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Research Paper

Episodic wind events induce persistent shifts in the thermal stratification of a reservoir (Rappbode Reservoir, Germany)

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Title:

Stratification dynamics in a reservoir under different wind conditions

Abstract

Stratification dynamics in reservoirs have a great impact on ecosystem functioning and biogeochemical cycling, and can be strongly influenced by wind events. In this study, a well-established one-dimensional hydrodynamic model (GLM) was used to investigate the response of stratification dynamics in Rappbode Reservoir to different wind conditions, in particular to episodic strong wind events. In years with increased wind speed, stratification duration and intensity were reduced. Episodic wind forcing by strong wind events are important determinants of thermal structure and can induce persisting shifts in the thermal structure that remain over the season until the next overturn. The results showed that reductions in stratification intensity were particularly distinct when the strong wind occurred in early summer. Strong wind events outside of this sensitive time window did not exert an important impact on the thermal dynamics of the reservoir. Our research confirms the decisive impact of wind speed on stratification of lakes and reservoirs. It effectively illustrates the sensitive time window of thermal dynamics to episodic wind events.

Keywords: Rappbode Reservoir/ Wind speed/ Stratification dynamics/ Strong wind events/ One-dimensional hydrodynamic model

1. Introduction

Stratification is a well-studied key property of standing waters (Boehrer and Schultze 2008). In stratified lakes, the density gradient along the vertical axis gives rise to a series of ecologically relevant biogeochemical gradients like oxygen, nutrients or dissolved metals (Boehrer and Schultze 2008). Therefore, stratification has a great impact on the biogeochemical cycling in lakes and reservoirs (Pöschke et al. 2015; Zhang et al. 2015; Schwefel et al. 2016; Bueche et al. 2017). For example, prolonged stratification will lead to increasing anoxia in lake bottom waters (Foley et al. 2012). Stratification onset is also a key event for planktonic organisms, namely phytoplankton: Stratification limits vertical mixing and the epilimnion offers high average light intensity that alleviates light limitation for algae (Sommer et al. 1986). In deep lakes, the onset of algal spring mass development therefore relies largely on thermal stratification. Additionally, intense vertical stratification, i.e., very steep density gradients that usually emerge when surface temperatures get very hot, can foster the growth and dominance of harmful cyanobacteria (Paerl and Huisman 2009; Cao et al. 2016). Therefore, given the significance of stratification for aquatic ecosystems, it is not surprising that numerous investigations have focused on the dynamics of thermal structure and its influencing factors. One-dimensional hydrodynamic models play an important role in this line of research because they can integrate the different meteorological and hydrological factors and provide quantitative predictions (Fang and Stefan 1999; Kerimoglu and Rinke 2013; Frassl et al. 2014; Snortheim et al. 2017).

Climate change has been shown to exert a strong influence on thermal dynamics of waters worldwide (Fink et al. 2014; O'Reilly and Sharma 2015; Piccolroaz et al. 2015; Wood et al. 2016; Jansen 2017; Piccolroaz et al. 2018). Kraemer et al. (2015) used a 1D hydrodynamic model to investigate the impacts of atmospheric warming on the thermal structure of Lake Geneva. The increasing air temperature was found to decrease the duration of complete mixing during winter. Fang and Stefan (1999) reported that an increasing stratification intensity of lakes can be expected under a doubled atmospheric CO_2 concentration. Sahoo et al. (2015) predicted an increase in stratification duration of Lake Tahoe as a result of climate warming. However, when evaluating the response of thermal dynamics to climate change, most studies focused on the effect of global warming and little attention has been paid to the influence of other meteorological factors, e.g. changing wind speed. Widespread reductions in wind speed have been observed over the past decades, a trend that is expected to continue in the future (Roderick et al. 2007; McVicar and Roderick 2010; Read et al. 2011). The decrease in wind speed has been associated with changes in surface processes, e.g., an increase in ground roughness and a decrease in sensible heat fluxes (Roderick et al. 2007; McVicar and Roderick 2010; Vautard et al. 2010; You et al. 2010). This phenomenon of reduced wind speeds, known as atmospheric stilling or wind stilling, may play a vital role in stratification dynamics. At the same time, increasing frequencies of storm events are reported (Easterling et al. 2000; Bromirski et al. 2003) that are likely to have profound effects on lakes (Rinke et al. 2009; Jennings et al. 2012). In summary, wind is an important aspect of climatic effects on lakes and appears to be understudied in comparison to the effects from temperature.

Butcher et al. (2015) applied a 1D hydrodynamic model to elucidate the responses of lake stratification structures to climate change and suggested that wind is an important influencing factor for the strength of stratification in deep lakes. Valerio et al. (2015) investigated the response of the thermal dynamics of Lake Iseo to climatic variations and concluded that wind changes will exert strong effects on deep mixing within the hypolimnion. Edlund et al. (2017) reported an increase in thermocline depth due to the stronger wind in eight wilderness lakes in USA. However, the response of stratification to variations in wind speed is still not completely understood and not yet sufficiently quantified. There are basically two different approaches in analysing wind effects: some studies applied global increases or decreases to wind velocity by simple linear factors and others focused more on the importance and scale of single events. A modelling study by Austin et al. (2011) just increased and decreased measured time series of wind velocity by ± 10% or 20% and found systematic effects on stratification phenology and heat fluxes. The study by Churchill and Kerfoot (2007), who made detailed measurements on heat flux and stratification in Portage Lake, pointed to the importance of short storm events. Our study was designed to combine both approaches, we studied the effects of global increases and decreases in wind speed and also specifically analysed the importance of wind events.

In addition, previous studies have shown that sudden changes in wind speed in a specific (i.e., sensitive) period can result in an abrupt variation of thermal structure. Jennings et al. (2012) analysed high-frequency water temperature data from a monitoring station on Lake Leane and found a sharp increase in thermocline depth following episodic strong wind events during early summer. Read et al. (2011) reported the sudden reduction of water column stability in Lake Annie during a tropical storm in mid-August. We therefore hypothesize that short-term extreme wind events can exert a significant influence on stratification dynamics. Considering the ecological consequences of sudden variations in thermal structure (Jennings et al. 2012), there is a need for a comprehensive understanding of the impact of episodic strong wind events on the physical dynamics within stratified lakes and reservoirs.

In this study, we used the Rappbode Reservoir as a test site to investigate the impact of wind speed on the stratification. The reservoir is the largest drinking water reservoir in Germany, it supplies drinking water for more than 1 million people. Previous studies documented the importance of wind for the hydrodynamics within the reservoir (Bocaniov et al. 2014). The aim of our study is to evaluate the sensitivity of stratification in the reservoir to changing wind speed by using a well-established one-dimensional hydrodynamic model. A particular aspect of our study is to assess the response of thermal dynamics to typical short-term strong wind events in order to identify the most sensitive time windows. Admittedly, 1D models may be insufficient to fully describe the 3D processes like internal waves(Bocaniov et al. 2014; Schwefel et al. 2016). An application of a 3D model would overcome these limitations but would be computationally very demanding without leading to different conclusions in the systematic scenarios we are studying.

2. Methods

2.1. Study site

Rappbode Reservoir is located in the eastern Harz Mountains, supplying drinking water to more than 1 million people in central eastern Germany (Figure 1, Rinke et al. 2013). It is the largest drinking water reservoir in Germany with a maximum volume of 1.13×10^8 m^3, a catchment area of 274.0 km^2, a mean depth of 28.6 m and a maximum depth of 89.0 m. Rappbode Reservoir is located in a valley and wind sheltering and channeling due to the surrounding hills can be observed. For a more detailed description of the orography refer to Rinke et al. (2013). The reservoir is the main water body of the Rappbode Reservoir System, a network of 6 water bodies used for flood protection, environmental flows, and drinking water supply (for more details refer to Rinke et al. 2013). It receives water from three smaller upstream reservoirs (Königshütte Reservoir, Hassel and Rappbode Pre-dams) and drains into Wendefurth Reservoir. The Rappbode Reservoir is a typical dimictic water body with mixing in spring and autumn. The reservoir experiences strong stratification in summer and weak stratification in winter with ice cover in some years.

2.2. Numerical model

The General Lake Model (GLM) version 2.2.0 is a 1D hydrodynamic model developed by the Aquatic EcoDynamics Research group at the University of Western Australia (Hipsey et al. (2014); Read et al. 2014). It simulates the variations of thermal structures and takes the influence of inflows/outflows, surface energy fluxes and ice cover into account. The code of GLM is open source and freely available.

GLM uses a Lagrangian layer structure, i.e., thickness and volume of each layer change dynamically during the runtime of the model. Minimum and maximum layer thickness can be adjusted by the user. Each layer has homogenous physical properties (Read et al. 2014). The heat budget in GLM consists of shortwave and longwave radiation as well as sensible and evaporative heat fluxes. For more information about the underlying model equations and hydrodynamic closures refer to Hipsey et al. (2014).

2.3. Model setup and input data

The forcing for running the model includes time-series of meteorological variables, hydrological data on inflows and outflows as well as the morphometric information given as surface area at different water depth (hypsometric curve). The latter was obtained from the reservoir authority (Talsperrenbetrieb Sachsen-Anhalt).

The following meteorological variables were obtained from a water quality monitoring buoy in the central basin of Rappbode Reservoir (see Rinke et al. 2013 and http://www.ufz.de/index.php?de=39919): air temperature, wind speed, shortwave radiation and relative humidity. Measurements were conducted at high-frequency (every 10 minutes) and subsequently averaged to hourly values. Data gaps were filled with meteorological data either measured at a nearby meteorological station at the Rappbode Pre-dam (see Rinke et al. 2013) or only shortwave radiation from a meteorological station in Harzgerode, which is operated by the German Weather Service, approximately 15 km away from Rappbode Reservoir. Cloud cover data were provided by the Harzgerode station because no cloud cover detection was realized on the buoy. Comparisons of meteorological data between the stations Harzgerode and Rappbode Reservoir showed that values from both stations are highly correlated and there is a relatively low bias between both time series (Table 1). Among the different meteorological variables, wind speed showed the largest deviations between the two stations because it is strongly influenced by local orographic features. A graphical comparison of both meteorological stations for the relevant meteorological variables is given in the Supporting Information (see Figure S-1). Since the replacement of missing values by measurements from Harzgerode was only done for solar radiation and not necessary for the other variables, the consequences from using data from Harzgerode for filling these gaps should be negligible. From these cloud cover data as well as air temperature, incident longwave radiation was computed based on the formula given by Henderson-Sellers (1986).

Hydrological data, i.e. daily aggregated inflow and outflow discharges, were provided by the reservoir authority. Inflow salinity and water temperature were available from a YSI-6200 probe (Yellow Springs, USA) deployed in the tributaries of the reservoir. These hydrological data were put into the GLM with a daily resolution.

The model was run and calibrated by using data from Jan 2nd to Dec 30th in the year 2015. The time step for the simulation output was one hour in order to be consistent with the hourly meteorological data. The initial conditions for water temperature and salinity were derived from a vertical profile measured with a Hydrolab DS5 probe (OTT Hydromet, Kempten, Germany) at the start of the year.

2.4. Model calibration

High-resolution CTD measurements, taken with a Hydrolab DS5 probe, were used to evaluate the performance of the model. The water temperature was observed every week and its measured interval was averaged to 0.3 m from the surface to the bottom of the reservoir. It was our intention to leave the internal mixing parameters of GLM unchanged as they are physically or empirically derived and transferable between different lakes (Read et al. 2014; Fenocchi et al. 2017; Bruce et al. 2018). We therefore restricted the calibration of GLM to the following three lake-specific parameters: wind factor (correcting the wind speed by a constant factor, see study site description above with respect to wind sheltering effects), light attenuation coefficient (K_w) and vertical turbulent mixing coefficient in the hypolimnion (C_{HYP}). All other parameters are considered to be lake independent as in the study of Weber et al. (2017) and should remain unchanged unless detailed empirical evidence for required parameter changes is available. The root-mean-square-error (RMSE) of water temperature was applied to assess the model performance:

$$\mathrm{RMSE}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}e_i^2} \tag{1}$$

where e_i is the difference between observed and simulated water temperature and n is the number of observations. We chose the RMSE as the model fit criteria because it is a standard indicator for model errors, used in many lake modeling studies (Schwefel et al. 2016; Weber et al. 2017).

2.5. Wind scenarios

Scenario S1: Stratification phenology in 2015 at different wind conditions

In order to show the effect of a different wind speed on the stratification in Rappbode Reservoir, we used the reference simulation of 2015 and compared the stratification phenology with simulations having wind speed increased by 10% and 20%.

Scenario S2: Sensitivity to wind speed under averaged meteorological conditions

In the local climate of Rappbode Reservoir, all meteorological variables except the cloud cover follow a specific seasonal pattern (see Figure S-2). Each individual year, however, has characteristic periods of cold/warm, windy/calm, wet/dry, etc. weather conditions making each year different from the others. These characteristic stochastic fluctuations of meteorological variables (i.e. weather) around the average seasonal pattern (i.e. climate) in a given year complicate the interpretation of model outcomes derived from a single year. In order to make the model outcome independent from a specific year, we calculated hourly averaged climatological conditions for all required meteorological variables based on long-term data of meteorological observations as outlined in Table 2 (see Figure S-2). Note, that for the calculation of average climatological conditions no measurements from the reservoir could be used because these time-series were too short. We therefore applied long-term meteorological conditions at nearby stations for the scenario simulations. This may include some minor differences in local meteorological conditions (compare Table 1) but such differences are unproblematic in a scenario-based approach where only relative differences between different scenarios are interpreted. These averaged climatological conditions, defined as the 50% quantile, represents the present, average climatic conditions in the region of Rappbode Reservoir. As inspired by a study by Persson and Jones (2008), we used the averaged meteorology as a reference scenario and compared model results with simulations using the 20%, 40%, 60%, 80%, and 100% quantile of wind speed. Note that all other meteorological variables were left unchanged at the 50% quantile, i.e., at the median values. Additionally, input data for inflow and outflows were kept the same as those in 2015. These quantile-based wind scenarios have a very artificial character in the sense that they have a strongly dampened annual cycle without any disturbing wind events. This artificial setting is helpful, however, to systematically analyse the effect of wind speed on stratification independent of short-term events.

Scenario S3: Effects of short-term wind events on stratification

This scenario focuses on the effects of short-lasting strong wind events on stratification. A typical strong wind event in Rappbode Reservoir has a duration of 1-2 days and reaches daily averaged values up to 10 m s^{-1} representing the 95% quantile of all wind speed recordings at Harzgerode station (see Table 2).

As a starting point we used the averaged meteorological conditions (see scenario S2) over the course of one year. We then created a series of simulations having a strong wind event (10 m s^{-1} for 2 days, see above) progressing over the whole year, i.e., the first simulation has the strong wind event on day 1-2, the second simulation from day 3-4, the third simulation from day 5-6, and so on. We completed this simulation series from the beginning to the end of one year.

Scenario S4: Effects of short-term wind events on stratification (seasonally varying)

The scenario S4 is basically the same as S3 but the wind speed applied in the wind event was not set to 10 m s^{-1} but to the maximum observed wind velocity at the respective day of the year (100% quantile in Figure 4). In this way, the wind velocity of the wind event becomes seasonally varying with approximately 25% lower wind speeds in summer compared to winter. The motivation to create the scenario S4 came from the fact that a 2-day lasting wind with 10 m s^{-1}, as applied in S3, is an extremely powerful event. The additional scenario S4 is therefore closer to the real local conditions at Rappbode Reservoir, while the scenario S3 may represents a strong wind event as it can be observed at other places in central Europe. We ran this scenario two times, in a first run we applied a wind event lasting over two days and in a second run we let the wind event to last only over 1 day.

2.6. Evaluation of simulations

We calculated five indices to evaluate the strength and duration of stratification in the different scenarios: Schmidt stability, open water stratification ratio, onset of stratification, 10 °C isotherm depth and hypolimnion temperature. These five indices were frequently used in related research (Fang and Stefan 2009; Butcher et al. 2015; Kraemer et al. 2015; Valerio et al. 2015; Schwefel et al. 2016). The Schmidt stability, reflecting the difference in potential energy between a stratified lake and the same lake at hypothetically mixed conditions (Schmidt 1928; Idso 1973; Boehrer and Schultze 2009; Boehrer et al. 2014), was defined as:

$$S = \frac{g}{A_0}\int_0^{z_{max}} (z - z_*)(\rho_z - \rho_*)A_z dz \quad (2)$$

where g is the gravitational acceleration, A_0 the surface area, ρ_z and A_z are the water density and area at depth z, z_* and ρ_* are the center depth of the volume and its corresponding density. The open water stratification ratio is defined as the fraction of simulation time in which the temperature difference between the top and bottom layer of the water is greater than 1 K (Fang and Stefan 2009). We used this ratio to evaluate the duration of stratification. The first time when the temperature difference between surface and bottom is larger than 1 K was defined as stratification onset. The hypolimnion temperature was calculated as the volume-weighted average water temperature in the hypolimnion. To define the hypolimnetic water body, we used the function “meta.depth()” from the R package “rLakeAnalyzer” (R Development Core Team 2016; Winslow et al. 2017). This function first defines the thermocline as the depth of the maximum density gradient found in the profile. An upper and lower end of the metalimnion was then derived by assuming a critical threshold in the density gradient of 0.1 kg m^{-4}, i.e., the value of the metalimnion depth is defined as the range around the thermocline where the density gradient is steeper than this threshold. Accordingly, the hypolimnion is then defined as the water masses between the lower end of the metalimnion and the lake bottom.

The R packages “glmtools” and “rLakeAnalyzer” were used for calculating the stratification indices mentioned above. Furthermore, these two packages were also applied for pre- and post-processing of the model simulations.

3. Results

3.1. Calibration results

After the calibration of water temperature for the year 2015, the parameter values for wind factor, light attenuation coefficient (K_w) and vertical turbulent mixing coefficient in the hypolimnion (C_{HYP}), respectively, were identified as 0.92, 0.87 m^{-1} and 5×10^{-6} m^2 s^{-1}. The values of these calibrated parameters are in a reasonable range for the local conditions in Rappbode Reservoir. Modelled water temperatures were in good agreement with measurements. The simulated mean water temperature was 6.33 °C for all measured depths, which is close to the observed temperature of 6.62 °C. The RMSE of vertical temperature profiles was 0.89 and the R^2 was 0.97 (n = 19081, see Figure 2). The RMSE in our study was in the range of that in other recent studies using GLM (Bueche et al. 2017; Fenocchi et al.

2017; Weber et al. 2017). The simulated hypolimnetic temperature at 50 m depth was slightly lower than the measured value. The modeled surface and metalimnion water temperature showed an excellent agreement with the observed data (Figure 3). In general, the calibrated model successfully reproduced the stratification phenology of the reservoir.

3.2. Statistical properties of wind velocity at Rappbode Reservoir

The analysis of 35 years of wind speed measurements at station Harzgerode revealed a clear seasonality with high wind speeds in winter and low wind speeds in summer (Figure 4). Absolute differences in seasonal wind speed remained low between the 20% and 60% quantile, but they became larger and more variable over the year for the 80%, 95% and 100% quantile. At the 20% quantile, wind speed was always lower than 4 m s^{-1} and calm conditions (wind speed < 2 m s^{-1}) prevailed over 54% of the year.

3.3. Scenario S1: Stratification phenology in 2015 at different wind conditions

Comparing the standard simulation of 2015 with simulations using 10% and 20% higher wind speed revealed that wind plays a significant role in stratification phenology, which could even result in variations of the hypolimnion temperature (Figure 5). Its mean increased from 4.9 °C in the 2015 reference simulation to 6.9 °C at 10% increased wind and further to 7.2 °C at 20% increased wind (Figure 5). Additionally, wind speed directly affected the isotherm depths of different temperatures. For example, the average depth of the 10 °C isotherm increased from 15.7 m in the 2015 reference simulation to 30.8 m at 10% increased wind and further to 33.0 m at 20% increased wind (Figure 5).

3.4. Scenario S2: Sensitivity to wind speed under averaged meteorological conditions

As can be seen in Figure 6 and 7, it is evident that wind speed had a significant influence on the stratification duration: the higher the wind speed the later the stratification started and the shorter the stratification lasted. When comparing the 20% with the 100% quantile scenario, the start date of stratification was delayed by one month (from April 14th to May 15th) and the stratification ratio was reduced by 17% (from 67% to 50%, see Figure 6). Also, Schmidt stability decreased markedly under increasing wind speed (Figure 7). For example, from the 20% to the 100% quantile of wind speed, the maximum Schmidt stability was reduced from 2803 to 1943 J m^{-2}, which corresponded to a reduction of 31% in stability. Finally, wind was an important factor on the variability of the 10 °C isotherm depth. At wind speed below the 80% percentile, the maximum 10 °C isotherm got shallower than 30 m. At 100% percentile, however, the maximum isotherm was deeper than 40 m (Figure 7).

3.5. Scenario S3: Effects of short-term wind events on stratification

Simulating a strong wind event (10 m s^{-1} over 48 h), progressing over the whole year, illustrated the sensitive time window of lake stratification against such winds. We used three indices to evaluate the sensitivity of the thermal dynamics against strong wind events: hypolimnetic water temperature, 10°C isotherm depth, and Schmidt stability.

Stratification strength decreased when a strong wind occurred between end of April and beginning of July, i.e. in early summer (Figure 8c). As a matter of fact, strong wind events had negligible effect during overturn, i.e. before mid April. A strong wind event after the beginning of July did not exert a significant impact on the evolution of thermal structure because the stability of the existing stratification was high enough to withstand the mixing forces from the wind event. Under a strong wind event between end of April and early July, the hypolimnetic temperature and the 10 °C isotherm depth in summer were increased by up to 10 °C and 45 m respectively. The Schmidt stability during this period was decreased to around 2500 J m^{-2}. Although a strong wind event after July did neither affect hypolimnion temperature nor the 10 °C isotherm, small reductions of Schmidt stability can be recorded due to intensified cooling by evaporation, which scales with wind velocity.

The later the strong wind event occurred in early summer, the warmer got the hypolimnion since the down-mixed surface waters had a higher temperature and more heat was transported downward. Given this higher hypolimnion temperature, convective mixing during the autumnal cooling was also earlier reaching the hypolimnion (see Figure 8a). In case of a strong wind in early July, for example, the hypolimnion temperature reached more than 10 °C and convective cooling reached the hypolimnion already in early October. In contrast to this, a strong wind in early May increased the hypolimnion temperature to around 6 °C but convective cooling affected the hypolimnion only in late November (Figure 8a).

In conclusion, it turned out that the sensitive time window of thermal dynamics to episodic wind events was from the end of April to the beginning of July. This was also verified by an apparent reduction of surface water temperature (> 4 ˚C) if the strong wind occurs on June 30th (Figure S-3). A short-term strong wind on April 9th (i.e. before the sensitive time window) and July 14th (i.e. after the sensitive time window), however, did not exert an important impact on the temperature in the top layer.

3.6. Scenario S4: Effects of short-term wind events on stratification (seasonally varying)

When applying less intense, seasonally varying wind speeds in the wind event, the resulting perturbations in stratification showed similar patterns like observed in scenario S3. The downward shift of the 10 °C isotherm (Figure 9) was, however, less strong than in S3 because the applied wind velocities were approximately 25% lower during summer. Nevertheless, in this scenario the duration of the sensitive time window for wind events was almost the same as in S3. We also applied two different durations of the wind event, lasting either over one or two days and clearly identified that the duration is an important factor for the impact of the wind event. The longer the wind is blowing, the stronger the effect on the stratification as indicated by the deepening of the 10 °C isotherm. Similar results can also be found for the hypolimnetic temperature and the Schmidt stability (Figure S-4 and S-5). This wind induced disturbance, however, remains only effective when the wind event occurs within a certain time window. Interestingly, the beginning and end of this sensitive time window is almost independent of the duration and strength of the wind event.

4. Discussion

In the paper, the one-dimensional hydrodynamic model GLM was used to investigate the evolution of thermal structure in the Rappbode Reservoir. First, the parameters wind factor, light attenuation coefficient and vertical turbulent mixing coefficient in the hypolimnion were calibrated. Although the hypolimnetic temperature was slightly underestimated, the calibrated model reproduced the stratification pattern well and captured the variation of the thermal structure over the whole year (Figure 3). The discrepancies between measured and simulated temperature may be associated with the insufficient modeling of three-dimensional processes (e.g., internal waves, upwelling, etc.), which can be important processes for vertical transport of heat below the epilimnion (Hodges et al. 2000). Previous research has confirmed the significant influence of internal wave activity on the stratification dynamics in Rappbode Reservoir (Bocaniov et al. 2014). Since a 1D model is not capable to fully account for these processes, a 3D simulation model may be used to evaluate the influence of three-dimensional processes on the thermal structure and its sensitivity to wind. Additionally, GLM uses a constant light attenuation coefficient (K_w) which cannot be changed during the simulation period. As indicated by Bueche et al. (2017), a lack of seasonal variation of K_w may also exert a negative influence on the simulation accuracy.

The calibrated model was then used to investigate the effect of wind variations on stratification. It should be noted that since the wind direction is neglected by the model, only the influence of changing wind speed was taken into account. Averaged seasonal conditions were used for the other meteorological variables to run the model. In this way, effects from variations in other meteorological variables on simulation results were excluded. By simulating seasonal wind forcings of different intensities (quantile scenarios, S2), the decisive influence of wind speed on the thermal structure was substantiated. It is apparent that a decrease in wind speed moved the 10 °C isotherm depth upwards, extended the duration of the stratification season, increased the Schmidt stability, and therefore reduced the vertical mixing (Figure 6 and 7). These findings extend those of previous research (Desai et al. 2009; Magee and Wu 2016) stating that decreasing wind speed reduces heat flux from the surface into deep layers due to lower mixing intensities. Under these conditions, the hypolimnion is more sheltered from the top layer and stratification can persist longer.

To our knowledge, this is the first study investigating the response of thermal stratification to seasonally changing wind, i.e. to episodic strong wind events, in detail. From Figure 8c, it can be seen that the maximum Schmidt stability decreased gradually when the strong wind took place from the end of April to the start of July (i.e., late spring and early summer). The strong wind event in the other periods, however, did not exert an important impact on the thermal dynamics of the reservoir. Before late April, stratification had not yet developed (Schmidt stability < 1000 J m^{-2}) and wind-induced mixing accordingly was not relevant. During May till June, stratification became stronger with Schmidt stability approaching 2000 J m^{-2}. In this period, however, the thermal structure of the reservoir is not stable enough to resist the influence of strong wind events. After this period, i.e. from mid July onwards, stratification is so intense and stable (stability > 2000 J m^{-2}) that the wind-induced mixing cannot penetrate into the deep hypolimnion. Our simulations show a marked warming of the hypolimnion in Rappbode Reservoir when a strong wind occurs at the right time of the year. Following such an event, hypolimnion temperature can be far higher than the usual 4 to 6 °C and reach values up to 10°C. Long term-temperature records from Rappbode Reservoir indeed showed warmer hypolimnion temperatures in some years and reached values up to 9 °C (Wentzky et al. 2018). This temperature is a little lower than in scenario S3 but given the high wind velocities and long durations in this scenario, a less intense hypolimnion warming *in situ* appears reasonable.

A difference should be noted when comparing our results with the studies of Lake Annie in the USA (Read et al. 2011; Jennings et al. 2012). In the latter, a strong mixing event in mid-August was observed as a result of high wind speed at that time (up to 8 m s^{-1}). In our study, however, the strong wind at that time did not show a strong influence on the thermal structures of the Rappbode Reservoir. The discrepancy could be attributed to the different morphometry of two lakes. As shown by the previous studies (Butcher et al. 2015; Magee and Wu 2016), lake morphometry exerts an important impact on stratification phenology. The deep basin of the Rappbode Reservoir (89m maximum depth) allows a very cold hypolimnion of 4-5 °C and this induces strong density gradients towards the surface. It indicates that the episodic strong wind in the hot summer cannot provide enough energy to alter its stratification structure. The maximum depth of Lake Annie, in contrast, is only 19 m. Under the strong wind event during midsummer, energy can be easily transferred into the deep hypolimnion to fully mix the water column.

Our scenarios S3 and S4 documented the importance of wind events for stratification phenology. It appears that not the average wind conditions predetermine the stratification phenology but rather the occurrence of strong wind events within a sensitive time window. Although wind strength and duration hardly affected the timing of this sensitive time window， the wind-induced perturbations on stratification phenology are, of course, affected by wind strength and duration. We did not evaluate how perturbations at shorter time-scales, e.g., sub-daily events, may influence the stratification dynamics in Rappbode Reservoir. Diurnal asymmetry in meteorological drivers can exert a strong impact on the thermal structure of different water systems (Ishikawa and Tanaka 2010; Snortheim et al. 2017) suggesting that more knowledge is required about the duration of a wind event necessary to be effective for changing stratification phenology. Consequently, future work should focus on the combined effect of diurnal and seasonally changing wind so that we can get a better understanding about the mechanisms of stratification variability.

We also noted that emerging patterns in the simulation results in Fig. 8 showed distinct fluctuations in their numerical values. The 10°C isotherm in scenarios with strong wind events within the sensitive time window, for example, varied between 40 m and 55 m over the summer (shown as yellow and red vertical bands in the contour). Also the Schmidt stability showed some of these fluctuations, partly even for strong wind events before April. We assume that sometimes small changes in the model input can show discontinuously strong effects in GLM due to its Lagrangian layer structure. Since GLM is self-optimizing the layer structure and dynamically adapts layer thicknesses, small changes can sometimes induce a distinctly different vertical structure in the model. These changing vertical discretizations are hardly visible in the contour plots for simulated temperature but affect derived variables like Schmidt stability or isotherm depth. These consequences from the dynamic Lagrangian model structure can induce slight discontinuities, but, of course, do not destroy the prominent patterns in simulation studies like ours. Moreover, the Langrangian model structure has many advantages in water bodies with subsurface inflows and outflows (e.g. in reservoirs) because of low numerical mixing and is therefore an important feature of GLM for its high transferability between different water bodies.

Finally, changes in thermal structure have a great impact on oxygen dynamics. An increase in stratification, e.g., as a consequence of wind stilling, will result in increased extent of anoxia, which will exert a negative influence on aquatic ecosystems. Based on this, to extend the present research, it is worthwhile to elucidate the quantitative relationship among dissolved oxygen concentration, stratification dynamics and wind changes in further studies. Strong wind events are, however, destabilising the stratification and lead to earlier overturn and shorter stratification period. In conclusion, the effects of wind are not easy to quantify, because they strongly depend on the timing and strength of key events and therefore have a highly stochastic component. Our study was able to characterize the sensitive time window when wind is highly effective and underpins the importance of short-term events. More systematic research is required to study the consequences of wind events in situ and how these events affect ecosystem features (e.g., Giling et al. (2017)) like nutrient cycling or plankton dynamics.

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Tables

Table 1: Comparison between the measured climate data in 2015 from the weather station at Harzgerode (DWD) and from the buoy on Rappbode Reservoir

Climate Variables	Mean DWD	Mean Buoy	Bias	r
Air Temperature (˚C)	8.65	8.51	0.14	0.98
Shortwave Radiation (W m^{-2})	201.85	209.98	-8.13	0.80
Wind Speed (m s^{-1})	3.71	3.19	0.52	0.72
Relative Humidity (%)	80.44	79.02	1.42	0.86

Table 2: Summary of data for meteorological drivers

Meteorological Drivers	Time Range	Data Source(Name of the Weather Station)	Location
Wind Speed	1981-2015	Harzgerode	51.65° N, 11.14° E
Air Temperature	1981-2015	Harzgerode	51.65° N, 11.14° E
Relative Humidity	1991-2015	Harzgerode	51.65° N, 11.14° E
Cloud	2008-2015	Harzgerode	51.65° N, 11.14° E
Precipitation	1995-2015	Harzgerode	51.65° N, 11.14° E
Shortwave Radiation	1981-2015	Halle	51.51° N, 11.95° E

Figures

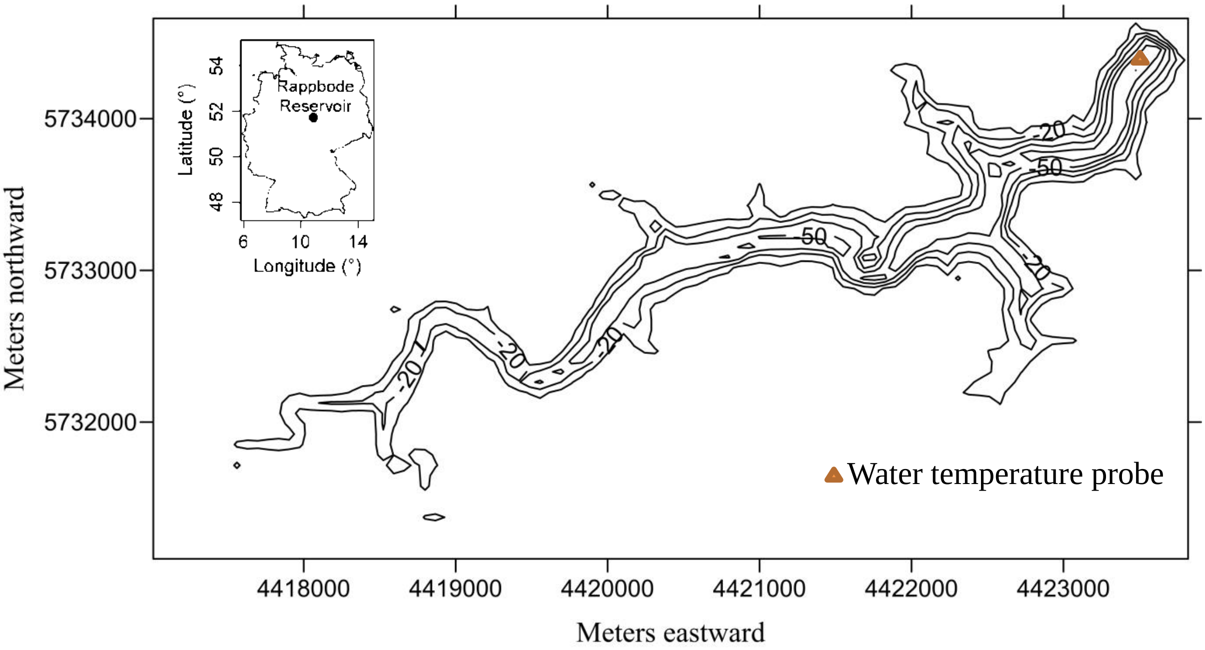

Figure 1: The location and contour map of Rappbode Reservoir.

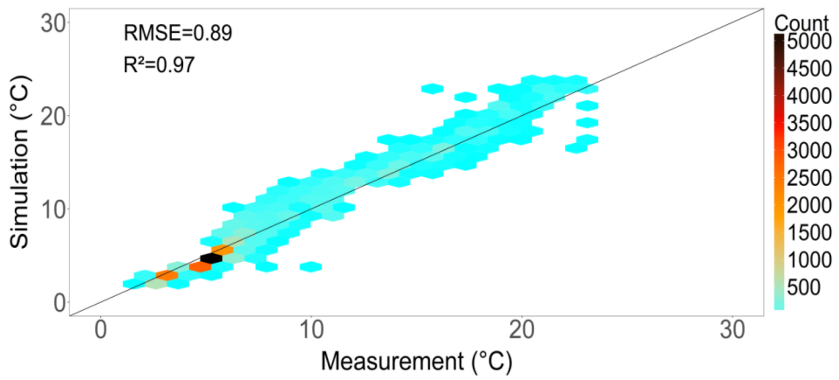

Figure 2: Comparison between simulated and measured water temperature for all depths (n = 19081). The color bar depicts the amount of samples per hexagon. The 1:1 line has a slope of one and an intercept of zero, indicating a perfect fit.

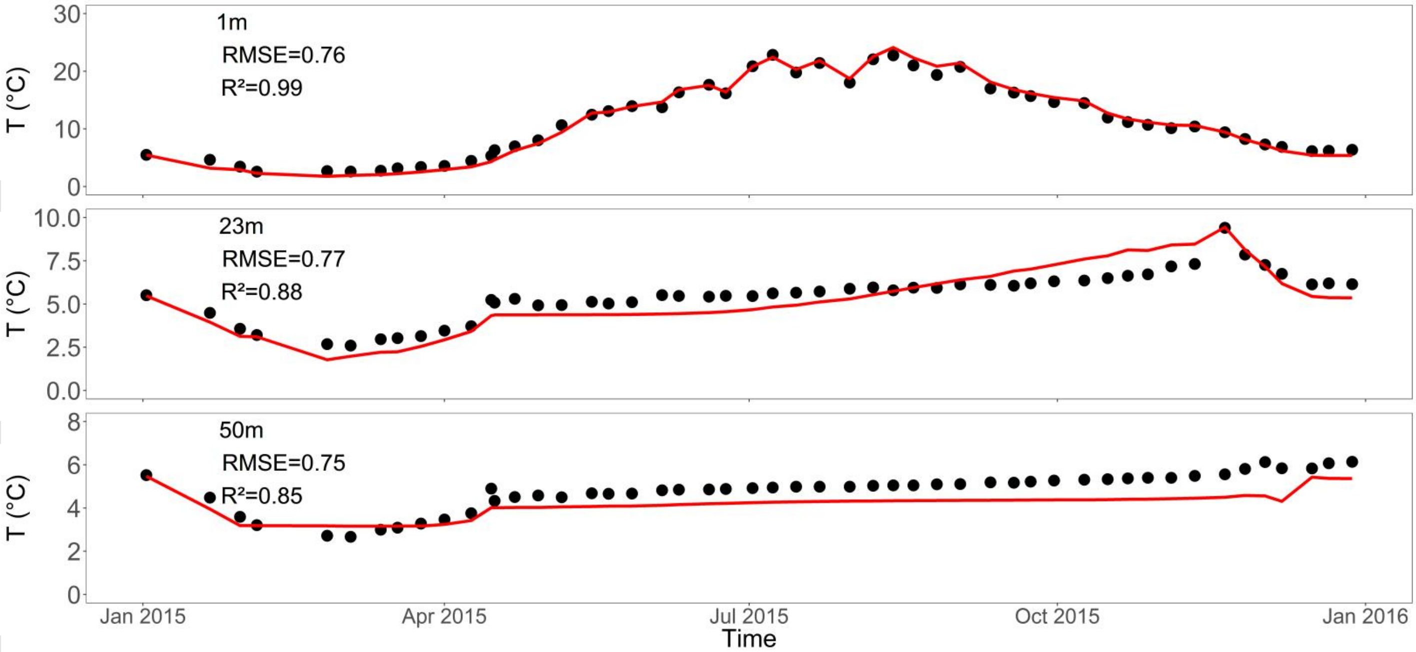

Figure 3: Simulated (red line) versus measured (black dot) water temperature at 1 m, 23 m and 50 m depths.

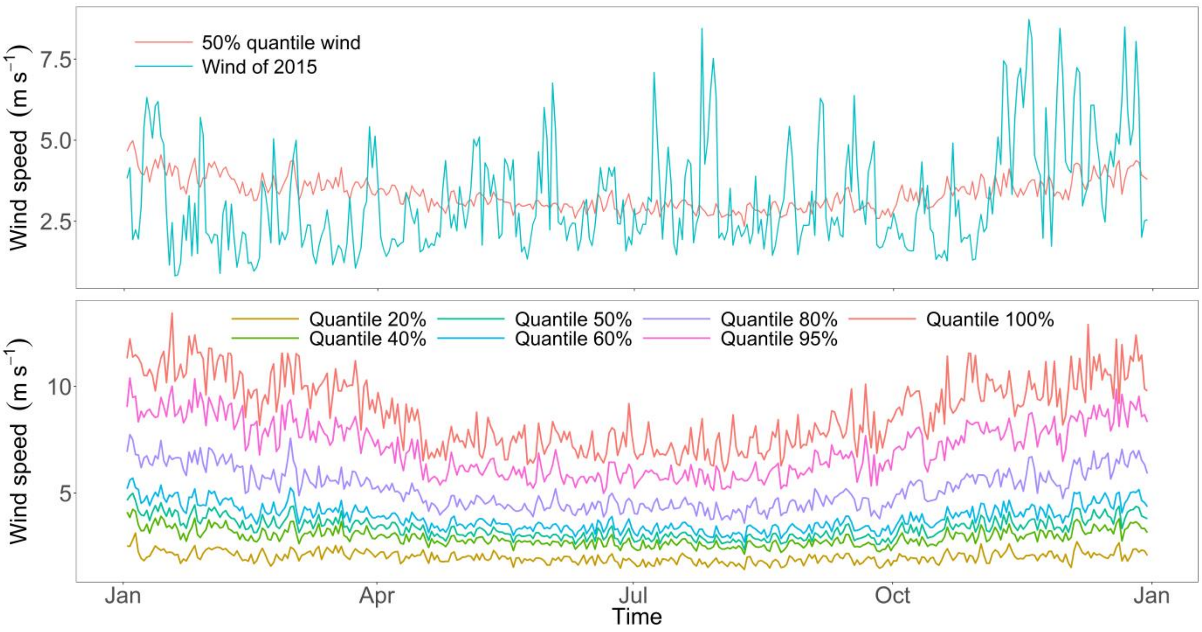

Figure 4: Comparison between daily median wind speed (calculated from 35 years of measurements) and daily averaged wind speed of 2015 (upper panel); long-term annual pattern of wind speed at Harzgerode station (lower panel).

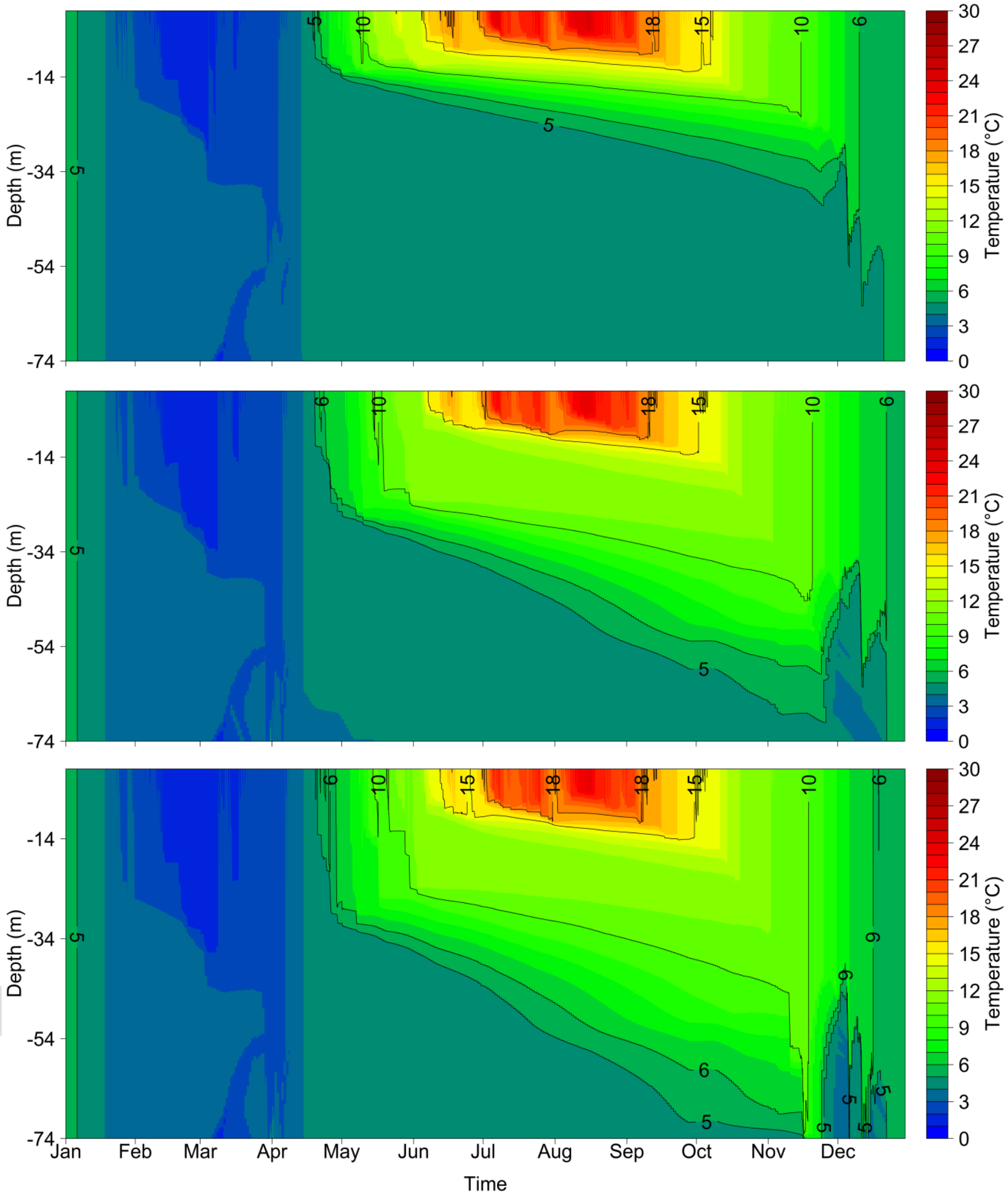

Figure 5: Water temperature under different wind scenarios. Temperature with wind speed measured in 2015 (top), wind speed from 2015 increased by 10% (middle) and 20% (bottom).

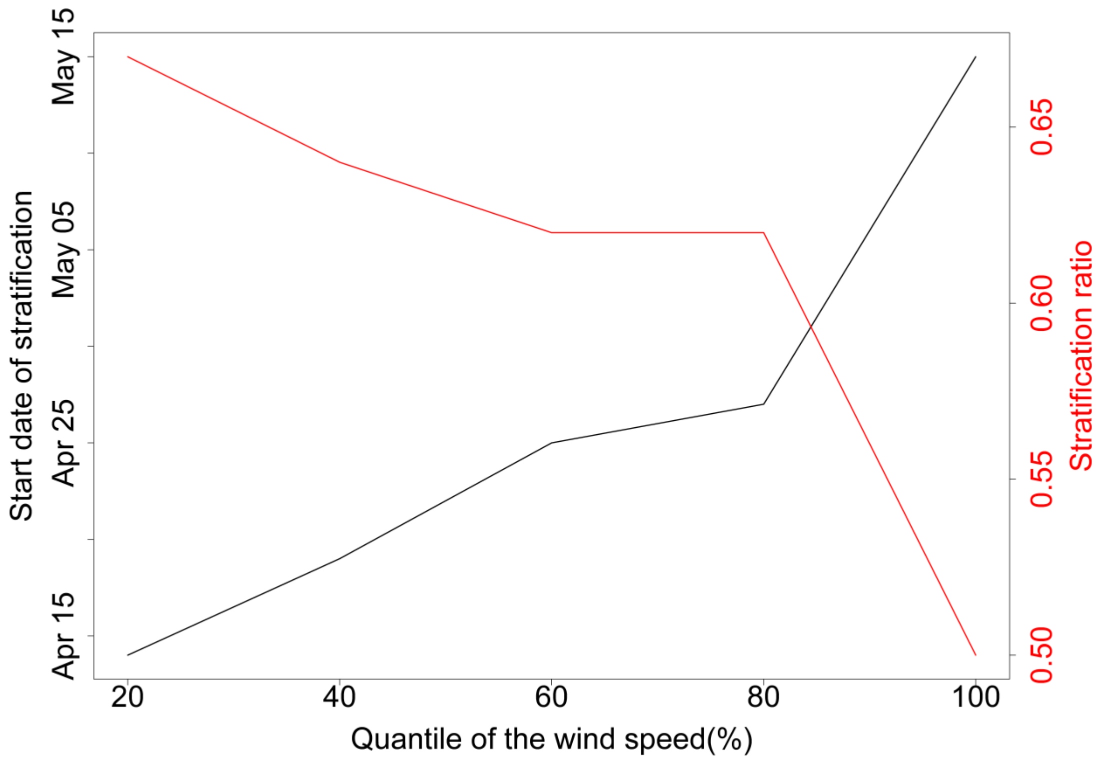

Figure 6: Comparison of stratification onset and open water stratification ratio under different wind forcing, given as quantiles of long-term wind speed observations.

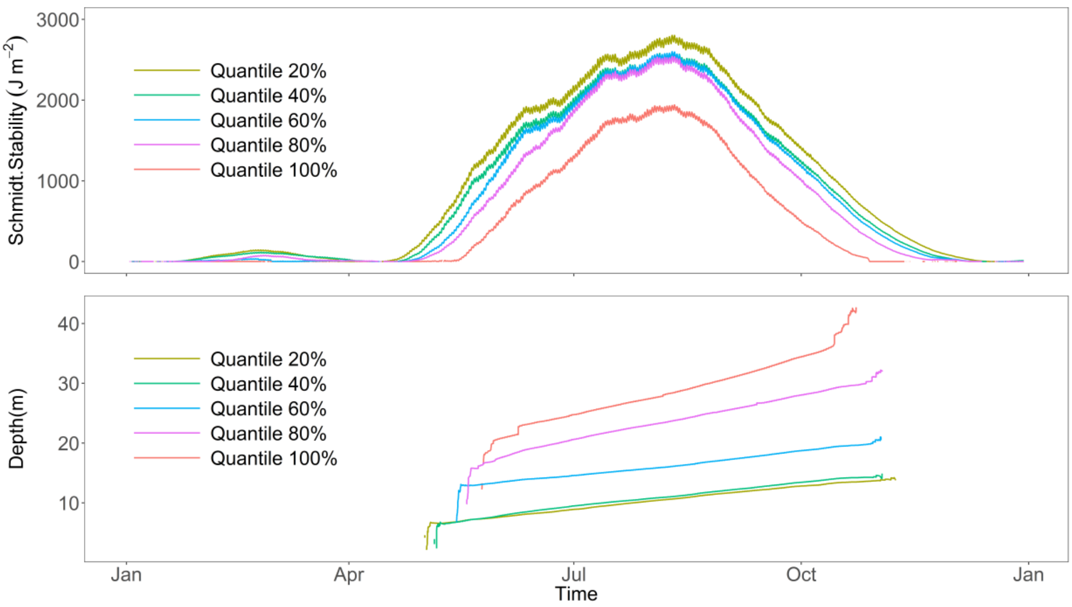

Figure 7: Comparison of Schmidt stabilities (top) and 10 °C isotherm depths (bottom) under different quantile wind scenarios.

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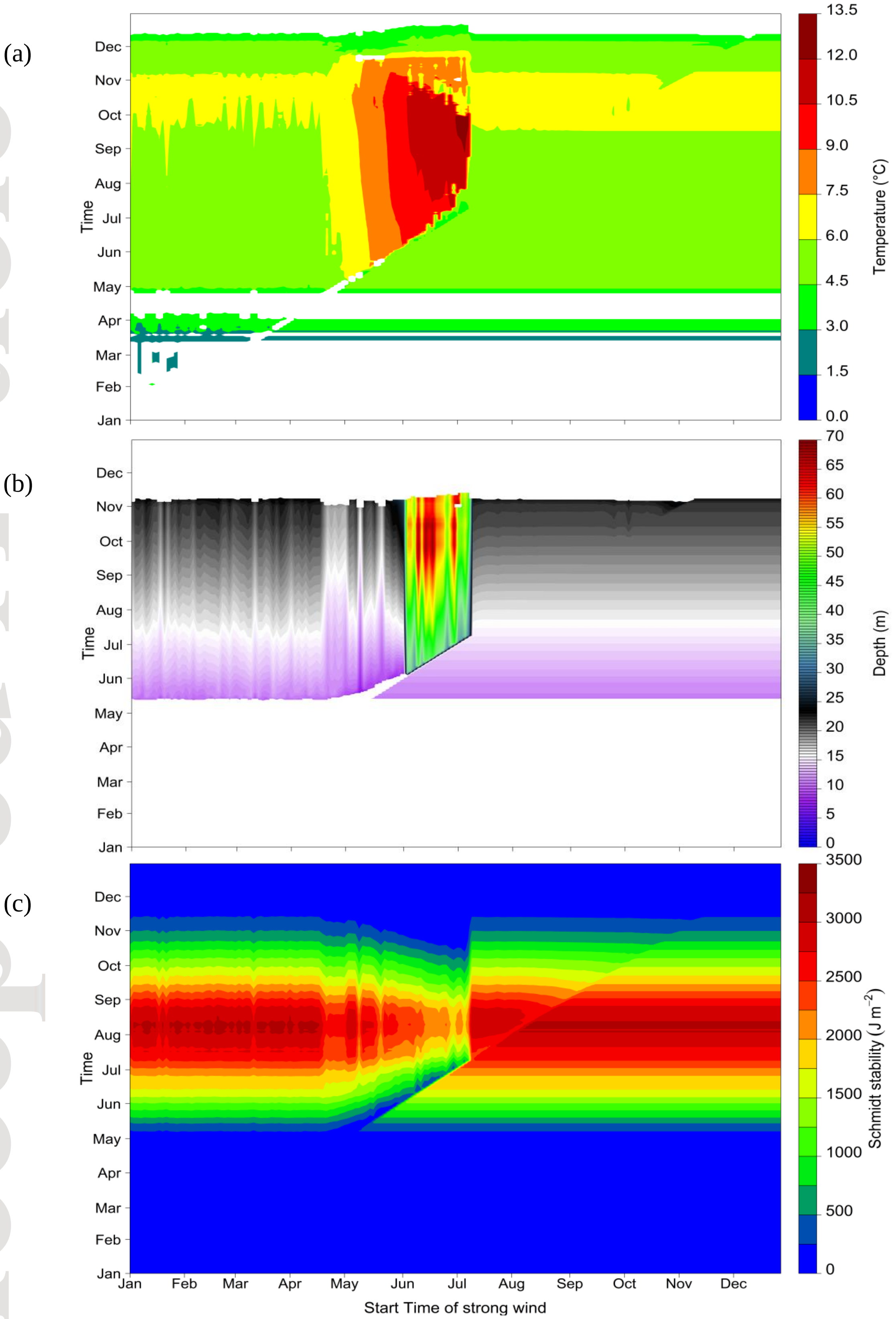

Figure 8: Hypolimnetic temperature (a), 10 °C isotherm depth (b) and Schmidt stability (c) modeled over the entire year (vertical axis) for different timing of the strong wind event (horizontal axis).

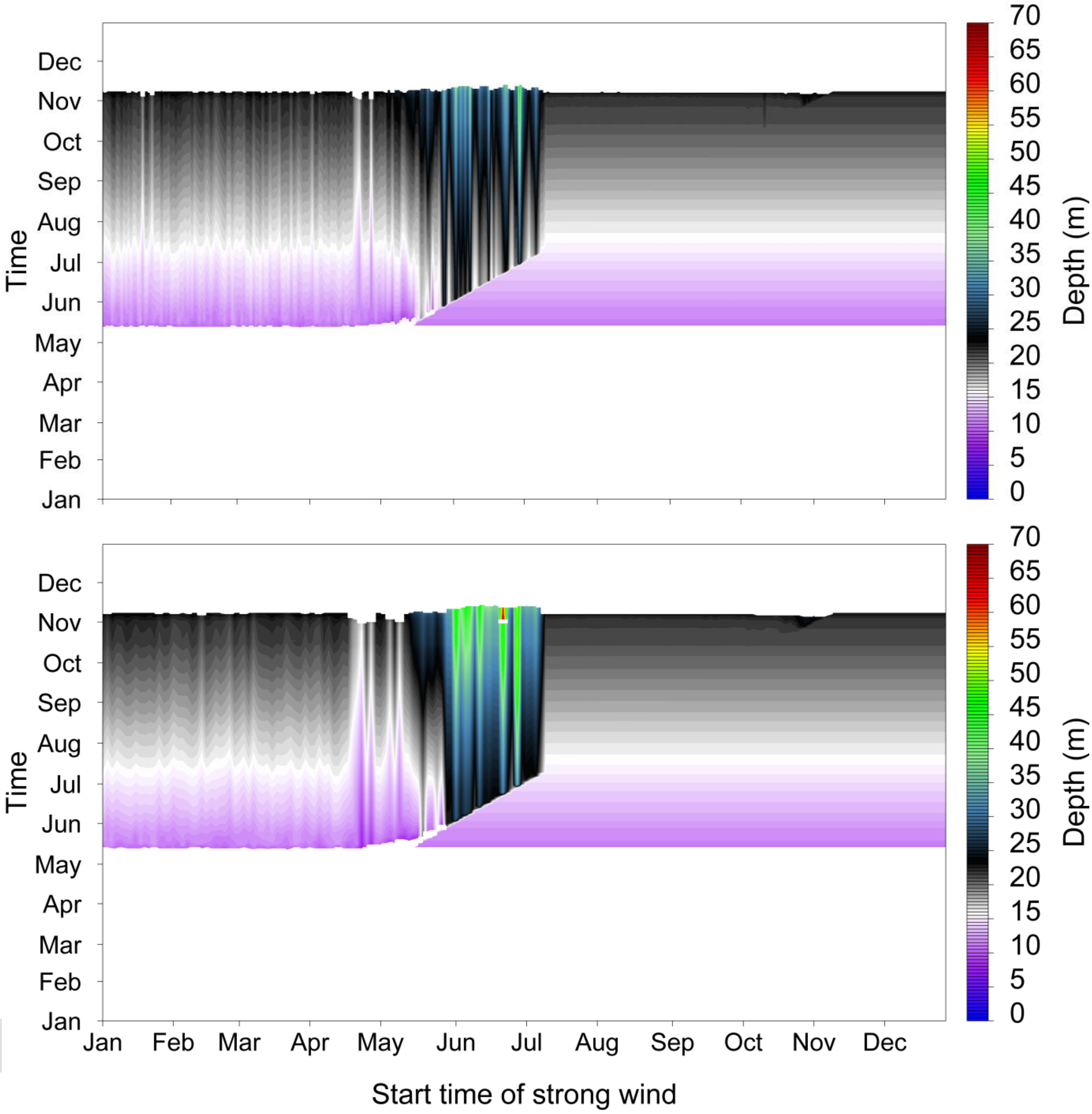

Fig 9: Depth of the 10 °C isotherm depth in the scenario S4 for a strong wind event lasting over either one (top) or two days (bottom) modeled over the entire year (vertical axis) for different timing of the strong wind event (horizontal axis).