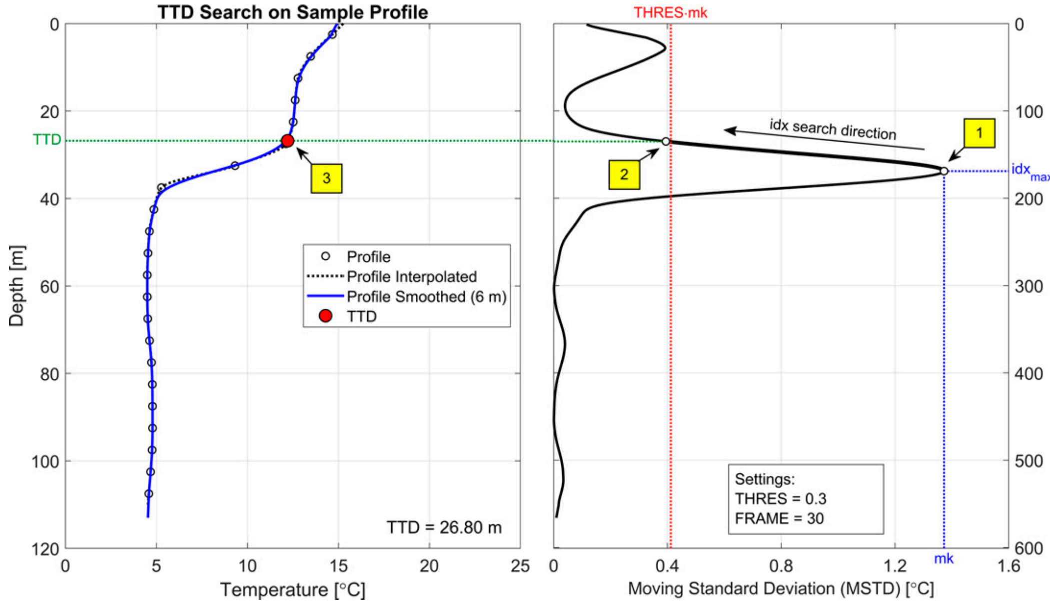

FIG. 4. An example of finding a TTD using the MovSTD algorithm. (left) Sample temperature profile and (right) the moving standard deviation of the profile. The yellow squares indicate 1) the maximum value of the MSTD curve, 2) the first index that meets the cutoff search condition of Eq. (1), and 3) the top of thermocline depth in the profile (TTD).

2. Materials and methods

a. Field data

This research uses in situ hydrographic data obtained by the Institute of Oceanology, Polish Academy of Sciences, during regular cruises of the research vessel S/Y *Oceania* (Rak and Wieczorek 2012). Data were recorded using a CTD (conductivity–temperature–depth) probe on a fixed measurement section extending between 13° and 20°E. The measuring section starts at Gdańsk Basin and then runs through the Słupsk Furrow toward Bornholm Basin and further to the Arkona Basin (Fig. 1).

The data used here were collected between January 2014 and December 2020. During this period, 15 research cruises were made. Seven of them were held in the fall (one in September, two in October, and four in November). Four cruises were carried out in winter (two in January and two in February). In spring there were also four cruises (all in May). There are no summer campaigns due to the ship's participation in the Arctic Expedition (AREX). For the purposes of this study, vertical profiles were averaged every 0.5 m. The data were used to validate the MovSTD algorithm.

b. EcoFish model

Detailed information on the EcoFish model is provided in (Janecki et al. 2021). Besides an extensive description, it includes a chapter on the validation of water temperature and salinity profiles used in this research. Here, we present only a brief summary and description of the model results that were used in this research.

EcoFish's horizontal resolution is 575 m (1/192°). The vertical resolution is 5 m for each layer with a total of 26 layers. Vertical discretization uses the *z* formulation, and the bottom topography is based on the Baltic Sea Bathymetric Database (BSBD) of the Baltic Sea Hydrographic Commission (Baltic Sea Hydrographic Commission 2013).

The EcoFish model domain covers an extended Gulf of Gdańsk region (Fig. 2). The data come from a 7-yr simulation of the model from 1 January 2014 to 31 December 2020. The simulation was preceded by a 2-yr spinup. EcoFish model has active satellite data assimilation for surface temperature. The results were recorded four times a day as 6-h averages and then converted to daily average.

c. MovSTD algorithm

This section introduces the MovSTD algorithm for determining the TTD and THD depths. In brief, the algorithm smooths the analyzed profile to eliminate short-term fluctuations and bimodal distribution, and then it creates a moving average of the smoothed profile's standard deviation (STD) to find its maximum value and the index (depth) for which it occurs. It proceeds to scan the STD curve upward for a value that meets the condition specified by Eq. (1). The index of the first point returned from the method indicates TTD/THD. The source code of the MovSTD algorithm is provided in the online supplemental material.

The result of this calculation depends on the values of three predefined parameters that, together with the analyzed individual profile, serve as input arguments for the method. The values of these parameters that are suitable

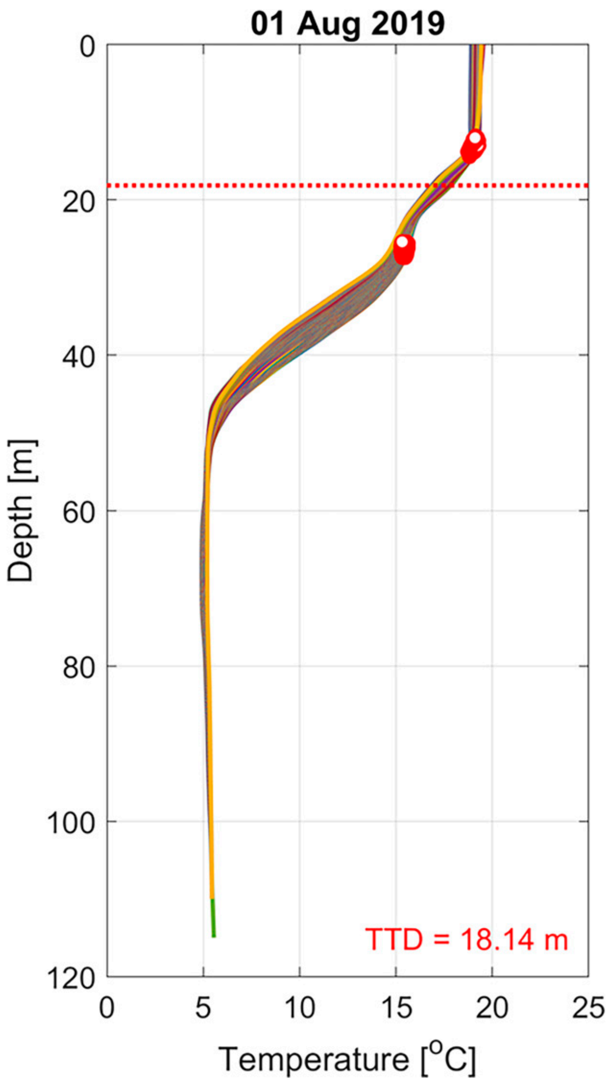

FIG. 5. Bimodal distribution of TTD. A group of temperature profiles of the EcoFish model with a visible bimodal distribution of TTD for 1 Aug 2019. Multicolored curves (orange, purple, green, etc.) represent individual vertical profiles. Red–white circles are the TTDs of the individual profiles. The dashed red line marks the average TTD for that day in the region analyzed.

for the Baltic Sea conditions were determined at the calibration stage, which is described in next section. The parameters are as follows:

- moving mean and moving STD sliding window (FRAME),
- standard deviation threshold (THRES), and
- profile's minimum standard deviation (MINSTD).

The flow diagram (Fig. 3) shows the step-by-step mechanism of finding TTD/THD in the MovSTD algorithm. The initial step is to cache the individual vertical profile of the variable analyzed (temperature or salinity). The precision of the MovSTD algorithm is closely related to the spatial resolution of the profile. If it is too coarse, the interpolation should be performed first. In this study, both the profiles from the EcoFish model and the in situ data were interpolated at a resolution of 0.2 m. The choice of this resolution was the result of our expert judgment. It is adequate to eliminate local spikes of in situ data and capture temperature/salinity variation at the same time. Calibration of the MovSTD algorithm was performed with this resolution selected. Therefore, the parameter values determined during the calibration stage will be appropriate for this data density. If one tries to use the MovSTD algorithm for profiles with a resolution other (mostly coarser) than 0.2 m, the FRAME parameter should be recalibrated.

In the next step, the STD condition is checked across the entire profile. If it is less than MINSTD, the algorithm returns not a number (NaN), which signals that the profile is homogeneous (isothermal or isohaline) and there is no visible thermocline/halocline. An attempt to use MovSTD here may result in receiving an erroneous value related to the local change in temperature/salinity, not the fact that there is a wedge in the profile analyzed.

If the above condition is met (when the STD of the profile is greater than MINSTD), the algorithm begins to smooth the profile using a moving average, with a step defined by the FRAME parameter.

We calculate the moving standard deviation (MSTD) of the smoothed vertical profile, which is the most important operation in the presented method. The result of this operation is used to determine the position where the greatest changes in value occur.

Now we find the maximum of the MSTD mk and the corresponding index idx_{max}. The idx is the depth measurement index from the surface (idx = 1) to the bottom (idx = N). In a profile reaching 120 m with a vertical resolution of 0.2 m, idx = 1 is 0-m depth, idx = 2 is 0.2 m, idx = 3 is 0.4 m, and so on up to idx = 601 for a depth of 120 m.

The index number idx_{max} is used as the starting point for the MSTD curve search. At this stage, the algorithm starts to check the cutoff condition in the direction of decreasing depth indexes (toward the surface). For each subsequent index, it is checked whether the MSTD value has fallen below the value of the product mk and the threshold parameter THRES [Eq. (1)]. The first index that meets this condition indicates the TTD (for the temperature profile) or THD (for the salinity profile):

$$\mathrm{MSTD(idx)} < \mathrm{THRES} \times \mathrm{mk}; \text{ where } \mathrm{THRES} \in (0, 1). \quad (1)$$

Here we present the description of the algorithm's steps on the sample temperature profile. The method works similarly for salinity profiles.

The analyzed sample temperature profile (Fig. 4) is an EcoFish model result for 3 October 2014 from the Gdańsk Deep location. Due to the coarse vertical resolution (5 m), it is subjected to the piecewise cubic Hermite interpolating polynomial (PCHIP) method with nodes every 0.2 m (black dotted line in Fig. 4). The interpolated value at a query point is based on a shape-preserving piecewise cubic interpolation of the values at neighboring grid points.

Since the profile's STD is 3.74°C, the condition of MINSTD = 0.7°C is met, which means that the profile is not isothermal and we can proceed to determine the TTD. In the next step, the profile is smoothed (solid blue line in Fig. 4) using a moving average with a sampling width of 30 indexes

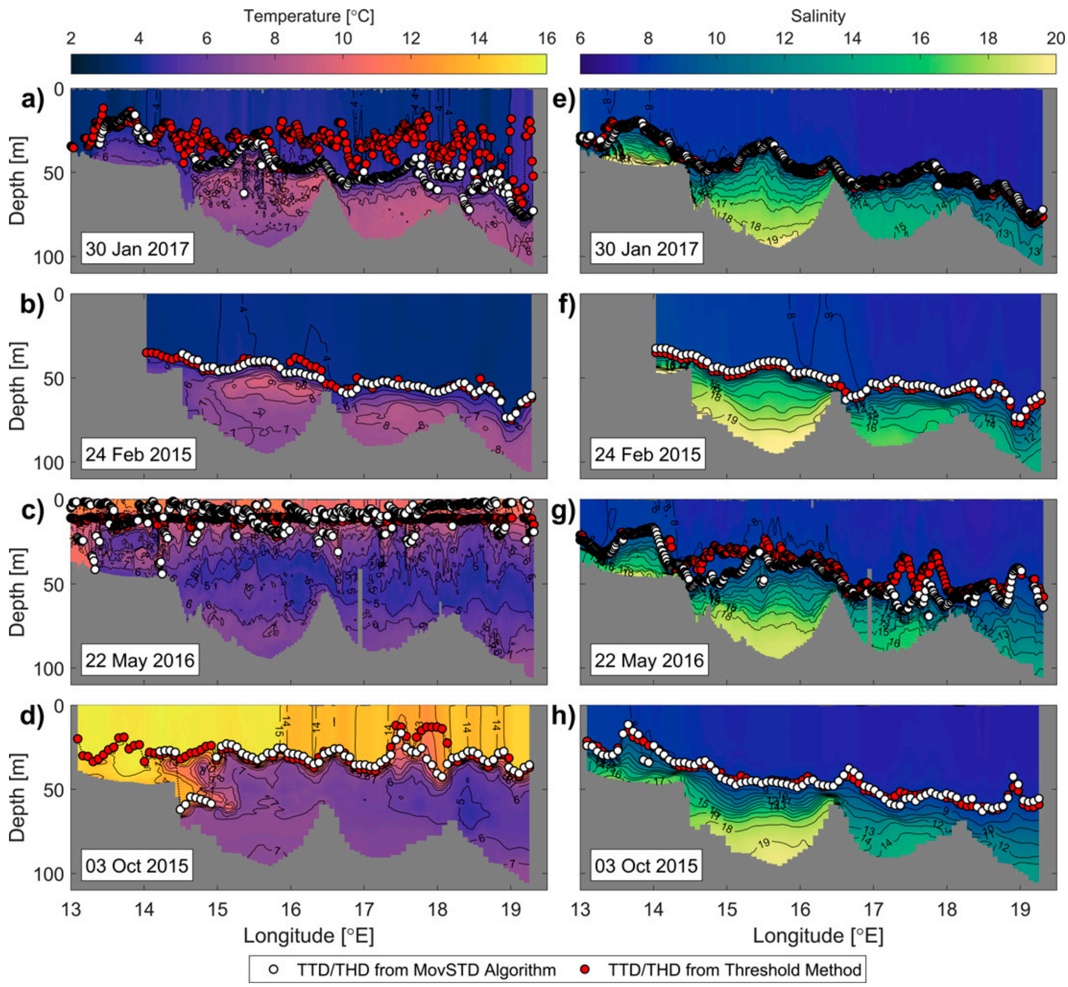

FIG. 6. MovSTD validation. Algorithm validation for temperature and salinity profiles from four representative S/Y *Oceania* cruises, which took place in January, February, May, and October. (a)–(d) Temperature profiles with TTDs marked. (e)–(h) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2°C$, $\Delta S = 0.5$.

(FRAME = 30), which corresponds to a width of 6 m for a profile resolution of 0.2 m. For the smoothed profile, the moving standard deviation (MSTD) is calculated using the same sampling width.

The algorithm determines the maximum value mk on the MSTD curve, which for the analyzed profile is 1.3725 and the corresponding depth index idx_{max} equal to 169 (yellow square 1 in Fig. 4). The MSTD curve is scanned from idx_{max} in the upward direction (descending indexes). The algorithm begins to search for the first index that meets the conditions of Eq. (1). After substituting the numerical values, we get

$$\mathrm{MSTD(idx)} < 0.3 \times 1.3725 = 0.4118. \quad (2)$$

The first index that meets the conditions is idx = 135, for which the MSTD is 0.3945 (yellow square 2 in Fig. 4). The index is then returned from the MovSTD algorithm, indicating that the top of the thermocline is located at a depth of 26.8 m (yellow square 3 in Fig. 4).

d. Parameterization

This section presents the parameterization and calibration process of the MovSTD algorithm. The TTD and THD depth values returned by the MovSTD algorithm depend on three input parameters. The appropriate selection of these parameters has a significant impact on the results obtained.

The FRAME parameter is responsible for smoothing the individual vertical profiles and the shape of the MSTD curve. The reason for its use is the need to eliminate the erroneous results obtained from the algorithm, related to the existence of inversions inside the profiles (especially temperature ones). The MovSTD method is based on the assumption that the presence of thermocline and halocline is associated with a strong gradient and unimodal distribution. Profiles with a multimodal (usually bimodal) distribution (Fig. 5) can be observed during the months when the seasonal thermocline starts to form. These additional modes, although relatively

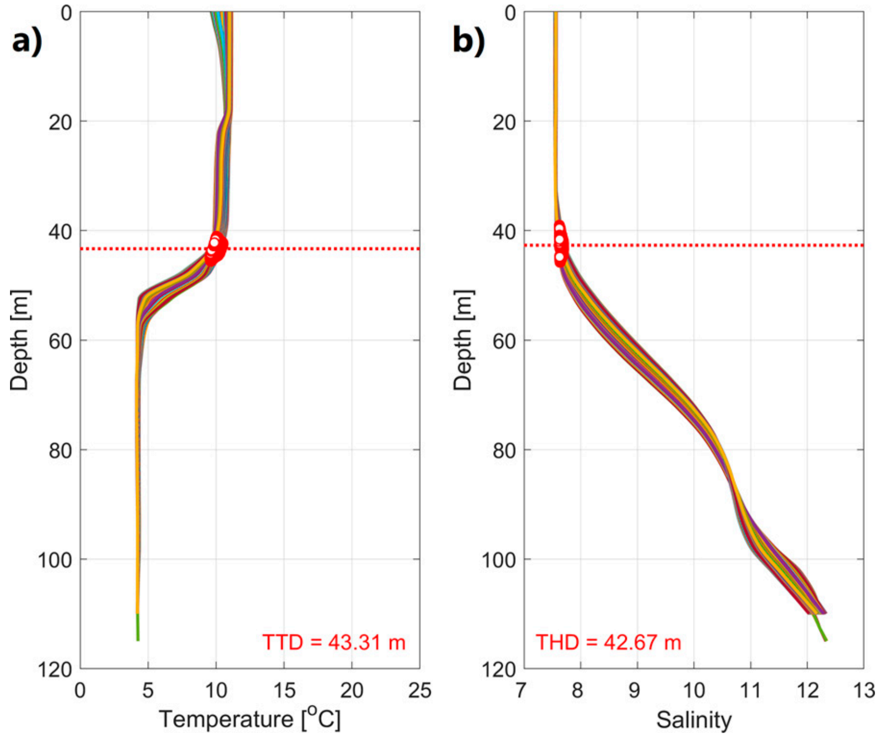

FIG. 7. Sample results from the MovSTD algorithm. EcoFish model (a) temperature and (b) salinity vertical profiles, 18 Nov 2018. Multicolored curves (orange, purple, green, etc.) represent individual vertical profiles. Red–white circles are the TTD/THD of the individual profiles. The dashed red line marks the average TTD/THD value for that day in the Gdańsk Deep region (110-m isobath).

narrow, may have a greater temperature gradient than that found in the thermocline. The use of a moving average of the profile and moving standard deviation allows to eliminate these additional modes and transform the profile into unimodal.

Selecting a FRAME that is too small can result in insufficient elimination of additional modes. However, a large value smooths the profile too much, causing the thermocline/halocline to stretch and making it difficult for the algorithm to find the correct depth of its top.

The THRES parameter is directly responsible for the step when MovSTD algorithm stops scanning the MSTD curve and returns the index indicating the top of thermocline/halocline depth. Selecting a THRES too high will meet the condition [Eq. (1)] too fast and terminate the TTD/THD search inside the thermocline/halocline rather than at their top, causing the depth to be overestimated (area between yellow square 1 and 2 on Fig. 4). On the other hand, a small THRES may cause an underestimation of the depth by terminating the MSTD curve search process too late, above the thermocline/halocline layer (left of yellow square 2 on Fig. 4). The correct determination of this parameter was the result of a visual examination of hundreds of profiles while using different THRES and choosing a value that would place the TTD/THD on the correct depth.

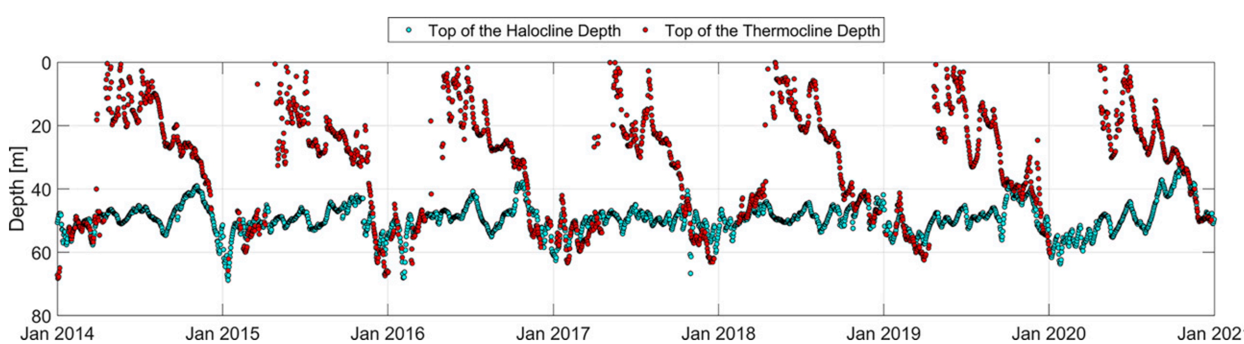

FIG. 8. TTD and THD time series. Top of thermocline (TTD) and halocline (THD) depth values time series obtained from MovSTD algorithm.

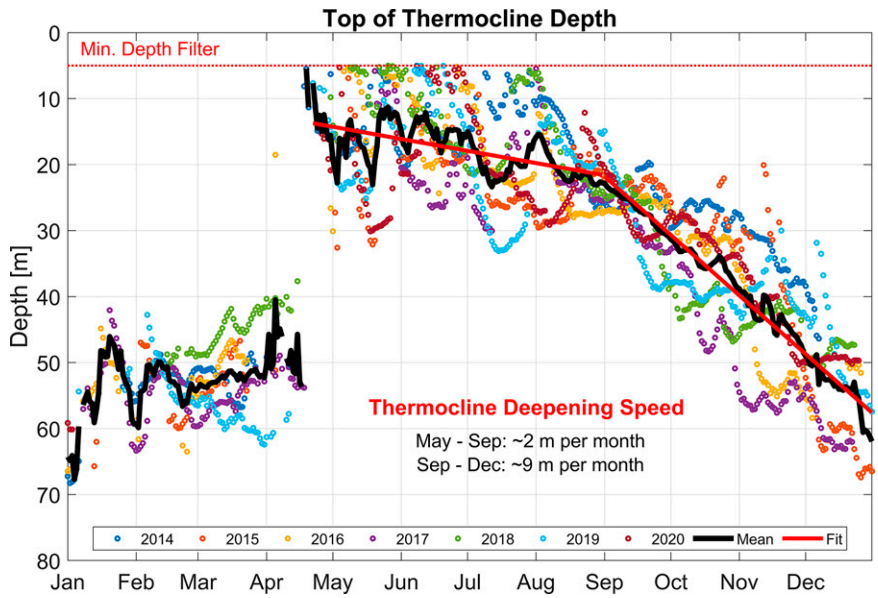

FIG. 9. Seasonal variability of the thermocline. Seasonal variability of the average TTD values from the MovSTD algorithm for the Gdańsk Deep region in the 2014–20 period.

The MINSTD parameter protects the method against returning erroneous values by omitting the search in homogeneously mixed profiles without thermocline (or halocline). If the STD of the data in the profile is less than MINSTD, the MovSTD algorithm does not start a search for TTD/THD and returns NaN.

e. Calibration

MovSTD algorithm calibration was carried out with the use of modeled temperature and salinity vertical profiles from the Gdańsk Deep region.

First, we used the MovSTD algorithm to obtain the TTDs/THDs of all individual profiles on each day in the 7-yr data interval. The next step was to calculate the region mean TTD/THD for each day and its standard deviation. After that we took all the daily STD values and calculated their mean. Since we did not analyze a single location, but the entire region of Gdańsk Deep, we assumed that there is a background daily STD related to the fact that the profiles in the analyzed area were not homogeneous. The addition to the daily STD value comes from the fact that for a given group of profiles,

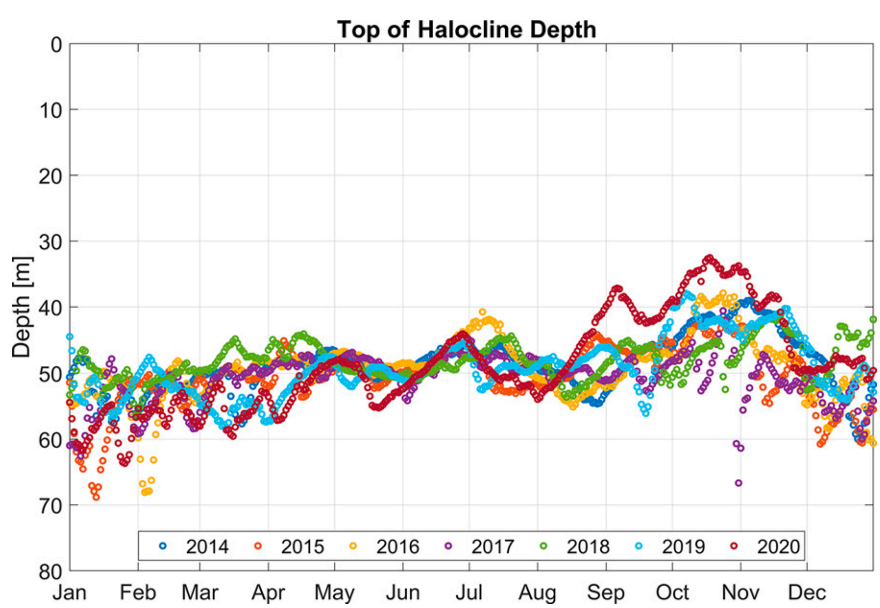

FIG. 10. Seasonal variability of the halocline. Seasonal variability of the average THD values from the MovSTD algorithm for the Gdańsk Deep region in the 2014–20 period.

TABLE A1. MovSTD algorithm calibration table. Boldface italic entries denote potential candidates for parameter values choice. Boldface non-italic entries are the combination of values that were chosen as the best set of input parameters for the MovSTD algorithm.

	Parameters			Mean STD (m)	
Pick	FRAME	THRES	MINSTD	TTD	THD
	20 (4 m)	0.20	0.60	1.76	1.62
	20 (4 m)	0.25	0.60	1.77	1.83
	20 (4 m)	0.30	0.60	1.77	2.25
	20 (4 m)	0.20	0.65	1.71	1.62
	20 (4 m)	0.25	0.65	1.73	1.83
	20 (4 m)	0.30	0.65	1.72	2.25
	20 (4 m)	0.20	0.70	1.65	1.62
	20 (4 m)	0.25	0.70	1.66	1.83
	20 (4 m)	0.30	0.70	1.67	2.25
	25 (5 m)	0.20	0.60	1.76	1.47
	25 (5 m)	0.25	0.60	1.68	1.61
	25 (5 m)	0.30	0.60	1.69	1.93
	25 (5 m)	0.20	0.65	1.70	1.47
	25 (5 m)	0.25	0.65	1.62	1.61
	25 (5 m)	0.30	0.65	1.64	1.93
	25 (5 m)	0.20	0.70	1.65	1.47
	25 (5 m)	0.25	0.70	***1.56***	1.61
	25 (5 m)	0.30	0.70	1.58	1.93
THD	**30 (6 m)**	**0.20**	**0.60**	1.75	***1.37***
	30 (6 m)	0.25	0.60	1.67	1.44
	30 (6 m)	0.30	0.60	1.63	1.66
	30 (6 m)	0.20	0.65	1.70	***1.37***
	30 (6 m)	0.25	0.65	1.61	1.44
	30 (6 m)	0.30	0.65	1.57	1.66
	30 (6 m)	0.20	0.70	1.63	***1.37***
	30 (6 m)	0.25	0.70	***1.56***	1.44
TTD	**30 (6 m)**	**0.30**	**0.70**	***1.51***	1.66

the MovSTD algorithm returned two groups of possible TTDs/THDs, creating a bimodal distribution (Fig. 5). Therefore, it was advisable to find a combination of input parameters such that the mean STD was as small as possible. For calibration, we choose three values for each parameter in the range that gave satisfactory results during the initial visual examination of the results. Table A1 in the appendix summarizes all combinations of parameters and mean STD values calculated using these parameters. The three sets of parameters with the smallest mean STD for salinity and temperature were selected as potential candidates for parameter determination and subjected to further examination to select the best combination of values. After analyzing the results, we decided that the MovSTD algorithm gives the most plausible estimations of TTDs/THDs using the following parameters:

For determining the TTD:

- FRAME: 30 (6 m),
- THRES: 0.3,
- MINSTD: 0.7°C.

For determining the THD:

- FRAME: 30 (6 m),
- THRES: 0.2,
- MINSTD: 0.6.

3. Results and discussion

a. *MovSTD algorithm validation and comparison with the threshold method*

The MovSTD algorithm was validated on data from all 15 available Baltic cruises on S/Y *Oceania* (Rak and Wieczorek 2012). This section presents the results for a selection of four representative cruises that occurred in January/February, late February, May, and early October (Fig. 6). The validation results for all cruises are in the appendix (Figs. A1–A5).

Validation revealed that the MovSTD algorithm correctly determines TTDs in the winter months (Figs. 6a,b), when there is a semi-isothermal cold water structure in the mixed layer, and a visible, well-established thermocline at greater depths. Very good results are also obtained for the October cruise (Fig. 6d), when the warm mixed water that has heated up in summer is in the upper layers, and then a rapid temperature drop is observed with a relatively thin thermocline. MovSTD algorithm gives satisfactory results in May (Fig. 6c), when the seasonal thermocline begins to form due to the heating of the surface layer; however, it should be noted that in these months a strong temperature variability is observed, which can sometimes cause underestimation or overestimation (visible spikes) of TTD.

Halocline does not have the same seasonal characteristics as thermocline. It is relatively constant for the entire section in each of the cruises, and the THDs are well determined. The increases in salinity that occur in the analyzed cruises are so strong and homogeneous (no bimodal distribution) that the MovSTD algorithm produces highly reliable results (Figs. 6e–h).

The MovSTD algorithm was compared with the threshold method. It is another common and fast way for determining the top of thermocline and halocline depths. It starts at the surface reference depth and continues to search the vertical profile, until a level is found where the water temperature (or salinity) differs from the reference value by a fixed threshold.

In this comparison, we used a surface reference depth of 10 m and a fixed threshold of 0.2°C (0.5 for salinity) proposed by de Boyer Montégut et al. (2004). These values were established for global climatology, and we acknowledge that we did not proceed with a dedicated calibration of this method for the Baltic Sea. Therefore, it was possible that it had performed worse than the MovSTD algorithm that was specifically calibrated for the Gdańsk Deep area.

The results obtained from the threshold method are similar to those from the MovSTD algorithm only in the case of a very clearly delineated thermocline. This is especially visible in the October section (Fig. 6d) and during the February cruise (Fig. 6b). For the May section, where a freshly formed thermocline can be observed, the threshold method fails. It yields the result practically in the first meters below the reference depth due to rapid local temperature fluctuations (Fig. 6c). The MovSTD algorithm is better in this case by adjusting to the nature and dynamics of the profile. The threshold method also fails for the January section (Fig. 6a), when it underestimates the thermocline, marking its top several meters above the actual TTD. In the case of salinity profiles, there is greater

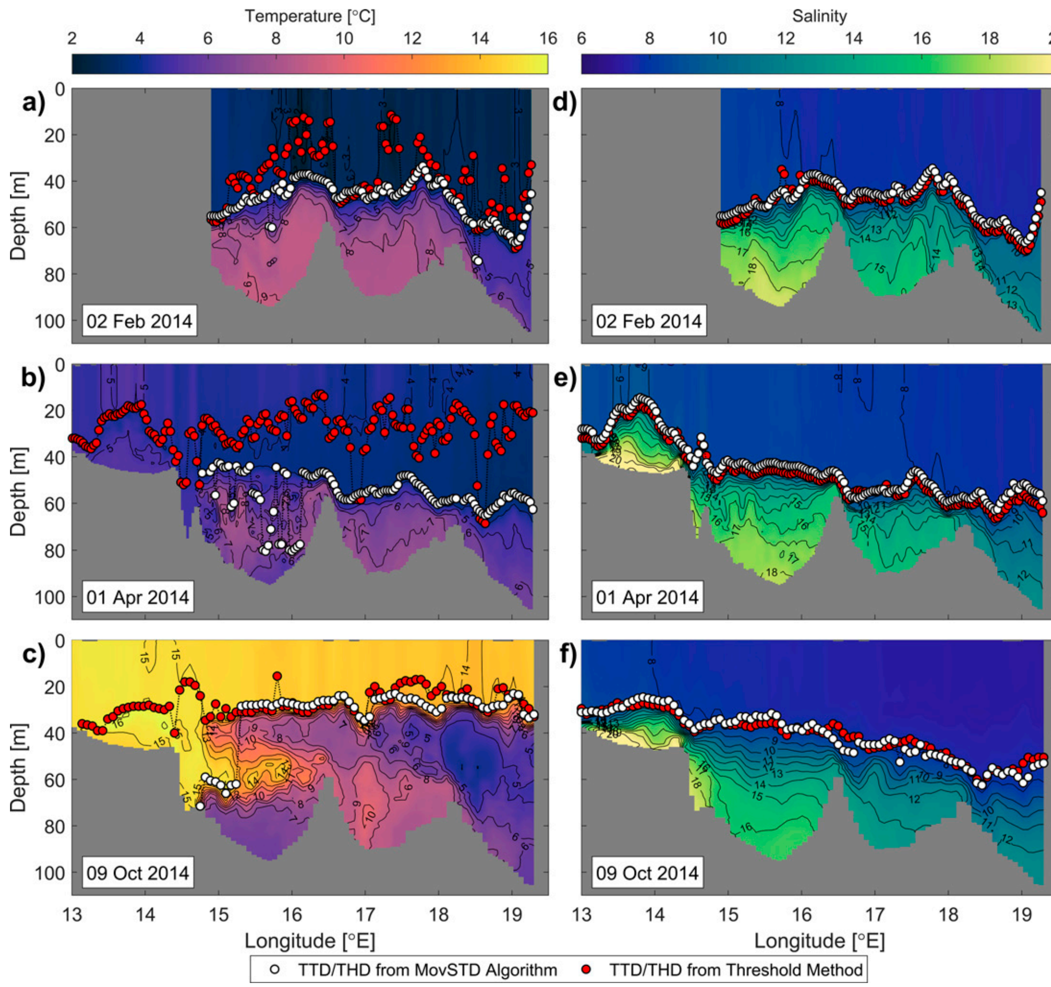

FIG. A1. MovSTD algorithm validation. Method validation using temperature and salinity profiles from S/Y *Oceania* cruises, which took place in February 2014, April 2014, and October 2014. (a)–(c) Temperature profiles with TTDs marked. (d)–(f) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2°C$, $\Delta S = 0.5$.

compatibility between the methods, although there are also discrepancies in favor of the MovSTD algorithm, especially during the May cruise (Fig. 6g).

b. Seasonal variability of the Gdańsk deep water vertical structure

Here, we analyze the seasonal variability of the water temperature and salinity in the Gdańsk Deep region with the use of model data. The analyzed profiles were taken from a 7-yr simulation of the EcoFish model for the period from 1 January 2014 to 31 December 2020 (Janecki et al. 2021). The border of the analyzed region is marked by the 110-m isobath (Fig. 2).

This region includes 1123 individual vertical profiles. Nine of them are profiles from the strict Gdańsk Deep, with a depth of 115 m, while the remaining 1114 are 110 m deep. The MovSTD algorithm was used to calculate TTDs and THDs for all individual profiles on each day from 1 January 2014 to 31 December 2020. We then calculated the mean TTD/THD to obtain one value per day for the entire region (Fig. 7).

As a result of these operations, a time series was created for the top of thermocline and halocline depths in the analyzed 7-yr period (Fig. 8).

To track the seasonal variability, the results are presented in one graph on a monthly scale, separately for the thermocline (Fig. 9) and the halocline (Fig. 10).

We filtered the results from 0- to 5-m depth on the TTD plot (Fig. 9). This procedure is related to the vertical resolution of the EcoFish model. The extreme near-surface interpolation node was the value for a depth of 2.5 m. Values from the layer between 0 and 2.5 m were obtained by linear extrapolation. Due to this, the algorithm's estimation of such a shallow TTD was a method error related to the postextrapolation large temperature gradient in this thin layer, rather than the fact that a real thermocline was present.

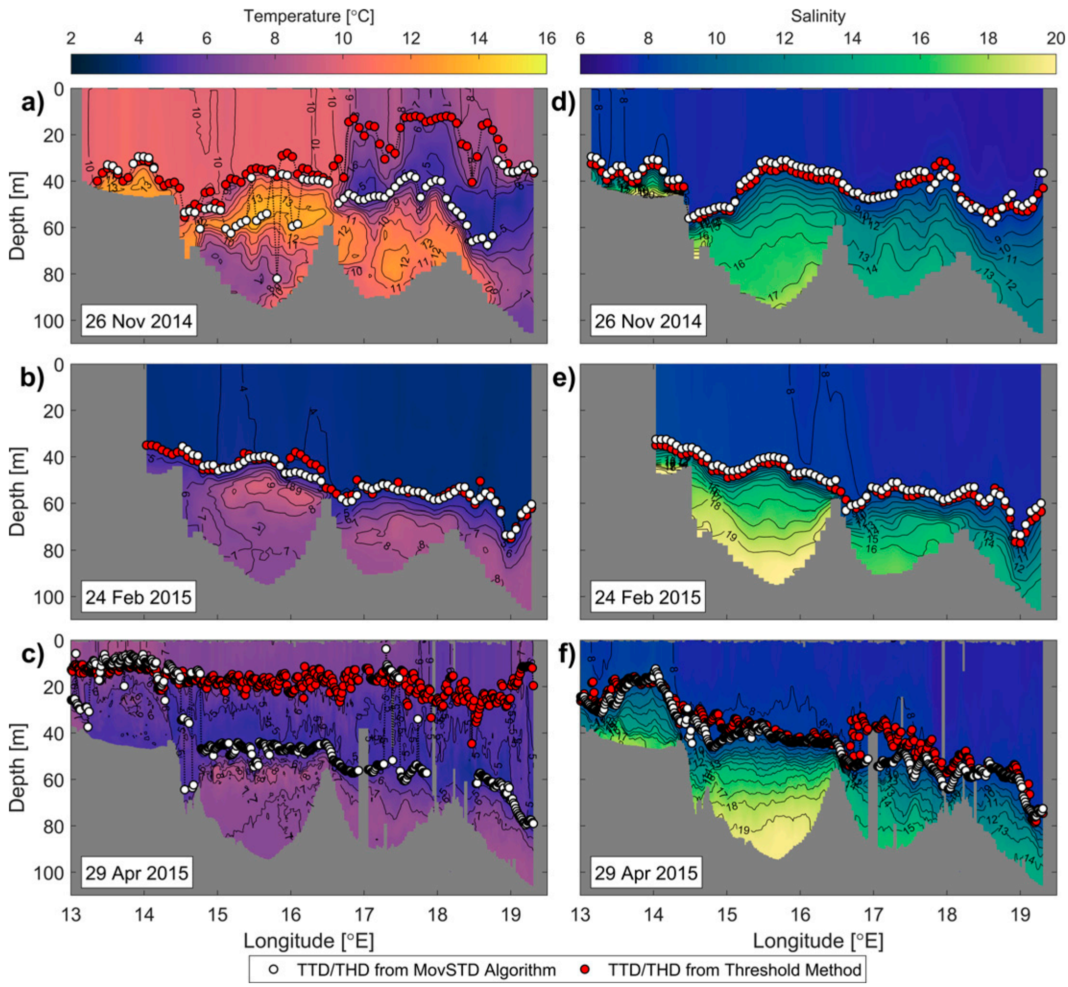

FIG. A2. MovSTD algorithm validation. Method validation using temperature and salinity profiles from S/Y *Oceania* cruises, which took place in November 2014, February 2015, and April 2015. (a)–(c) Temperature profiles with TTDs marked. (d)–(f) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2$°C, $\Delta S = 0.5$.

Supplying heat energy to the upper layers of the sea creates a thermocline (Fig. 9). In the analyzed region of the southern Baltic, the thermocline starts to form in May. As a result of further heating of the upper layers and mixing processes, the thermocline systematically deepens until it reaches the maximum depth defined by the halocline, which happens around December (Fig. 8). The deepening speed of the thermocline is not constant. Due to the slow heating of the upper layers and the influence of the cold intermediate layer (CIL), the initial deepening occurs at a speed of about 2 m month^{-1}. From September to December, after reaching the depth of the CIL, the deepening of the thermocline accelerates and occurs at a speed of about 9 m month^{-1}. When the upper layers are mixed by winter storms, they become homogeneous. This, with calm deep water below the thermocline, creates a two-layer structure visible from January to mid-April.

The top of halocline, which marks the maximum depth of the thermocline and is the lower limit of the CIL, is most stable in the summer months of May–September. However, as the intensity and strength of the winds that force the advection processes increase, the halocline becomes unstable, rapidly changing its depth. The change in the depth of the halocline top in Gdańsk Deep is about 50 ± 15 m (Fig. 10).

4. Conclusions

The MovSTD algorithm works correctly both on in situ data, as confirmed by validation on the S/Y *Oceania* sections, and for model data from the EcoFish model.

The results from the MovSTD algorithm when tested on model data from the Gdańsk Deep region showed that the top of the halocline depth is relatively permanent and is located at about 50 m. Noticeable changes in the depth of the halocline can also be observed in the 7-yr period analyzed. From August to November, the THD begins to appear higher, at depths between 35 and 50 m. In addition, between

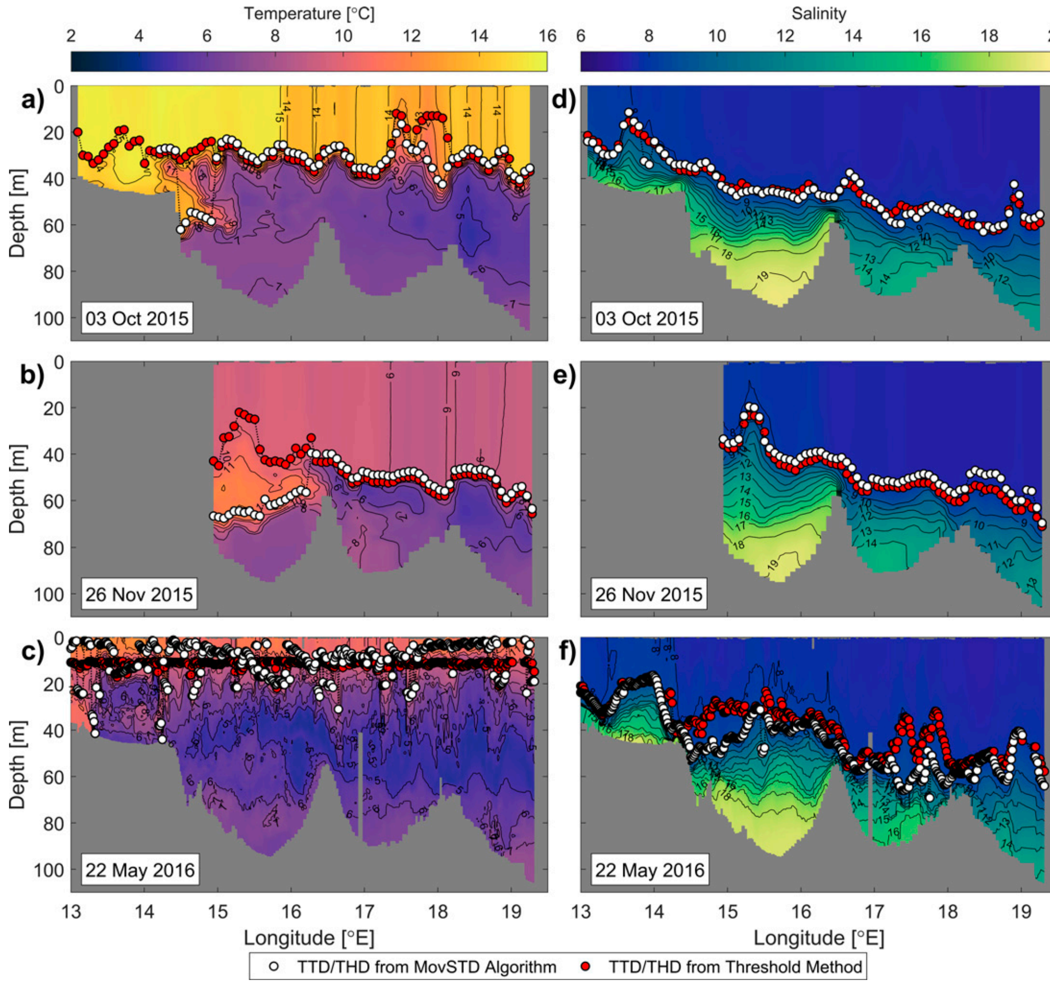

FIG. A3. MovSTD algorithm validation. Method validation using temperature and salinity profiles from S/Y *Oceania* cruises, which took place in October 2015, November 2015, and May 2016. (a)–(c) Temperature profiles with TTDs marked. (d)–(f) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2°C$, $\Delta S = 0.5$.

January and February 2015 and 2016 it reached instantaneous values of 70 m deep. However, it can be said that THD does not show significant seasonal variability and the vertical structure of salinity in the Gdańsk Deep is rather stable.

The situation is different for the thermocline. We can observe a strong seasonal variability here. A fresh thermocline begins to form in May due to the heating of the surface layer (forced by air temperature and sunlight). Its deepening speed from May to September is about 2 m month^{-1}. In the following months, as a result of water mixing and increased wind forcing, the thermocline deepening accelerates, reaching greater depths at a speed of about 9 m month^{-1}. At the turn of the year, this process stops, and until April thermocline occurs at the same depth as the halocline.

The values of the three predefined parameters (FRAME, THRES, and MINSTD) determined at the calibration stage are optimal for use in the Gulf of Gdańsk area. The one-to-one transfer of these values to other locations (different seas) may reduce the accuracy and/or correctness of the results obtained from the MovSTD algorithm. However, they can be used as an initial estimate and then refined by repeating the calibration steps described in section 2e. Still, the method's versatility, combined with its low computational complexity, makes the algorithm a fast and robust tool for processing large amounts of data with high horizontal and temporal resolution.

This method can also be easily extended with additional functionality that allows the determination of the bottom of the thermocline and halocline depth. It can be accomplished by searching the MSTD curve toward greater depth instead of toward the surface. Extending the algorithm to such an element will consequently allow for the calculation of thermocline and halocline thickness. When properly calibrated, it is also possible to use the algorithm to analyze dissolved oxygen concentration profiles and further to detect hypoxic and anoxic zones. This work will be the subject of upcoming papers.

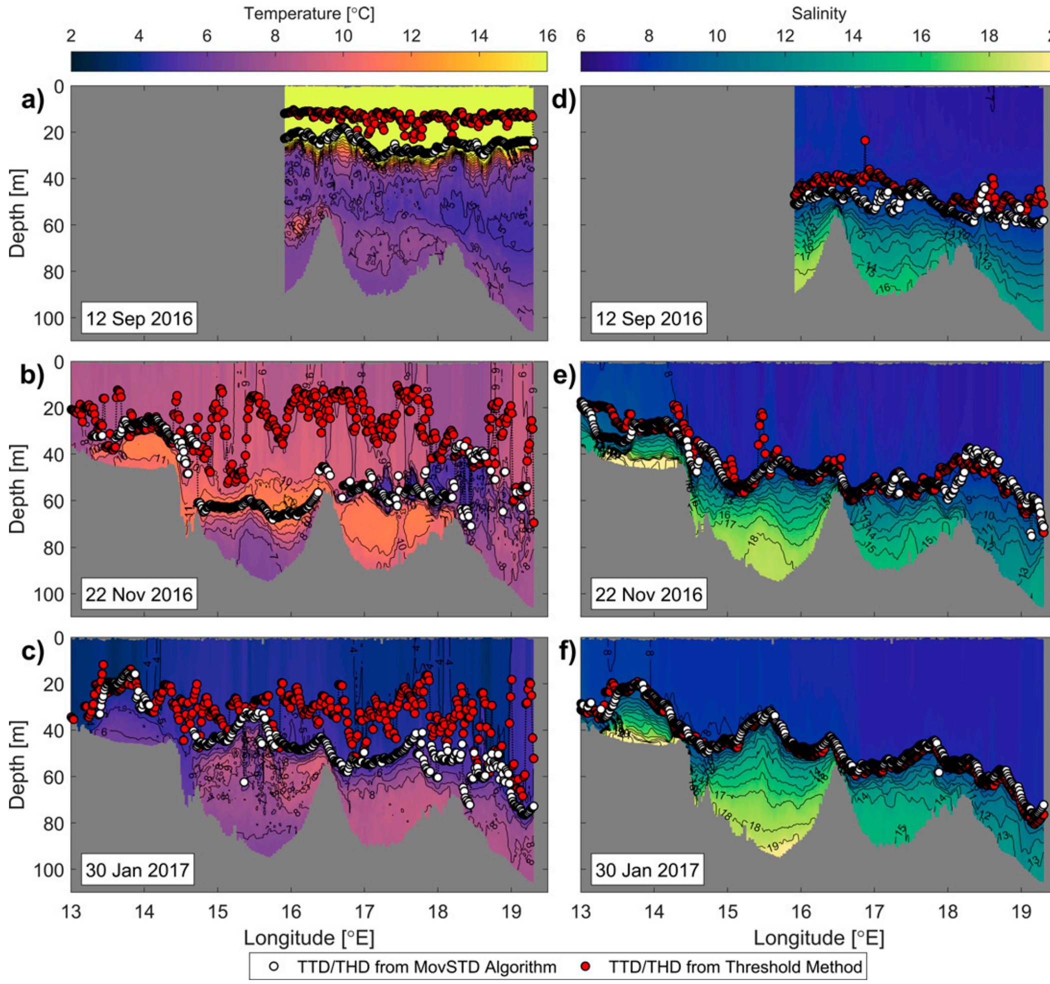

FIG. A4. MovSTD algorithm validation. Method validation using temperature and salinity profiles from S/Y *Oceania* cruises, which took place in September 2016, November 2016, and January 2017. (a)–(c) Temperature profiles with TTDs marked. (d)–(f) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2°C$, $\Delta S = 0.5$.

The lack of a separate calibration for the threshold method in the comparison (section 3a) may seem unfair and provoke the feeling that this was done deliberately to exalt the MovSTD algorithm. However, this was not our intention. Our creation of a new method was, in fact, dictated by the fact that the threshold method was not well suited to the Gulf of Gdańsk area. Nevertheless, our goal was not to replace the threshold method with a better one, but rather to propose an additional tool to the set of methods for determining the TTD/THD already available in the literature. A tool that in some regions may be a better choice (and worse in others) than the available methods.

Acknowledgments. Partial support for this study was provided by the project "Knowledge transfer platform FindFish—Numerical Forecasting System for the Marine Environment of the Gulf of Gdańsk for Fisheries," funded by the European Union through European Regional Development Fund Contract RPPM.01.01.01-22-0025/16-00. Some elements of the EcoFish model (i.e., river runoff data) are based on the solutions developed during the WaterPUCK project funded by National Centre for Research and Development of Poland within the BIOSTRATEG III program BIOSTRATEG3/343927/3/NCBR/2017. Calculations were carried out at the Academic Computer Centre in Gdańsk. The authors declare that they have no competing interests. We are grateful to the anonymous reviewers for valuable comments on earlier versions of the manuscript.

Data availability statement. All EcoFish model results and S/Y *Oceania* database presented in this study are available on request from the corresponding author. All other data and code are present in the paper, the online supplemental material, and section 2.

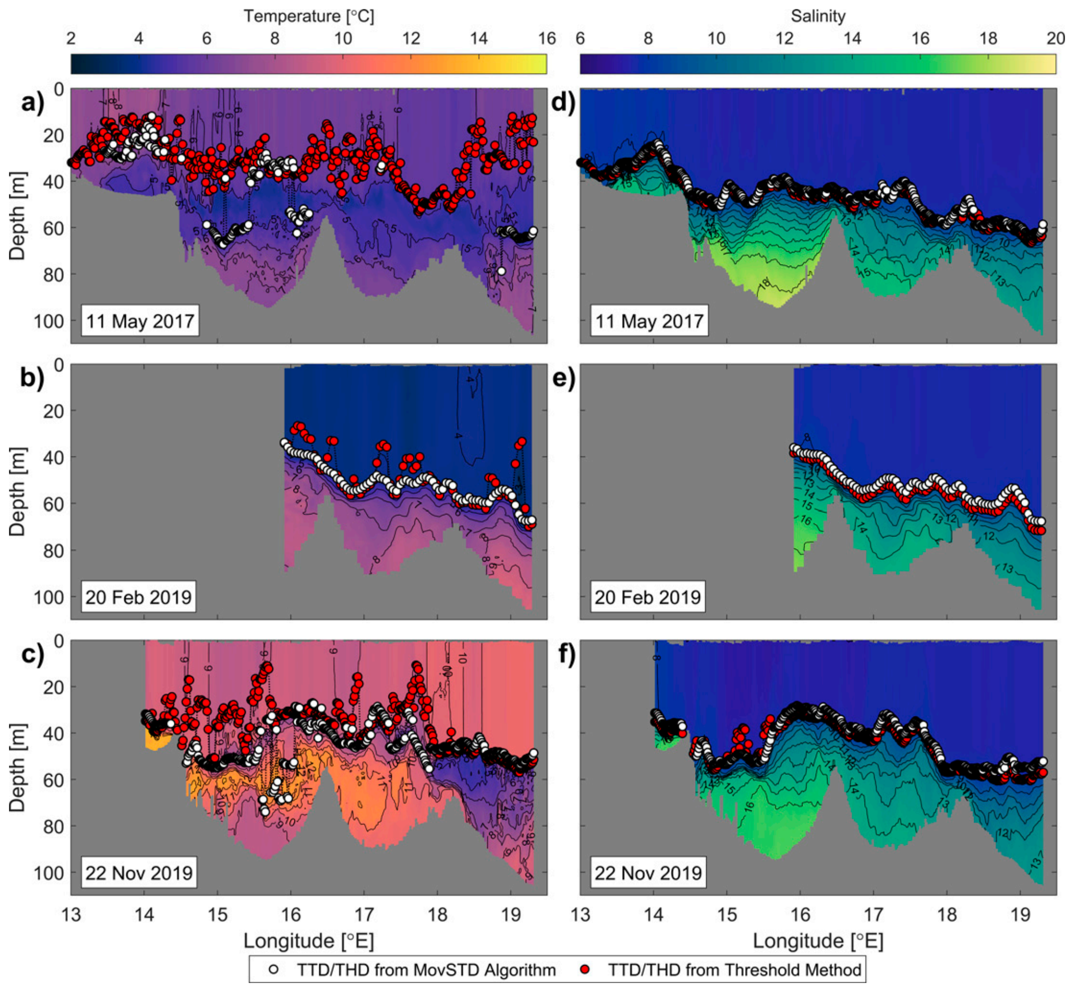

FIG. A5. MovSTD algorithm validation. Method validation using temperature and salinity profiles from S/Y *Oceania* cruises, which took place in May 2017, February 2019, and November 2019. (a)–(c) Temperature profiles with TTDs marked. (d)–(f) Salinity profiles with THDs marked. The white dots are the results of the MovSTD algorithm. The red dots were obtained using the threshold method with $\Delta T = 0.2°C$, $\Delta S = 0.5$.

APPENDIX

MovSTD Calibration and Validation

Here we present a calibration table (Table A1) that allowed for a correct determination of MovSTD algorithm input parameters. Figures A1–A5 show MovSTD algorithm validation. It was carried out using temperature and salinity profiles from all S/Y *Oceania* cruises that took place between January 2014 and December 2020.

REFERENCES

Baltic Sea Hydrographic Commission, 2013: Baltic Sea Bathymetry Database Version 0.9.3. http://data.bshc.pro/#2/58.6/16.2.

Chen, D., A. J. Busalacchi, and L. M. Rothstein, 1994: The roles of vertical mixing, solar radiation, and wind stress in a model simulation of the sea surface temperature seasonal cycle in the tropical Pacific Ocean. *J. Geophys. Res.*, **99**, 20 345–20 359, https://doi.org/10.1029/94JC01621.

De Boyer Montégut, C., G. Madec, A. S. Fischer, A. Lazar, and D. Iudicone, 2004: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *J. Geophys. Res.*, **109**, C12003, https://doi.org/10.1029/2004JC002378.

Dong, S., J. Sprintall, S. T. Gille, and L. Talley, 2008: Southern ocean mixed-layer depth from Argo float profiles. *J. Geophys. Res.*, **113**, C06013, https://doi.org/10.1029/2006JC004051.

Dzierzbicka-Głowacka, L., A. Nowicki, M. Janecki, B. Szymczycha, P. Piotrowski, P. Pieckiel, and G. Łukasiewicz, 2018: Structure of the FindFish Knowledge Transfer Platform. *Fish. Aquat. Life*, **26**, 193–197, https://doi.org/10.2478/aopf-2018-0021.

Foltz, G. R., S. A. Grodsky, J. A. Carton, and M. J. McPhaden, 2003: Seasonal mixed layer heat budget of the tropical Atlantic Ocean. *J. Geophys. Res.*, **108**, 3146, https://doi.org/10.1029/2002JC001584.

Grelowska, G., E. Kozaczka, and D. Witos-Okrasińska, 2018: Vertical temperature stratification of the Gulf of Gdansk water. *2018 Joint Conf. - Acoustics*, Ustka, Poland, Institute of Electrical and Electronics Engineers, 1–6, https://doi.org/10.1109/ACOUSTICS.2018.8502387.

Holte, J., and L. Talley, 2009: A new algorithm for finding mixed layer depths with applications to Argo data and subantarctic mode water formation. *J. Atmos. Oceanic Technol.*, **26**, 1920–1939, https://doi.org/10.1175/2009JTECHO543.1.

Janecki, M., D. Dybowski, J. Jakacki, A. Nowicki, and L. Dzierzbicka-Glowacka, 2021: The use of satellite data to determine the changes of hydrodynamic parameters in the Gulf of Gdańsk via Ecofish model. *Remote Sens.*, **13**, 3572, https://doi.org/10.3390/rs13183572.

Kara, A. B., P. A. Rochford, and H. E. Hurlburt, 2000: An optimal definition for ocean mixed layer depth. *J. Geophys. Res.*, **105**, 16 803–16 821, https://doi.org/10.1029/2000JC900072.

——, A. J. Wallcraft, and H. E. Hurlburt, 2003: Climatological SST and MLD predictions from a global layered ocean model with an embedded mixed layer. *J. Atmos. Oceanic Technol.*, **20**, 1616–1632, https://doi.org/10.1175/1520-0426(2003)020<1616:CSAMPF>2.0.CO;2.

Karagali, I., J. Høyer, and C. Hasager, 2012: SST diurnal variability in the North Sea and the Baltic Sea. *Remote Sens. Environ.*, **121**, 159–170, https://doi.org/10.1016/j.rse.2012.01.016.

Leppäranta, M., and K. Myrberg, 2009: Topography and hydrography of the Baltic Sea. *Physical Oceanography of the Baltic Sea*, Springer, 41–88, https://doi.org/10.1007/978-3-540-79703-6_3.

Longhurst, A., 1995: Seasonal cycles of pelagic production and consumption. *Prog. Oceanogr.*, **36**, 77–167, https://doi.org/10.1016/0079-6611(95)00015-1.

Lorbacher, K., D. Dommenget, P. P. Niiler, and A. Köhl, 2006: Ocean mixed layer depth: A subsurface proxy of ocean-atmosphere variability. *J. Geophys. Res.*, **111**, C07010, https://doi.org/10.1029/2003JC002157.

Lukas, R., and E. Lindstrom, 1991: The mixed layer of the western equatorial pacific ocean. *J. Geophys. Res.*, **96**, 3343–3357, https://doi.org/10.1029/90JC01951.

Marshall, J., and F. Schott, 1999: Open-ocean convection: Observations, theory, and models. *Rev. Geophys.*, **37**, 1–64, https://doi.org/10.1029/98RG02739.

Masson, S., P. Delecluse, J.-P. Boulanger, and C. Menkes, 2002: A model study of the seasonal variability and formation mechanisms of the barrier layer in the eastern equatorial Indian Ocean. *J. Geophys. Res.*, **107**, 8017, https://doi.org/10.1029/2001JC000832.

Monterey, G., and S. Levitus, 1997: Seasonal variability of mixed layer depth for the World Ocean. NOAA Atlas NESDIS 14, 96 pp.

Morel, A., and J.-M. André, 1991: Pigment distribution and primary production in the western Mediterranean as derived and modeled from coastal zone color scanner observations. *J. Geophys. Res.*, **96**, 12 685–12 698, https://doi.org/10.1029/91JC00788.

Noh, Y., C. J. Jang, T. Yamagata, P. C. Chu, and C.-H. Kim, 2002: Simulation of more realistic upper-ocean processes from an OGCM with a new ocean mixed layer model. *J. Phys. Oceanogr.*, **32**, 1284–1307, https://doi.org/10.1175/1520-0485(2002)032<1284:SOMRUO>2.0.CO;2.

Obata, A., J. Ishizaka, and M. Endoh, 1996: Global verification of critical depth theory for phytoplankton bloom with climatological in situ temperature and satellite ocean color data. *J. Geophys. Res.*, **101**, 20 657–20 667, https://doi.org/10.1029/96JC01734.

Polovina, J. J., G. T. Mitchum, and G. T. Evans, 1995: Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the central and north pacific, 1960–88. *Deep-Sea Res. I*, **42**, 1701–1716, https://doi.org/10.1016/0967-0637(95)00075-H.

Rak, D., and P. Wieczorek, 2012: Variability of temperature and salinity over the last decade in selected regions of the southern Baltic Sea. *Oceanologia*, **54**, 339–354, https://doi.org/10.5697/oc.54-3.339.

Rao, R. R., R. L. Molinari, and J. F. Festa, 1989: Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean: 1. Description of mean monthly mixed layer depth, and sea surface temperature, surface current, and surface meteorological fields. *J. Geophys. Res.*, **94**, 10 801–10 815, https://doi.org/10.1029/JC094iC08p10801.

Schneider, N., and P. Müller, 1990: The meridional and seasonal structures of the mixed-layer depth and its diurnal amplitude observed during the Hawaii-to-Tahiti Shuttle experiment. *J. Phys. Oceanogr.*, **20**, 1395–1404, https://doi.org/10.1175/1520-0485(1990)020<1395:TMASSO>2.0.CO;2.

Spall, M. A., R. A. Weller, and P. W. Furey, 2000: Modeling the three-dimensional upper ocean heat budget and subduction rate during the subduction experiment. *J. Geophys. Res. Oceans*, **105**, 26 151–26 166, https://doi.org/10.1029/2000JC000228.

Sprintall, J., and D. Roemmich, 1999: Characterizing the structure of the surface layer in the Pacific Ocean. *J. Geophys. Res.*, **104**, 23 297–23 311, https://doi.org/10.1029/1999JC900179.

Thompson, R. O. R. Y., 1976: Climatological numerical models of the surface mixed layer of the ocean. *J. Phys. Oceanogr.*, **6**, 496–503, https://doi.org/10.1175/1520-0485(1976)006<0496:CNMOTS>2.0.CO;2.

Thomson, R. E., and I. V. Fine, 2003: Estimating mixed layer depth from oceanic profile data. *J. Atmos. Oceanic Technol.*, **20**, 319–329, https://doi.org/10.1175/1520-0426(2003)020<0319:EMLDFO>2.0.CO;2.

Weller, R. A., and A. J. Plueddemann, 1996: Observations of the vertical structure of the oceanic boundary layer. *J. Geophys. Res.*, **101**, 8789–8806, https://doi.org/10.1029/96JC00206.

Zhang, R.-H., and S. E. Zebiak, 2002: Effect of penetrating momentum flux over the surface boundary/mixed layer in a *z*-coordinate OGCM of the tropical pacific. *J. Phys. Oceanogr.*, **32**, 3616–3637, https://doi.org/10.1175/1520-0485(2002)032<3616:EOPMFO>2.0.CO;2.