

Future alterations of thermal characteristics in a medium-sized lake simulated by coupling a regional climate model with a lake model

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Abstract

Regional climate models (RCM) provide site-specific meteorological data at a suitable spatial resolution for the estimation of future climate-driven changes in aquatic ecosystems. In this study, we used meteorological data from the RCM weather-situation-based regionalization method (WETTREG), available for Germany, to force a one-dimensional hydrodynamic lake model to simulate climate-induced changes on the summer thermal stratification of Lake Ammersee in southern Germany. **In comparison to** the period of 2002–2010, an extension by 22 days of the summer stratification period was simulated for 2042–2050. Further, a vertical shift in the position of metalimnion and thermocline within the lake was not detected, but a slight increase in the metalimnion thickness during mid-summer of 1 m was simulated. Along with these changes in stratification patterns, warming for the epilimnion water temperatures during summer stratification and for the entire water body in winter were simulated for the future. By contrast the hypolimnion temperatures are simulated to decrease during the summer stratification. In addition to simulating future limno-physical aspects, the investigation demonstrates that the RCM data of the WETTREG projection are suitable for conducting climate change impact studies.

Keywords

Thermal stratification, regional climate model WETTREG, hydrodynamic modeling, thermocline characteristics, climate change impact, Lake Ammersee

Acronyms:

RCM: Regional climate model

WETTREG: Wetterlagen-basierte Regionalisierungsmethode (engl: weather-situation based regionalization method)

DYRESM: Dynamic Reservoir Simulation Model

OMS: observed meteorology simulation past

WSP: WETTREG-simulations past

DOY: Day of the year

PDF: Probability density function

41 1. Introduction

42 Climate change not only affects global climatic patterns, it also impacts processes and interactions on
43 a regional scale, e. g., on that of smaller ecosystems. As alterations in local climate conditions vary
44 for different regions (Mooij et al. 2005) generalities should not be drawn (Hamburg et al. 2012;
45 Kotlarski et al. 2012). In the difficult task of making predictions with sufficient detail including small
46 or medium-sized ecosystems (Straile et al. 2010) specific local meteorological data are essential for
47 estimating future climate-driven changes in ecosystems (Skeffington et al. 2010). Regional climate
48 models (RCM), providing data with a suitable resolution and a realistic representation of regional
49 scales features (Dubois et al. 2012), have proven useful for conducting studies on the impact of
50 climate change on a local scale (Christensen et al. 2001; Samuelsson 2010; Frueh et al. 2011).

51 The sensitivity of lake-ecosystems to changes in their environment makes lakes to be sentinels of
52 climate change (Adrian et al. 2009; Williamson et al. 2009a). Alterations in the local meteorology as
53 the driving force for the processes of lake warming, cooling, and mixing will affect the physical
54 limnology (Jones et al. 2010; Winder 2012; Sahoo et al. 2013). By simulating lake water temperatures
55 with hydrodynamic models, these limno-physical alterations can be projected onto the variations in
56 the temperature profiles. A suitable approach, albeit it is still in its infancy (Elliott et al. 2005), to
57 simulate future lake conditions as a response to climatic change is to force hydrodynamic lake
58 models with RCM data (Weinberger and Vetter 2012). The knowledge regarding changes in lakes,
59 which might result from climate, is vital for future water management (Niedda and Pirastru 2012).
60 Therefore, in this study, we applied data from the RCM WETTREG (Wetterlagen-basierte
61 Regionalisierungsmethode: weather-situation based regionalization method (Spekat et al. 2010)),
62 which is available for Germany, to detect the impact of climate change on an ecosystem by
63 estimating future conditions of a medium-sized lake. The hydrodynamic lake model DYRESM
64 (Dynamic Reservoir Simulation Model) was forced by WETTREG projection data to simulate the
65 vertical distribution of past and future water temperatures of Lake Ammersee in southeast Germany.
66 WETTREG data have been used previously for climate change impact studies in urban areas (Frueh et
67 al. 2011) and for river flood conditions (Huang et al. 2013), and input data for future hydrological
68 modeling and the uncertainty analysis in southern Germany (Danneberg et al. 2011; Ebert et al.
69 2011). However, this is the first time that they have been used for future estimations of a complex
70 system such as a lake.

71 Because it controls both the energy fluxes and the distribution of nutrients and oxygen by preventing
72 vertical mixing during summer (Straile et al. 2003; Belolipetsky et al. 2010; Beletsky et al. 2012;
73 Golosov et al. 2012), the thermal stratification of dimictic lakes in temperate regions is one of the
74 most important regulators of the limno-physics of a lake-ecosystem (Braig et al. 2010). Increasing
75 surface water temperature can enhance the stability of stratification in lakes (Livingstone 2003;
76 Trolle et al. 2011). As an indicator of this, the depth of the metalimnion, its vertical extent and its
77 phenology can be derived easily from the vertical distribution of lake water temperature provided by
78 a one-dimensional lake model. Therefore, detecting changes in the extent and duration of the
79 summer thermal stratification in future simulations forced with WETTREG data provides an
80 expedient to the investigation of the impact of climate change.

81 The aim of this study is to process WETTREG projection data to drive DYRESM, in order to compare
82 past and future lake conditions. Thus we focus on the following changes resulting from simulations
83 forced with WETTREG projection data to depict the climate change impact on the limno-physics of
84 the lake: (i) the distribution of water temperatures, (ii) the onset and end of the lake stratification,

85 (iii) the vertical and temporal extent of the seasonal formation of the metalimnion, and (iv) the
86 thermocline depth.

87 **2. Study site**

88 Our study site is the pre-alpine Lake Ammersee situated 35 km southwest from Munich/SE-Germany
89 (47°59'N, 11°7'E) (see Fig. 1). The lake has a surface area of 46.6 km², a volume of 1.8×10^9 m³, an
90 average depth of 36.6 m, and a maximum depth of 83.7 m. Like most lakes nearby and on the
91 eastern Alpine Foothills, the basin of Lake Ammersee has a glacial-morphological origin. Because of
92 this analogous genesis and comparable climatic conditions, Lake Ammersee is considered
93 representative of most of the eastern pre-alpine lakes (Danis et al. 2004; Vetter and Sousa 2012). The
94 mixing regime of the lake is dimictic. A complete ice cover is rare and last occurred in 2006. The main
95 tributary is the River Ammer, which enters the lake from the south and contributes about 80 % of the
96 total annual discharge of the lake. In total, the lake has a catchment area of 993 km² (Schaumburg
97 1996) and is drained by the Amper River in the north. The residence time for the lake is estimated to
98 be 2.7 years (Lenhart 1987; Dokulil et al. 2006).

99 **3. Models, methods and data pre-processing**

100 **3.1 Model descriptions**

101 *3.1.1 DYRESM*

102 For our study, the one-dimensional hydrodynamic model DYRESM (v4.0.0-b2) was used to simulate
103 the vertical distribution of lake water temperature forced by the meteorological data derived from
104 the WETTREG projections. DYRESM was developed by the Centre of Water Research (CWR) of the
105 University of Western Australia (Imberger et al. 1978; Imberger and Patterson 1981). The model is
106 process-based, using the Lagrangian approach of splitting and merging horizontal layers of uniform
107 properties (Imerito 2007). Thus, layer thicknesses are variable but stay within user-defined limits
108 (Antenucci and Imerito 2003; Tanentzap et al. 2007). DYRESM has been applied to several different
109 lakes and reservoirs around the world (Han et al. 2000; Gal et al. 2003; Abeyasinghe et al. 2005;
110 Tanentzap et al. 2007; Rinke et al. 2010; Trolle et al. 2011; Weinberger and Vetter 2012; Bueche and
111 2014). In comparison with other one-dimensional lake models, DYRESM satisfactorily reproduces the
112 variability of the water temperature in lake profiles and the seasonal thermocline (Perroud et al.
113 2009).

114 The model input files and the process scheme are described in more detail in our previous study
115 (Bueche and Vetter 2014). A precise description of the variable model parameters stored in the input
116 files, as well as the original mathematical equations used for the model calculations, are given by
117 Antenucci and Imerito (2003).

118 The one-dimensional approach of DYRESM is very appropriate for simulating the vertical distribution
119 of lake water temperatures, while focusing on alterations in the thermal stratification in this study.
120 This is due to negligible heterogeneities in the horizontal gradients compared with the vertical ones,
121 especially when stratification is established (Perroud et al. 2009; Belolipetsky et al. 2010), and, above
122 all, it is valid for lakes with a simple bathymetry such as Lake Ammersee (see Figure 1). The model
123 results represent the distribution of lake water temperatures in the profile over the deepest point
124 (83.72 m) in the lake.

125 DYRESM has already been calibrated and validated for Lake Ammersee (Bueche and Vetter 2014). In
126 this previous study, we detected very high sensitivity of the model to changes in the meteorological
127 input data, which provides the sound basis for this investigation into the impact of climate change.

128 3.1.2 WETTREG

129 The meteorological data required to force the hydrodynamic model simulations for Lake Ammersee
130 were derived from the RCM WETTREG, which provided past as well as future data. In contrast to
131 numerical RCMs such as REMO (Jacob et al. 2007), WETTREG is a statistical downscaling approach
132 (Enke et al. 2005). The regional climate projections of WETTREG were forced by data from the global
133 climate model ECHAM5 (Hagemann et al. 2006; Roeckner et al. 2006). It uses the statistical
134 relationships between large-scale atmospheric patterns and local climate, and the characteristics of
135 regional climate for different weather types (Kreienkamp et al. 2010b; Huang et al. 2013).
136 Relationships derived from past or present climate conditions were applied to the future simulations
137 of the global models. This allows the creation of new time series of characteristics that are
138 significantly different from the current climate, the so-called Trans Weather patterns (Spekat et al.
139 2010; Frueh et al. 2011; Kreienkamp et al. 2011). WETTREG data are only available for locations with
140 climate observations, because of the need for observation data to derive the correlation matrices for
141 the observation period, in order to calculate climatic predictions (Huang et al. 2013). For this
142 purpose, the dense network of meteorological stations of the German Weather Service was the basis
143 of the WETTREG projections. Climatic data were provided for 387 stations and additional
144 precipitation data for 2943 stations across Germany (Kreienkamp et al. 2010a). WETTREG data are
145 calculated for the period 1961–2100. For each station, ten simulations are produced (hereafter called
146 realizations), which are equally probable and constitute variants of the projected climate (Huebener
147 et al. 2011; Kreienkamp et al. 2011). The RCM of WETTREG provided 10 climate variables with daily
148 resolution, which are specified in Table 1.

149 3.2 Model forcing data

150 To facilitate a consistent comparison between the model results forced by different meteorological
151 input data, a similar period of time was expedient. Reliable observed meteorological, together with
152 hydrological input data for Lake Ammersee (Bueche and Vetter 2014) to drive the hydrodynamic
153 model, were available for the period 07/2001–2010. Accordingly, all simulation periods were
154 determined for the duration of nine and a half years. Therefore, simulations of past conditions for
155 both, forced by observed and by WETTREG projection data, were executed for the exact same
156 timeframe of 07/2001–2010. The period of 07/2041–2050 was chosen for future calculations using
157 the RCM data. As it is practicable (Fang and Stefan 2009), the results of the first six months were
158 excluded in order to eliminate possible effects of initial conditions. Thus, the results of the
159 simulations were processed only for the periods 2002–2010 and 2042–2050 consisting of nine
160 complete years.

161 We implemented WETTREG climate projections based on the IPCC A1B emission scenario. Assuming
162 rapid economic development with global population growth reaching a peak at the middle of the
163 21st century and a balanced use of fossil and non-fossil resources for the future the global mean air
164 temperature is predicted to increase by about 3 K between 1990 and 2100 in this scenario
165 (Nakicenovic et al. 2000; Solomon et al. 2007).

166 All the meteorological input parameters (air temperature, wind speed, precipitation, cloud cover,
167 vapor pressure, and global radiation) required by DYRESM could be derived from the WETTREG data

168 (see also Table 1). According to the temporal resolution of WETTREG projections, the water
 169 temperatures were simulated within a daily resolution. Diessen is the closest station to the lake (see
 170 Fig. 1), situated close to the shore. Here only precipitation data were provided, which could be used
 171 without any pre-processing. All other meteorological input data were available only for stations from
 172 the wider surrounding area (Fig. 1). To obtain data valid for the lake, we conducted a GIS-based
 173 spatial interpolation, applying the IDW (Inverse Distance Weighted) method using the equation (Eq
 174 1) modified after Mitas and Mitasova (1999):

$$v = \frac{\sum_{i=1}^n v_i / d_i^p}{\sum_{i=1}^n 1 / d_i^p} \quad \text{Eq 1}$$

175
 176 where v is the interpolated value, n is the number of points, v_i are the given values at the n points, d_i
 177 is the distance to the defined location of the value to be calculated, and p is a coefficient. p is
 178 typically taken as 2 (Mitas and Mitasova 1999) and similarly, we determined $p=2$ for our study.
 179 Accounting for the different elevations of the WETTREG-stations, the values of air temperature (daily
 180 mean, Table 1) were corrected to the reference level of the lake surface (533 m a.s.l.). After Weischet
 181 (1980), the vertical gradient of air temperature is expected to be in the range between 0.5 and 0.8 K
 182 per 100 m. In this study, we used the gradient of 0.6 K / 100 m, which has already been applied to
 183 the observed air temperature data for Lake Ammersee (Danis et al. 2003; Bueche and Vetter 2014).
 184 An analysis of the WETTREG wind speed data for the four stations Attenkam, Kaufering, Munich-
 185 Nymphenburg, and Kaufbeuren, yielded a bias of values too high for Attenkam. Hence, data for this
 186 station were not considered when interpolating wind speed values for the simulation. Taking into
 187 account that wind velocities on the lake surface are expected to be much stronger than represented
 188 by measured onshore stations, a multiplication factor was applied to the wind data. As this is
 189 practicable (Hornung 2002; Perroud et al. 2009; Rinke et al. 2010), the calibration of this factor for
 190 Lake Ammersee was executed simultaneously with the other lake specific parameters of DYRESM
 191 (Bueche and Vetter 2014). Global radiation is the only meteorological parameter required by
 192 DYRESM, which is not supplied by the WETTREG data, but reliable values could be derived easily from
 193 sunshine duration data. Therefore, a formula known as the Angström-PreScott equation (Martínez-
 194 Lozano et al. 1984; Gueymard et al. 1995), modified after Angström (1924) and Prescott (1940), was
 195 applied to calculate global radiation values. Yorukoglu and Celik (2006) give the equation (Eq 2) as
 196 follows:

$$\frac{H}{H_0} = a + b \frac{S}{S_0} \quad \text{Eq 2}$$

197
 198 where H is the estimated value from sunshine records, H_0 is the extraterrestrial radiation on a
 199 horizontal surface, S is the given sunshine duration, and S_0 is the astronomical day duration (i.e., day
 200 length). The coefficients a and b are site-specific depending on geographical position and the day of
 201 the year. They have been estimated in a study about long-term behavior of sunshine duration and
 202 global radiation for southern Germany (KLIWA 2008), commissioned by local environment agencies
 203 and the German Weather Service. Accordingly, a can be assumed as a constant value of 0.20 for the
 204 entire area of southern Germany; b was calculated specifically for pre-alpine conditions specified in
 205 Table 2. Additionally, Yorukoglu and Celik (2006) provided an overview of all the required definitions
 206 and equations used to apply the Angström-PreScott formula (Eq 2). Sunshine duration data were only
 207 available for the Kaufering, Kaufbeuren, and Munich-Nymphenburg stations. The spatial
 208 interpolation of global radiation values was executed after converting them from sunshine records of

209 these three stations. All series of the WETTREG data lack information for the 29 February occurring in
 210 leap years; thus, values for these days were calculated from the arithmetic mean of the dates before
 211 and after.

212 The hydrodynamic model requires hydrological input data of inflows (discharge, water temperature,
 213 salinity) and outflows (discharge). Discharge values within daily resolution were provided by the
 214 Bavarian Environment Agency for the Weilheim and Stegen gauging stations (Fig. 1) for the period
 215 1961–2100. These data were simulated using the hydrological model WaSiM-ETH (Water Balance
 216 Simulation Model) forced by the WETTREG meteorological data. The model was established at ETH
 217 Zurich (Schulla 2012) and consists of several sub models which apply physically based algorithms.
 218 WaSiM is suitable for long-term water balance and climate change applications (Jasper et al. 2004;
 219 Beckers et al. 2009). Model runs for all WETTREG-realizations were conducted and the results
 220 subsequently averaged for each day. The daily average of the observed runoff data (2002–2010) for
 221 Ammer River amounts to $15.6 \text{ m}^3\text{s}^{-1}$. The WETTREG-driven WaSiM simulations of runoff yield a
 222 reduction in the daily average of $18.3 \text{ m}^3\text{s}^{-1}$ to $14.2 \text{ m}^3 \text{ s}^{-1}$ from the past (2002–2010) to the future
 223 period (2042–2050). **The hydrographs of monthly averages of runoff data sets (Fig. S1 of the Online
 224 Resource) depict two peaks for the observed and the future simulated runoff, one occurring in spring
 225 (due to snow melt) and another during late summer (due to precipitation). This hydrological regime
 226 was also described by Ludwig (2000) for River Ammer in the 2nd half of the 20th century. The
 227 hydrograph of the simulated runoff data for the past shows only one peak during summer. The
 228 reasons for this are twofold. First, snowmelt and summer precipitation maximum are overlapping in
 229 time for the past scenario. And second, higher precipitation values occur during summer, which also
 230 caused the overestimation compared to the measured data.**

231 Stegen gauging station represents the outflow of Lake Ammersee, and its modeled data were used as
 232 input withdrawal data. The very high accordance in linear regression of observed runoff data for
 233 Weilheim and Fischen gauging stations of $R^2 = 0.97$ for the period of 1975–1999 enables reliable
 234 simulated discharge data to be calculated for the Ammer River, the main tributary to the lake.
 235 Considering that the River Ammer contributes about 80 % of all inflows to Lake Ammersee, it was the
 236 only implemented inflow to the hydrodynamic model. To ensure a stable water balance of the lake,
 237 the discharge data of the inflow had to contain the unknown runoff amounts of all other smaller
 238 inflows. For this reason, a water balance analysis, e.g. such as the one by Baumgartner and Liebscher
 239 (1996), was carried out for each realization and its corresponding simulation period. To identify the
 240 missing amount of total runoff, all water influxes to the lake (the known inflow and precipitation)
 241 were subtracted from all water effluxes (outflow and evaporation). This value, similarly apportioned,
 242 was then added to the daily inflow runoff values. No water temperatures from any inflow were
 243 available for the WETTREG projections. A linear regression of measured water temperatures (T_W) and
 244 observed air temperatures (2001–2010) revealed a high accordance of $R^2 = 0.86$ for positive air
 245 temperatures (T_A ; $T_W = (0.667 * T_A) + 3.312$) and a moderate accordance of $R^2 = 0.42$ ($T_W = (0.306 * T_A) +$
 246 3.613) for negative ones, which is still adequate, considering that negative air temperatures during
 247 winter will not have an influence on the thermal summer stratification. Hence, water temperatures
 248 were calculated from the relationship with the WETTREG air temperatures. For salinity data, no
 249 dependence on any available data was determined, and thus the observed data for the Ammer River
 250 for the period 2002–2010 was transferred to all other simulation runs.

251 3.3 Processing of simulation results

252 All processing of the simulation results was carried out separately for each simulation run. The
 253 simulated water temperatures for all WETTREG projection realizations of both simulation periods,

254 2002–2010 in the past and 2042–2050 in the future (in total 20 simulation runs), as well as the
255 output of the simulation forced with observed meteorological data, were processed for the following
256 depths with daily resolution: 0–20 m every meter and 20–80 m every five meters.
257 Stratification periods and metalimnion characteristics were derived from the vertical distribution of
258 the simulated water temperatures. The parameters were also processed separately in daily
259 resolution for each year of each realization. Heat budget of Lake Ammersee could be considered as
260 independent of the previous year, especially during summer stratification. Hence, 10 realizations
261 with 9 years yielded 90 independent samples and a maximum sample size $n_{\max} = 90$ was available for
262 all statistical analyses and both, past and future WETTREG simulations. Averages and standard
263 deviations were calculated from the processed parameters in order to analyze spatial changes, such
264 as depth of metalimnion boundaries and the thermocline.

265 **3.4 Characteristics of thermal stratification**

266 The thermal stratification period of summer starts when surface temperatures exceed the 4°C
267 threshold and the lake water can be mixed only to a limited depth (Boehrer and Schultze 2008; Lee et
268 al. 2012). As it is practicable, a lake can be defined as stratified when the temperature gradient
269 between the surface and deep waters exceeds a determined threshold (Wagner and Adrian 2011)
270 and this approach was applied to Lake Ammersee in the present investigation. A gradient of 2.0 K
271 between surface and 40-m depth temperature was used to define the lake as stratified. The thermal
272 stratification period was determined as lying between the first and the last day of the year when the
273 gradient exceeds this threshold of 2 K. However, to ensure a continuous period of stratified
274 conditions, the stratification period was defined as lying between the days of the year when the
275 thermal gradient did consistently exceed 0.5 K.

276 During the stratification period, a separate layer called metalimnion which contains the sharp
277 temperature gradient (thermocline) during the summer stagnation (Boehrer and Schultze 2008), was
278 established between epi- and hypolimnion. The thermocline depth was marked by the plane in the
279 water column of the maximum rate of decrease in temperature (Hutchinson 1957; Gorham and
280 Boyce 1989). Changes in the spatial characteristics of thermal stratification patterns in the water
281 column were indicated by alterations in the metalimnion layer characteristics (depth, thickness).
282 According to Hutchinson (1957), a temperature gradient of 1 Km⁻¹ was taken to mark the boundaries
283 of the metalimnion. In detail, the uppermost and the deepest depth featuring this gradient within
284 the water column were taken. Waters within the epilimnion exhibiting strong gradients, which occur
285 often in contact with the surface but show a demarcation to the metalimnion by weak gradients,
286 were not taken into account.

287 The date of metalimnion establishment was defined as the first day of the year when a gradient of 1
288 Km⁻¹ could be indicated in the column and after which this gradient occurred continuously at least in
289 one layer in the water column. The last date was marked by the first day in autumn without a
290 gradient over 1 Km⁻¹.

291

292 4. Results

293 4.1 Changes in water temperatures

294 4.1.1 Past conditions

295 The lake simulations driven using the WETTREG projection data were expected to deviate from
 296 simulations forced by observed meteorological data. For this reason, before comparing simulation
 297 results for the past and future, the deviations in simulation results for the past (2002–2010) were
 298 examined for the simulations forced by the observed meteorological data (past observed
 299 meteorology simulation/ OMS) and by the WETTREG projected data (WETTREG-simulations past/
 300 WSP). Hence, the differences in the simulated water temperatures were calculated for several
 301 depths shown in Figure 2.

302 From mid-December to the end of March the WSP-temperatures differed from the OMS only in a
 303 small range at all depths (-0.5 K – +0.8 K). From early April to November strong deviations occurred,
 304 both positive as well as negative. In spring and early summer, when the thermal stratification was
 305 developing, WSP-temperatures in layers near the lake surface (0 m, 4 m) were simulated to be
 306 colder than in the OMS by at least 1 K, and by up to more than 3 K. In the same period, temperatures
 307 at depths of 12-50 m in this graph, which could be ascribed to lower metalimnion and hypolimnion
 308 (Vetter and Sousa 2012), were simulated higher in the WSP. This characteristic intensified during
 309 summer, especially for 12 and 16 m with over 1 K deviation in late summer and up to more than 2 K
 310 in October. However, deviations in the temperatures in the upper layers decreased with time in this
 311 period, but remained negative (September – November). A short period of several days during the
 312 middle of August was the exception, when temperature differences in all layers were positive, even
 313 for the surface.

314 4.1.2 Future conditions

315 In order to illustrate changes in water temperature simulated using the WETTREG projection data for
 316 the past (WSP) and future (WETTREG-simulations future/ WSF) calculations were again made of
 317 deviations in temperature of WSF and WSP. Figure 3 displays the resulting difference values for the
 318 same depths depicted for the past conditions (Fig. 2). Figure 3 shows the following major
 319 observations that have to be considered for the WSF: (i) warmer conditions for the depth 0–12 m
 320 during the complete year; (ii) slightly **increased** water temperatures during the winter throughout
 321 the entire water body (especially from mid-December to mid-March), which exceed 1 K difference
 322 only on the surface; and (iii) a decreasing difference in water temperatures with increasing depth
 323 (over 2 K at the surface) up to slightly negative differences for the depth of 16 m and deeper during
 324 the summer stratification.

325 4.2 Changes in stratification

326 Focusing on climate-induced alterations in the thermal stratification of the lake, the changes in
 327 stratification period and metalimnion characteristics were derived from the vertical distribution of
 328 simulated water temperatures. In average an extension of the stratification period was simulated for
 329 the future resulting from an earlier onset (13 days, 102 to 90 day of the year (DOY)) and a later
 330 cessation of the stratification (9 days, 329 to 338 DOY). The probability density function (PDF) of the
 331 simulated dates (given in DOY) of onset and end of the thermal summer stratification are presented
 332 in Figure 4 (respectively plotted for past and future). Additionally shown in this figure are box-and-

333 whisker charts derived from the density functions. The bold lines inside the boxes show the medians
 334 of the data. The boxes indicate the interquartile ranges (IQR, difference between 75th and 25th
 335 percentile). The IQR measures the spread of the data and is a robust scale parameter (Hannachi et al.
 336 2003). The whisker ends mark the most extreme value not beyond threshold of 1.5 times the
 337 interquartile range to the box edges and samples beyond the whiskers, outliers, are shown
 338 individually by black dashes. The PDFs of the stratification onset show by their peaks a shift to an
 339 earlier establishment in the future. The peaks of the plots for the end of the stratification shift to
 340 later date in the future. The maximum density increases from 0.04 to 0.05, equally for onset and end.
 341 The medians of the past data series lie beyond the future boundaries of the boxes. The same applies
 342 vice versa to the future medians and the past IQRs. This indicates a significant extension of the
 343 thermal stratification period for the future. Further features can be inferred from the PDFs and box-
 344 plots in Figure 4. The density functions for the onset date of both past and future show almost the
 345 same lowest value. Although simulated to establish earlier in the future, **the onset is still not taking**
 346 **place** before this date. The PDF of the stratification end in the future depicts a secondary maximum
 347 of about 0.01 probability density at the DOY 300. **Therefore**, the phenomenon of extreme early
 348 cessation of stratification in the season still can be expected to occur occasionally for the future,
 349 despite a projected in average later end of stratification.

350 Alterations in spatial and temporal stratification patterns are indicated by the characteristics of
 351 metalimnion. Figure 5 illustrates alterations of the boundaries of this layer ((5a) upper and (5b) lower
 352 boundary). For the future upper boundary the average was simulated as being located almost at the
 353 same depth for August but shallower by 1 – 2 m afterwards and about 1 m before. The average of
 354 the future lower metalimnion boundary was simulated to be about 1 m deeper until mid- September
 355 and afterwards to be located at a similar depth as the past average until the end of October. In
 356 combination, the results show an extended metalimnion thickness for the entire period excluding
 357 April and early May. Regarding the vertical position of the metalimnion in the water column, no shift
 358 was detected for the entire period. Examining the standard deviations of both layer boundary
 359 depths, a smaller range of 2 - 3 m in both vertical directions was detected in the autumn months.
 360 Accordingly, depth variations in metalimnion boundaries in the late season were decreasing including
 361 extreme deviations from the average of the boundary depths.

362 Figure 5 also shows temporal changes in the establishment of metalimnion. Similar to the
 363 stratification period, future metalimnion emerged earlier and disappeared later. In other words, for
 364 the frequency of metalimnion occurrence for at least 50 % of the simulated **samples** ($n \geq 45$) this
 365 means a 5 d earlier onset and 15 days later end and for a frequency between 10 % and 50 % ($9 \leq n <$
 366 45) 15 days earlier and an 8 d later end. The period for metalimnion occurrence of 10 – 50 % in spring
 367 was simulated not only to start earlier, but also to last longer.

368 Temporal patterns of thermocline changes (Figure 6) were equal to the metalimnion characteristics.
 369 Alterations in the average of thermocline depth were simulated for the periods after the
 370 establishment of metalimnion up to mid-June (April to mid-May: between 0.5 m and 2 m deeper
 371 average future thermocline; mid-May to mid-June: up to 1 m **shallower**) and for mid-September to
 372 the cessation of metalimnion (between 1 m and 2 m **shallower**). For the latter period, the future
 373 standard deviation exhibited a decrease in its range of 2 m to 3 m. This pattern was accompanied by
 374 the behavior of metalimnion boundaries in the late season. During May an increase in this parameter
 375 by 0.5 to 4 m was detected for the future standard deviation range, but almost no changes were
 376 simulated for the summer.

377 **5. Discussion**

378 **5.1 Past conditions**

379 When comparing the water temperatures of the OMS and WSP, changes in water temperature and
 380 stratification characteristics can be identified which are induced only by the differing meteorological
 381 input data. Temperature alterations between OMS and WSP (period 2002–2010, presented in Figure
 382 2) reveal very notable differences. Characteristics of all the deviations in water temperature can be
 383 linked strongly to the structure of the summer thermal stratification. Colder conditions in the upper
 384 layers of the WSP (0–8 m) and simultaneous warmer temperatures in deeper layers, especially
 385 between 12–16 m, are indicative of a later establishment of metalimnion, as well as a weaker
 386 gradient within it. Accordingly, the thickness of the epilimnion is greater in WSP than in OMS. As the
 387 decisive factor for the epilimnion thickness (Boehrer and Schultze 2008) differences in wind speeds
 388 have induced those deviations, because the depth of vertical mixing during stratified conditions is
 389 strongly related to wind velocities. As it was not an objective of our study, we waived a validation of
 390 past WETTREG data with meteorological observations. This has already been done by Kreienkamp et
 391 al. (2010a), who verified that the WETTREG projection data were able to reproduce well the climatic
 392 observations for the period 1971–2000. In detail, no significant deviations could be found for air
 393 temperature, but slight overestimations were determined for wind speed (on average about $+0.7 \text{ ms}^{-1}$
 394 1 for the daily mean values) and sunshine duration (on average about $+0.1 \text{ h}$ for the daily mean).
 395 Hence the presented differences in the simulation results are to be ascribed to deviations in the
 396 WETTREG projection data relative to the observed climatic condition. However, by using the same
 397 model approach with an equal basis for meteorological forcing data, the delivered relative
 398 alterations between past and future are reliable which is evidenced by exact dates and statistics. For
 399 this reason, the results of the future projections were compared only with the simulations driven by
 400 the same meteorological source of the RCM WETTREG projection data.

401 It is to be mentioned here that these results can be transferred only in a limited way to real
 402 conditions in this quantitative detail. The approach of adapting the RCM input data by means of a
 403 bias-correction was not applied, as this is usual only for dynamic RCM data (Mudelsee et al. 2010;
 404 Ebert et al. 2011), such as REMO (Weinberger and Vetter 2012). Thus comparisons of the presented
 405 future simulations with simulations forced by observed meteorological data for the past, or even
 406 with in-situ measurements of past conditions of the lake as done by Weinberger and Vetter (2014),
 407 similarly would be significant only to a limited extent, and thus were disregarded in this study.

408 **5.2 Estimation of future conditions**

409 The differences, induced by changed climatic conditions, between the simulated past and future
 410 water temperatures point out clearly remarkable alterations for the future (Figure 3). Since the air
 411 temperature shows the most intense difference ($+1.6 \text{ K}$ in average) of all meteorological input
 412 variables for the study area between past and future simulation periods, it must be named as the
 413 main reason for the altering water temperatures. Additional driving forces for this process are
 414 increasing global radiation ($+8 \text{ Wm}^{-2}$ on average), but also a slightly simulated reduction in wind
 415 speed (-0.1 ms^{-1} on average). The indicated differences in climatic variables are in accordance with
 416 the values calculated for all of Germany by Kreienkamp et al. (2010a). Warming in the upper layers
 417 (surface, epilimnion and upper metalimnion; 0–12 m) during the summer owing to changing climatic
 418 conditions was already investigated for past conditions of Lake Ammersee by Vetter and Sousa
 419 (2012), as well as for other northern pre-alpine lakes (Livingstone 2003; Adrian et al. 2009), and for

420 lakes in other climatic zones (Coats et al. 2006; Austin and Colman 2007; Rimmer et al. 2011).
421 Therefore, this reaction of the lake estimated by the WETTREG projections corresponds to the
422 anticipated continuation of the process already initiated by a warming climate. Arvola et al. (2010)
423 summarized a weak trend of rising winter water temperatures in lakes throughout Europe for the
424 past few decades. Thus, the simulated higher future winter water temperatures throughout the
425 entire water column of Lake Ammersee represent the ongoing nature of this process; however the
426 values seem to be too high. The projected moderate warming of the complete water body during
427 winter in this period is also in accordance with the specific mixing regime of Lake Ammersee. The
428 influence of meteorological forcing on water temperatures of a dimictic lake during winter is
429 normally interrupted by ice cover. The fact that Lake Ammersee rarely freezes completely (Bueche
430 and Vetter 2014) causes an enhanced sensitivity of the lake to warming climatic conditions during
431 winter. This makes the resulting magnitude of the increase in the future winter water temperatures
432 of the WETTREG projections very plausible. The prediction of a decrease in metalimnetic and
433 hypolimnetic water temperatures during the summer months at first seem to be contrary to a
434 warming climate. But it can be assumed that this is a consequence of an earlier onset of the thermal
435 stratification (Weinberger and Vetter 2014). Stratified conditions prevent the transport of heated
436 surface water by mixing into deeper layers (Livingstone 2003; Straile et al. 2010) which induces
437 warming of hypolimnion waters. As simulated for the future the period of vertical heat transport to
438 the hypolimnion shortens due to an earlier onset of stratification and less heating takes place. This
439 described phenomenon was also simulated by Hondzo and Stefan (1993) and observed by Tanentzap
440 et al. (2008) for other sites.

441 All the simulated results for the future metalimnion characteristics match the discussed simulated
442 differences in water temperatures, especially during the summer. This is especially true for the
443 significant earlier onset of the summer thermal stratification (Fig. 4). The total extension of the
444 stratification period of 22 days is in accordance with the results from the future estimations by
445 Perroud and Goyette (2010) for Lake Geneva and by Weinberger and Vetter (2014) for Lake
446 Ammersee with RCM data of REMO. While stratification period and metalimnion characteristics are
447 seen to change temporally, no essential spatial alterations could be detected in the thickness of
448 metalimnion (only 1 m increase) or in the vertical shift in the thermocline depth.

449 Consequently, the thermal gradient within the metalimnion was also simulated to increase for the
450 future due to the increased epilimnion and decreased hypolimnion water temperatures, which can
451 be used as a general measure of the stratification intensification (Jones et al. 2010). A smaller
452 standard deviation of future average metalimnion boundary depths in the late season (Fig. 5)
453 seemed to be in contrast to the expected increase in extreme events in the future (Beniston et al.
454 2007). However, due to the detected intensification of stratification in this period the future
455 metalimnion and the stratification pattern in general was more resistant to extreme meteorological
456 influences than in the past.

457 The projected alterations in water temperature and stratification patterns could also have an impact
458 on a lake's mixing behavior (Winder 2012). Due to the considerable extension of the stratification
459 period (the prolongation is an increase of about 9 % to the simulated average period during the year
460 of the past), time slots in spring and autumn for circulations will shorten. This could lead to a
461 decrease in holomictic events or even induce a change in the mixing regime to a monomictic lake.
462 The lake chemistry and biology will also be affected by the simulated alterations of the limno-
463 physical processes (Adrian et al. 2009; Wagner and Adrian 2009). The metalimnetic oxygen
464 minimums occurring during the summer stagnation in Lake Ammersee will intensify due to an earlier
465 onset of stratification, which might have a great influence on fish population in the lake (Joehnk and

466 Umlauf 2001). Another effect of incomplete mixing would be low oxygen concentrations in deep
467 waters (Straile et al. 2003). A consequence of changes in stratification is also the strong impact on
468 phytoplankton in the lake (Wagner and Adrian 2011). This could lead to a biomass increase by an
469 earlier phytoplankton bloom due to an earlier onset of stratification, but also to a decrease in
470 biomass due to reduced vertical mixing of nutrients (Bayer et al. 2013).

471 **6. Conclusions**

472 In this study, we used RCM data of WETTREG to analyze climate-induced changes in an aquatic
473 ecosystem. It was shown for the first time that WETTREG projection data are suitable for the
474 investigation of future impacts of climate change on lakes in general. By coupling these RCM data
475 with a hydrodynamic model, reliable simulation results from lake limno-physics were derived and
476 significant changes in the future stratification characteristics projected. For the period 2042–2050, a
477 significantly longer summer thermal stratification period was detected resulting from both an earlier
478 onset and a later cessation, and a stronger thermal gradient within the metalimnion, but with no
479 spatial shift within the water column. Along with these stratification changes, warmer water
480 temperatures in epilimnion temperatures during summer stagnation and in the entire water body
481 during winter were simulated. It is also shown that warmer climatic conditions induce not only
482 heating in the lake but also **slightly reduced** temperatures in hypolimnion as a result from altered
483 warming patterns.

484 Based on easily applicable meteorological data, this modeling study not only enhances local research
485 on the reaction of limno-physical aspects, such as the prediction of changes in the mixing behavior of
486 Lake Ammersee (i.e., Danis et al. (2004) and Weinberger and Vetter (2014)) and many other
487 comparable pre-alpine lakes, it also reduces the lack of knowledge in the field of investigation into
488 the impact of climatic change on lakes (MacKay et al. 2009). It now can be used to achieve the next
489 level of estimating the impact of climate change on lake-ecosystems by simulating all physical,
490 chemical and biological responses of a coupled lake model, for example using the General Lake
491 Model – Framework for Aquatic Biochemical Models (GLM-FABM). Hence, this study is an additional
492 contribution to the understanding of future changes in lakes, the sentinels, integrators and
493 regulators of climate change (Williamson et al. 2009b).

494

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740 Figure Legends

741 Figure 1: Location of Lake Ammersee with its catchment area, bathymetry, tributaries and the
 742 location of the WETTREG stations (with elevation a.s.l.) as well as gauging stations used in this study

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744 Figure 2: Differences ($T_{WSP} - T_{OMS}$) in simulated water temperatures forced by WETTREG projection
 745 data to simulation results driven by observed meteorological data for the period 2002-2010. The
 746 differences in daily resolution are shown in the course of the year for the depths 0m, 4m, 8m, 12m,
 747 16m, 20m, and 50m (WSP are represented by the mean simulation results of all realizations).

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749 Figure 3: Differences ($T_{WSP} - T_{WSF}$) in simulated water temperatures between the periods 2002-2010 to
 750 2042-2050 both forced by WETTREG projection data. The differences in daily resolution are shown in
 751 the course of the year for the depths 0m, 4m, 8m, 12m, 16m, 20m, and 50m

752 Figure 4: Probability density function of the simulated dates for onset and end of stratification period
 753 driven by WETTREG projection data for past (2002-2010, black graphs) and future (2042-2050, grey
 754 graphs). The box-and-whisker charts represent the median of the data series by the thick lines inside
 755 the boxes. The edges of the boxes indicate the lower (left) and upper (right) quartile (25th and 75th
 756 percentile). The whisker ends mark the most extreme value not beyond threshold of 1.5 times the
 757 interquartile range (IQR, difference between 75th and 25th percentiles) to the box edges and samples
 758 beyond the whiskers, outliers, are shown individually by black dashes.

759 Figure 5: Simulated depths of metalimnion layer boundaries (a) upper, b) lower) in the course of a
 760 year driven, by WETTREG projection data for past (2002-2010) and future (2042-2050). The averages
 761 are displayed by solid lines. The standard deviations are represented by the edges of the illustrated

762 polygons. The metalimnion boundaries are visualized for two percentage ranges of indication counts
763 of all samples ($n_{\max} = 90$): 10% - 50% and $\geq 50\%$. The percentage range of $< 10\%$ is not shown

764 Figure 6: Thermocline depths in the course of the year simulated for the past (2002-2010) and the
765 future (2042-2050) forced by WETTREG projection data. The averages are displayed by solid lines.
766 The standard deviations are represented by the edges of the illustrated polygons. Values are shown,
767 if a metalimnion is indicated, in the water column for at least $\geq 50\%$ of the respective day of the year.

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