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Numerische Modellierung des Wärme- und Stoffhaushaltes des Ammersees

vorgelegt von
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Kurzzusammenfassung

Aquatische Systeme, wie Seen, sind aufgrund ihrer Sensitivität wertvolle Indikatoren für die Art und Intensität des Einflusses des Klimawandels. Durch Änderungen in den regionalen klimatischen Bedingungen werden die internen Prozesse in limnischen Systemen beeinflusst. Mit Hilfe von numerischen Modellen können die komplexen Prozesse in Seen unter der Berücksichtigung externer Einflüsse abgebildet und dadurch realitätsnahe Ergebnisse zur räumlichen und zeitlichen Verteilung der Temperaturen und gelöster Stoffe im Wasserkörper bereitgestellt werden.

In der vorliegenden Arbeit werden numerische Modelle auf den Ammersee als Untersuchungsgebiet angepasst. Ziel ist es, anhand hydrodynamischer sowie ökologischer Modellierungen Untersuchungen zur Forschungsfrage der Auswirkungen des Klimawandels auf Seen durchzuführen. Es wird dadurch einerseits zu einer Verbesserung des Prozessverständnisses für limnologische Systeme beigetragen und andererseits die numerische Modellierung als vielseitiges Werkzeug für Untersuchungen zu sowohl spezifischen als auch integrativen limnologisch-geographischen Fragestellungen bereitgestellt.

Die Untersuchungen werden am Ammersee durchgeführt, welcher im bayerischen Alpenvorland liegt. Er besitzt eine maximale Tiefe von ca. 83 m. Das Durchmischungsregime des Sees ist momentan als dimiktisch und der trophische Zustand als mesotroph mit Tendenzen der Reoligotrophierung einzustufen.

Die Modellierungen umfassen Simulationen zu verschiedenen Fragestellungen. Das hydrodynamische Modell DYRESM wird anhand gemessener limnologischer Daten für den Ammersee kalibriert und validiert. DYRESM modelliert dabei die zeitliche und räumliche Verteilung der Wassertemperaturen im vertikalen Tiefenprofil des Sees. Mittels des kalibrierten Modells werden vergangene und zukünftige limno-physikalische Prozesse unter der Verwendung von meteorologischen Daten des regionalen Klimamodells WettReg2010 simuliert. Da zur Ermittlung der Verhältnisse für Vergangenheit und Zukunft meteorologische Daten dieser gleichen Projektion verwendet werden, können aus den Abweichungen in den Simulationsergebnissen direkt Veränderungen abgeleitet werden. Des Weiteren wird der Einfluss von unterirdischen Zuflüssen in den Ammersee auf die Simulation der Wassertemperaturen mit DYRESM untersucht. Dabei wird sich den Eigenschaften der noch nicht quantifizierten Grundwasserzuströme in einem iterativen Verfahren angenähert. Ferner wird das ökologische Seemodell GLM-FABM für den Ammersee angepasst und kalibriert. Dabei werden im Rahmen dieser Arbeit Wassertemperaturen sowie die Konzentrationen ausgewählter gelöster Stoffe (Sauerstoff, anorganische Stickstoffverbindungen, Silizium und Phosphor) simuliert.

Durch die Kalibrierung des Modells DYRESM auf den Ammersee konnten plausible Werte für die simulierten Wassertemperaturen erzielt werden, welche im Rahmen der Validierung überprüft und bestätigt wurden. Dazu wurden statistische Gütemaße aus den Abweichungen der simulierten

Ergebnisse zu den gemessenen Felddaten ermittelt. Der MAE liegt bei 0,80 K bzw. 0,76 K, der RMSE bei 1,01 K bzw. 0,98 K und der ME bei -0,23 K bzw. bei -0,42 K. Durch die Sensitivitätsanalyse der Modellierungsergebnisse in Bezug auf Veränderungen von einzelnen meteorologischen Variablen sowie der Temperatur des Zuflusses wird die Verwendbarkeit von DYRESM für die Simulation von zukünftigen Einflüssen des Klimawandels auf den See nachgewiesen. Die größten Änderungen in den Simulationsergebnissen werden dabei durch Modifikationen in den Variablen Lufttemperatur und Windgeschwindigkeit induziert.

Auf Basis von WettReg2010-Daten wurden die Wassertemperaturen für die Zeiträume 2002 – 2010 und 2042 – 2050 simuliert und die Veränderungen zwischen diesen Zeitspannen ermittelt. Neben einer durchschnittlich simulierten erhöhten Temperatur von 1,49 K (max. 2,88 K) im sommerlichen Epilimnion und einer schwächeren simulierten Erwärmung, im Mittel 0,50 K, für die gesamte Wassersäule außerhalb der Stagnationsphasen, wurde auch eine Abkühlung im Hypolimnion abgeleitet. Die Abnahme der Temperaturen im Hypolimnion beträgt im Mittel 0,09 K und maximal 0,63 K. Für die Schichtungsdauer wird in Zukunft eine durchschnittliche Verlängerung von 22 Tagen im Jahr mit einem früheren Einsetzen der Schichtung von 13 Tagen (im Mittel) simuliert. Für die Tiefe und Mächtigkeit des Metalimnions sowie für die Tiefe der Thermokline wurden Veränderungen unter 1,0 m abgeleitet.

Für die Berücksichtigung von unterirdischen Zuflüssen in der Modellierung in Form von spezifischen Angaben in den Eingangsdaten liefert DYRESM plausible Resultate. Durch die iterative Anpassung der Variablen Zuflusstiefe, Salinität und Volumen für die hydrogeologischen Begebenheiten in den Eingangsdaten der Modellierung wurde sich den Verhältnissen im Untersuchungsgebiet angenähert. Durch die Implementierung des Grundwasserzufluss mit einer Zuflusstiefe von 6 m, einer konstanten Salinität (mit dem Mittelwert des Oberflächenzuflusses) und einem Volumen von 70 % der unbekannten Zuflüsse zum Ammersee konnte eine Reduzierung der Fehlerwerte für die simulierten Wassertemperaturen erzielt werden.

Die Anpassung des ökologischen Modells GLM-FABM auf den Ammersee konnte erfolgreich durchgeführt werden. Für die simulierten Wassertemperaturen beträgt der MAE 0,63 K, der RMSE 0,89 K und der ME -0,01 K. Diese Fehlerwerte sind geringer als die der Modellierungsergebnisse für den Ammersee mit DYRESM. Für alle in die Simulation implementierten gelösten Stoffe werden Ergebnisse erzielt, welche auf Modifikationen in den Parametereinstellungen mit plausiblen Änderungen in den Modellierungsergebnissen reagieren. Die Abweichungen der simulierten Stoffkonzentrationen zu den Felddaten müssen jedoch noch weiter reduziert werden, um eine korrekte Abbildung der Verhältnisse anhand der Modellierung zu gewährleisten.

Im Rahmen dieser Arbeit wurde eine Basis zur Verwendung der numerischen Modellierung als Werkzeug zur Untersuchung von limnologischen Forschungsfragen am Ammersee erarbeitet und angewendet. Anhand der durchgeführten Simulationen konnten quantitative Aussagen zum potentiellen Einfluss des Klimawandels auf den Ammersee erzielt und die Möglichkeit einer zusätzlichen Spezifizierung der hydrologischen Eingangsdaten in der hydrodynamischen Modellierung mit DYRESM erfolgreich umgesetzt werden. Mit der Anpassung des Modells GLM-FABM für den Ammersee wurde eine essentielle Ausgangsbasis für die ökologische Modellierung bereitgestellt. An die Ergebnisse dieser Arbeit kann nahtlos mit einer erweiterten, automatischen Kalibrierung des Modells angeknüpft werden. In weiterführenden Untersuchungen könnten dann mittels des ökologischen Modells unter der Verwendung von Daten regionaler Klimamodelle potentielle Veränderungen im Durchmischungsverhalten, der Trophie und der Limnologie des Ammersees simuliert und analysiert werden.

Summary

Aquatic ecosystems are sensitive to changes in their environment and this makes them sentinels of climate change. The internal processes in limnetic systems are influenced by alterations in climatic conditions in their environment. The complex processes in lakes can be reproduced by numeric models taking also external influences into account. The models provide realistic results of the spatial and temporal distribution of lake water temperatures, dissolved oxygen, and nutrients.

In this thesis numerical modeling is applied to the study area of Lake Ammersee. The objective is to investigate the impact of climate change on lakes using hydrodynamic and ecological models. On the one hand, this leads to a further understanding of processes in limnetic systems and on the other hand, numerical modeling as a versatile tool is prepared for investigation of specific issues as well as for more integrative approaches of limnological and geographical research questions.

The study area, Lake Ammersee, is situated in the northern Alpine foothills of Germany. The lake has a maximum depth of ca. 83 m. The mixing regime currently is dimictic and the trophic status is characterized as mesotrophic.

The modeling incorporates four issues. First, the hydrodynamic lake model DYRESM is calibrated and validated for Lake Ammersee using observed limnological data. DYRESM simulates the spatial and temporal distribution of the water temperatures in the vertical profile of the lake. Second, future limno-physical processes are simulated using the calibrated model forcing it with meteorological data from the regional climate model WettReg2010. By forcing the model with WettReg2010 data, simulations of past and future conditions can be conducted on an equal basis, which allows for a direct comparison of the results. Furthermore, the influence of sub-terrestrial inflows on the simulation with DYRESM is investigated. The characteristics of subsurface inflows, which have not been yet quantified, are estimated using an iterative process. In addition, the open-access ecological lake model GLM-FABM is applied and calibrated to Lake Ammersee. Using this model, water temperatures, dissolved oxygen and nutrient levels (inorganic nitrogen compounds, reactive silica, and phosphorus) are simulated.

As a result of the calibration and validation of DYRESM the errors of the simulated water temperatures to the field data could be reduced to a MAE of 0,80 K and 0,76 K, respectively, a RMSE of 1,01 K and 0,98 K, respectively, and to a ME of -0,23 K and -0,42 K, respectively. The sensitivity analysis of the model to separate modifications of all the meteorological input variables and also the water temperature of the tributary validates the applicability of DYRESM for the simulation of potential impacts of climate change on Lake Ammersee. The most extreme alterations of the simulated water temperatures are induced by modifications in the variables of air temperature and wind speed.

Based on WettReg2010 projections water temperatures are simulated for the periods 2002 – 2010 and 2042 – 2050 and deviations are investigated. The results show an increase of 1,49 K on average (max. 2,88 K) in epilimnion temperatures during summer stratification and an increase of 0,50 K in average for the entire water profile during unstratified conditions. For the hypolimnion during stratification a slight decrease of 0,09 K (max. 0,64) is found. In comparison to the past period, an extension of the summer stratification period by 22 days is simulated for the future period with an earlier onset of 13 days on average. For the position in the vertical water column of the metalimnion and the thermocline depth a vertical shift of beneath 1,0 m is detected.

DYRESM provides plausible results when the estimated subsurface inflow is included in the input data of the model and thus a stable simulation can be attested. Simultaneously, the hydrogeological conditions in the study area could be determined approximately for the variables of the depth of inflow (6 m), salinity (constant value of the average surface inflow), and volume (70 % of the unknown inflow amount to Lake Ammersee).

The ecological lake model GLM-FABM is applied successfully to Lake Ammersee. The statistics for the simulated water temperatures exhibit smaller values than for the calibrated model DYRESM: MAE = 0,63 K, RMSE = 0,89 K, ME = -0,01 K. Simulations for all implemented limno-chemical variables react to modifications in the model settings with plausible alterations, but deviations to the measured data for dissolved oxygen and nutrients are considered to be still too high to represent an acceptable reproduction.

In this thesis a system of numerical modeling as a tool for the investigation of limnological research parameters was developed and applied. The resulting simulations generated quantitative projections for the potential influence of climate change on Lake Ammersee. Furthermore, the feasibility of the additional specification of hydrological input data for the hydrodynamic modeling with DYRESM was successfully tested. By adapting the ecological model GLM-FABM for Lake Ammersee, an essential basis is provided for further ecological modeling studies, and an automatic calibration approach could instantly be applied. In further investigations potential changes in the mixing regime, trophic status, and limno-biological aspects using regional climate model data could be simulated and analyzed.

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1. Einleitung

1.1. Forschungsrahmen

Aquatische Ökosysteme sind sehr sensitiv gegenüber äußeren Einflüssen und stellen daher durch ihre Reaktionen wichtige Indikatoren für den Klimawandel dar (Adrian et al. 2009; Williamson et al. 2009; Bueche & Vetter 2014b). Die Änderungen in den klimatischen Bedingungen in der Umgebung von Seen beeinflussen direkt deren Wärmehaushalt und somit auch alle limno-physikalischen Prozesse, den Stoffhaushalt und die Biologie eines Sees (Wagner & Adrian 2009; Jones et al. 2010; Sahoo et al. 2013). Dies beinhaltet u. a. Veränderungen in der Schichtungsdauer und -stabilität, dem Durchmischungsverhalten, der Phänologie der Eisbedeckung (O'Reilly et al. 2003; Livingstone et al. 2010; Mishra et al. 2011; Winder 2012), sowie die Verteilung von Sauerstoff und Nährstoffen bzw. die Trophie eines Sees (Straile et al. 2003; Kirilova et al. 2009; Vetter & Sousa 2012). Durch die starken Wechselbeziehungen zwischen Chemismus und biologischen Prozessen im Gewässer ist davon auch die Verteilung und Zusammensetzung des Phytoplanktons und des Zooplanktons in Seen betroffen (Huber et al. 2008; Rinke et al. 2010; Wagner & Adrian 2011; Winder & Sommer 2012). Aus diesen Zusammenhängen ergibt sich der Forschungsbedarf, wie Seen auf ein sich veränderndes Klima reagieren und welche Bedingungen in der Zukunft zu erwarten sind (Dibike et al. 2011).

Hydrodynamische und ökologische Seemodelle können komplexe Prozesse in limnischen Systemen realitätsnah simulieren. Durch deren Anwendung können die Verhältnisse in Seen zeitlich sowie räumlich hochaufgelöst abgebildet werden. Bei den Simulationen wird sowohl die Interaktion zwischen Atmosphäre und dem Wasserkörper durch die meteorologischen Eingangsdaten als auch der Einfluss des Einzugsgebietes durch die hydrologischen Inputdaten berücksichtigt. Diese Seemodelle bieten daher die Möglichkeit, zukünftige Bedingungen zu simulieren und quantitativ abschätzen zu können (Danis et al. 2004; Perroud et al. 2009; Jones et al. 2010).

Die aktuelle Herausforderung, die prognostizierten Trends des globalen Wandels auf regionale Maßstäbe zu übertragen und konkrete Auswirkungen auf eine bestimme Region vorherzusagen (Hupfer & Nixdorf 2011), kann mit Hilfe von regionalen Klimamodellen bewerkstelligt werden. Die regionalen Klimamodelle stellen hierfür Daten in einer geeigneten räumlichen Auflösung bereit, welche Muster auf regionalem Maßstab abbilden können (Dubois et al. 2012). Somit können durch den Antrieb der hydrodynamischen und ökologischen Seemodelle mit Daten aus regionalen Klimamodellen statistisch auswertbare Simulationen von zukünftigen Verhältnissen in limnischen Systemen bereitgestellt werden (Samuelsson 2010).

Die Wechselbeziehungen von limno-physikalischen Prozessen und dem Stoffhaushalt von Seen mit der Umgebung sind grundlegende Forschungsfragen der Landschaftsökologie. Dabei dient die numerische Modellierung als wichtiges Werkzeug zur Untersuchung der ablaufenden Prozesse und

Interaktionen. Durch die Anwendung mehrerer Modellierungsansätze in dieser Arbeit werden Aspekte aus unterschiedlichen Fachdisziplinen mit in die Forschung einbezogen. Dies schließt neben Themen der Limnologie und der Landschaftsökologie hydrologische, klimatologische, meteorologische, biogeographische und hydrogeologische Gesichtspunkte mit ein. Durch die Verknüpfung der unterschiedlichen Fachdisziplinen, kombiniert mit dem Fokus auf zeitliche und räumliche Veränderungen im System See, wird in dieser Arbeit ein integrativer Forschungsansatz der Geographie angewendet. Diesen Forschungsrahmen verfolgt auch das Projekt LAGO (**L**imnologische **A**uswirkungen des **G**lobalen Wandels in **O**berbayern, finanziert durch das Bayerische Landesamt für Umwelt) an der Ludwig-Maximilians-Universität München. Die Arbeit wurde im Rahmen dieses Forschungsprojektes angefertigt.

Es handelt sich um eine kumulative Dissertation, deren Kern drei Publikationen darstellen, welche alle in wissenschaftlichen Fachzeitschriften veröffentlich sind (alle peer-reviewed und in Erstautorenschaft):

- **Publikation I:** *Simulating water temperatures and stratification of a pre-alpine lake with a hydrodynamic model: calibration and sensitivity analysis of climatic input parameters* (Bueche & Vetter 2014b, siehe Kap. 4.1 und Anhang A)
- **Publikation II:** *Future alterations of thermal characteristics in a medium-sized lake simulated by coupling a regional climate model with a lake model* (Bueche & Vetter 2015, siehe Kap. 4.2 und Anhang B)
- **Publikation III:** *Influence of groundwater inflow on water temperature simulations of Lake Ammersee using a one-dimensional hydrodynamic lake model* (Bueche & Vetter 2014a, siehe Kap. 4.3 und Anhang C)

In den folgenden Kapiteln wird auf den aktuellen Stand der Forschung (Kap. 1.2) eingegangen und die Zielstellungen der Arbeit werden erläutert (Kap. 1.3). Darauf folgen eine Vorstellung des Untersuchungsgebietes (Kap. 2) und die Beschreibung der angewandten Modelle und Methoden (Kapitel 3). Im Anschluss (Kapitel 4.1 - 4.3) erfolgt jeweils eine Zusammenfassung zu den drei bereits publizierten Artikeln (Bueche & Vetter 2014b, a, 2015, siehe Anhang). Darin werden neben den Methoden auch die wichtigsten Erkenntnisse der Publikationen zusammengefasst und diskutiert. Zusätzliche in dieser Arbeit erzielte Ergebnisse befinden sich in Vorbereitung zur Veröffentlichung und werden daher in Kap. 4.4 detaillierter vorgestellt.

1.2. Stand der Forschung

Zahlreiche Studien weisen bereits auf rezente Reaktionen von limnischen Systemen auf geänderte klimatische Bedingungen in diversen Regionen der Erde hin (O'Reilly et al. 2003; Hampton et al. 2008; MacIntyre et al. 2009; Schneider & Hook 2010; Rimmer et al. 2011; Dokulil 2013; Hamilton et al.

2013; Sahoo et al. 2013). Die Thematik rückte Livingstone (2003) mit der Veröffentlichung seiner Untersuchungen zur Entwicklung des Genfer Sees vermehrt in den Fokus der Seenforschung. In dieser Studie detektiert Livingstone für den See eine Erwärmung der Wassertemperaturen in Folge des Anstiegs der Lufttemperatur in der 2. Hälfte des 20. Jahrhunderts, sowohl im Epilimnion als auch im Hypolimnion, eine Zunahme der Schichtungsstabilität und eine Verlängerung der Schichtungsdauer für den gleichen Zeitraum.

Trolle et al. (2012) dokumentieren eine wachsende Bedeutung der numerischen Modellierung von aquatischen Ökosystemen in den letzten zwanzig Jahren. Nach Joehnk & Umlauf (2001) können eindimensionale Modelle zur Abbildung des Wärmehaushaltes verwendet werden, welche die Wassertemperaturverteilung im vertikalen Profil über dem tiefsten Punkt eines Wasserkörpers simulieren. Dieser eindimensionale Ansatz ist trotz der Vereinfachung der realen Bedingungen zur Abbildung der Schichtungsverhältnisse in Seen plausibel anwendbar, da im Vergleich zu den vertikalen Temperaturgradienten die Unterschiede in horizontaler Richtung vernachlässigbar sind (Perroud et al. 2009; Belolipetsky et al. 2010). Dies trifft vor allem auf Seen mit einer einfachen Beckenstruktur, wie die des Ammersees (siehe Abb. 1, S. 7), zu. Im Vergleich zu anderen eindimensionalen Modellen bildet DYRESM (**Dy**namic **R**eservoir **S**imulation **M**odel; Modellbeschreibung siehe Kap. 3.1) die Variabilität der Temperaturen in der Wassersäule und die saisonale Sprungschicht befriedigend ab (Perroud et al. 2009). DYRESM wurde bereits für Simulationsstudien an Seen weltweit in unterschiedlichen Klimazonen angewendet (Han et al. 2000; Gal et al. 2003; Abeysinghe et al. 2005; Tanentzap et al. 2007; Rinke et al. 2010; Trolle et al. 2011; Bayer et al. 2013; Valerio et al. 2014). Das eindimensionale und vertikale Schichtungsmodell GLM (**G**eneral **L**ake **M**odel) wurde 2012 vorgestellt (Hipsey et al. 2014; siehe auch Kapitel 3.2). Es wurden bereits die ersten Studien zur Verwendung von GLM veröffentlicht (Read et al. 2014; Yao et al. 2014). Zur Simulation des Stoffhaushaltes (gelöster Sauerstoff, Nährstoffe, Phytoplankton) kann GLM mit biochemischen Modulen (**F**ramework for **A**quatic **B**iochemical **M**odels, FABM) der ***A**quatic **E**co**d**ynamics (AED) modelling library* gekoppelt werden (Bruggeman & Bolding 2014). Diese Modellkopplung wurde im Laufe des Jahres 2013 in einem iterativen Prozess verbessert und der Modellierer-Community zugänglich gemacht. Modellierungsergebnisse zu Simulationen mit dem gekoppelten GLM-FABM sind noch nicht veröffentlicht worden.

Die Verwendung von hydrodynamischen Modellen für die Simulation zukünftiger Verhältnisse in Seen ist eine häufig angewandte Methode (z. B. Boyce et al. 1993; Stefan et al. 1998; Lehman 2002; Sahoo et al. 2011). Die Repräsentation der zukünftigen meteorologischen Verhältnisse durch Daten aus regionalen Klimamodellen ist hingegen selten. Als Beispiele sind hier die Arbeiten von Perroud & Goyette (2010) und Weinberger & Vetter (2014) zu nennen. Die Daten des regionalen Klimamodells WettReg (**Wett**erlagen-basierte **Reg**ionalisierungsmethode; Kreienkamp et al. 2010a, b) wurden in der limnologischen Modellierung noch nicht verwendet. In Studien zur Simulation des Klimawandeleinflusses auf Seen wurde die Sensitivität des jeweiligen hydrodynamischen Modells hinsichtlich Änderungen in den einzelnen meteorologischen Größen entweder nicht untersucht oder eine entsprechende Analyse nur für die Variable Lufttemperatur durchgeführt (z. B. bei Peeters et al. 2002; Jones et al. 2010; Bayer et al. 2013).

Zum Untersuchungsobjekt Ammersee (Kap. 2) liegen bereits eine Vielzahl von limnologischen Studien vor. Eine umfassende Studie zur Thermik, zum Stoffhaushalt und zur Biologie des Sees hat Lenhart (1987) veröffentlicht. Untersuchungen zur limnologischen Entwicklung wurden danach von der bayerischen Wasserwirtschaft weitergeführt (Schaumburg 1996), wie z. B. auch zur Reoligotrophierung des Sees (Lenhart 2000). In einer aktuelleren Veröffentlichung des LAGO-Projektes untersuchen Vetter & Sousa (2012) in welchem Maße der Klimawandel zu diesem Prozess beitragen kann. Die rezenten Entwicklungen bezüglich der Biologie im Ammersee behandeln Ernst et al. (2001), Ernst et al. (2009) und Hingsamer et al. (2014). In einer Modellierungsstudie simulieren Joehnk & Umlauf (2001) die Sauerstoffverteilung im See, inkl. der Ausbildung des metalimnischen Sauerstoffminimums, und weisen gleichzeitig auf die Wichtigkeit von weiteren Modellierungsstudien hin. Danis et al. (2004) prognostizieren für den Ammersee eine starke Abnahme holomiktischer Durchmischungsphasen ab dem Jahr 2020, welche sie anhand der simulierten Schichtungsverhältnisse im See bestimmen. Die zukünftigen klimatischen Bedingungen werden dabei von einem globalen Zirkulationsmodell für die Atmosphäre abgeleitet. Brey (2013) entwickelt in Rahmen seiner Dissertation an der Fakultät für Geowissenschaften der Ludwig-Maximilians-Universität München, ein Modell zur Simulation der Wasseroberflächentemperatur des Ammersees und erzielt Modellierungsergebnisse für die Zukunft auf Basis von Daten des regionalen Klimamodells REMO. Bei der Simulation wird jedoch nur der Einfluss der Lufttemperatur berücksichtigt. Ferner ist im Rahmen des Projektes LAGO die kumulative Dissertation von Weinberger (2014) entstanden. In dieser Arbeit wird das Modell DYRESM nach einer Kalibrierung auf den Ammersee (Weinberger & Vetter 2012) mit Daten des regionalen Klimamodells REMO betrieben und aus der Simulation der zukünftigen Wassertemperaturen limno-physikalische Eigenschaften abgeleitet (Weinberger & Vetter 2014).

In den in diesem Kapitel zitierten Modellierungsstudien wurden zur Simulation des Wärmehaushaltes von Seen ausschließlich Oberflächenzuflüsse berücksichtigt. Dies gilt sowohl für die Arbeiten zum Ammersee als auch für alle Studien, in welchen DYRESM auf andere natürliche Seen angewandt wurde. Der potentielle Einfluss von unterirdischen Zuflüssen auf die thermale Struktur blieb dabei stets unberücksichtigt. Die Möglichkeit, unterirdische Zuflüsse zu Seen in der Simulation mit DYRESM zu implementieren, wurde bisher noch nicht wissenschaftlich getestet. Benötigte Daten zu Grundwasserzuströmen zur Durchführung entsprechender Untersuchungen am Ammersee wurden bisher weder erhoben noch Angaben dazu in der Literatur veröffentlicht. Simulationen zur raumzeitlichen Verteilung gelöster Stoffe im Ammersee wurden bislang nur für den Sauerstoff durchgeführt (Joehnk & Umlauf 2001). Stoffkonzentrationen anderer Stoffe und deren Interaktionen, um beispielsweise Aussagen zum trophischen Zustand treffen zu können, wurden dabei nicht modelliert.

1.3. Zielsetzung der Arbeit

Das grundlegende Ziel des Projektes LAGO ist die Erforschung der möglichen zukünftigen Auswirkungen des Klimawandels auf den Ammersee. Zur Untersuchung dieser Fragestellung sollen im Rahmen dieser Arbeit numerische Modelle auf das Untersuchungsgebiet angepasst und zur Bearbeitung konkreter limnologischer Forschungsfragen angewendet werden. Dadurch wird zu einer Verbesserung des Prozessverständnisses für limnologische Systeme beigetragen und die numerische Modellierung als vielseitiges Werkzeug für die Untersuchung von sowohl spezifischen als auch integrativen Fragestellungen der limnologischen Forschung im Untersuchungsgebiet bereitgestellt.

Zunächst soll die räumliche und zeitliche Verteilung der Wassertemperaturen im Ammersee durch die Simulation mit dem hydrodynamischen Modell DYRESM adäquat abgebildet werden. Neben der Fortführung der Kalibrierung des Modells für den Ammersee von Weinberger & Vetter (2012) wird die aktuelle Datenlage zu verfügbaren meteorologischen und hydrologischen Messwerten ermittelt. Die Daten werden auf Verwendbarkeit geprüft und zur Simulation aufbereitet. Die Validierung der Modellergebnisse anhand gemessener Wassertemperaturdaten wird ebenfalls vorgenommen.

Das kalibrierte und validierte Modell soll auf die Sensitivität der Simulationsergebnisse gegenüber Veränderungen in meteorologischen Variablen sowie der Temperatur des Zuflusses untersucht werden. Diese Untersuchung soll gewährleisten, dass Auswirkungen des Klimawandels auf die Wassertemperaturen des Ammersees durch die Simulationen mit DYRESM abgebildet werden können.

Im nächsten Schritt soll der zukünftige Wärmehaushalt des Ammersees durch den Antrieb des Modells mit Daten eines regionalen Klimamodells abgeleitet werden. Dabei werden erstmals Daten des regionalen Klimamodells WettReg2010 in der limnologischen Modellierung verwendet. Die Simulationen werden für einen Zeitraum in der Vergangenheit und der Zukunft durchgeführt, um die Modellierungsergebnisse für beide Zeitspannen auf der gleichen Datengrundlage zu erstellen und Veränderungen für die zukünftigen Verhältnisse direkt ableiten zu können. Der Fokus soll dabei auf Änderungen in den Schichtungsverhältnissen im See liegen, welche eine der Hauptsteuerungsfaktoren für alle physikalischen, chemischen und biologischen Prozesse in einem dimiktischen See darstellen (Braig et al. 2010).

In einem weiteren Untersuchungsschwerpunkt wird die Möglichkeit der Implementierung von unterirdischen Zuflüssen mit ihren individuellen Eigenschaften in der hydrodynamischen Modellierung mit DYRESM für den Ammersee angewendet. Dabei soll der Einfluss dieser Maßnahme auf die simulierten Wassertemperaturen untersucht werden. Zur Durchführung dieser Untersuchung werden verschiedene Szenarien zu den unbekannten hydrogeologischen Bedingungen für das Untersuchungsgebiet aufgestellt und in die Simulation implementiert. Ein weiteres Ziel dabei ist, sich den realen Bedingungen durch die Analyse der induzierten Veränderungen auf die simulierten Wassertemperaturen für die jeweiligen Szenarien bestmöglich anzunähern.

Ferner soll das 2013 vorgestellte ökologische Seemodell GLM-FABM auf den Ammersee angepasst werden, um neben Modellierungen zur Wassertemperatur die Simulation von Teilen des Stoffhaushaltes zu ermöglichen. Hauptaugenmerk soll dabei auf der Simulation der zeitlichen und räumlichen Verteilung des gelösten Sauerstoffs liegen. Des Weiteren wird die Simulation folgender gelöster Stoffe vorgenommen:

- Sauerstoff (*dissolved oxygen*, DO)
- Silizium (*reactive silica*; Si-SiO_2)
- Stickstoff (Nitrat-Stickstoff, N-NO_3 und Ammonium-Stickstoff, N-NH_4)
- Phosphor (gelöster, reaktiver Phosphor, P-PO_4)

2. Das Untersuchungsgebiet

Als Untersuchungsgebiet für diese Arbeit dient der im bayerischen Alpenvorland gelegene Ammersee. Das Seebecken hat eine glazialmorphologische Genese, weist eine Nord-Südausrichtung auf und hat eine einfache Beckenstruktur (Abb. 1, S. 7). Der See besitzt eine maximale Tiefe von 83,7 m und eine mittlere Tiefe von 37,5 m (Nixdorf et al. 2004). Das Volumen beträgt ca. 1,8 Mio. m³ und die Wasseroberfläche nimmt 46,6 km² ein. Die theoretische Wassererneuerungszeit des Sees beträgt 2,7 Jahre (Lenhart 1987). Die Größe des Einzugsgebiets wird von Schaumburg et al. (2005) mit 993 km² angegeben. Der Hauptzufluss in den See ist die Ammer, welche ca. 80 % des jährlichen Zuflusses liefert (Nixdorf et al. 2004). Weitere nennenswerte Zuflüsse sind die Rott, der Kienbach und der Fischbach. Der See wird durch die Amper im Norden entwässert. Der See weist nur selten eine geschlossene Eisdecke auf, was letztmalig für das Jahr 2006 dokumentiert ist (Bueche & Vetter 2014b). Das Durchmischungsregime wird trotzdem in der allgemeinen Literatur einhellig als dimiktisch klassifiziert (Joehnk & Umlauf 2001; Kucklentz et al. 2001; Nixdorf et al. 2004; Ernst et al. 2009). Nach Kucklentz et al. (2001) ist der natürliche Zustand des Sees oligotroph. Durch eine gesteigerte Nährstoffzufuhr, bedingt durch die Intensivierung der Landwirtschaft im Einzugsgebiet und die Einleitung kommunaler und zum Teil industrieller Abwässer, hatte der See Anfang der 1980er Jahre einen eutrophen Zustand erreicht (Vetter & Sousa 2012). Nach einer durch

Wasserreinhaltungsmaßnahmen eingeleitete Reoligotrophierungsphase befindet sich der Ammersee derzeit in einem mesotrophen Zustand (Schaumburg et al. 2005). Weitere Beschreibungen und Abbildungen zum Untersuchungsgebiet befinden sich in den im Rahmen dieser Arbeit entstandenen **Publikationen I, II und III** (Bueche & Vetter 2014b, a, 2015; siehe Anhang)**.**

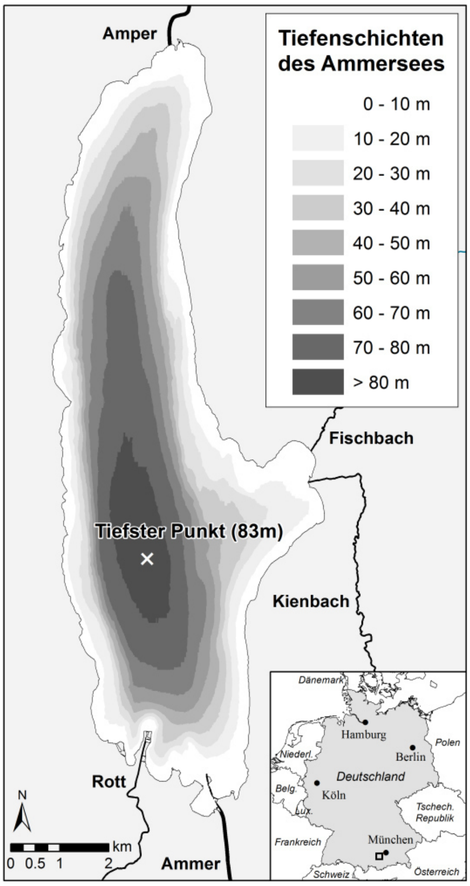


Abb. 1: Das Untersuchungsgebiet - Die Bathymetrie des Ammersees
(Datengrundlagen: Geobasisdaten © Bayerische Vermessungs-verwaltung, www.geodaten.bayern.de; Daten Bathymetrie: Bayerisches Landesamt für Umwelt)

3. Hydrodynamische Modelle

3.1. DYRESM

Das eindimensionale Modell DYRESM (**D**ynamic **R**eservoir **S**imulation **M**odel, Version v4.0.0-b2) wurde am *Centre of Water Research* der *University of Western Australia* entwickelt (Imberger et al. 1978; Imberger & Patterson 1981). Mit dem Modell kann die vertikale Verteilung der Wassertemperatur, der Salinität und der Dichte in natürlichen Seen oder Talsperren simuliert werden. Dafür sind folgende Eingabedaten erforderlich:

- Daten zur Morphometrie
- Meteorologische Daten in täglicher Auflösung (Lufttemperatur, Windgeschwindigkeit, Niederschlag, Dampfdruck, langwellige Einstrahlung oder Bewölkungsgrad, Globalstrahlung)

- Hydrologische Daten von den Zuflüssen in täglicher Auflösung (Durchfluss, Temperatur, Salinität) und vom Abfluss des Sees (Durchflusswerte)
- Initialprofile (Wassertemperatur, Salinität)
- Für die hydrodynamische Simulation erforderliche seespezifische Parameter zur Prozessdynamik im Wasserkörper (während der Kalibrierung auf das Untersuchungsgebiet anzupassen)

Die Simulation basiert auf einer variablen Layerstruktur, der sogenannten „Lagrangian“ Methode (Imerito 2007). Diese sieht vor, dass horizontale Schichten mit gleichen Eigenschaften gebildet werden. Die vertikale Position kann sich durch den Einfluss äußerer Bedingungen (Meteorologie, Zuflüsse) ändern. Die maximale und minimale Mächtigkeit der einzelnen Layer sowie deren maximale Anzahl ist durch den Benutzer zu spezifizieren (Antenucci & Imerito 2003). Die Vermischung sowie der Tiefentransport werden durch Fusion und Trennung einzelner Schichten berechnet (Hornung 2002). Weitere Details zu DYRESM, inklusive Abbildungen zum schematischen Aufbau und zur Funktionsweise der Lagrangian’schen Layerstruktur, und Angaben zu den benötigten Inputdaten sind in **Publikation I** (Anhang A) enthalten.

3.2. GLM-FABM

Das hydrodynamische Modell GLM (**G**eneral **L**ake **M**odel, v1.4) ist ein „open-access“ Modell und wurde auf Initiative des ***G**lobal **L**ake **E**cological **O**bservatory **N**etwork* (GLEON) in Zusammenarbeit mit dem ***A**quatic **E**cosystem **Mo**delling **N**etwork* (AEMON) entwickelt. Mit GLM können die vertikalen Profile zur Wassertemperatur, Salinität und Dichte eines Sees simuliert werden (Hipsey et al. 2014). Dem Modell liegt, wie DYRESM, ein eindimensionaler Ansatz zugrunde und es basiert ebenfalls auf der Lagrangian Methode (siehe Kapitel 3.1). Zudem werden zur Simulation mit GLM die gleichen Eingabedaten wie bei DYRESM benötigt. Ausnahme ist dabei die meteorologische Variable Dampfdruck, welche bei GLM durch Angaben zur relativen Luftfeuchte [%] ersetzt wird. Zusätzlich kann bei den Daten zum Niederschlag zwischen Regen und Schnee differenziert werden.

Zur Simulation des Stoffhaushaltes (z. B. gelöster Sauerstoff, Nährstoffe, Phytoplankton) kann GLM mit biochemischen Modulen (**F**ramework for **A**quatic **B**iochemical **M**odels, FABM) der ***A**quatic **Ecod**ynamics (AED) modelling library* gekoppelt werden, welche ebenfalls frei verfügbar sind. In Abb. 2 (S. 9) sind die zur Simulation benötigten Informationen in den jeweiligen Konfigurations-Dateien (.nml) und Input-Dateien (.csv) und deren Verknüpfungen zueinander aufgezeigt. In der zentralen Konfigurations-Datei GLM.nml sind die Verweise zu den anderen Dateien hinterlegt. Zu jedem Simulationslauf speichert GLM-FABM alle Ergebnisse in täglicher Auflösung in einer Ausgabedatei im netCDF-Format. Ebenfalls automatisch wird eine Datei im csv-Format erzeugt, in der mehrere gängige limnologische Parameter berechnet und bereitgestellt werden. Zusätzlich kann der Benutzer

Ergebnisserien für zu definierende Variablen gesondert für bestimme Tiefen erzeugen lassen (csv-Format).

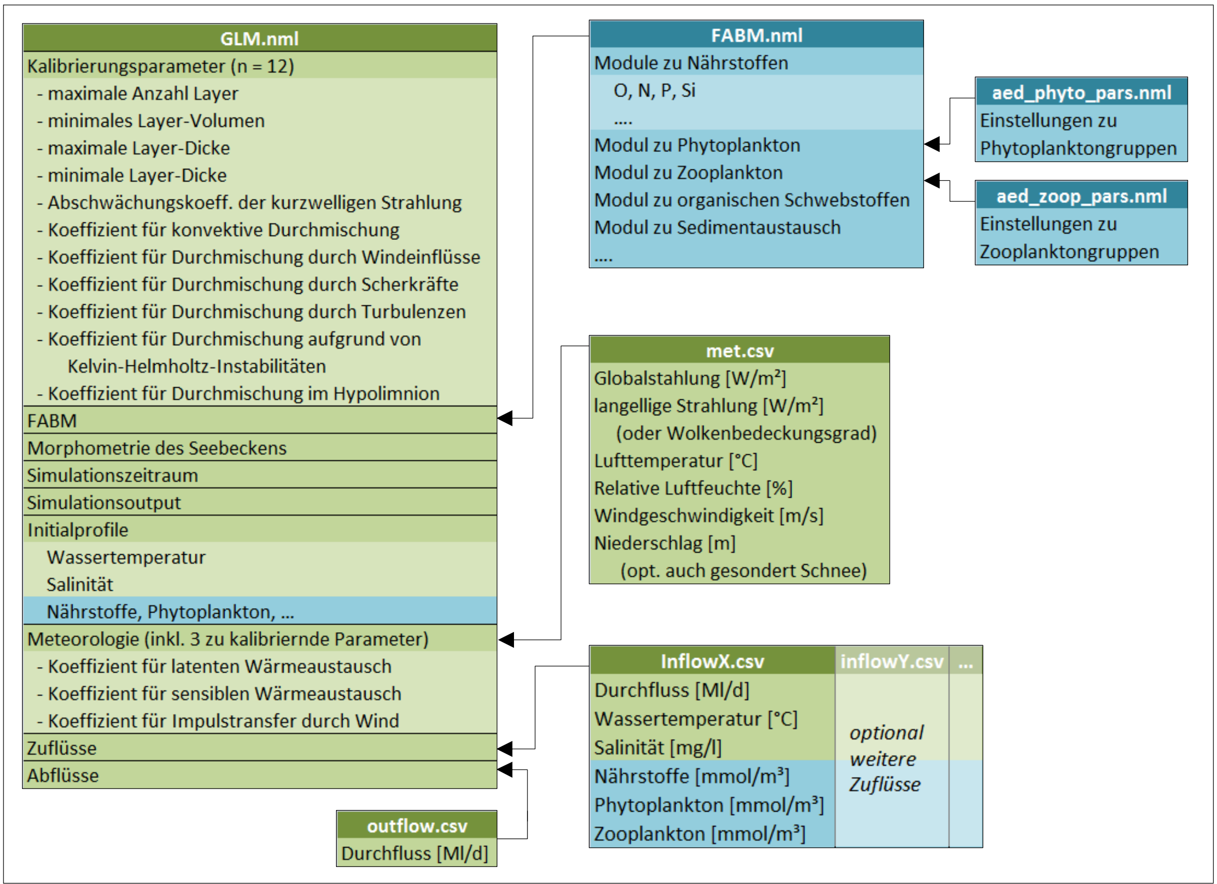


Abb. 2: Inhalte der Konfigurations- (.nml) und Input-Dateien (.csv) für GLM und FABM. Die für die Simulation mit GLM benötigten Informationen sind mit Grüntönen hinterlegt. Zusätzlich benötigte Dateien und Informationen für die Simulation mit FABM sind im Blauton markiert

3.3. Datengrundlagen und Modellkalibrierung

Die Verfügbarkeit und Aufbereitungsmethodik der verwendeten meteorologischen und hydrologischen Eingangsdaten sowie die vorhandenen limnologischen Felddaten sind ausführlich in den **Publikationen I** und **III** (Anhang A und C) dieser kumulativen Dissertation beschrieben. Die **Publikation I** enthält ebenfalls ein Kapitel zur Durchführung der Kalibrierung und Validierung von DYRESM sowie zu den in dieser Arbeit verwendeten statistischen Gütekriterien zur Abschätzung des Fehlers in den Simulationsergebnissen: RMSE (*root mean square error*), MAE (*mean absolute error*) und ME (*mean error*). Beschreibungen zum regionalen Klimamodell WettReg2010 befinden sich in **Publikation II** (Anhang B). Daher wird an dieser Stelle auf erneute Beschreibungen und Erläuterungen verzichtet und auf die Publikationen verwiesen.

Zur Simulation mit GLM-FABM konnten größtenteils die Eingangsdaten der Modellierung mit DYRESM übernommen werden. Die zusätzlich benötigten Daten zur relativen Luftfeuchte lagen ebenfalls für die meteorologischen Stationen Rothenfeld und Westerschondorf der Bayerischen Landesanstalt für Landwirtschaft in täglicher Auflösung vor. Die Lage der Stationen ist der *Figure 1* in

Publikation I (Anhang A) zu entnehmen. Als Eingangsdaten für die Simulation wurden die Werte von Rothenfeld verwendet und vorhandene Datenlücken mit Werten von Westerschondorf gefüllt. Messdaten zum Niederschlag wurden in den Eingangsdaten als Schnee definiert, wenn das Mittel der Lufttemperatur des gleichen Tages unter 1,0 °C lag, wie ebenfalls angewendet von Springer et al. (in revision).

Zur Limnochemie wurden Felddaten vom Wasserwirtschaftsamt Weilheim (WWA WM) für den Zeitraum 1985 – 2010 zur Verfügung gestellt. Die zeitliche und räumliche Auflösung ist analog zu denen der Wassertemperaturmessdaten (siehe **Publikation I,** Anhang A). Messdaten zum DO, $N\text{-}NO_3$, $Si\text{-}SiO_2$ und ***D**issolved **O**rganic **M**atter* (DOC) liegen kontinuierlich für den gesamten Simulationszeitraum vor. Die Daten zum DOC enthalten im Jahr 2006 für zwei Messtermine und für 2008 an einem Termin keine Werte. Messwerte zum $N\text{-}NH_4$ liegen in einem heterogenen Bild vor. Die Daten wurden nur in 0,01-Schritten (mg/l) aufgenommen und liegen im gesamten Zeitraum mehrheitlich unter der Bestimmungsgrenze von 0,01 mg/l. Gleiches gilt für Messdaten zum $P\text{-}PO_4$, für welches die Konzentration für über 50 % der Messungen unter der Bestimmungsgrenze von 0,005 mg/l angegeben wird.

Zur Simulation des Stoffhaushaltes des Ammersees mit GLM-FABM wurden in den Eingangsdaten zum Zufluss Informationen zu folgenden Stoffen hinzugefügt (alle in mmol/l):

- DO
- $Si\text{-}SiO_2$
- $N\text{-}NO_3$ und $N\text{-}NH_4$
- $P\text{-}PO_4$
- DOC

Die Daten wurden am Pegel Fischen (Lage siehe *Fig. 1* der **Publikation II,** Anhang B) ebenfalls vom WWA WM im zweiwöchentlichen Rhythmus erhoben. Die Werte zwischen den jeweiligen Messterminen wurden durch lineare Interpolation ermittelt. Nach Pottgiesser & Sommerhäuser (2008) sind sowohl die Ammer als auch die anderen Zuflüsse des Ammersees gemäß ihres Gewässertypes nicht planktonführend. Demnach wurden keine Werte zum Phytoplankton oder Chlorophyll-*a* für den Zufluss implementiert.

Als Simulationszeitraum zur Kalibrierung von GLM-FABM auf den Ammersee wurde die Zeitspanne 01/2004 – 10/2008 gewählt. Der Beginn liegt in einer Phase mit homothermen Verhältnissen in der Wassersäule und ist somit von den vorherigen Schichtungsbedingungen unbeeinflusst. Zusätzlich konnten die Messewerte vom 12.01.2004 zur Definition der Initialprofile verwendet werden. Die ersten Monate einer Simulation werden in der Modellierung üblicherweise als “Warmlaufphase“ angesehen (Fang & Stefan 2009; Rinke et al. 2010; Yao et al. 2014). Daher wurden die Ergebnisse des Zeitraumes 01/2004 – 10/2004 bei der Ermittlung der Gütekriterien nicht berücksichtigt. Der

Kalibrierungszeitraum wurde somit auf vier Jahre festgelegt, welcher sich gleichzeitig über vier komplette hydrologische Jahre erstreckt: 11/2004 – 10/2008. Dabei werden ebenfalls vier abgeschlossene Zirkulationszyklen abgedeckt, in welchen der Ammersee sowohl monomiktische als auch dimiktische Zirkulationsperioden aufwies.

Die Kalibrierung zu GLM-FABM wurde manuell durchgeführt. Im Vergleich zu DYRESM haben bei der Simulation mit GLM-FABM auch Änderungen in den Eingangsdaten und Parametern zum Stoffhaushalt Einfluss auf die Ergebnisse der Wassertemperatur. Daher wurde auf eine exakte Kalibrierung von GLM zur Simulation der Wassertemperaturen am Ammersee ohne FABM verzichtet. Nach der Aktivierung von FABM erfolgte die Adaption auf den Ammersee ebenfalls durch eine manuelle Anpassung der Parameter. Dies umfasste sowohl die Kalibrierungsparameter der GLM.nml (siehe Abb. 2, S. 9) als auch die spezifischen Prozessparameter zu den jeweiligen Nährstoffen in FABM.nml. Dabei konnte bei jedem Parameter auf einen voreingestellten (*default*) Wert zurückgegriffen werden. Diese Werte basieren alle auf Angaben aus der entsprechenden Basisliteratur (Hipsey et al. 2013). Zur Simulation der in Kapitel 1.3 genannten Stoffe wurden mit GLM-FABM folgende AED-Module aktiviert:

- aed_oxygen (Prozessparameter zum gelösten Sauerstoff)
- aed_silica (Prozessparameter zum Silizium)
- aed_nitrogen (Prozessparameter zum anorganischen Stickstoff)
- aed_phosphorus (Prozessparameter zum Phosphor)
- aed_organic_matter (Prozessparameter zu organischen Schwebstoffen)
- aed_carbon (Prozessparameter zu anorganischen Kohlenstoffverbindungen)
- aed_sedflux (Prozessparameter zum Austausch der gelösten Stoffe mit dem Sediment)
- aed_phytoplankton (Einstellungen zum Phytoplankton)

Die Eigenschaften des Phytoplanktons werden gesondert durch Prozessparameter in der Konfigurationsdatei aed_phyto_pars.nml (Abb. 2, S. 9) beschrieben. Die Parameter wurden auf Basis der Eigenschaften der dominierenden Phytoplankton-Gruppen im Ammersee während des Simulationszeitraums gesetzt: Diatomeen, Dinophyceae und Cyanobakterien. Hierzu konnte auf die *Default*-Werte für die jeweiligen Gruppen zurückgegriffen werden. Das Zooplankton wurde in den Simulationen nicht berücksichtigt.

4. Methoden, Ergebnisse und Diskussion

Der wesentliche Anteil der im Dissertationsvorhaben angewandten Methoden und erzielten Ergebnisse sowie deren Diskussion wurde in drei wissenschaftlichen Publikationen in internationalen Fachzeitschriften (in Erstautorenschaft, peer-reviewed) veröffentlicht.

In **Publikation I** (Anhang A) werden die Ergebnisse zur Kalibrierung und Validierung von DYRESM auf den Ammersee vorgestellt. Des Weiteren wird eine Sensitivitätsanalyse der Simulationsergebnisse des kalibrierten Modells hinsichtlich Änderungen in den meteorologischen Variablen sowie der Temperatur des Zuflusses vorgenommen und präsentiert.
In **Publikation II** (Anhang B) wird auf Basis des kalibrierten Modells DYRESM die zukünftige Verteilung (2042 - 2050) der Wassertemperaturen im Ammersee simuliert. Als meteorologische Eingangswerte werden Daten des regionalen Klimamodells WettReg2010 verwendet. Anhand der Simulationsergebnisse werden Änderungen im räumlichen und zeitlichen Auftreten der sommerlichen Temperaturschichtung zwischen der Vergangenheit und der Zukunft abgeleitet.
Publikation III (Anhang C) untersucht die Auswirkungen der Berücksichtigung von angenommenen, unterirdischen Zuflüssen auf die Simulationsergebnisse mit DYRESM am Ammersee und leitet daraus mögliche Rahmenbedingungen für die Grundwasserzuströme im Untersuchungsgebiet ab.
Die Ergebnisse zu den 3 Publikationen werden in den jeweiligen Kapiteln 4.1, 4.2 und 4.3 knapp zusammengefasst. Für detaillierte Informationen wird auf die jeweilige Publikation im Anhang verwiesen. Die noch nicht veröffentlichten Methoden und Ergebnisse zur Simulation mit GLM-FABM werden im Kap. 4.4 vorgestellt.

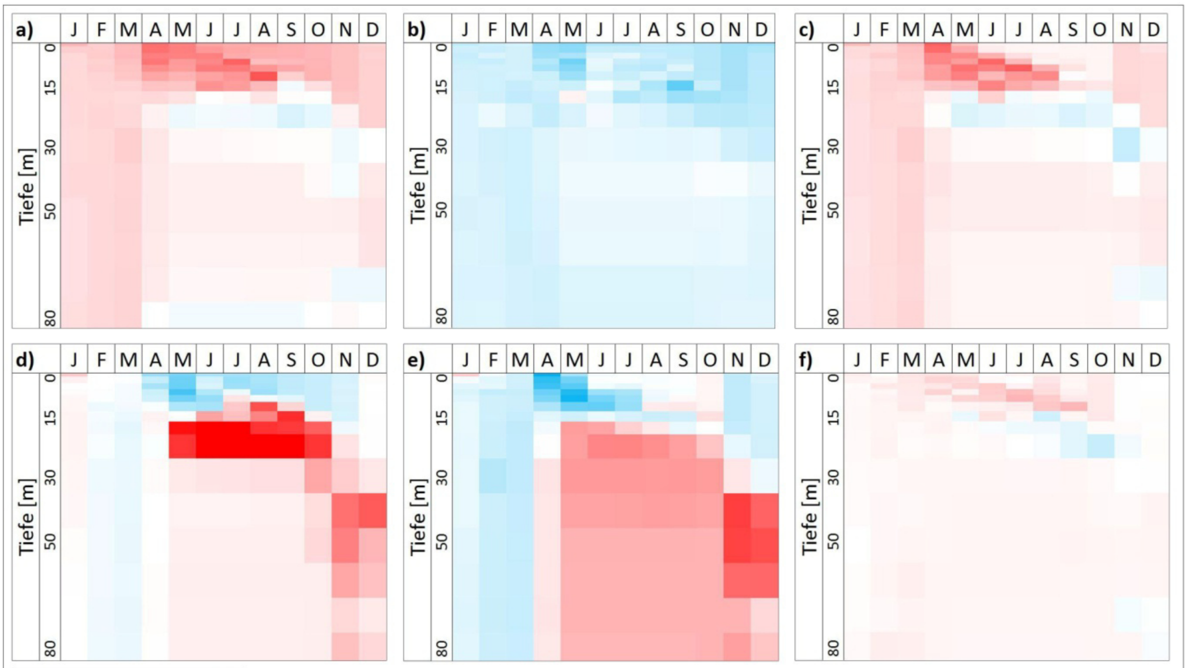
4.1. Kalibrierung und Validierung von DYRESM und Sensitivitätsanalyse der Simulationsergebnisse hinsichtlich Veränderungen in meteorologischen Variablen (Publikation I)

Anhang A: Bueche T., Vetter M. (2014): Simulating water temperatures and stratification of a pre-alpine lake with a hydrodynamic model: calibration and sensitivity analysis of climatic input parameters. ***Hydrological Processes****, 28(3): S. 1450-1464.*

In Rahmen dieser Studie wurde das hydrodynamische Modell DYRESM für den Ammersee kalibriert (2002 – 2007) und validiert (2008 – 2011). Für die Simulationsergebnisse zur Wassertemperatur ergeben sich für die Kalibrierung folgende Gesamtfehlerwerte: RMSE: 1,01 K, MAE: 0,80 K, ME: -0,23 K (siehe auch *Table V* in **Publikation I,** Anhang A). Die Simulation unterschätzt die Wassertemperaturen leicht in den oberflächennahen Schichten (0 bis 6 m Tiefe) mit einem minimalen ME von -0,03 K. Im Hypolimnion (20 m Tiefe bis Grund) werden die Wassertemperaturen ebenfalls zu niedrig simuliert (minimaler ME-Wert von -0,54 K). Für das Metalimnion ergibt sich eine Überschätzung (maximaler ME bei 8 m Tiefe von 0,40 K). Die höchsten RMSE-Werte mit 1,79 K ergeben sich ebenfalls im Metalimnion für die Tiefe von 13 m. Für die Validierung des Modells zeigt sich durch fast ausschließlich negative ME-Werte in der Wassersäule eine generelle Unterschätzung der Wassertemperaturen, jedoch liegen die Gesamtwerte des RMSE und des MAE unter denen der Kalibrierung. Die Fehlerwerte für die Simulation am Ammersee liegen in vergleichbaren Größenordnungen mit Kalibrierungsstudien zu anderen Seen (Burger et al. 2008; Trolle et al. 2008a;

Trolle et al. 2008b; Perroud et al. 2009) und bescheinigen eine erfolgreiche Anpassung des Modells auf den Ammersee.

Die Sensitivität des Modells gegenüber Veränderungen in meteorologischen Variablen sowie der Temperatur des Zuflusses wurde anhand separater Simulationsläufe mit Modifikationen in jeweils nur einer der Variablen untersucht. Für jede Variable wurden zudem unterschiedliche Modifikationen vorgenommen. Die Ergebnisse dieser Analyse zeigen, dass die Modellierung mit DYRESM am Ammersee für Veränderungen unterschiedlich sensitiv ist. Der Grad der Sensitivität lässt sich aus den Abweichungen in den Simulationsergebnissen ableiten. Die höchste Sensitivität lässt sich für die Variablen Lufttemperatur und Windgeschwindigkeit feststellen. In Abb. 3 sind die induzierten Veränderungen in den simulierten Wassertemperaturen für eine Auswahl an Modifikationen visualisiert. Ihr ist zu entnehmen, dass auch Modifikationen einer Variable in nur einer Jahreszeit, hier im Winter (c), f)), Veränderungen in den Simulationsergebnissen hervorrufen. Des Weiteren wird gezeigt, dass Änderungen in der Temperatur des Zuflusses Abweichungen in den Modellierungsergebnissen bewirken. Dies zeigt, dass ein sich änderndes Klima auch indirekt über die Zuflüsse Einfluss auf die thermischen Bedingungen des Sees hat. Die Ergebnisse der Sensitivitätsanalyse bestätigen, dass potentielle Auswirkungen des Klimawandels auf die Wassertemperaturen des Ammersees durch die Simulation mit DYRESM abgebildet werden können.



a) Lufttemperatur +0,5 °C; b) Lufttemperatur: -0,5 °C; c) Lufttemperatur: Winter (Nov-Apr): +0,5°C / Sommer (Mai-Okt): keine Veränderung; d) Windgeschwindigkeit: ×1,1; e) Windgeschwindigkeit: Winter (Nov-Apr): ×1,2 / Sommer (Mai-Okt): keine Veränderung; f) Zuflusstemperatur: +0.5°C

Abb. 3: Durch Modifizierung von meteorologischen Eingangsvariablen sowie der Temperatur des Zuflusses bewirkte Veränderungen in der simulierten Wassertemperatur [K] mit DYRESM.

4.2. Simulierung zukünftiger Wassertemperaturen und Schichtungsbedingungen mit DYRESM unter der Verwendung von Daten des regionalen Klimamodells WettReg2010 (Publikation II)

Angang B: BUECHE T., VETTER M. (2015): Future alterations of thermal characteristics in a medium-sized lake simulated by coupling a regional climate model with a lake model. ***Climate Dynamics,*** *44(1-2): 371-384.*

Zur Modellierung zukünftiger Veränderungen der Wassertemperaturen im Wasserkörper des Ammersees wurden meteorologische Daten des regionalen Klimamodells WettReg2010 verwendet. Die Simulationen wurden mit dem kalibrierten und validierten Modell DYRESM (siehe Publikation I, Anhang A) durchgeführt. Die WettReg2010-Daten liegen für den Zeitraum 1961 – 2100 vor. Dies ermöglicht vergleichende Simulationen für Verhältnisse in der Vergangenheit und der Zukunft, da für beide Zeiträume die meteorologischen Eingangsdaten auf der gleichen Basis ermittelt wurden. Die Simulationen wurden für die Zeiträume 2002 – 2010 und 2042 – 2050 mit WettReg2010-Daten für das IPCC-Emissionsszenario A1B durchgeführt. Das Szenario beschreibt eine zukünftige Welt mit raschem Wirtschaftswachstum, mit einer ab der Mitte des 21. Jahrhunderts rückläufigen Weltbevölkerung und einer einhergehenden Verringerung der regionalen Unterschiede im Pro-Kopf-Einkommen. Dabei wird die rasche Einführung von neuen und effizienten Technologien und eine ausgeglichene Nutzung aller verfügbaren Energiequellen angenommen (Nakicenovic et al. 2000; Solomon et al. 2007). Für jedes Szenario werden 10 WettReg2010-Datenreihen bereitgestellt, die sogenannten Realisationen. Diese sind alle gleich wahrscheinlich und spiegeln die mögliche Variabilität in den projizierten Daten wieder (Huebener et al. 2011; Kreienkamp et al. 2011). Für jede Realisation wurde in dieser Arbeit ein separater Simulationslauf mit DYRESM durchgeführt.

In Abb. 4 (S. 15) sind die Abweichungen zwischen den Simulationsergebnissen zur Vergangenheit und Zukunft visualisiert. Sie zeigt, dass während der sommerlichen Schichtung für das Epilimnion eine Erwärmung von durchschnittlich 1,49 K bis maximal 2,88 K simuliert wird. Während des Winters und den Zirkulationsphasen (Mitte Dezember bis Mitte April) wird ein leichter Anstieg der Wassertemperaturen im gesamten Wasserkörper modelliert (im Mittel 0,50 K; max. 1,62 K). Die Temperaturen im Hypolimnion während der Sommerstagnation zeigen hingegen eine leichte Abkühlung von durchschnittlich 0,09 K und maximal 0,63 K.

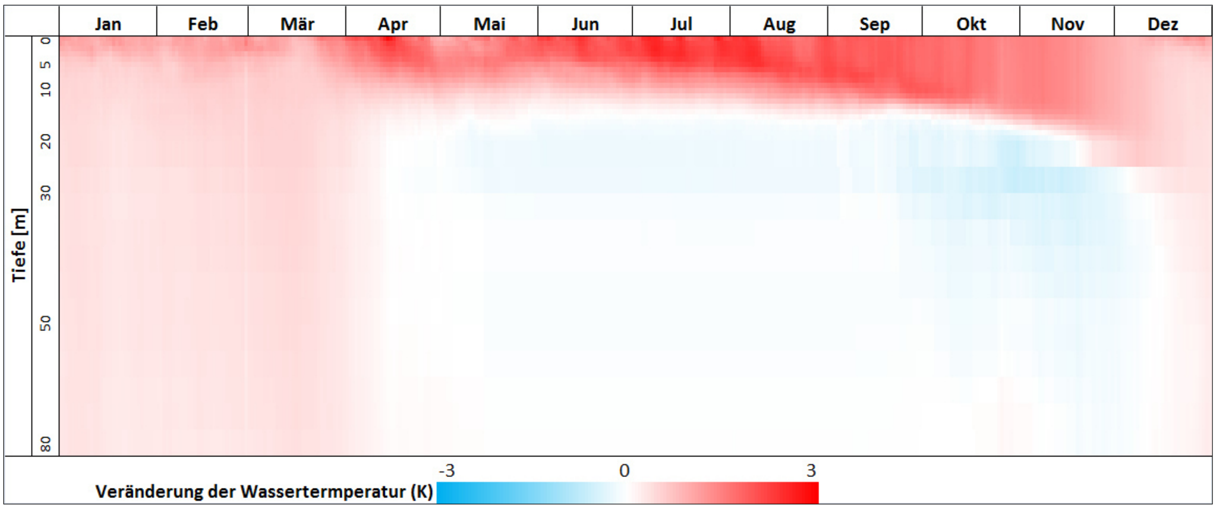


Abb. 4: Abweichung der Wassertemperaturen zwischen den Simulationsergebnissen auf Basis von WettReg2010-Daten zur Vergangenheit (2002 – 2010) und der Zukunft (2042 – 2050). Für beide Zeiträume wurden die Simulationsergebnisse für alle Realisationsläufe gemittelt.

Diese Entwicklung ist durch die frühere Ausbildung der Schichtung zu erklären (Stefan et al. 1993), welche den Transport von an der Seeoberfläche erwärmten Wasser in tiefer gelegenere Schichten frühzeitig unterbindet. Es kann angenommen werden, dass dieser Prozess durch den höheren vertikalen Gradienten der Wassertemperaturen und der damit verbundenden höheren Schichtungsstabilität verstärkt wird. Dieser Effekt kann auch durch die zukünftig über den Winter gespeicherten höheren Temperaturen („carry-over"; Peeters et al. 2002) nicht abgefangen werden.

Aus den Simulationsergebnissen zur Wassertemperatur wurde die Dauer der sommerlichen Schichtung sowie der Jahresgang der Mächtigkeit des Metalimnions und der Tiefe der Thermokline (Tiefe des größten Temperaturgradienten im vertikalen Profil) abgeleitet. Für die Schichtungsdauer ergibt sich für die Zukunft im Vergleich zur Vergangenheit im Mittel eine Verlängerung von 22 Tagen. Diese setzt sich aus einem früheren Schichtungsbeginn im Jahr (13 Tage im Mittel) und einer späteren Auflösung (9 Tage im Mittel) der Schichtung zusammen. Die Wahrscheinlichkeits-dichtefunktionen für die simulierten Zeitpunkte des Einsetzens und Auflösens der Schichtung (Tag im Jahr) und die daraus abgeleiteten Boxplot-Diagramme sind in Abb. 5 (S. 16) visualisiert. Die Mediane der jeweiligen Datenreihen sind als dickere Linien innerhalb der Boxen dargestellt. Sie liegen für die Zeitreihen der Zukunft nicht im Bereich des jeweiligen IQR (*innerquartile range*, repräsentiert durch die Grenzen der Boxen) für die Werte der Vergangenheit. Gleiches gilt umgekehrt für die Mediane der Zeitreihen der Vergangenheit im Bezug auf die IQR der Zukunft. Anhand dieser Tatsache lässt sich die deutliche Verlagerung der beiden Ereignisse (Beginn sowie Auflösung der geschichteten Verhältnisse im See) erkennen. Die zeitliche Verlagerung der jeweiligen Maxima in der relativen Häufigkeitsdichte und deren Anstieg um etwa 20 % von 0,04 auf 0,05 bekräftigt diese Erkenntnis.

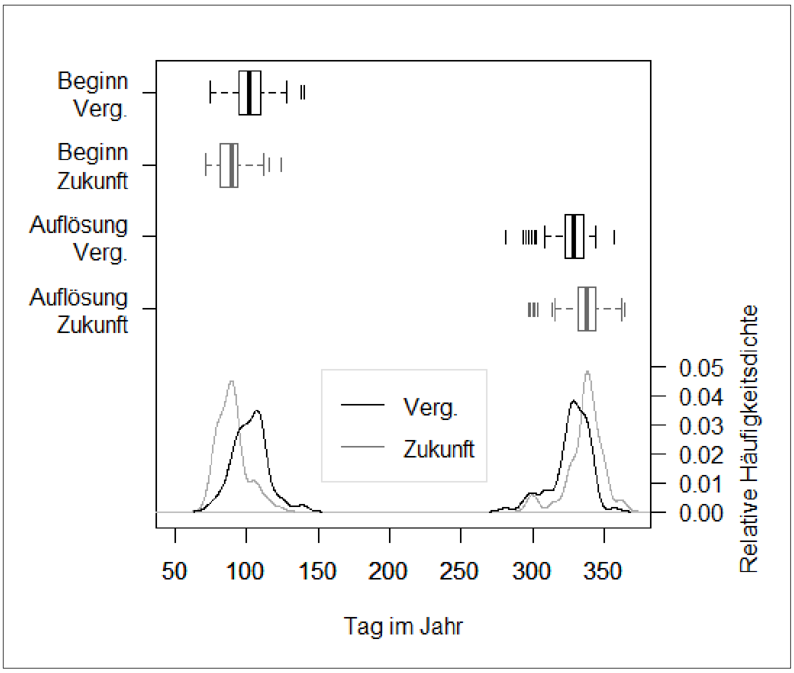


Abb. 5: Wahrscheinlichkeitsdichtefunktionen (*probability density functions*) und Boxplot-Diagramme für die simulierten Daten zum Beginn und Auflösen der Temperaturschichtung in der Wassersäule unter der Verwendung von WettReg2010-Daten. Die Striche außerhalb der Antennen geben Ausreißer außerhalb des 1,5-fachen IQR (*interquartile range*) an.

(verändert nach Bueche & Vetter 2015, Publikation II)

Die Lage des Metalimnions im vertikalen Profil und dessen Mächtigkeit sowie die Tiefe der Thermokline sind den Modellierungsergebnissen nach geringer Veränderung unterworfen. Es wurden jeweils Veränderungen bzw. vertikale Verlagerungen zwischen Vergangenheit und Zukunft von maximal einem Meter ermittelt.

4.3. Der Einfluss von unterirdischen Zuflüssen auf die Simulation der Wassertemperaturen mit DYRESM (Publikation III)

Anhang C: BUECHE T., VETTER M. (2014): Influence of groundwater inflow on water temperature simulations of Lake Ammersee using a one-dimensional hydrodynamic lake model. ***Erdkunde****, 68(1): S. 19-31.*

Simulationen der Wassertemperaturen mit DYRESM wurden bisher, sowohl in dieser Arbeit (**Publikation I** & **II,** s. Anhang A und B) als auch für andere natürliche Seen (z. B. Gal et al. 2003; Tanentzap et al. 2007; Mooij et al. 2010; Bayer et al. 2013), ohne die Berücksichtigung von unterirdischen Zuflüssen durchgeführt. Daher wurde im Rahmen dieser Studie der Einfluss der Implementierung unterirdischer Zuflüsse auf die Simulation mit DYRESM untersucht.

Im Rahmen einer Wasserhaushaltsanalyse wurde das Volumen der unbekannten Zuflüsse zum Ammersee empirisch ermittelt (siehe **Publikation I,** Anhang A). Es kann angenommen werden, dass ein Anteil dieses Volumens dem See unterirdisch zufließt. Zur Abbildung der unbekannten Bedingungen der Grundwasserzuströme im Untersuchungsgebiet wurden verschiedene Szenarien (n = 36) für die Variablen Tiefe, Volumen (als Anteil des unbekannten Zuflusses) und Salinität der unterirdischen Zuströme zum Ammersee erstellt. Die Temperatur der unterirdischen Zuflüsse kann aus der Jahresdurchschnittstemperatur abgeleitet werden (Boehrer & Schultze 2008) und wurde für alle Szenarien gleich mit konstant 8,65 °C angesetzt.

Für jedes Szenario wurden die Wassertemperaturen mit DYRESM erneut simuliert und die Differenzen zu den Felddaten ermittelt. Diese Differenzen wurden anschließend mit den Abweichungen der Simulationsergebnisse der Modellkalibrierung verglichen, in der das gesamte Zuflussvolumen als oberirdisch angenommen wird. Durch eine Verbesserung der Abbildung der gemessenen Temperaturverhältnisse durch das Modell kann somit von einer Annäherung an die herrschenden hydrogeologischen Verhältnisse ausgegangen werden.

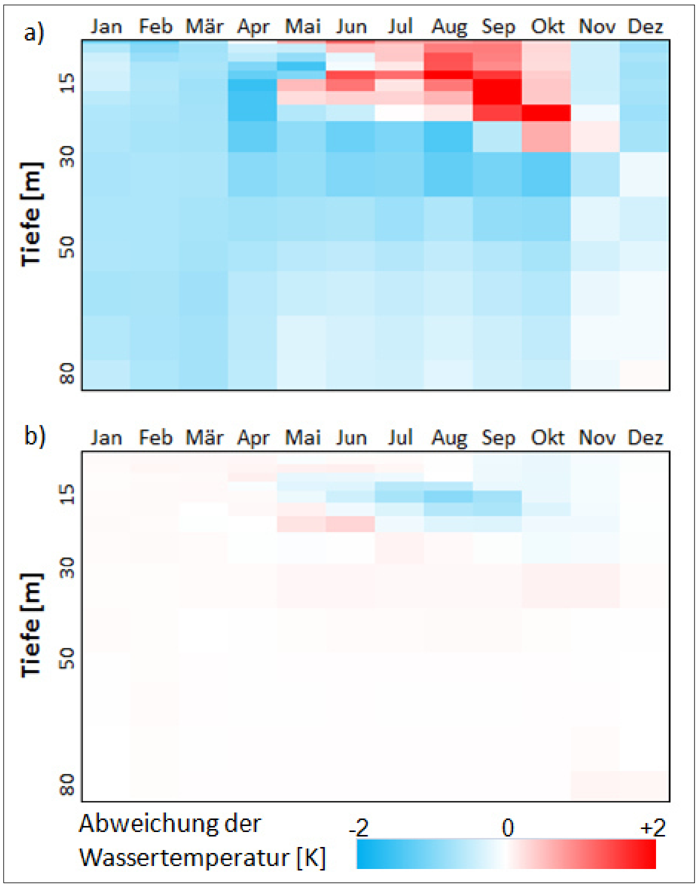


Abb. 6: a) mittlere Abweichungen der simulierten Wassertemperaturen [K] im Monat von den Felddaten für das Ergebnis der Kalibrierung und b) die durch Anwendung der abgeänderten Einstellungen zum Zufluss gemäß dem Szenario 4.7 induzierten Abweichungen

(verändert nach Bueche & Vetter 2014a, Publikation III)

Die größten Verbesserungen der Simulationsergebnisse gegenüber der Kalibrierung konnten für folgende Zuflussbedingungen (Szenario 4.7, siehe *Table 1* in **Publikation III**, Anhang C) erzielt werden: 6 m Tiefe, konstante Salinität von 0,233 (entspricht dem Durchschnitt des oberirdischen Zuflusses im Simulationszeitraum) und 70 % des Volumens der unbekannten Zuflüsse. In Abb. 6 ist die räumlich und zeitliche Verteilung der Abweichungen der simulierten Wassertemperaturen für das kalibrierte

Modell und die durch die Berücksichtigung der unterirdischen Zuströme (Eigenschaften gemäß Szenario 4.7) in der Simulation induzierten Veränderungen visualisiert. Es ist zu erkennen, dass für die Bereiche mit den größten Differenzen durch die Anwendung des Szenarios eine Reduktion der Fehler bewirkt wird und somit die Ausprägungen der Fehler abgeschwächt werden. Hier sind vor allem die positiven Abweichungen im Metalimnion (bei ca. 15 m Tiefe) während den Sommer- und Herbstmonaten sowie die einheitlich negativen Abweichungen der Kalibrierung während des Winters und im sommerlichen Hypolimnion zu nennen. Insgesamt wird der RMSE zwar nur um 0,04 K vermindert, die Abnahme ergibt sich jedoch durch eine Reduktion des Fehlers in nahezu jeder einzelnen Tiefenschicht. Durch diese Untersuchung konnte bestätigt werden, dass DYRESM zur Simulation von Seewassertemperaturen verwendet werden kann, wenn unterirdische Zuflüsse bei der Modellierung berücksichtigt werden. Durch die Implementierung war es gleichzeitig möglich, die Charakteristik der Grundwasserzuströme zum Ammersee abzuschätzen.

4.4. Simulationen mit GLM-FABM

In diesem Kapitel werden die Ergebnisse zur manuellen Kalibrierung des ökologischen Seemodells GLM-FABM für den Ammersee vorgestellt. Ziel dieser Untersuchung ist die Abbildung der raum-zeitlichen Verteilung der Wassertemperatur sowie der Konzentrationen von DO, N-NO_3, N-NH_4, Si-SiO_2 und P-PO_4 in den Simulationsergebnissen.

4.4.1. Simulation der Wassertemperaturen

Nach der manuellen Kalibrierung des Modells werden in den simulierten Ergebnissen zur Wassertemperatur (Abb. 7, S. 19) alle Phasen des Wärmehaushaltsjahres eines dimiktischen Sees (sommerliche Schichtung, Homothermie und inverse Schichtung) abgebildet. Die größten Abweichungen von den gemessenen Werten werden während der Sommerstagnation für das Metalimnion simuliert. Dabei sind die Ausprägungen dieser Abweichungen von Jahr zu Jahr unterschiedlich. 2005 sind die Temperaturen vornehmlich zu niedrig (< -2,0 K), wohingegen 2006 und 2008 zu hohe Werte (> 2,0 K) für diesen Tiefenbereich simuliert werden.

Diese Heterogenität wird auch durch die erhöhten RMSE-Werte von über 1,75 K bis maximal 2,02 K im metalimnischen Bereich (8 – 16 m, siehe Tab. 1, S. 20) wiedergegeben. Diese sind im Vergleich zu den RMSE-Werten in diesem Bereich für die Simulationen mit dem kalibrierten Modell DYRESM um mehrere Zehntelgrad höher. Die Gesamtfehlerwerte (Tab. 1, S. 20) liegen für alle drei Gütemaße unter denen der Kalibrierung von DYRESM (siehe **Publikation I,** Anhang A). Die maximalen Fehler (RMSE), gemittelt für jeden Monat und differenziert nach der jeweiligen Tiefe, liegen im Mai bei 16 m Tiefe (3,73 K) und im September in einer Tiefe von 10 m (3,70 K). Diese befinden sich in einer vergleichbaren Größenordnung wie die entsprechenden maximalen RMSE-Werte für die Kalibrierung von DYRESM (3,63 K in 13 m Tiefe, **Publikation I**, Anhang A).

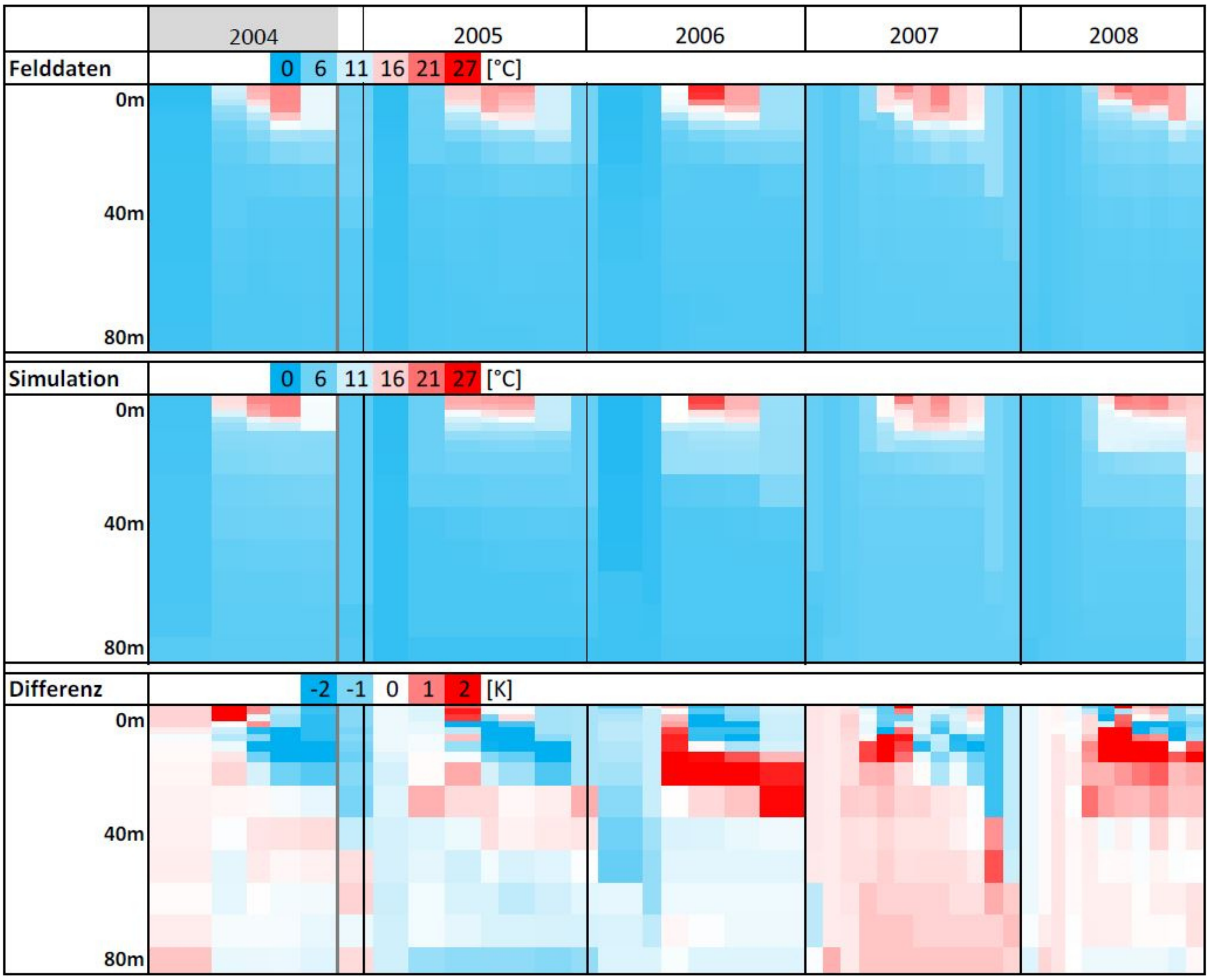


Abb. 7: Gemessene (oben) und mit GLM-FABM simulierte (mitte) Wassertemperaturen und deren Differenz (unten) für den Zeitraum 2004 - 10/2008. Ergebnisse in der grau hinterlegten Zeitspanne im Jahr 2004 wurden nicht zur Berechnung der Gütekriterien einbezogen.

Die im Vergleich zur Kalibrierung von DYRESM niedrigeren Gesamtfehlerwerte der Kalibrierung für GLM-FABM lassen sich auf geringere Abweichungen im Hypolimnion zurückführen (z. B. RMSE < 0,50 K für die Tiefe 40 m – Grund; siehe Tab. 1, S. 20). Dieser Tiefenbereich repräsentiert einen größeren Anteil (36,6 %) am Volumen des Sees als der metalimnische Bereich (20,5 %). Daher ergeben sich trotz höherer RMSE-Werte von bis zu 0,60 K für sechs einzelne Tiefen (4 – 13 m) geringere Gesamtfehlerwerte. Die Abweichungen der simulierten Wassertemperaturen zu den Felddaten befinden sich für beide Modelle, GLM-FABM und DYRESM, nach der jeweiligen Kalibrierung in den gleichen Größenordnungen. Dies gilt sowohl für die Gesamtabweichungen und -fehlerwerte als auch für die maximalen Fehler für monatliche Mittel der einzelnen Tiefen. Demnach kann festgestellt werden, dass das GLM-FABM zur Simulation der limnologischen Verhältnisse und zur Abbildung der Wassertemperaturen am Ammersee verwendet werden kann. Dabei zeigt die Anpassung von GLM-FABM eine bessere Übereinstimmung der Simulationsergebnisse mit den Felddaten als in der Modellierungsstudie von Read et al. (2014), welche für Modellierungen an 434 Seen mit GLM (ohne FABM) einen Gesamt-RMSE von 2,78 K angeben. Dieser Wert wird durch die erfolgte Kalibrierung des Modells am Ammersee um über ein K unterschritten, obwohl in dieser Arbeit durch die Aktivierung von FABM komplexere ökologische Prozesse mit Einfluss auf die Wassertemperaturen in der Simulation berücksichtigt wurden als bei der Anwendung von GLM ohne FABM.

Tab. 1: Vergleich der RMSE-, MAE- und ME-Werte für die Simulation der Wassertemperaturen mit GLM-FABM und DYRESM. Die Gesamtwerte repräsentieren das volumengewichtete Mittel der gesamten Wassersäule

(Werte für DYRESM nach Bueche & Vetter (2014b), Publikation I)

	GLM-FABM			DYRESM		
Tiefe [m]	RMSE	MAE alle [K]	ME	RMSE	MAE alle [K]	ME
0	0,86	0,65	-0,19	1,14	0,95	0,01
2	0,72	0,54	-0,27	1,00	0,84	-0,03
4	0,92	0,65	-0,32	0,89	0,74	-0,02
6	1,53	1,00	-0,83	1,07	0,85	-0,02
8	1,77	1,15	-0,71	1,53	1,07	0,41
10	2,02	1,34	-0,38	1,40	1,05	0,40
13	1,91	1,35	0,11	1,79	1,20	0,29
16	1,97	1,36	0,65	1,42	0,97	0,10
20	1,04	0,75	0,27	1,13	0,85	-0,55
30	0,61	0,45	0,23	0,99	0,86	-0,63
40	0,28	0,22	0,03	0,78	0,67	-0,44
50	0,32	0,27	-0,12	0,66	0,58	-0,37
60	0,31	0,26	0,03	0,64	0,57	-0,29
70	0,28	0,23	0,05	0,61	0,53	-0,22
80	0,45	0,37	-0,06	0,62	0,53	-0,17
gesamt	**0,89**	**0,63**	**-0,01**	**1,01**	**0,80**	**-0,23**

4.4.2. Simulation gelöster Stoffe

Die Simulationsergebnisse zum Sauerstoffgehalt und deren Abweichungen zu den gemessenen Felddaten sind in Abb. 8 (S. 21) visualisiert. Die simulierten DO-Konzentrationen weisen einen Jahresgang auf, welcher vergleichbar zu dem in den Felddaten ist. In den simulierten Daten ist dieser Jahresgang durch eine Abnahme des Sauerstoffgehaltes während der sommerlichen Schichtung gekennzeichnet (z. B. eine Abnahme von 2,8 mg/l im Verlauf des Jahres 2005, gemittelt über die gesamte Wassersäule). Das in den gemessenen Daten besonders ausgeprägten Konzentrations-Minimum im Herbst im Tiefenbereich des Metalimnions (ca. 15 m Tiefe; Sep. 2006: 7,5 mg/l; Okt. 2007: 6,2 mg/l) wird jedoch nicht abgebildet. Die Zehrung am Grund bis zu Konzentrationen unter 5,0 mg/l wird in den Simulationsergebnissen zwar durch die geringsten Werte im jeweiligen gesamten vertikalen Profil wiedergegeben, ist aber in der Simulation schwächer ausgeprägt als in den Felddaten. Die maximalen RMSE-Werte für die Simulation ergeben demnach sich jeweils gegen Ende der Jahre am Grund (3,6 mg/l im Dezember) und in 16 m Tiefe (3,1 mg/l im Oktober). Im Winter (Januar – März) liegen die Werte niedriger bei 0,5 – 0,7 mg/l. Für den Gesamt-RMSE wurde der Wert

1,2 mg/l ermittelt. In den Simulationsergebnissen ist eine generelle Zunahme der DO-Konzentrationen über den Simulationszeitraum hinweg zu erkennen. Diese Tendenz ist in den Felddaten nicht festzustellen und zeigt sich in negativen Differenzwerten (rot) zu Beginn und positiven (blau) zum Ende des Simulationszeitraums (Abb. 8, unten).

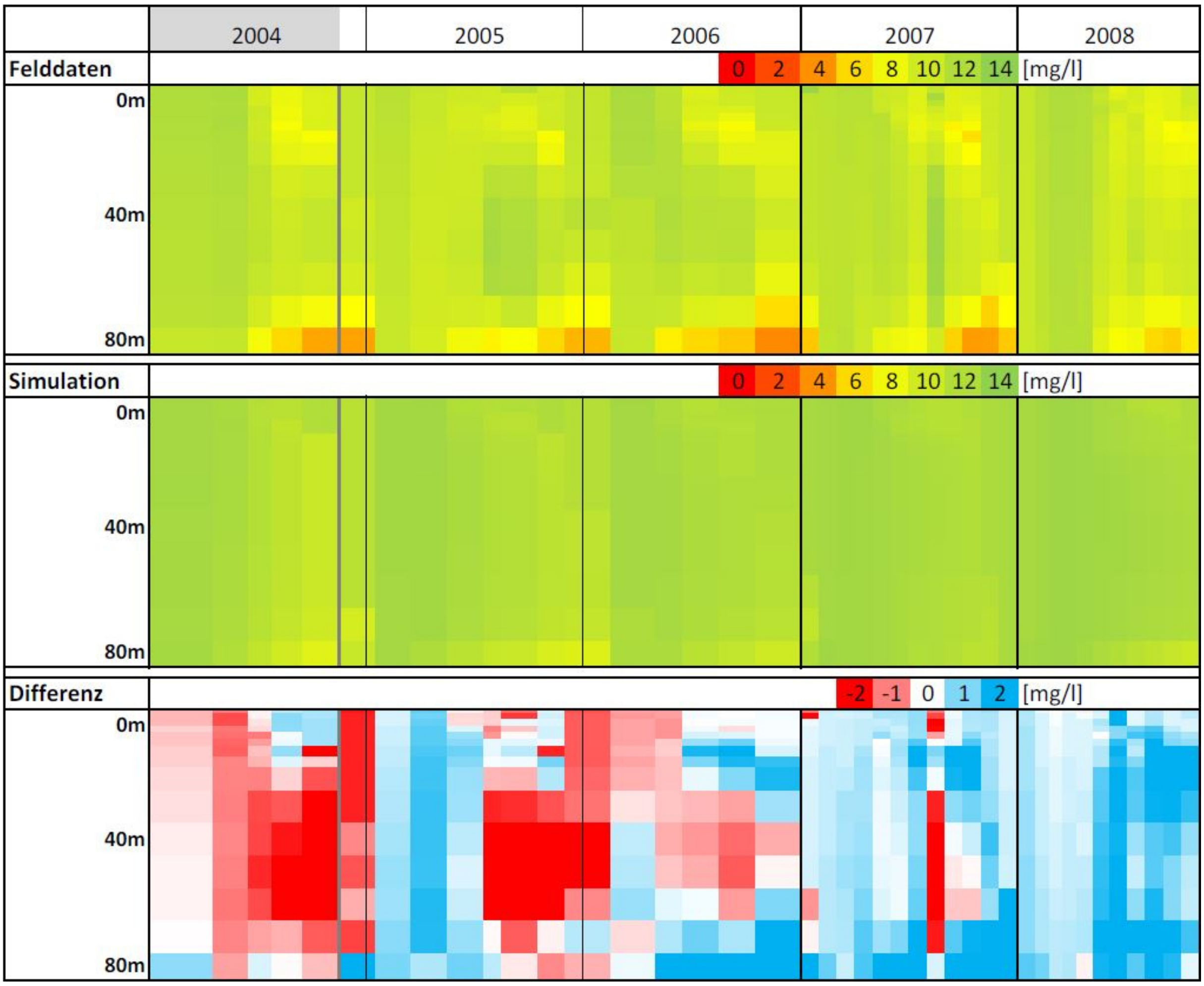


Abb. 8: Gemessene (oben) und mit GLM-FABM simulierte (mitte) Konzentrationen zum gelösten Sauerstoff und deren Differenz (unten) für den Zeitraum 2004 - 10/2008. Ergebnisse in der grau hinterlegten Zeitspanne im Jahr 2004 wurden nicht zur Berechnung der Gütekriterien einbezogen.

Die Ergebnisse zum N-NO_3 (Abb. 9, S. 22), zum N-NH_4 (nicht dargestellt, Beschreibung zu Datenlage siehe Kap. 3.3), zum Si-SiO_2 (Abb. 10, S. 23) und zum DOC (nicht dargestellt, Beschreibung zu Datenlage siehe Kap. 3.3) weisen einen Abnahmetrend der Konzentrationen über den gesamten Simulationszeitraum hinweg auf. Diese Tendenz ist den Felddaten für alle vier Stoffe nicht zu entnehmen. Die gemessenen N-NO_3-Werte zeigen einen ausgeprägten Jahresgang mit niedrigen Konzentrationen (< 1,0 mg/l) im Epilimnion (0 – 10 m) während der sommerlichen Schichtung. Den simulierten Konzentrationen ist dieser Jahresgang ebenfalls zu entnehmen, jedoch in geringerer Ausprägung als in den Felddaten. Dies resultiert in positiven Differenzwerten im Epilimnion in jedem Sommer des Simulationszeitraums. Vergleichbar zum N-NO_3 weist das Si-SiO_2 einen ausgeprägten Jahresgang in den gemessenen Daten auf (Abb. 10, S. 23). Dieser lässt sich auf eine Zehrung im

Epilimnion während der sommerlichen Schichtung bis zu Werten unter 1,0 mg/l sowie auf hohe Konzentrationen bis über 6,0 mg/l während des gleichen Zeitraums über dem Grund des Sees zurückführen. In den simulierten Daten ist dieser Jahresgang zwar ebenfalls abgebildet, jedoch sind die beschriebenen Phänomene weitaus weniger stark ausgebildet, was sich in Differenzwerten über 1,0 mg/l und unter -1,0 mg/l niederschlägt.

Die simulierte Verteilung des P-PO_4 (Abb. 11, S. 23) weist, wie die des N-NO_3 und des Si-SiO_2, einen Jahresgang mit niedrigen Konzentrationen (< 0,0025 mg/l) im Epilimnion während der Sommerstagnation und hohen Konzentrationen (> 0,006 mg/l) über dem Grund zwischen den Durchmischungsphasen auf. Ebenfalls ist ein Trend mit zunehmenden Konzentrationen im Profil über den gesamten Simulationszeitraum hinweg festzustellen. Ein Vergleich mit den Werten der Studie von Lenhart (1987) bescheinigt generell eine gute Übereinstimmung in den Konzentrationen und deren räumlichen und zeitlichen Muster. Ein Abgleich mit den Felddaten für den Simulationszeitraum ist aufgrund der inkonsistenten Datenlage (siehe Kap. 3.3) nicht möglich. Somit kann der Trend in den simulierten Daten nicht bewertet werden.

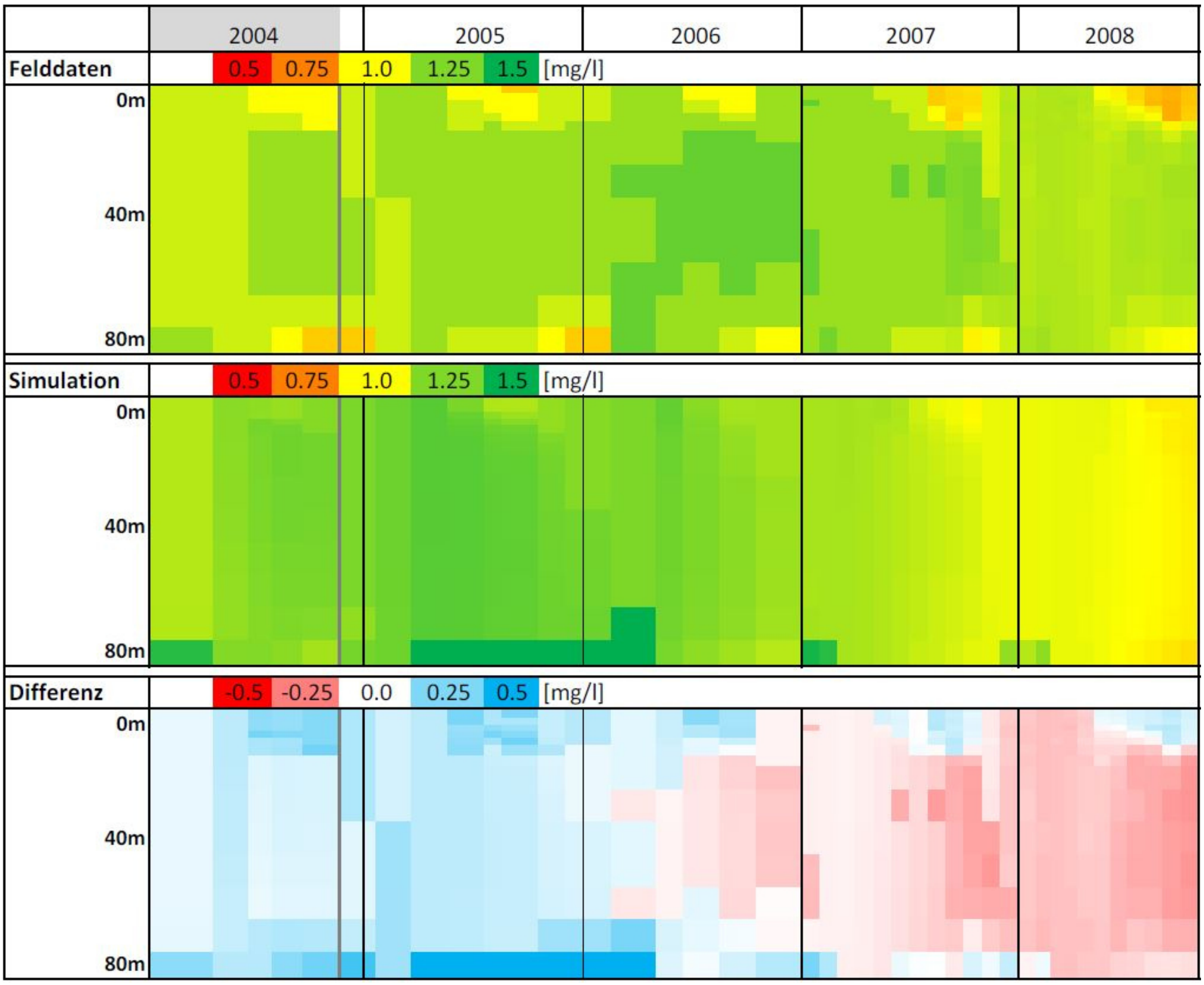


Abb. 9: Gemessene (oben) und mit GLM-FABM simulierte (mitte) Konzentrationen zum Nitrat-Stickstoff (N-NO_3) und deren Differenz (unten) für den Zeitraum 2004 - 10/2008. Ergebnisse in der grau hinterlegten Zeitspanne im Jahr 2004 wurden nicht zur Berechnung der Gütekriterien einbezogen.

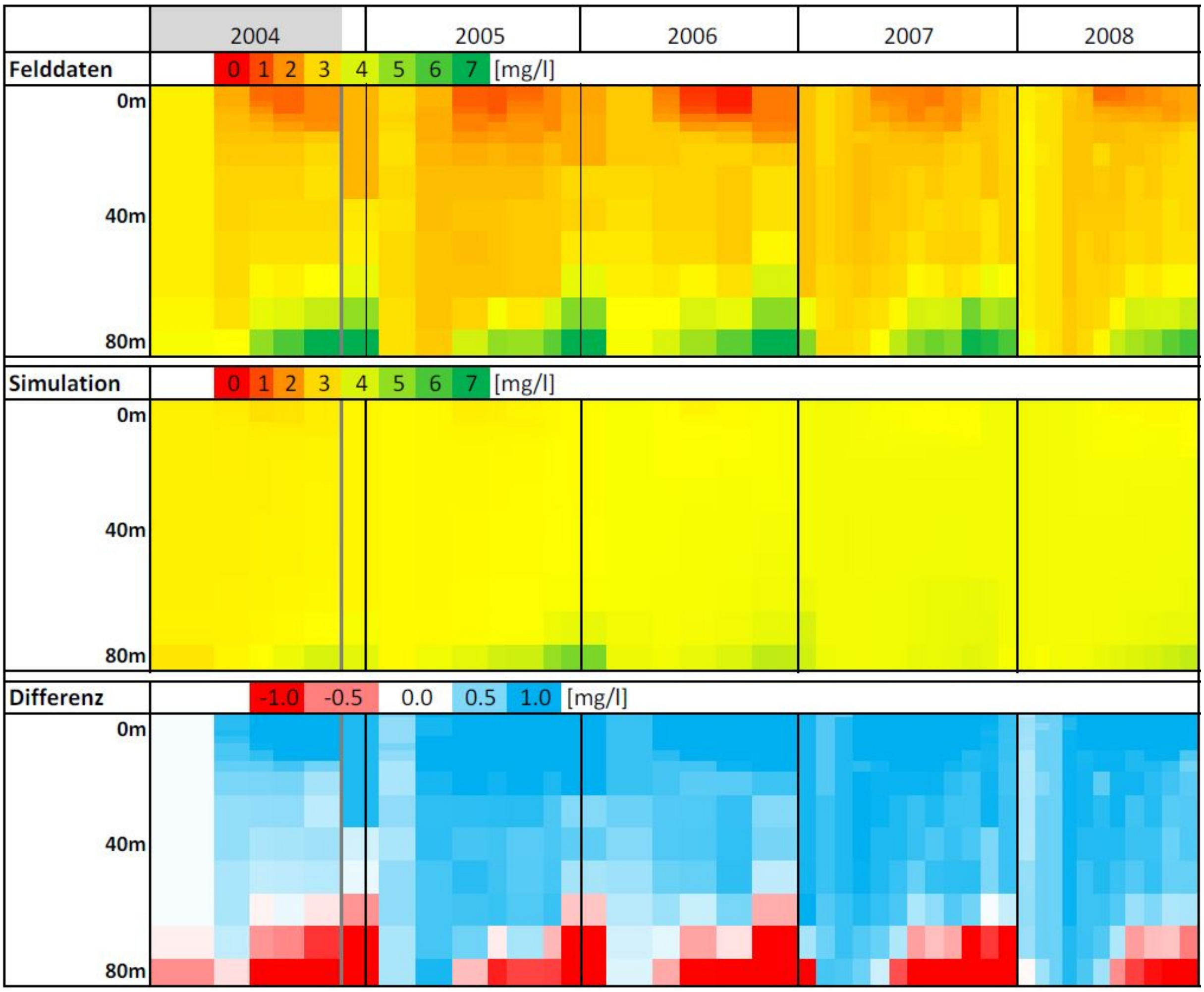


Abb. 10: Gemessene (oben) und mit GLM-FABM simulierte (mitte) Konzentrationen zum gelösten Silizium (Si-SiO_2) und deren Differenz (unten) für den Zeitraum 2004 - 10/2008. Ergebnisse in der grau hinterlegten Zeitspanne im Jahr 2004 wurden nicht zur Berechnung der Gütekriterien einbezogen.

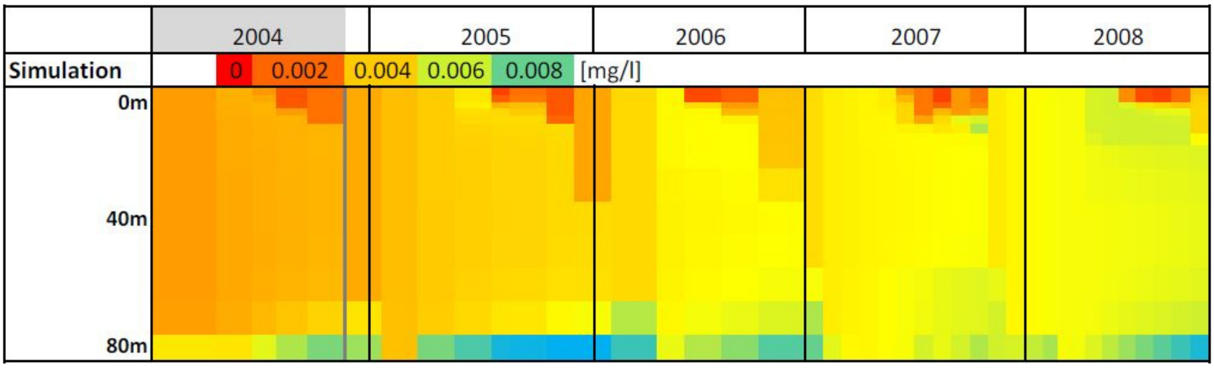


Abb. 11: Mit GLM-FABM simulierte Konzentrationen zum gelösten, reaktiven Phosphat (P-PO_4) für den Zeitraum 2004 - 10/2008. Ergebnisse in der grau hinterlegten Zeitspanne im Jahre 2004 wurden nicht zur Berechnung der Gütekriterien einbezogen.

Für die Simulation der DO-Konzentrationen im Ammersee mit GLM-FABM konnte bereits im Rahmen dieser manuellen Kalibrierung eine Annäherung der Reproduktion der realen Sauerstoffverteilung erreicht werden. Dennoch muss sie aufgrund der fehlenden Abbildung der jahreszeitlichen Muster (Ausbildung des metalimnischen Sauerstoffminimums, Zehrung über dem Grund) noch als nicht ausreichend eingestuft werden, um anhand der Verteilung das Zirkulationsverhalten des Sees

ableiten zu können. Um dies zu gewährleisten muss auch der fehlerhafte Trend der ansteigenden DO-Konzentrationen über den Simulationszeitraum hinweg eliminiert werden.
Anhand der Anpassung des Modells auf den Ammersee wurde für die gelösten Stoffe N-NO_3, N-NH_4, Si-SiO_2 und P-PO_4 jeweils eine stabile Simulation erreicht, welche auf Änderungen in den Parametereinstellungen realistisch reagiert. Aufgrund der verbleibenden Fehler, vornehmlich die Zu- oder Abnahmetrends über den Simulationszeitraum hinweg, muss die Kalibrierung des gekoppelten Modells GLM-FABM für den Stoffhaushalt als noch nicht abgeschlossen bewertet werden. Eine Analyse der Messdaten für den Zufluss zeigt, dass die Trends in der simulierten Verteilung der jeweiligen Stoffe nicht auf veränderte Konzentrationszufuhren durch den Zufluss zurückzuführen sind.

5. Zusammenfassung und Ausblick

Im Rahmen der vorliegenden Dissertation wurden Simulationen von limno-physikalischen Prozessen und der Verteilung gelöster Stoffe im Ammersee durchgeführt. Hierfür konnte das hydrodynamische Modell DYRESM durch die Aufbereitung und Qualitätsprüfung der verfügbaren meteorologischen und hydrologischen Eingangsdaten sowie der Anpassung der seespezifischen Parameter erfolgreich für den Ammersee kalibriert und validiert werden. Durch die anschließende Sensitivitätsanalyse der simulierten Wassertemperaturen hinsichtlich Veränderungen in den klimatischen Bedingungen konnte die Verwendbarkeit für Simulationen von zukünftigen Einflüssen des Klimawandels auf den See nachgewiesen werden.
Durch den Antrieb des kalibrierten und validierten Modells mit Daten des regionalen Klimamodells WettReg2010 konnten aussagekräftige Simulationen für zukünftige Verhältnisse am Ammersee durchgeführt werden. Dabei wurden WettReg-Datenreihen erstmals in der limnologischen Modellierung verwendet. Die Daten des statistischen regionalen Klimamodells gehen sowohl direkt als meteorologische Eingangsdaten als auch indirekt als Basis für die Ermittlung der hydrologischen Eingangsdaten in die Simulation mit ein. Der gewählte Ansatz ermöglicht einen direkten Vergleich der auf der gleichen Grundlage ermittelten vergangenen und zukünftigen Verhältnisse anhand einer statistischen Auswertung. So konnte eine Verlängerung der Schichtungsdauer im See für die Zukunft festgestellt werden.
Anhand der Berücksichtigung unterirdischer Zuflüsse bei der Modellierung der Wassertemperaturen mit DYRESM konnte gezeigt werden, dass das Modell für diese Fragestellung realistische Ergebnisse simuliert. Durch die Implementierung unterirdischer Zuflüsse war es gleichzeitig möglich, die Charakteristik der Grundwasserzuströme zum Ammersee abzuschätzen.
Die Anpassung des gekoppelten ökologischen Seemodells GLM-FABM auf den Ammersee konnte erfolgreich umgesetzt werden. Obwohl die Verteilung der Wassertemperaturen bereits

zufriedenstellend reproduziert wird, bedarf es zur Simulation der gelösten Stoffe noch eine weitere Kalibrierung der Modellparameter. Die vorgestellten Simulationen stellen eine fundierte Basis für die Modellierung des Stoffhaushaltens am Ammersee dar. Zur weiteren Kalibrierung des Modells ist jedoch eine Anwendung eines automatischen Kalibrierungsansatzes nötig, da die Komplexität der Prozesse durch eine große Anzahl an seespezifischen Parametern abgedeckt wird, deren Anpassung manuell nicht zu leisten ist. Zudem wird es als sinnvoll erachtet zusätzliche AED-Module in der Modellierung zu aktivieren, um weitere Interaktionen und Rückkopplungen zwischen den simulierten Stoffen zu berücksichtigen. Dies wiederum hätte eine weitere Erhöhung der Komplexität des Kalibrierungsvorgangs zur Folge.

Im Rahmen dieser Arbeit wurde eine Basis zur Verwendung numerischer Modelle in der limnologischen Forschung am Ammersee erarbeitet und durch die Anwendung auf spezifische Fragestellungen die vielseitige Verwendbarkeit der numerischen Modellierung als unverzichtbares Werkzeug in diesem Forschungsbereich aufgezeigt. Anhand der durchgeführten Simulationen konnten quantitative Aussagen zum potentiellen Einfluss des Klimawandels auf den Ammersee erzielt und die Möglichkeit einer zusätzlichen Spezifizierung der hydrologischen Eingangsdaten in der hydrodynamischen Modellierung mit DYRESM erfolgreich umgesetzt werden. Des Weiteren wurde durch die Simulation des Stoffhaushaltes mit dem 2012/2013 vorgestellten Modell GLM-FABM die Grundlage geschaffen um in einem nächsten Schritt potentielle Veränderungen in der Trophie, dem Durchmischungsverhalten und der Limnobiologie des Ammersees zu modellieren. Die erzielten Simulationsergebnisse stellen einen wichtigen Beitrag in der Weiterentwicklung der limnologischen Modellierung dar und ermöglichen einen Vergleich mit Ergebnissen von Studien an anderen Seen in verschiedenen Klimazonen. Sie tragen zudem zur Verbesserung des Prozessverständnisses von limnologischen Systemen bei und helfen noch offene Fragen, gerade hinsichtlich der Auswirkungen des Klimawandels auf Seen, zu klären. Unabdingbar ist dafür der Austausch mit der internationalen Forschungsgemeinschaft, welcher durch die Verwendung des Modells GLM-FABM gewährleistet wird.

Ein integrativer Forschungsansatz zur Simulation zukünftiger Verhältnisse in Seen ist die zusätzliche Modellierung der Stoffeinträge in den Seekörper über dessen Zuflüsse. Um die Stoffeinträge realitätsnah nachbilden zu können, ist deren Input über die Zuflüsse durch die zusätzliche Modellierung mit Hilfe eines Einzugsgebietsmodells (wie z. B. mit dem **S**oil and **W**ater **A**ssessment **T**ool, SWAT) nötig. Unter der Verwendung regionaler Klimamodelle für diese Modellierungen kann dieser umfassender Ansatz zur Simulation zukünftiger Verhältnisse in Seen verfolgt werden, in dem nicht nur atmosphärische Einflüsse auf den See, sondern zusätzlich auch Veränderungen im Einzugsgebiet, wie etwa in der Landnutzung, berücksichtigt werden. Die Grundlagen der limnologischen Modellierung zur Umsetzung dieses Simulationsansatzes am Ammersee werden mit dieser Arbeit bereitgestellt.

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Anhang A

Publikation I:

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Simulating water temperatures and stratification of a pre-alpine lake with a hydrodynamic model: calibration and sensitivity analysis of climatic input parameters

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Abstract

We report on the calibration of the one-dimensional hydrodynamic lake model DYRESM to simulate the water temperature conditions of the pre-alpine Lake Ammersee (South-east Germany) which is representative of deep and large lakes in this region. Special focus is given to the calibration in order to reproduce the correct thermal distribution and stratification including the time of onset and duration of summer stratification. To ensure the application of the model to investigate the impact of climate change on lakes, an analysis of the model sensitivity under stepwise modification of meteorological input parameters (air temperature, wind speed, precipitation, global radiation, cloud cover, vapor pressure, and tributary water temperature) was conducted. The total mean error of the calibration results is –0.23°C, the root mean square error amounts to 1.012°C. All characteristics of the annual stratification cycle were reproduced accurately by the model. Additionally, the simulated deviations for all applied modifications of the input parameters for the sensitivity analysis can be differentiated in the high temporal resolution of monthly values for each specific depth. The smallest applied alteration to each modified input parameter caused a maximum deviation in the simulation results of at least 0.26°C. The most sensitive reactions of the model can be observed through modifications of the input parameters air temperature and wind speed. Hence the results show that further investigations at Lake Ammersee, such as coupling the hydrodynamic model with chemo-dynamic models to assess the impact of changing climate on biochemical conditions within lakes, can be carried out using DYRESM.

KEY WORDS Lake Ammersee, hydrodynamic modeling, lake stratification, sensitivity analysis, climate variability

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Introduction

Like many ecosystems, lakes are especially sensitive to changes in their environment. Hence, they are good sentinels of changes in climatic conditions in the catchment area as well as at the lakes themselves (Magnuson *et al.*, 1997; Hostetler and Small, 1999; Adrian *et al.*, 2009; Schindler, 2009; Williamson *et al.*, 2009). Climate-driven changes in lake water temperatures have an impact on the intensity of stratification, depth of thermocline, temperatures in the entire water column, and intensity of stratification as well as on lake dynamics, for example, mixing regimes (King *et al.*, 1999; Peeters *et al.*, 2002; Nickus *et al.*, 2010; Dibike *et al.*, 2011). Those changes can provoke alterations in the functioning of limnetic ecosystems (Gerten and Adrian, 2000; Straile *et al.*, 2010). In the last two decades the impact of climate change on lakes has gained increasing significance both in the public domain and in research (Livingstone *et al.*, 2005; Rinke *et al.*, 2010). Trolle et al. (2012) has documented a growing importance of numeric modeling for the same period. Particular case studies on this topic have been conducted in the last years (Fang and Stefan, 2009; Verburg and Hecky, 2009; Rempfer *et al.*, 2010). But more knowledge about the reactions of lakes to climate variability is still needed in order to be able to assess the conditions in the future and their changes in relation to the past and present (Huang *et al.*, 2010; Dibike *et al.*, 2011). Only lake-specific modeling can provide the required quantitative and temporal forecasting (Danis *et al.*, 2004; MacKay *et al.*, 2009; Williamson *et al.*, 2009).

Any changes in lakes are represented in its heat balance and thermal structure, which also influence basic chemo-dynamic characteristics of the system of the water body (King *et al.*, 1999; Jones *et al.*, 2010; Mishra *et al.*, 2011). Subsequently, alterations in the lake heat budget also have effects on phytoplankton biomass (Burger *et al.*, 2008; Huber *et al.*, 2008). Hence, to predict future conditions in lakes, considering the changing climate, knowledge about variations in physical lake variables and heat balance due to alterations of climate conditions is essential. Furthermore, to investigate changes in the mixing, duration, and stability of stratification or surface temperature, it is necessary to examine the vertical profiles of water temperature, because vertical temperature gradients are larger than horizontal ones (Perroud *et al.*, 2009). One-dimensional numeric models, which simulate multiannual cycles of water temperature, can be used to investigate changes in the lake thermal structure (Tanentzap *et al.*, 2007; Fang and Stefan, 2009). If they are forced by various meteorological data to represent present or future conditions, they allow changes in lake dynamics and temperatures to be evaluated accurately.

Therefore, in our investigation we applied the hydrodynamic model DYRESM (Dynamic Reservoir Simulation Model; (Imberger *et al.*, 1978; Imberger and Patterson, 1981) to Lake Ammersee in southeast Germany. Continuous measurements of many limnological parameters of this lake, including water temperatures of the vertical profile, are available for the last 30 years. Lake Ammersee is considered to be representative of most of the eastern pre-alpine lakes because of the comparable climate conditions, its genesis and resulting morphometry, and its size (Danis *et al.*, 2004; Vetter and Sousa, 2012). Successful calibration and validation of the used model are essential foundations for valid future predictions. Further, an analysis of the sensitivity of the model to modification of meteorological input parameters ensures that it is possible to identify variations in the lake water temperatures induced by changing climatic conditions in the model simulations, and simultaneously gives the opportunity to examine the simulated changes considering the impact of specific input parameters.

The objectives of this study are (i) to present the characteristics and the quality of calibration and validation of the hydrodynamic lake model using statistical parameters, which were calculated for generated simulation results, (ii) to show that all characteristics of the annual limno-physical cycle

(e. g. summer stratification, winter inverse stratification, or homeothermy) are represented in the simulated lake thermal structure used for the calibration results, and (iii) to analyze the sensitivity of the model to separate modifications of all meteorological input parameters [air temperature (AT), wind speed (WS), precipitation (PC), global radiation (GR), cloud cover (CC), vapor pressure (VP), and also the water temperature of the tributaries (WT)].

Methods

Study site

Lake Ammersee is a pre-alpine lake situated 35 km southwest of Munich (47°59′ N, 11°7′ E) (Fig. 1). The glacial-morphological origin of the lake basin is typical of pre-alpine lakes nearby and of the whole of the eastern Alpine Foothills. The trophic state of the lake under natural conditions is potentially oligotrophic (Kucklentz, 2001). Lake Ammersee is characterized by current dimictic circulation conditions. The occurrence of complete ice-cover is rare and can be expected only once every few years; it last occurred in 2006. The lake has a volume of 1.8×10^9 m³, a surface area of 46.6 km², an average depth of 38.6 m, and a maximum depth of 83.7 m. The catchment area covers an area of 993 km² (Schaumburg, 1996). The lake is drained by the River Amper in the north. River Ammer, located in the south, is the main tributary and contributes about 80% of the total annual discharge of the lake. The residence time of the water is approximately 2.7 years (Lenhart, 1987). Especially before 1980 the lake was characterized by eutrophic conditions due to intensive land use in the catchment area (Lenhart, 1987; Vetter and Sousa, 2012). As a result of immense management activities, a process of reoligotrophication has set in since then, which has led to improved trophic conditions nowadays. The lake reacts clearly in terms of limno-physical values (e.g. Schmidt stability) to climate variations (Vetter and Sousa, 2012).

In this investigation, the epilimnion is defined as the layer of water between the surface and a depth of 7 m, and the metalimnion as the layer of water between 7 and 18 m. The hypolimnion refers to water between a depth of 18 m and the deepest point of the lake.

Model description

In this study the one-dimensional hydrodynamic model DYRESM (v4.0.0-b2) was used to predict the vertical distribution of lake water temperature and salinity. However no investigations regarding salinity were carried out in this study. The model has been developed by the Centre for Water Research (CWR) of the University of Western Australia (Imberger et al., 1978; Imberger and Patterson, 1981). DYRESM is a process-based model which uses the Lagrangian approach of splitting and merging horizontal layers of uniform properties in response to physical processes (see Fig. 2). The model's predictions are driven by volume changes of the layers produced by inflows, outflows, and mixing, which change layer thickness and position to accommodate volume changes. Layer thicknesses are variable and their limits have to be defined by the user (Imerito, 2007; Tanentzap et al., 2007). In comparison to other one-dimensional lake models, DYRESM reproduces the variability of lake water temperature profiles and the seasonal thermocline satisfactorily (Perroud et al., 2009) and has been applied in several investigations in different study areas all around the world (Han et al., 2000; Gal et al., 2003; Rinke et al., 2010; Trolle et al., 2011).

The original version of DYRESM interrupts simulations when water temperatures are subject to cooling below 0°C. In order to enable simulations in temperate zones like the pre-alpine area, the CWR in cooperation with University of Constance has developed and provided a modified model

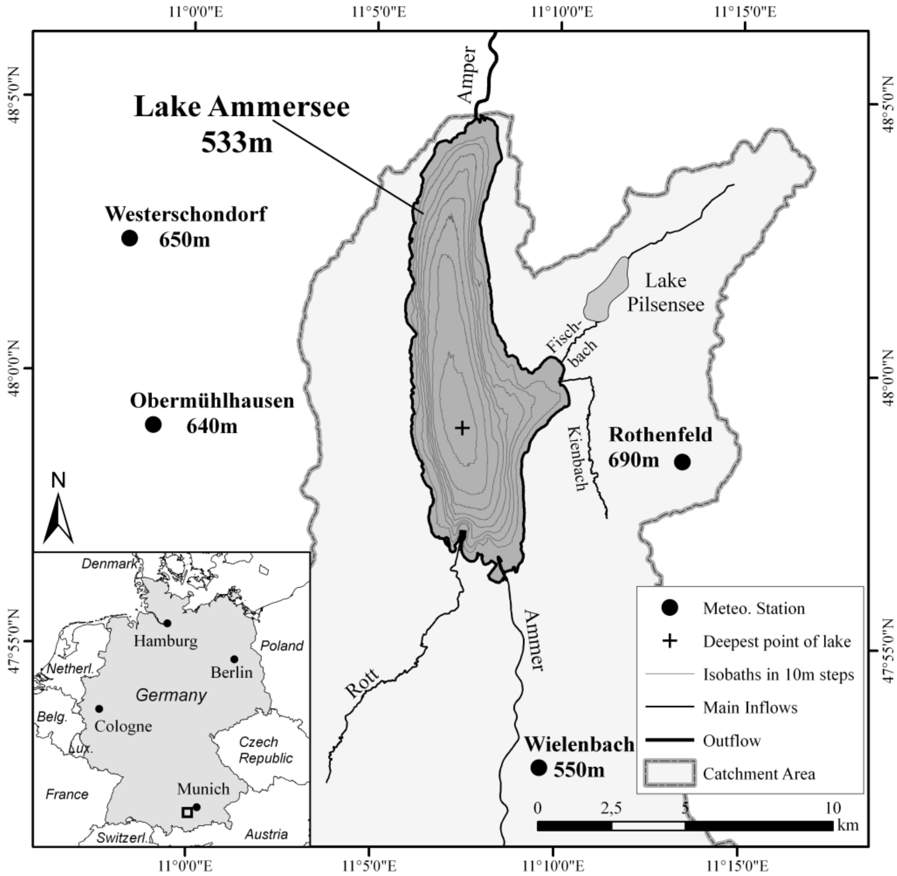

Figure 1. Map of Lake Ammersee (longitude and latitude with locations) of the meteorological stations (black dots) with the information of elevation above sea level. The black cross marks the deepest point of the lake. The grey lines within the lake are contour lines in 10 m intervals displaying the bathymetry of the lake. The light grey area is the catchment area of the lake with its main inflows (thin black lines) and outflow (thick black line)

version which sets any simulated water temperature below freezing point to 0°C. Taking into account that the deep and large lakes in the eastern pre-alpine region rarely freeze completely and that the duration of occurrence is short, the error introduced by avoiding any formation of ice cover and the subsequent almost complete halt of energy fluxes between atmosphere and water surface is not significant for this investigation.

Any settings for the modeling process have to be stored in different input files. A schematic overview on the DYRESM simulation process is given by Figure 3. The simulation period (starting day, duration, and output interval) and specific configuration data (e. g. limits of layer thickness or light extinction coefficient) are assembled in the configuration file (.cfg). Because a smaller temporal resolution is advisable for longer simulation periods (several years), a daytime output resolution was chosen for this modeling approach. Accordingly, all model-forcing input parameters had to be adapted to this temporal resolution. Physical data, lake morphometry, and the number of inflows including more detailed descriptions of their entry areas are specified in the morphometry file (.stg). Hydrological data of tributaries (discharge, temperature, and salinity) are supplied by the inflow file (.inf) and discharge rates of the outflow are supplied by the withdrawal file (.wdr). Meteorological data (AT, WS, PC, VP, and short and long wave radiation) are provided by the meteorological file (.met). DYRESM offers the opportunity to estimate the net long wave radiation from the cloud cover fraction using an integrated program code, which was applied in this study. Conditions in the vertical profile (water temperature and salinity) at the start of the simulation are given in the initial profile

file (.pro). Variable model parameters affecting the limno-physical processes in the lake (e. g. vertical mixing, heat fluxes) are defined in the parameter file (.par). Further details and a precise description of the variable model parameters of the configuration and parameter file as well as the original mathematical equations used by the model are given by Imerito (2007).

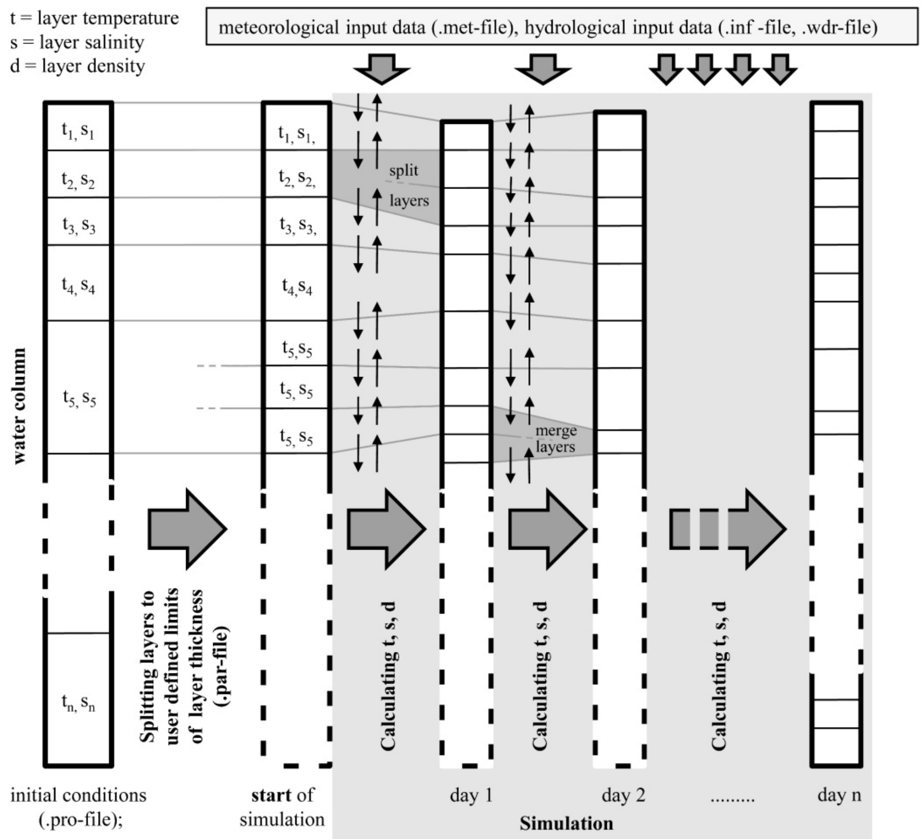

Figure 2. Schematic illustration of the DYRESM procedure applying the Lagrangian approach according to the descriptions of Imerito (2007)

Model-forcing data

For the calibration lake water temperatures were simulated for period of 6 years and 5 months (July 2001 – November 2007). Starting the simulation with an initial profile representing the summer stagnation, the first 6 months were not taken into account for the calibration analysis to ensure the independence of the simulation results from the initial conditions. According to that the calibration period was determined from January 2002 to November 2007. The simulation run for the model validation was conducted for the period January 2007 – April 2011. To generate independent validation statistics of calibration and exclude potential influences of errors from the simulation beginning, the results from 2007 were not taken into account when calculating validation statistics. Hence, the validation statistics values refer to a period of 3 years and 4 months.

Field data of the vertical lake profile at the deepest point were provided by the Water Management Agency Weilheim and are available for the simulation periods in bimonthly or monthly form, measured at 15 depths (0–10 m in 2-m steps, 10–20 m in 3-m steps, and 20–80 m in 10-m steps). It can be assumed that the available data are able to represent any stratification conditions in the water column in an accurate way. Water temperatures and salinity for the initial conditions in the vertical profile could be retrieved from these observations as well as all the data required to compare the model results with the measured conditions.

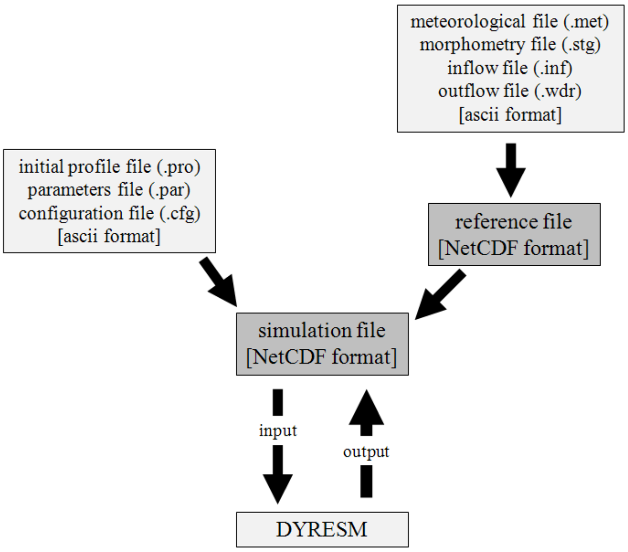

Figure 3. DYRESM simulation process based on DYRESM user manual (Antenucci and Imerito, 2003)

Meteorological conditions were observed at several stations in the immediate environment of the lake (Fig. 1): Obermühlhausen (Omh), Rothenfeld (Rfd), Westerschondorf (Wsd), and Wielenbach (Wbh). Because none of those stations provide measurements of all meteorological input parameters, which are required to force the model, parameters were retrieved from various stations. Table I gives an overview of the data used from the meteorological stations. AT and WS data for model forcing were obtained by calculating first the daily means for the stations Wsd and Rfd separately and then the arithmetic mean for each day from the data of both stations. The deepest point of the lake is almost centered between Wsd and Rfd (Fig. 1). Daily mean values were only generated if at least 22 of 24 measurements per day were available. Otherwise missing values were calculated by linear regression between both data rows (Rfd and Wsd) ($R^2AT = 0.994$, $R^2WS = 0.766$). To account for the different elevations of the meteorological stations with respect to the lake surface (Fig. 1), the observation data were corrected using the well-known vertical gradient of AT (–0.6°C/100 m). This was also applied by Danis et al. (2003). The wind velocities on the lake surface, especially in the center of the waterbody, are expected to be much stronger than WS values measured at onshore stations, which are reduced by topography and vegetation. Hence, a multiplication factor was applied to the wind data as this is practicable (Hornung, 2002; Perroud et al., 2009; Rinke et al., 2010). This multiplication factor was calibrated for the study site as well. An analysis was carried out with the goal of comparing all available GR values with mean monthly sums for the entire region of Lake Ammersee retrieved from the German Weather Service. The linear

Table I. Meteorological stations, their operators, the used parameters for model forcing, and the available measurements per day

Station	Operator	Used parameters	Measurements / day
Obermühlhausen	Private	PC	288
Rothenfeld	BRfA	AT, WS, GR, PC	24
Westerschondorf	BRfA	AT, WS, GR, PC	24
Wielenbach	GWS	CC, VP	3

BRfA = Bavarian State Research Center for Agriculture; GWS = German Weather Service; AT = air temperature; WS = wind speed; PC = precipitation; GR = global radiation; CC = cloud cover; VP = vapor pressure.

regression of data from Wsd showed the best accordance (R^2_{Wsd} = 0.988). So daily mean values (calculated if at least 22 of 24 hourly measurements were available) from this station were used for model forcing. Missing values in the data set were filled by calculation of linear regression between data rows of stations Wsd and Rfd (R^2_{GR} = 0.929). Concerning the nature of spatial variability of PC, this input value for modeling was averaged over the daily sums of three stations surrounding the lake: Wsd, Rfd, and Omh. Values of days on which one or more measurements were missing were not included in the calculation. Daily means of CC and VP were averaged considering three measurements a day, respectively.

Hydrological data (discharge, water temperature, and salinity) were provided by the Bavarian Environment Agency. The required hydrological input parameters were available for the main tributary Ammer and additional discharge data were available for the tributaries Rott and Kienbach (Fig. 1). It can be assumed that the water temperature of River Ammer is representative of all water amounts flowing into the lake. Additionally, most of the discharge and suspended material are supplied by this inflow. So River Ammer was the only tributary implemented in the model. The runoff amounts of Rott and Kienbach were added to the inflow volumes of River Ammer. The execution of a water balance analysis, for example after Baumgartner and Liebscher (1996), for the period 2001–2011 indentified a missing amount of 257175.6 m³ of daily runoff. This difference represents the unknown inflow of smaller tributaries and subterrestrial input and was added in the simulation to the daily inflow value of River Ammer as well to ensure a stable water balance.

The morphometric conditions of the lake have been derived by a GIS analysis of the lake basin. This was implemented in the model by specification of the layer surface of each height in 1 m steps starting from the lake bottom. All necessary raw data considering the morphometry could be retrieved from echo-sounder measurements executed in 2004 and 2006 and supplied by the Bavarian Environment Agency.

Calibration and sensitivity analysis approach

This study is based on a previous status of the calibration of DYRESM to Lake Ammersee (Weinberger and Vetter, 2012). After receiving more accurate meteorological data this investigation focusing on the sensitivity of the model of the climatic conditions could be conducted. The calibration of the model in this study was executed in several steps, where the variable model parameters and the wind multiplication factor were improved gradually. Within one step, several simulations were implemented based on the same adjustment, varying only one parameter in an appropriate range while holding the other coefficients constant. Each simulation result was compared with the field data and evaluated separately. After each step, a new basis representing the best simulation results was determined for the next set of calibration runs. This procedure was repeated until the simulation results reached a satisfactory accordance with the measured water temperatures. The final specifications of the DYRESM model parameters after the calibration for Lake Ammersee are listed in Table II. Those settings were also used for simulations of validation and sensitivity analysis.

After the validation, analysis of the sensitivity of DYRESM to changes in meteorological input parameters and the tributary water temperature was conducted in the same way as the calibration process. Input parameters were modified separately in four to eight variations in which the daily values were increased and decreased, respectively. This was realized by adding offset values to the daily data or multiplying them by a factor. The method of modification (multiplication or addition) depended on the range of values of the respective parameter. Table III shows the theoretical range

Table II. Calibrated DYRESM model parameters and specifications for Lake Ammersee

Parameter	Set Value
Wind multiplication factor	1.5
Configuration file	
Light extinction coefficient	0.25 m^{-1}
Minimal layer thickness	0.25 m
Maximal layer thickness	3.0 m
Activate non-neutral atmos. Stability	true
Parameter file	
Bulk aerodynamic momentum transport coefficient	0.0022
Mean albedo of water	0.08
Emissivity of water surface	0.96
Critical wind speed	3.0 m s^{-1}
Shear production efficiency	0.08
Potential energy mixing efficiency	0.2
Wind stirring efficiency	0.4
Effective surface area coefficient	1.0×10^7
Vertical mixing coefficient	200

Table III. Data ranges of theoretical and observed values for all meteorological input parameter water temperatures of the tributary

Input parameter	Theoretical range of values		Range of observed values	
	min	max	min	max
AT (°C)	- ∞	+ ∞	-14.3	26.8
WS (ms^{-1})	0	+ ∞	0	13.6
PC (mm)	0	+ ∞	0	55.8
GR (Wm^2)	0	+ ∞	3.7	458.2
CC (%)	0	1	0	1
VP (hPa)	0	+ ∞	1.6	21.4
WT (°C)	0	+ ∞	0.8	22.9

The theoretical ranges of value are defined by the potential maximum and minimum value. Ranges of observed values for the simulation period are specified by maximum and minimum in the data rows. AT = air temperature; WS = wind speed; PC = precipitation; GR = global radiation; CC = cloud cover; VP = vapor pressure; WT = water temperatures of the tributary.

of values of each parameter and their minimum and maximum values in the measured data of the simulation period. Zero is a common value for the parameters WS (daily means) and PC (daily sums). When increasing or decreasing the observed values of these parameters by multiplication, the value 0 still occurs in the modified data. Simultaneously the maximum value changes as intended and thus the extension of the total value ranges of the inputted data also changes. Daily average data of the input parameter CC have a value range of 0 to 1. Modifications of CC values were also obtained by multiplication by a factor. All resulting values > 1 were set back to 1 to keep all values in the defined range. So after the modifications, CC data still ranged between values of 0 and 1. AT values, which range from positive to negative, cannot be multiplied to achieve only a decrease or an increase in one modification process. Hence, this input parameter was added to offset values (positive or negative, respectively). For the sensitivity analysis, WT values were only increased. They were added to offset values analogously to modifications of AT. The modifications of GR and VP were also carried out by addition. Multiplying values by any factor would modify the higher values more than the lower ones and change the total value range of the data. Because of the large range of GR data (Table III), this effect would be too extreme for GR values to carry out a reasonable analysis. In contrast to WS and PC data, in VP data ranges the value 0 is only theoretical. It is not imperative to include 0 for representative VP data either before or after modification. Due to this fact and the effect of multiplication described above, modification by addition is more reasonable for VP data. Table IV overviews the variations applied to each parameter. Values of AT and WT were added to reasonable offset values. Data of GR and VP were added to values which represent a percentage of the mean of the value range of the observed data (Table III). For the input parameters modified in this way, offset values representing deviations of 2% and 5% were calculated. In a few cases GR values would have been negative after the modification. These values were set to a value of 0 for the sensitivity analysis. To examine reactions in the model results when conditions change only in the winter (November–April) or summer half-year (May–October), the data of the meteorological parameters AT, WS, and PC were modified only in one half-year respectively. This determination of summer and winter complies with the onset and breakdown of summer stratification in Lake Ammersee (Ernst et al. 2009). The direct dependence of GR on CC and their interrelation were not investigated in this study and were thus not accounted for in the sensitivity analysis. By varying both parameters separately, the reaction of DYRESM to changes in GR could be analyzed.

Table IV. Modifications of the input parameters applied in the sensitivity analysis

Parameter	Variations of parameter					Inter-seasonal variations			
	+	++	+++	-	--				
AT (°C)	+0.5	+1.0	+2.0	-0.5		0/++	+/0	+/++	
WS	×1.1	×1.2	×1.5	×0.9		0/++	++/0	-/0	
PC	×1.02	×1.05		×0.98	×0.95	0/+++	+++/0	---/0	0/---
GR (Wm^{-2})	+4.58	+11.46		-4.58	-11.46				
CC	×1.02	×1.05		×0.98	×0.95				
VP (hPa)	+0.198	+0.495		-0.198	-0.495				
WT (°C)	+0.5	+1.0	+1.5						

AT = air temperature; WS = wind speed; PC = precipitation; GR = global radiation; CC = cloud cover; VP = vapor pressure; WT = water temperatures of the tributary. The number of symbols is representing the intensity of the variation (+: increase, –: decrease). 0 means no change. The first symbol of the inter-seasonal variations represents the winter half-year (November–April), and the second the summer half-year (May–October).

Statistical analysis

To qualify the error between simulation results of calibration runs, the validation run, and the field measurements, three statistical variables were calculated for all depths separately. The statistical values for each depth were averaged over the calibration period after each simulation run. Two of the variables are the non-negative statistics mean absolute error (MAE) and root mean square error (RMSE). RMSE ≥ MAE is valid for almost all cases. The degree by which RMSE exceeds MAE is an indicator of the extent of outliers in the data (Legates and McCabe, 1999). The third statistical value is the mean error (ME) considering the direction of deviation (warmer or colder). The chosen statistical values are used frequently and enable comparisons to be made with other ecological modeling studies (Chao *et al.*, 2007; Burger *et al.*, 2008; Perroud *et al.*, 2009), which are described in the discussion chapter. Total errors of simulation runs for the total water column were calculated by weighting each error value according to its volume proportion of the total lake, represented by its depth. Analysis and comparisons of the simulation runs could be simplified by colorizing (not shown in this paper) the statistical data according to their values.

Results

Calibration

The best model results of all calibration simulation runs were achieved by applying the model parameters and specifications shown in Table II. The characteristics of the annual water temperatures were simulated in an accurate way for all depths (Fig. 4). The highest seasonal amplitude of water temperatures in the lake water column occurs at the surface (Fig. 4(a)). This amplitude is represented by the simulated water temperatures in all years. The variability of surface temperatures during the summer (e.g. 2007) is satisfactorily reproduced in the model results as well. Epilimnetic temperatures are also characterized by strong seasonal differences. This layer is represented by the depth of 6 m in Figure 4(b). Simulation results show an accurate analogy to the

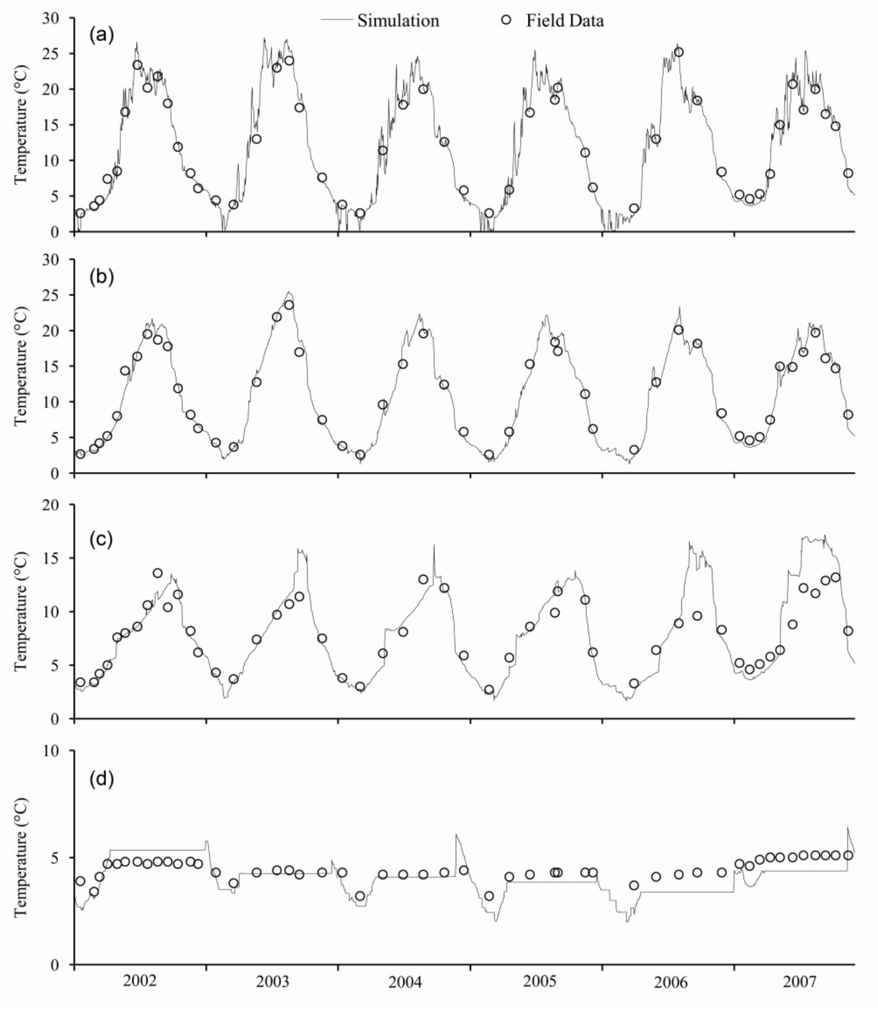

Figure 4. Simulated water temperatures (solid line) and observed temperatures (black circles) on the surface (a), at the depths of (b) 6 m, (c) 13 m, and (d) 70 m for the period of 01 January 2002 to 30 November 2007

measured data. During the summer stratification, water temperatures within the metalimnion (represented by the depth of 13 m in Fig. 4(c)) exhibit very high differences, with temperature gradients above of more than 1 Km^{-1} (Hutchinson 1957). Good analogies with metalimnetic summer temperatures are simulated in the years 2002, 2004, and 2005. But in all years of the calibration period there is at least one intense deviation of the simulated data from the field data (> 2 °C), and these deviations mostly occur in the summer. Except in summer 2002 all of these intense deviations result from an underestimation in the simulation results. Cooling of metalimnetic water temperatures during the winters was simulated satisfactorily. Water temperatures of the deep hypolimnion (represented by the depth of 70 m in Fig. 4(d)) are subject to only slight overall variability, but the simulation results retrace the colder hypolimnion temperatures in the winters (e.g. 2002, 2004, and 2005). Additionally, the characteristic constant temperatures in spring, summer, and autumn are represented very well by the simulation results. Deviations from the observed data are both positive (2002) and negative (2006, 2007), but are generally small.

The total RMSE, MAE, ME, and specified values for 15 separated depths are shown in Table V. All three total values reveal an accurate overall adaption of DYRESM to Lake Ammersee. The absolute maximum (0.028°C) of all deviations of ME at depths of 0 to 6 m is very small. In combination with RSME values of around 1°C in these depths of the lake water column, and a maximum difference of 0.226 °C compared to MAE values, this indicates a very satisfactory representation of epilimnion temperatures (0–7 m), which includes only a small amount of extreme deviations of simulation results from the field data. The calibration result overestimates water temperatures in the most intense way for the metalimnion (7 to 18 m), where ME ranges from 0.104°C up to 0.406°C. A difference of about 0.5°C between RMSE and MAE for all four calculated values of the metalimnion and the relatively high RMSE and MAE values indicate more, and more extreme, deviance of the

Table V. Calculated statistics for the calibration and validation period - total and separated values for layers represented by 15 depths

	Calibration			Validation		
Depth (m)	RMSE	MAE	ME	RMSE	MAE	ME
0	1.137	0.949	0.012	1.295	0.995	-0.242
2	0.996	0.842	-0.028	1.182	0.913	-0.387
4	0.890	0.738	-0.019	1.125	0.863	-0.166
6	1.066	0.845	-0.016	1.692	1.171	-0.042
8	1.525	1.069	0.406	1.863	1.278	0.150
10	1.402	1.053	0.402	1.667	1.199	-0.277
13	1.785	1.201	0.290	1.087	0.856	-0.570
16	1.420	0.968	0.104	1.345	1.071	-0.716
20	1.125	0.849	-0.554	1.168	0.983	-0.845
30	0.991	0.862	-0.634	0.734	0.643	-0.563
40	0.783	0.665	-0.438	0.636	0.515	-0.385
50	0.657	0.584	-0.368	0.620	0.452	-0.306
60	0.640	0.573	-0.289	0.534	0.391	-0.317
70	0.612	0.532	-0.219	0.539	0.367	-0.283
80	0.623	0.531	-0.173	0.509	0.345	-0.262
total	1.012	0.803	-0.230	0.976	0.757	-0.419

RMSE, root mean square error; MAE, mean absolute error; ME, mean error.

simulation from observations for the metalimnion than for the epi- and hypolimnion. But a maximum RMSE value of 1.785°C attests to a moderately good simulation of metalimnion temperatures. The highest absolute ME values (–0.438°C to –0.634°C) were calculated for the upper hypolimnion (18–45 m). Small RMSE and MAE values show a more general but not intense underestimation of water temperatures in this layer. ME is also negative for all the lower hypolimnetic depths (45–80 m) but has small absolute values (0.173°C to 0.386°C). This indicates a small underestimation by the simulation results. Both RMSE and MAE, plus the difference between them, show their smallest values for the entire water column in the lower hypolimnion, indicating that no extreme variations were simulated for deep hypolimnion water temperatures and the simulation results represent the conditions accurately (see also Fig. 4(d)). Considering monthly averaged ME values (not shown), a constant underestimation of water temperatures can be detected in the column for the colder seasons beyond the summer stratification (November–April). During the distinctive stratification period (June–October) ME values increase to become positive for the epi- and metalimnion, with the highest values occurring in September (up to 3.625 °C in 13 m). In contrast, monthly hypolimnetic temperatures are underestimated for this period in the model results. The highest values of monthly averaged RMSE and MAE were calculated for the period of June to September for the depths of 8 m and 13 m. Simultaneously, all values in the metalimnion are overestimated in the simulation results.

Different stratification conditions appear in Lake Ammersee annually. All of them were simulated by the model results. Figure 5 shows exemplary homeothermy (a), inverse winter stratification (b), and summer stratification (c,d) on selected days of the calibration period. A constant water temperature of about 4°C in the entire water column is prerequisite for the lake overturn and is reproduced very accurately verified by Figure 5(a). Inverse stratification in winter is

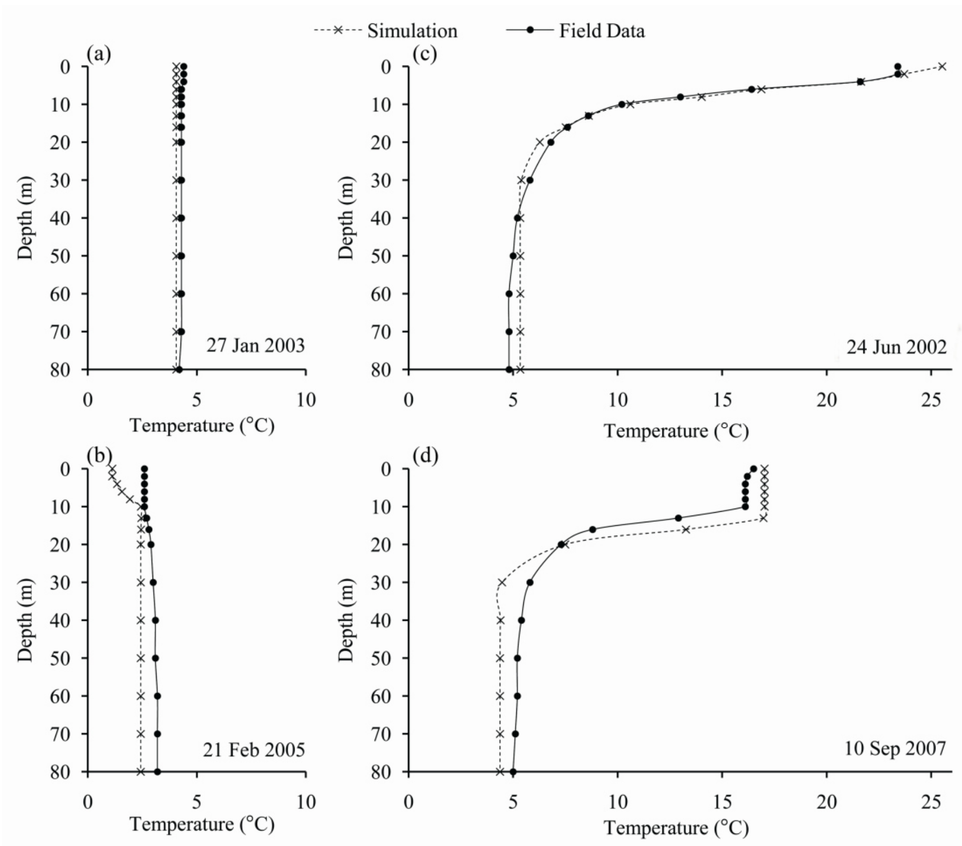

Figure 5. Water temperature profiles of the simulated (dotted line with crosses) and measured (solid line with points) data on (a) 21 January 2003, (b) 21 February 2005, (c) 24 June 2002, and (d) 10 September 2007

characterized by stratifying the coldest water temperatures at the surface. For Lake Ammersee, warmer temperatures (up to a maximum of 4 °C) occur already at slight depths. Figure 5(b) demonstrates the simulation of the inverse stratification by the calibrated model. On the selected day, the intensity of the shown stratification of the simulation results is higher than in the observed conditions, which can be detected by its colder temperatures at the surface and in the epilimnion. Different phases of summer stratification are shown in Figures 5(c) and 5(d). Conditions of very intense stratification can be observed in midsummer, for example on June 24, 2002. This thermal condition in the water column is reproduced exactly by simulation, including the characteristic formation of a layer with a very high thermal gradient (thermocline) within the metalimnion. Lake stratification in late summer is characterized by temperatures at the surface and in the epilimnion which are significantly lower than in midsummer. But a high thermal gradient is still present in the metalimnion. These conditions (Fig. 5(d)), including constant water temperatures inside the epilimnion, were satisfactorily simulated by DYRESM. It should be mentioned that there are deviations between the simulation results and field data for the metalimnion. The location of the thermocline is shallower in the observed conditions than in the model results.

Validation

The total RMSE, MAE, ME, and specified values for 15 separated depths of the validation simulation are also shown in Table V. In comparison to the calibration values, RMSE and MAE are slight higher in the depths 0-10 m und slight smaller in the rest of the water column. The only high deviations to calibration values of 0.698°C for RMSE and 0.345°C for MAE show up in the depth of 13 m. The total values are smaller for both, RMSE and MAE. ME values are smaller in all depths than for the calibration, which leads consequently to a more negative total ME value (deviation: -0.198°C).

Sensitivity analysis

The modifications of input parameters exhibit impacts on the model results with variable specifications. Those resulting changes in water temperature can occur at different depths and in different seasons to varying degrees. Figures 6 and 7 show the monthly averaged changes in water temperatures, which are the result of modifications in the respective input parameters. January represents winter conditions, April represents spring, July represents summer, and October represents autumn. The figures contain a selection of all executed simulations (Table III).

A constant increase in AT of 1.0°C (Fig. 6(a)) effects almost constant higher winter water temperatures of about +0.35°C at all depths with the exception of the surface. Here the increase of the water temperatures is more intense: up to 0.55°C. In all other seasons, a higher increase is modeled for depths of 0–18 m (epi- and metalimnion). The strongest warming effect takes place in summer in the epilimnion, with a maximum of about 1°C. Hypolimnetic water temperatures increase weakly in summer and autumn with the exception of the upper layer boundary, where temperatures decrease slightly. Results of simulations, which were forced with modified AT in a different way (0.5°C and 2.0°C constant increase), show the same characteristics of changes (graphs not shown). Figure 6(b) shows the variation for a constant decrease in AT of 0.5°. In all seasons and depths the water temperature decreases with more variations in the epi- and metalimnion. Changes in the water temperature for inconstant modifications of AT are shown in Figures 6(c) and 6(d). No modifications of AT in winter and spring effect almost no deviation in water temperatures for these seasons. The increase in AT of 1°C in the summer half-year causes increasing epi- and metalimnetic temperatures, which is similar to the characteristics of the variations in summer and autumn shown in Figure 6(a). Variations in the upper hypolimnion with both types of modification (constant for the

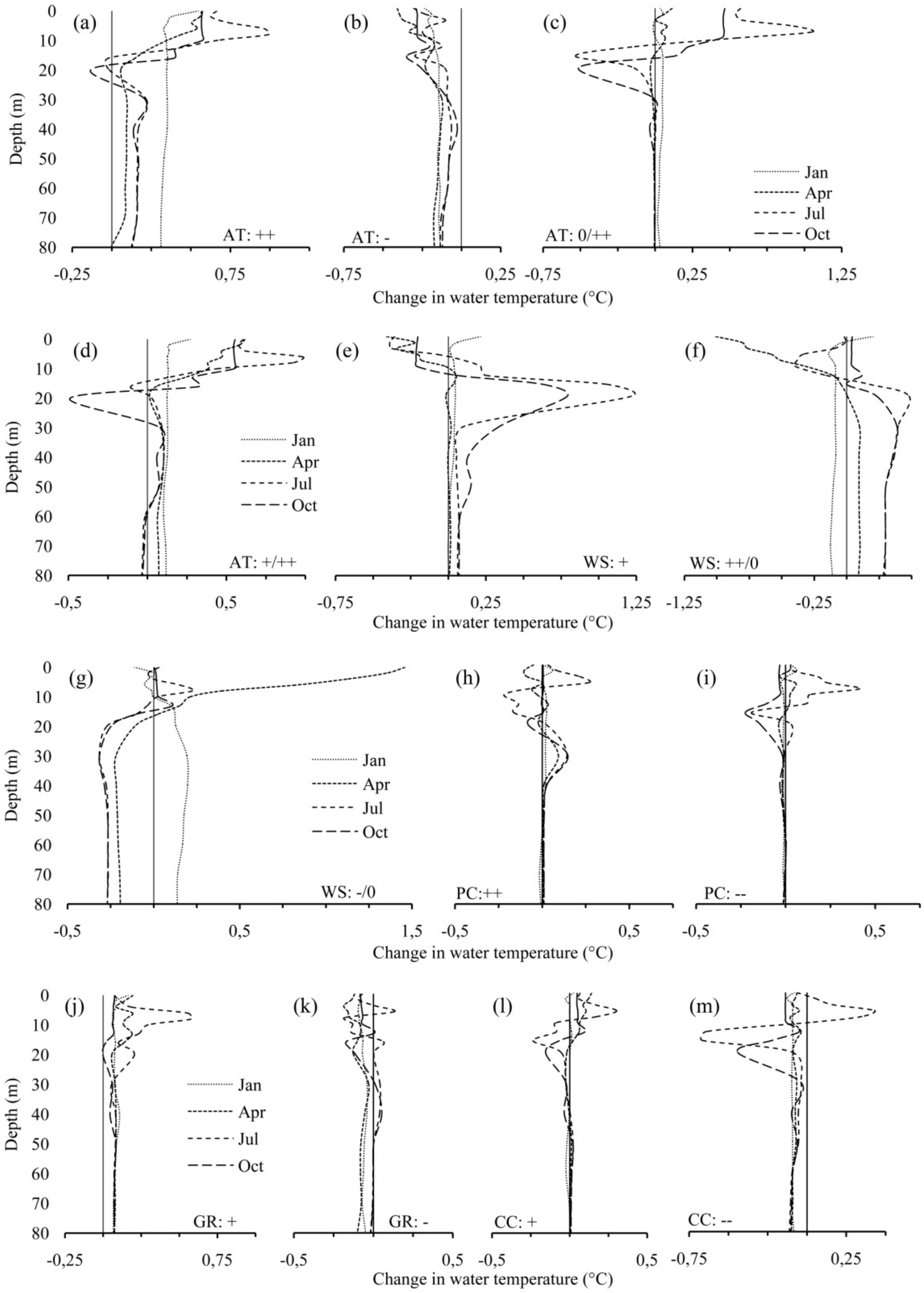

Figure 6. Changes in water temperatures after the separate modifications of the meteorological input parameters. The four graphs represent monthly average changes of January (dotted lines), April (short dashed lines), July (moderate dashed lines), and October (long dashed lines). The modification is described in each panel by +, -, and 0. + represents a rise of the input parameter, - represents a reduction, and 0 represents no modification (similar to Table 3). One symbol represents a small modification, two moderate modifications and three high modification. If symbol(s) are separated by /, the symbol(s) before / represent modification during winter half-year (November–April), the symbol(s) after represent modification during summer half-year (May–October). Results are shown for modifications in AT values of +1.0°C (a), -0.5°C/±0 (b), ±0/+1.0°C (c), +0.5°C/+1.0°C (d), in WS values of ×1.1 (e), ×1.2/×0 (f), ×0.9/×0 (g), in PC values of ×1.05 (h), × 0.95 (i), in GR values of +4.58 Wm^{-2} (j), -4.58 Wm^{-2} (k), in CC values of ×1.02 (l) and ×0.95 (m).

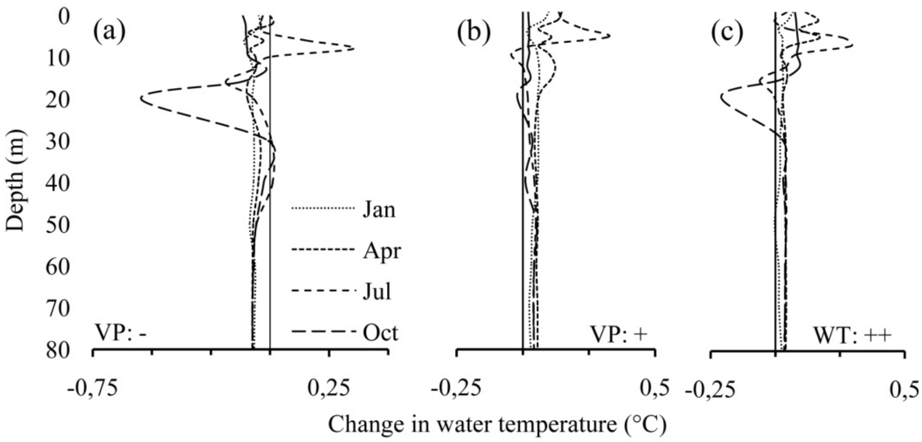

Figure 7. As in Fig. 6; Results are shown for modifications in VP values of + 0.198 hPa (a), -0.198 hPa0 (b) and in WT values of +1.0°C (c).

entire period and differences between summer and winter half-years) also conform to each other, but the decrease in Figure 6(c) is more pronounced. Water temperatures < 30 m are not subject to any change in all seasons. Increases of 0.5 °C in the winter half-year and 1°C in the summer half-year (Fig. 6(d)) show a mixture of specifications from the Figures 6(a)–(c).

Due to the intensification of WS by multiplying input values by a constant factor of 1.1, the water temperatures increase in the simulation of the upper hypolimnion in the autumn and especially in summer (Figure 6(e)). The maximum variations of +1.22°C in summer and +0.79°C in autumn can be characterized as very intense. In contrast, winter and spring temperatures in this layer are not subject to notable changes. The modification of WS also effects a decrease in temperature in the epilimnion with the exception of the winter season, when surface temperatures even increase slightly. Two simulation runs were executed in which WS values were only modified in the winter half-year. Results for the increased WS values (multiplication factor = 1.2) are shown in Figure 6(f); results for the decreased WS values (multiplication factor = 0.9) are shown in Figure 6(g). In both results the most noticeable graph is the one showing the change in spring temperatures. The temperature change at the surface is > 1.0°C and < –1.0°C, respectively. Temperatures in the hypolimnion decrease in winter and increase during the rest of the year (Fig. 6(f)) and vice versa (Fig. 6(g)).

Modifications in PC cause only slight changes in water temperature. For modifications in both directions – increase (multiplication factor = 1.05; Fig. 6(h)) and reduction (multiplication factor = 0.95; Fig. 6(i)) – summer temperatures show the highest variation.

The constant rise in GR input values of 4.58 Wm^{-2} effects a very slight increase in hypolimnetic water temperatures in all seasons (Fig. 6(j)). Only epilimnetic temperatures in summer react with moderate warming of up to 0.5°C. Variations induced by a reduction of GR input values of 4.58 Wm^{-2} (Fig. 6(k)) stay in the range of –0.25°C to 0.15°C for the entire water column. Within this range, decreasing temperatures predominate.

DYRESM simulates slight changes in winter and spring water temperatures when CC is increased by a multiplication factor of 1.02 (Fig. 6(l)). Deviations in summer are higher and are positive for the epilimnion and negative for the metalimnion. A reduction of CC by a multiplication factor of 0.95 (Fig. 6(m)) effects small negative deviations in the hypolimnion in all seasons. This also applies to winter and spring temperatures in the epi- and metalimnion. In contrast, autumn water temperatures decrease by a value of up to –0.44°C at the boundary of the meta- and hypolimnion. Summer temperatures react with very intense deviations to warmer temperatures in the epilimnion and colder temperatures in the metalimnion. Thus it is notable that the surface temperature in summer is subject to almost no change.

When VP values were modified by adding 0.198 hPa (Fig. 7(a)), small increases in water temperatures were simulated for all depths and seasons. Exceptions are the summer temperatures in the epilimnion, which increase up to a maximum of 0.32°C. By subtracting 0.198 hPa (Fig. 7(b)) from the VP input values, a small decrease in temperature was modeled by DYRESM for all depths and seasons with two notable exceptions. First, metalimnetic and upper hypolimnetic temperatures in autumn decrease very intensely (up to a maximum of –0.55°C). Second, epilimnetic temperatures in summer increase up to a maximum of 0.35°C, which is an equivalent level to the variations in simulation results due to raised VP values in this layer. Stronger modifications (not shown) show the same formation with a stronger development.

The influence on the simulations resulting from changing the water temperature of the inflow is shown in Figure 7(c). A constant rise of 1.0°C only effects noticeable variations in temperature in the epilimnion in spring and summer (increase) and in the metalimnion and upper hypolimnion in autumn. The shape of the graphs in Figure 7(c) is representative of all other modifications of WT values (Table III), because they show the same characteristics of changes (graphs not shown).

Discussion

This study analyzes the results of calibration and validation of the one-dimensional hydrodynamic lake model DYRESM to Lake Ammersee as well as the model's sensitivity to changes in meteorological parameters and inflow water temperatures. After the calibration process, deviations remained between DYRESM model results and observed field data. In general, the generation of errors can be attributed to the following factors: (1) the internal algorithm of lake dynamics of DYRESM, (2) errors in the field measurements, (3) too few calibration runs with multivariate model parameter combinations (Tanentzap *et al.*, 2007), (4) the incorrect application of the model, (5) errors in the execution of the calibration, and (6) uncertainties in using onshore meteorological data for model forcing. Considering these multiple sources of errors, the calculated total errors of the simulation results (see Table V) attest a satisfactory representation of the observed conditions. A more detailed assessment is discussed below.

Surface water temperatures were simulated accurately. Because of the very quick response of the lake surface water temperatures to weather conditions and the resulting high temporal variability as described above, deviations from observed data (RMSE = 1.137°C, MAE = 0.949°C) emerge on an expected scale. The ME of 0.012°C evidences that the simulation does not over- or underestimate continuously but deviates in both directions, positive and negative, to the same degree. The deviations in the monthly average do not exceed 1°C in either direction. This accuracy is quite adequate for reproduction of the surface temperature, especially when it is examined over a period of several years. The calculated errors for the epilimnion excluding the surface (2–6 m) are slightly lower than those for the surface. In the uppermost depths of the metalimnion (8 m) the error (RMSE = 1.525°C) is considerably higher than in the epilimnion. These higher deviations at the upper boundary of the metalimnion can be attributed to the fact that the thermocline layer of the stratified lake simulated by DYRESM is too deep during the summer stratification. An overestimation of the simulation temperatures at this depth (8 m) is the result. But the volume-weighted calculated total RMSE for the epilimnion is 1.008°C (not shown in Table IV), which is significantly lower than the RMSE value of 1.444°C. This RMSE value has been designated as an accurate reproduction of epilimnion temperature by Trolle *et al.* (2008b). Burger *et al.* (2008) calculated an only slightly smaller RMSE value of 0.97°C for near-surface water temperatures.

The assumption formulated above that the simulated thermocline is too low has also been observed by Boyce *et al.* (1993). Hence, the occurrence of the highest values of RMSE and MAE in the entire column in the metalimnion can be particularly ascribed to that. Perroud *et al.* (2009) described an increase in RMSE values of up to 3°C in metalimnion depths during the warm season. Analogous to those results, the monthly averaged RMSE values calculated in our study show a maximum of about 3°C for a depth of 13 m in September. But the annual average in this layer is considerably smaller. Continuous positive ME values for the metalimnion confirm the assumption of an overestimation of metalimnion temperatures as a consequence of the fact that the simulated thermocline is too deep, especially for the late season (Perroud *et al.*, 2009). As described in the results, the highest differences in ME values within one year in a layer were calculated for the metalimnion water temperatures, and occur between summer stratification phases and the winter half-year. Considering this, the simulation of metalimnion water temperatures by DYRESM has to be assessed as offering only a moderate reproduction.

The simulated temperatures for the hypolimnion in Lake Ammersee (18 m to bottom) are underestimated for every season, with the maximum underestimation occurring for its upper depths (18–45 m) during the summer stratification. This results from a combination of two facts. The first is the slightly cooler temperatures in the entire water column outside the summer stratification, which already causes colder water temperatures in the hypolimnion at the onset of stratification. Because long wave radiation was prescribed only by daily average CC in this study, the high sensitivity of DYRESM to this input parameter (Gal *et al.*, 2003) could be responsible for this underestimation (Burger *et al.*, 2008). The second is the insufficient heat diffusion in deeper layers during the summer stratification by the model, which has already been investigated (Perroud *et al.*, 2009). Very small values of RMSE, MAE, and absolute ME at a depth of 80 m during the whole period show that lake bottom water temperatures can be simulated by DYRESM very satisfactorily. This can also be confirmed by the total RMSE value of 0.842°C for the hypolimnion, which is almost analogous to the RMSE value of 0.873°C calculated and designated as an accurate reproduction of hypolimnion temperatures by Trolle *et al.* (2008a; 2008b).

Examining all of the results discussed up to this point, it can be assumed that the formation of summer stratification modeled by DYRESM is too stable but its onset and duration were reproduced accurately. But the deviations between observed and simulated water temperatures resulting from modeling the thermocline at too deep a location can still be assessed as accurate. This is especially applicable to investigations over longer periods of several years in order to investigate changes in water temperatures, lake heat budget, and lake bottom water temperatures. Additionally, all the characteristic dynamics of a dimictic deep lake were simulated properly in the calibration period including the formation of inverse stratification, homeothermy, and all phases of summer stratification (Fig. 5). In general, it can be detected that the winter inverse stratification was simulated too strongly by DYRESM. This is characterized by water temperatures considerably below 4°C, not only in water near the surface but also in the entire epilimnion or even in the metalimnion. It can be assumed that the amount of energy loss during the cold season is overestimated by model simulations. The limited ability to include the influence of an incomplete ice cover in a one-dimensional lake simulation and the prevention of ice cover by DYRESM in general may explain this fact. However, to reproduce the lake heat budget as well as the water temperatures in spring, summer, and autumn accurately, this is not very meaningful.

The results of the model validation confirm the accurate model calibration. Even smaller total volume weighted values of RMSE and MAE in comparison to the calibration values testify this assessment. These total values are the result of almost solely slight higher and smaller RMSE and MAE values. The only depth with notable higher values of RMSE and MAE is 13 m. As discussed above, difficulties in simulation metalimnion temperatures including the thermocline during the summer with DYRESM are known and also described by Tanentzap *et al.* (2007) and Rinke *et al.* (2010). It can be assumed that higher deviations in the validation simulations in the presented range are the result of adapting the model parameters especially for the years used for calibration (Weinberger and Vetter, 2012). More negative ME values in all depths can also be ascribed to this fact.

When using a modeling approach to investigate the climate-induced alterations of physical lake parameters, it is essential that the model is sensitive to changes in climatic variables. Selected model results for modified AT (Fig. 6(a)–(d)) demonstrate that DYRESM reproduces all expected reactions of water temperatures. Increased AT will lead to simulation of (1) warmer epilimnion temperatures, especially in summer, and (2) colder temperatures in the upper hypolimnion during summer and autumn. Both variations can be attributed to an earlier onset of summer stratification, which is induced by the warmer AT, and the subsequent shallower position of the thermocline. In consequence of the earlier onset of summer stratification, heat flux from the epilimnion in deeper layers is prevented and more energy remains in the epilimnion. Subsequently this energy lacks in the upper hypolimnion to heat this layers of the lake. Furthermore, warmer hypolimnion temperatures (3) are simulated, since the AT is also increased in the winter half-year. A decrease in AT causes the model to simulate (4) colder temperatures in the entire water column. The differences between Figures 6(a) and 6(c) show that the model is able to satisfactorily reproduce changes induced by seasonal variations. Furthermore it can be detected that deep hypolimnion temperatures are only subject to change if modifications of AT values in the winter half-year are conducted. The impact of modifications of WS values becomes apparent in Figures 6(e)–(g). The increase of WS effects a deeper location of the thermocline, represented by warmer temperatures at a depth of around 20 m in the summer half-year. The impact of different energy inputs into deeper layers forced by wind-induced mixing during winter is represented in Figures 6(f) and 4(g). These contrary modifications resulted in formations which approximately reflect each other along the vertical axis for all depths and seasons in the simulation. The high degree of changes in water temperatures due to the modified WS values may be caused by applying too high factors (Table IV). Modifications of PC result in smaller degree of changes in the simulated water temperature (Figs. 6(h) and 6(i)). This simulation output is consistent with the assumption that the influence of the amount of PC is very small. But, regardless, it is shown that the DYRESM model is sensitive to changes in PC. Even small changes in GR effect variations in lake water temperatures (Figs. 6(j) and 6(k)). Especially, increased GR values cause the epilimnetic temperatures to rise in summer, representing a higher energy input. When CC values are increased, DYRESM simulates noticeable changes in water temperatures only in the epi- and metalimnion in summer (Fig. 6(l)). The same effect with additional colder autumn temperatures at a depth of about 20 m (Fig. 6(m)) can be observed for greater decreases in CC values. One explanation may be the separate modifications of the input parameters GR and CC, which are strongly related. Even small decreases in VP effect changes in simulated water temperatures. Colder temperatures at the depth of 20 m in autumn indicate longer duration of the summer stratification, which prevents heat exchange from the epilimnion into deeper layers. According to the simulation results, the extension of the stratification period could be a result of higher epilimnion temperatures during the summer. By increasing the VP values, DYRESM simulates a noticeable warming in summer in the epilimnion only. Figure 7(c) projects the alterations caused by a moderate increase in WT, and suggests the idea that not only meteorological but also water temperatures of inflows have an impact on the lake water temperatures (Rueda and Schladow, 2009; Rimmer *et al.*, 2011). This is also accurately reproduced by DYRESM.

Summary and Conclusions

In summary, it can be noticed that simulations of water temperatures by DYRESM are sensitive to changes in all meteorological parameters as well as to changes in the water temperature of the inflow. When the model was forced with modified input parameters, all simulation results yielded deviations from the simulation results obtained when it was forced with the initial settings. All those deviations are in accordance with the expected influence that alterations of each respective input parameter would have on the heat budget and the dynamics of the lake. As expected, the greatest influences can be detected for modifications of AT and WS values. Varying only one meteorological input parameter is not representative of the conditions of a changing climate. Additionally, constant alterations are not able to project single extreme events or strong seasonal changes. However, this modification approach is suitable to observe the sensitivity of the model to changes in meteorological input conditions, because the direct influence of each input parameter can be examined separately.

In conclusion, as shown in this paper, it is possible to use the hydrodynamic lake model DYRESM to simulate changes in the water temperatures of Lake Ammersee in changing climate conditions. The model meets the requirements of representing apposite water temperatures and reproducing all annual stratifications as well as being sensitive to changes in meteorological input parameters. The predicted change in the climate may have an impact on the stratification conditions and mixing behavior of lakes (Danis *et al.*, 2003; Danis *et al.*, 2004). This study was able to show that DYRESM is also able to simulate those internal thermal characteristics and, additionally, that the model provides robust and reliable results for long-term simulations over multiple years. The execution of the sensitivity analysis has shown that the model reproduces changes with at least monthly resolution which can be accurately differentiated in all depths and layers. Hence, this study provides another contribution demonstrating the potential application of model techniques to investigate the impact of climate change on lakes and to help to reduce the lack of knowledge in this field of research (Fang and Stefan, 2009; MacKay *et al.*, 2009; Williamson *et al.*, 2009). It was possible to determine that the model meets the requirements for coupling with regional climate models in order to carry out simulations of potential future conditions. Furthermore, after this successful calibration and validation of the model on the study site, it is now possible to use a coupled thermo- and chemo-dynamic model (DYRESM-CAEDYM) to investigate the future ecological conditions of Lake Ammersee.

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Anhang B

Publikation II:

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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

ABBREVIATIONS

RCM	Regional climate model
WETTREG	Wetterlagen-basierte Regionalisierungs-methode (engl: weather-situation based regionalization method)
DYRESM	Dynamic reservoir simulation model
OMS	Observed meteorology simulation past
WSP	WETTREG-simulations past
WSF	WETTREG-simulations future
DOY	Day of the year
PDF	Probability density function

ELECTRONIC SUPPLEMENTARY MATERIAL
The online version of this article (DOI:10.1007/s00382-014-2259-5) contains supplementary material, which is available to authorized users.

1. Introduction

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

The sensitivity of lake-ecosystems to changes in their environment makes lakes to be sentinels of climate change (Adrian et al. 2009; Williamson et al. 2009a). Alterations in the local meteorology as the driving force for the processes of lake warming, cooling, and mixing will affect the physical limnology (Jones et al. 2010; Winder 2012; Sahoo et al. 2013). By simulating lake water temperatures with hydrodynamic models, these limno-physical alterations can be projected onto the variations in the temperature profiles. A suitable approach, albeit it is still in its infancy (Elliott et al. 2005), to simulate future lake conditions as a response to climatic change, is to force hydrodynamic lake models with RCM data (Weinberger and Vetter 2012). The knowledge regarding changes in lakes, which might result from climate, is vital for future water management (Niedda and Pirastru 2012).

Therefore, in this study, we applied data from the RCM WETTREG [Wetterlagen-basierte Regionalisierungsmethode: weather-situation based regionalization method (Spekat et al. 2010)], which is available for Germany, to detect the impact of climate change on an ecosystem by estimating future conditions of a medium-sized lake. The hydrodynamic lake model DYRESM (Dynamic Reservoir Simulation Model) was forced by WETTREG projection data to simulate the vertical distribution of past and future water temperatures of Lake Ammersee in southeast Germany. WETTREG data have been used previously for climate change impact studies in urban areas (Frueh et al. 2011) and for river flood conditions (Huang et al. 2013), and input data for future hydrological modeling and the uncertainty analysis in southern Germany (Danneberg et al. 2011; Ebert et al. 2011). However, this is the first time that they have been used for future estimations of a complex system such as a lake.

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

The aim of this study is to process WETTREG projection data to drive DYRESM, in order to compare past and future lake conditions. Thus we focus on the following changes resulting from simulations forced with WETTREG projection data to depict the climate change impact on the limno-physics of the lake: (i) the distribution of water temperatures, (ii) the onset and end of the lake stratification, (iii) the vertical and temporal extent of the seasonal formation of the metalimnion, and (iv) the thermocline depth.

2. Study site

Our study site is the pre-alpine Lake Ammersee situated 35 km southwest from Munich/SE-Germany (47°59′ N, 11°7′ E) (see Fig. 1). The lake has a surface area of46.6 km^2, a volume of 1.8×10^9 m^3, an average depth of 36.6 m, and a maximum depth of 83.7 m. Like most lakes nearby and on the eastern Alpine Foothills, the basin of Lake Ammersee has a glacial-morphological origin. Because of this analogous genesis and comparable climatic conditions, Lake Ammersee is considered representative of most of the eastern pre-alpine lakes (Danis et al. 2004; Vetter and Sousa 2012). The mixing regime of the lake is dimictic. A complete ice cover is rare and last occurred in 2006. The main tributary is the River Ammer, which enters the lake from the south and contributes about 80 % of the total annual discharge of the lake. In total, the lake has a catchment area of 993 km^2 (Schaumburg 1996) and is drained by the Amper River in the north. The residence time for the lake is estimated to be 2.7 years (Lenhart 1987; Dokulil et al. 2006).

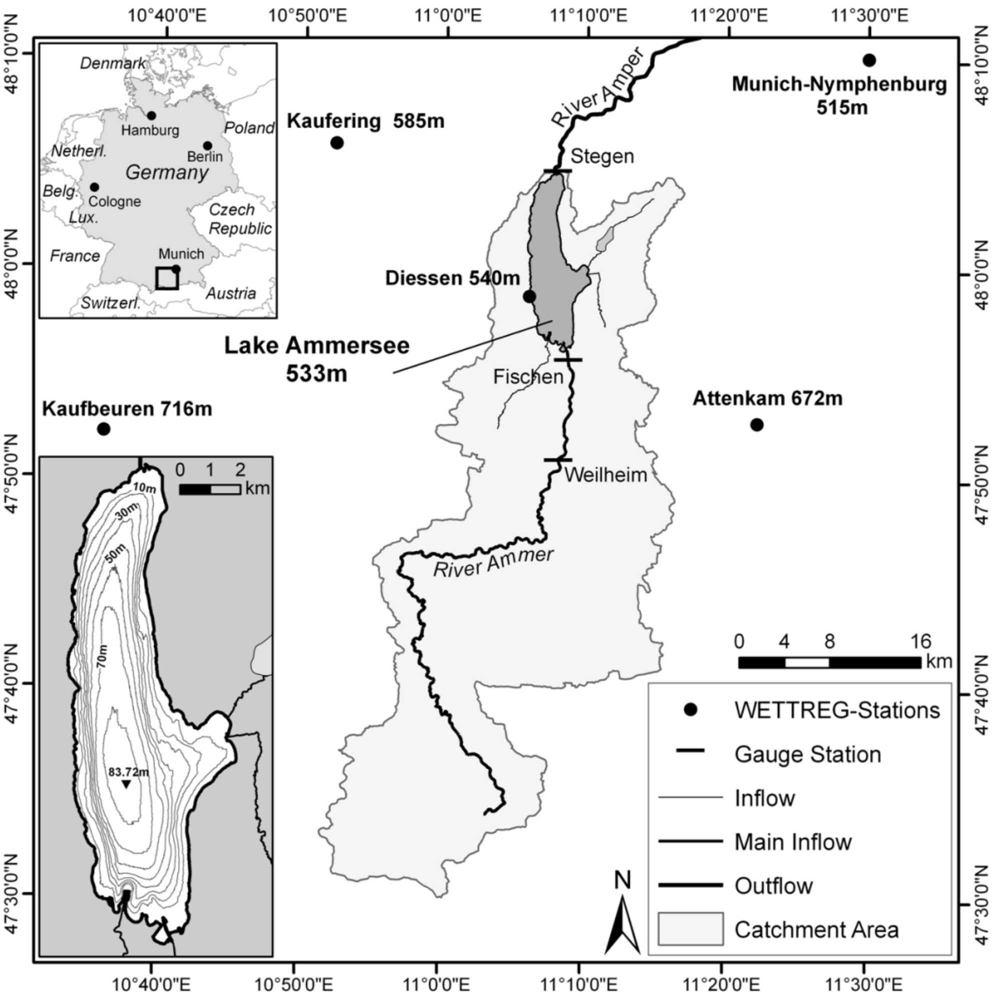

Fig. 1 Location of Lake Ammersee with its catchment area, bathymetry, tributaries and the location of the WETTREG stations (with elevation a.s.l.) as well as gauging stations used in this study

3. Models, methods and data pre-processing

3.1. Model descriptions

3.1.1. Dyresm

For our study, the one-dimensional hydrodynamic model DYRESM (v4.0.0-b2) was used to simulate the vertical distribution of lake water temperature forced by the meteorological data derived from the WETTREG projections. DYRESM was developed by the Centre of Water Research (CWR) of the

University of Western Australia (Imberger et al. 1978; Imberger and Patterson 1981). The model is process-based, using the Lagrangian approach of splitting and merging horizontal layers of uniform properties (Imerito 2007). Thus, layer thicknesses are variable but stay within user-defined limits (Antenucci and Imerito 2003; Tanentzap et al. 2007). DYRESM has been applied to several different lakes and reservoirs around the world (Han et al. 2000; Gal et al. 2003; Abeysinghe et al. 2005; Tanentzap et al. 2007; Rinke et al. 2010; Trolle et al. 2011; Weinberger and Vetter 2012; Bueche and Vetter 2014). In comparison with other one-dimensional lake models, DYRESM satisfactorily reproduces the variability of the water temperature in lake profiles and the seasonal thermocline (Perroud et al. 2009).

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

The one-dimensional approach of DYRESM is very appropriate for simulating the vertical distribution of lake water temperatures, while focusing on alterations in the thermal stratification in this study. This is due to negligible heterogeneities in the horizontal gradients compared with the vertical ones, especially when stratification is established (Perroud et al. 2009; Belolipetsky et al. 2010), and, above all, it is valid for lakes with a simple bathymetry such as Lake Ammersee (see Fig. 1). The model results represent the distribution of lake water temperatures in the profile over the deepest point (83.72 m) in the lake. DYRESM has already been calibrated and validated for Lake Ammersee (Bueche and Vetter 2014). In this previous study, we detected very high sensitivity of the model to changes in the meteorological input data, which provides the sound basis for this investigation into the impact of climate change.

1.1.1. WETTREG

The meteorological data required to force the hydrodynamic model simulations for Lake Ammersee were derived from the RCM WETTREG, which provide past as well as future data. In contrast to numerical RCMs, such as REMO (Jacob et al. 2007), WETTREG is a statistical downscaling approach (Enke et al. 2005). The regional climate projections of WETTREG were forced by data from the global climate model ECHAM5 (Hagemann et al. 2006; Roeckner et al. 2006). It uses the statistical relationships between large-scale atmospheric patterns and local climate, and the characteristics of regional climate for different weather types (Kreienkamp et al. 2010b; Huang et al. 2013). Relationships derived from past or present climate conditions were applied to the future simulations of the global

Table 1: Climatic Parameter an provided by WETTREG in daily resolution

Climatic Parameter	Unit
Maximum of air temperature	(°C)
Average of air temperature	(°C)
Minimum of air temperature	(°C)
Sum of precipitation	(mm)
Average of relative humidity	(%)
Average of pressure	(hPa)
Average of vapor pressure	(hPa)
Sum of sunshine duration	(h)
Average of cloud cover	(octas)
Average of wind speed	(ms^{-1})

models. This allows the creation of new time series of characteristics that are significantly different from the current climate, the so-called Trans Weather patterns (Spekat et al. 2010; Frueh et al. 2011; Kreienkamp et al. 2011). WETTREG data are only available for locations with climate observations, because of the need for observation data to derive the correlation matrices for the observation period, in order to calculate climatic predictions (Huang et al. 2013). For this purpose, the dense network of meteorological stations of the German Weather Service was the basis of the WETTREG projections. Climatic data were provided for 387 stations and additional precipitation data for 2943 stations across Germany (Kreienkamp et al. 2010a). WETTREG data are calculated for the period 1961–2100. For each station, ten simulations are produced (hereafter called realizations), which are equally probable and constitute variants of the projected climate (Huebener et al. 2011; Kreienkamp et al. 2011). The RCM of WETTREG provided 10 climate variables with daily resolution, which are specified in Table 1.

3.2. Model forcing data

To facilitate a consistent comparison between the model results forced by different meteorological input data, a similar period of time was expedient. Reliable observed meteorological, together with hydrological input data for Lake Ammersee (Bueche and Vetter 2014) to drive the hydrodynamic model, were available for the period 07/2001–2010. Accordingly, all simulation periods were determined for the duration of nine and a half years. Therefore, simulations of past conditions for both, forced by observed and by WETTREG projection data, were executed for the exact same timeframe of 07/2001-2010. The period of 07/2041–2050 was chosen for future calculations using the RCM data. As it is practicable (Fang and Stefan 2009), the results of the first 6 months were excluded in order to eliminate possible effects of initial conditions. Thus, the results of the simulations were processed only for the periods 2002–2010 and 2042–2050 consisting of nine complete years.

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

All the meteorological input parameters (air temperature, wind speed, precipitation, cloud cover, vapor pressure, and global radiation) required by DYRESM could be derived from the WETTREG data (see also Table 1). According to the temporal resolution of WETTREG projections, the water temperatures were simulated within a daily resolution. Diessen is the closest station to the lake (see Fig. 1), situated close to the shore. Here only precipitation data were provided, which could be used without any pre-processing. All other meteorological input data were available only for stations from the wider surrounding area (Fig. 1). To obtain data valid for the lake, we conducted a GIS-based spatial interpolation, applying the IDW (Inverse Distance Weighted) method using the equation (Eq. 1) modified after Mitas and Mitasova (1999):

$$v = \sum_{i=1}^{n} v_i / d_i^{\,p} / \sum_{i=1}^{n} 1/d_i^{\,p} \tag{1}$$

where v is the interpolated value, n is the number of points, v_i are the given values at the n points, d_i is the distance to the defined location of the value to be calculated, and p is a coefficient. p is typically taken as 2 (Mitas and Mitasova 1999) and similarly, we determined p = 2 for our study.

Accounting for the different elevations of the WETTREG-stations, the values of air temperature (daily mean, Table 1) were corrected to the reference level of the lake surface (533 m a.s.l.). After Weischet (1980), the vertical gradient of air temperature is expected to be in the range between 0.5 and 0.8 K per 100 m. In this study, we used the gradient of 0.6 K/100 m, which has already been applied to the observed air temperature data for Lake Ammersee (Danis et al. 2003; Bueche and Vetter 2014).

An analysis of the WETTREG wind speed data for the four stations Attenkam, Kaufering, Munich-Nymphenburg, and Kaufbeuren, yielded a bias of values too high for Attenkam. Hence, data for this station were not considered when interpolating wind speed values for the simulation. Taking into account that wind velocities on the lake surface are expected to be much stronger than represented by measured onshore stations, a multiplication factor was applied to the wind data. As this is practicable (Hornung 2002; Perroud et al. 2009; Rinke et al. 2010), the calibration of this factor for Lake Ammersee was executed simultaneously with the other lake specific parameters of DYRESM (Bueche and Vetter 2014). Global radiation is the only meteorological parameter required by DYRESM, which is not supplied by the WETTREG data, but reliable values could be derived easily from sunshine duration data. Therefore, a formula known as the Angström-Prescott equation (Martínez-Lozano et al. 1984; Gueymard et al. 1995), modified after Angström (1924) and Prescott (1940), was applied to calculate global radiation values. Yorukoglu and Celik (2006) give the equation (Eq. 2) as follows:

$$\frac{H}{H_0} = a + b\frac{S}{S_0} \qquad (2)$$

where H is the estimated value from sunshine records, H_0 is the extraterrestrial radiation on a horizontal surface, S is the given sunshine duration, and S_0 is the astronomical day duration (i.e., day length). The coefficients a and b are site-specific depending on geographical position and the day of the year. They have been estimated in a study about long-term behavior of sunshine duration and global radiation for southern Germany (KLIWA 2008), commissioned by local environment agencies and the German Weather Service. Accordingly, a can be assumed as a constant value of 0.20 for the entire area of southern Germany; b was calculated specifically for pre-alpine conditions specified in Table 2. Additionally, Yorukoglu and Celik (2006) provided an overview of all the required definitions and equations used to apply the Angström-Prescott formula (Eq. 2). Sunshine duration data were only available for the Kaufering, Kaufbeuren, and Munich-Nymphenburg stations. The spatial interpolation of global radiation values was executed after converting them from sunshine records of these three stations. All series of the WETTREG data lack information for the 29 February occurring in leap years; thus, values for these days were calculated from the arithmetic mean of the dates before and after.

The hydrodynamic model requires hydrological input data of inflows (discharge, water temperature, salinity) and outflows (discharge). Discharge values within daily resolution were provided by the Bavarian Environment Agency for the Weilheim and Stegen gauging stations (Fig. 1) for the period 1961–2100. These data were simulated using the hydrological model WaSiM-ETH (Water Balance Simulation Model) forced by the WETTREG meteorological data. The model was established at ETH Zurich (Schulla 2012) and consists of several sub models which apply physically based algorithms. WaSim is suitable for long-term water balance and climate change applications (Jasper et al. 2004; Beckers et al. 2009). Model runs for all WETTREG-realizations were conducted and the results subsequently averaged for each day. The daily average of the observed runoff data (2002–2010) for Ammer River amounts to 15.6 m^3s^{-1}. The WETTREG-driven WaSim simulations of runoff yield a reduction in the daily average of 18.3–14.2 m^3s^{-1} from the past (2002–2010) to the future period (2042–2050). The hydrographs of monthly averages of runoff data sets (Fig. S1 of the Online Resource) depict two peaks for the observed and the future simulated runoff, one occurring in spring (due to snow melt) and another during late summer (due to precipitation). This hydrological regime was also

Table 2 Values of the coefficient b of the Angström-Prescott equation calculated for pre-alpine conditions in Germany by KLIWA (2008)

Month	J	F	M	A	M	J	J	A	S	O	N	D
Coeff. b	0.73	0.74	0.74	0.67	0.63	0.63	0.61	0.60	0.62	0.63	0.65	0.70

described by Ludwig (2000) for River Ammer in the 2nd half of the 20th century. The hydrograph of the simulated runoff data for the past shows only one peak during summer. The reasons for this are twofold. First, snowmelt and summer precipitation maximum are overlapping in time for the past scenario. And second, higher precipitation values occur during summer, which also caused the overestimation compared to the measured data.

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

3.3. Processing of simulation results

All processing of the simulation results was carried out separately for each simulation run. The simulated water temperatures for all WETTREG projection realizations of both simulation periods, 2002–2010 in the past and 2042–2050 in the future (in total 20 simulation runs), as well as the output of the simulation forced with observed meteorological data, were processed for the following depths with daily resolution: 0–20 m every meter and 20–80 m every five meters.

Stratification periods and metalimnion characteristics were derived from the vertical distribution of the simulated water temperatures. The parameters were also processed separately in daily resolution for each year of each realization. Heat budget of Lake Ammersee could be considered as independent of the previous year, especially during summer stratification. Hence, 10 realizations with 9 years yielded 90 independent samples and a maximum sample size n_{max} = 90 was available for all statistical analyses and both, past and future WETTREG simulations. Averages and standard deviations were calculated from the processed parameters in order to analyze spatial changes, such as depth of metalimnion boundaries and the thermocline.

3.4. Characteristics of thermal stratification

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

During the stratification period, a separate layer called metalimnion which contains the sharp temperature gradient (thermocline) during the summer stagnation (Boehrer and Schultze 2008), was established between epi- and hypolimnion. The thermocline depth was marked by the plane in the water column of the maximum rate of decrease in temperature (Hutchinson 1957; Gorham and Boyce 1989). Changes in the spatial characteristics of thermal stratification patterns in the water column were indicated by alterations in the metalimnion layer characteristics (depth, thickness). According to Hutchinson (1957), a temperature gradient of 1 Km^{-1} was taken to mark the boundaries of the metalimnion. In detail, the uppermost and the deepest depth featuring this gradient within the water column were taken. Waters within the epilimnion exhibiting strong gradients, which occur often in contact with the surface but show a demarcation to the metalimnion by weak gradients, were not taken into account. The date of metalimnion establishment was defined as the first day of the year when a gradient of 1 Km^{-1} could be indicated in the column and after which this gradient occurred continuously at least in one layer in the water column. The last date was marked by the first day in autumn without a gradient over 1 Km^{-1}.

4. Results

4.1. Changes in water temperatures

4.1.1. Past conditions

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

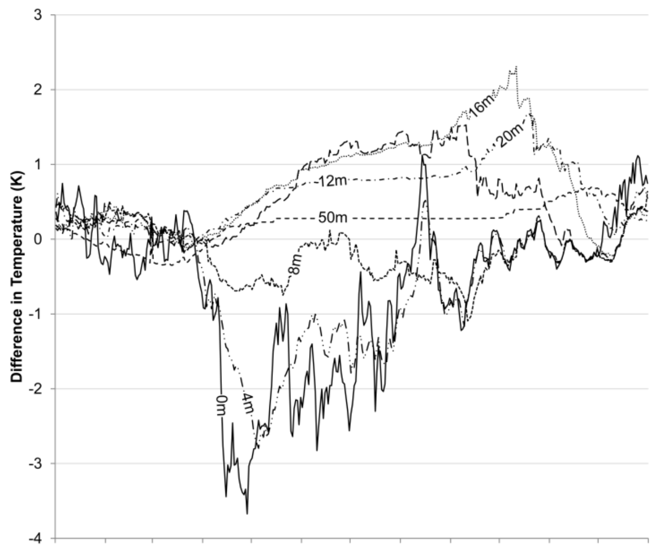

Fig. 2 Differences (T_{WSP}–T_{OMS}) in simulated water temperatures forced by WETTREG projection data to simulation results driven by observed meteorological data for the period 2002–2010. The differences in daily resolution are shown in the course of the year for the depths 0, 4, 8, 12, 16, 20, and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

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

4.1.2. Future conditions

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

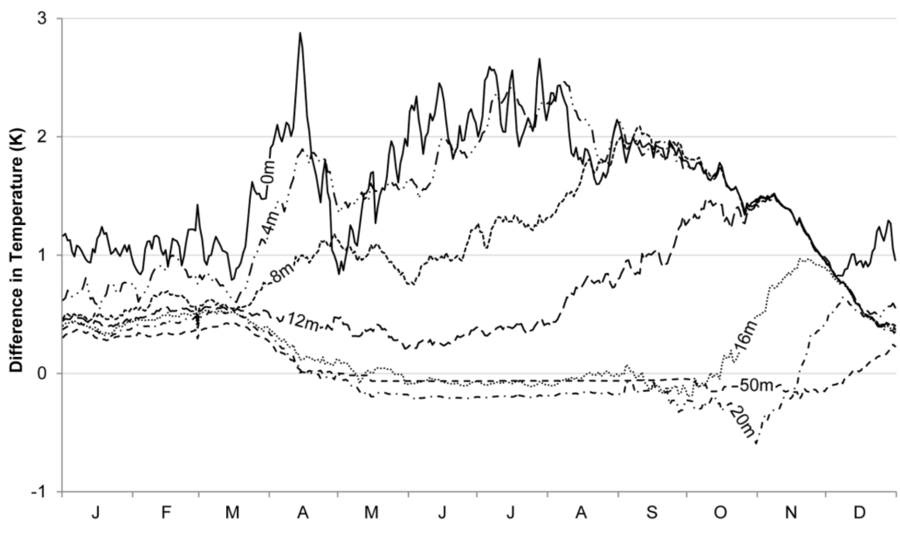

Fig. 3 Differences (T_{WSP}–T_{WSF}) in simulated water temperatures between the periods 2002–2010 to 2042–2050 both forced by WETTREG projection data. The differences in daily resolution are shown in the course of the year for the depths 0, 4, 8, 12, 16, 20, and 50 m

4.2. Changes in water temperatures

Focusing on climate-induced alterations in the thermal stratification of the lake, the changes in stratification period and metalimnion characteristics were derived from the vertical distribution of simulated water temperatures. In average an extension of the stratification period was simulated for the future resulting from an earlier onset (13 days, 102–90 day of the year (DOY)) and a later cessation of the stratification (9 days, 329–338 DOY). The probability density function (PDF) of the simulated dates (given in DOY) of onset and end of the thermal summer stratification are presented in Fig. 4 (respectively plotted for past and future). Additionally shown in this figure are box-and-whisker charts derived from the density functions. The bold lines inside the boxes show the medians of the data. The boxes indicate the interquartile ranges (IQR, difference between 75th and 25th percentile). The IQR measures the spread of the data and is a robust scale parameter (Hannachi et al. 2003). The whisker ends mark the most extreme value not beyond threshold of 1.5 times the interquartile range to the box edges and samples beyond the whiskers, outliers, are shown individually by black dashes. The PDFs of the stratification onset show by their peaks a shift to an earlier establishment in the future. The peaks of the plots for the end of the stratification shift to later date in the future. The maximum density increases from 0.04 to 0.05, equally for onset and end. The medians of the past data series lie beyond the future boundaries of the boxes. The same applies vice versa to the future medians and the past IQRs. This indicates a significant extension of the thermal stratification period for the future. Further features can be inferred from the PDFs and box-plots in Fig. 4. The density functions for the onset date of both past and future show almost the same lowest value. Although simulated to establish earlier in the future, the onset is still not taking place before this date. The PDF of the stratification end in the future depicts a secondary maximum of about 0.01 probability density at the DOY 300. Therefore, the phenomenon of extreme early cessation of stratification in the season still can be expected to occur occasionally for the future, despite a projected in average later end of stratification.

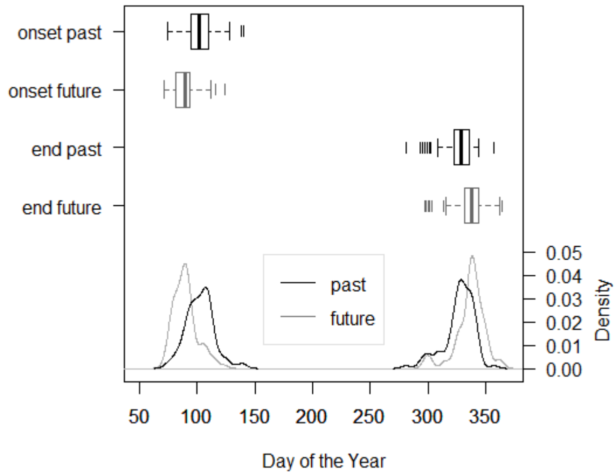

Fig. 4 Probability density function of the simulated dates for onset and end of stratification period driven by WETTREG projection data for past (2002–2010, *black graphs*) and future (2042–2050, *grey graphs*). The box-and-whisker charts represent the median of the data series by the *thick lines* inside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

Alterations in spatial and temporal stratification patterns are indicated by the characteristics of metalimnion. Figure 5 illustrates alterations of the boundaries of this layer ((5a) upper and (5b) lower boundary). For the future upper boundary the average was simulated as being located almost at the same depth for August but shallower by 1–2 m afterwards and about 1 m before. The average of the future lower metalimnion boundary was simulated to be about 1 m deeper until mid-September and afterwards to be located at a similar depth as the past average until the end of October. In combination, the results show an extended metalimnion thickness for the entire period excluding April and early May. Regarding the vertical position of the metalimnion in the water column, no shift was detected for the entire period. Examining the standard deviations of both layer boundary depths, a smaller range of

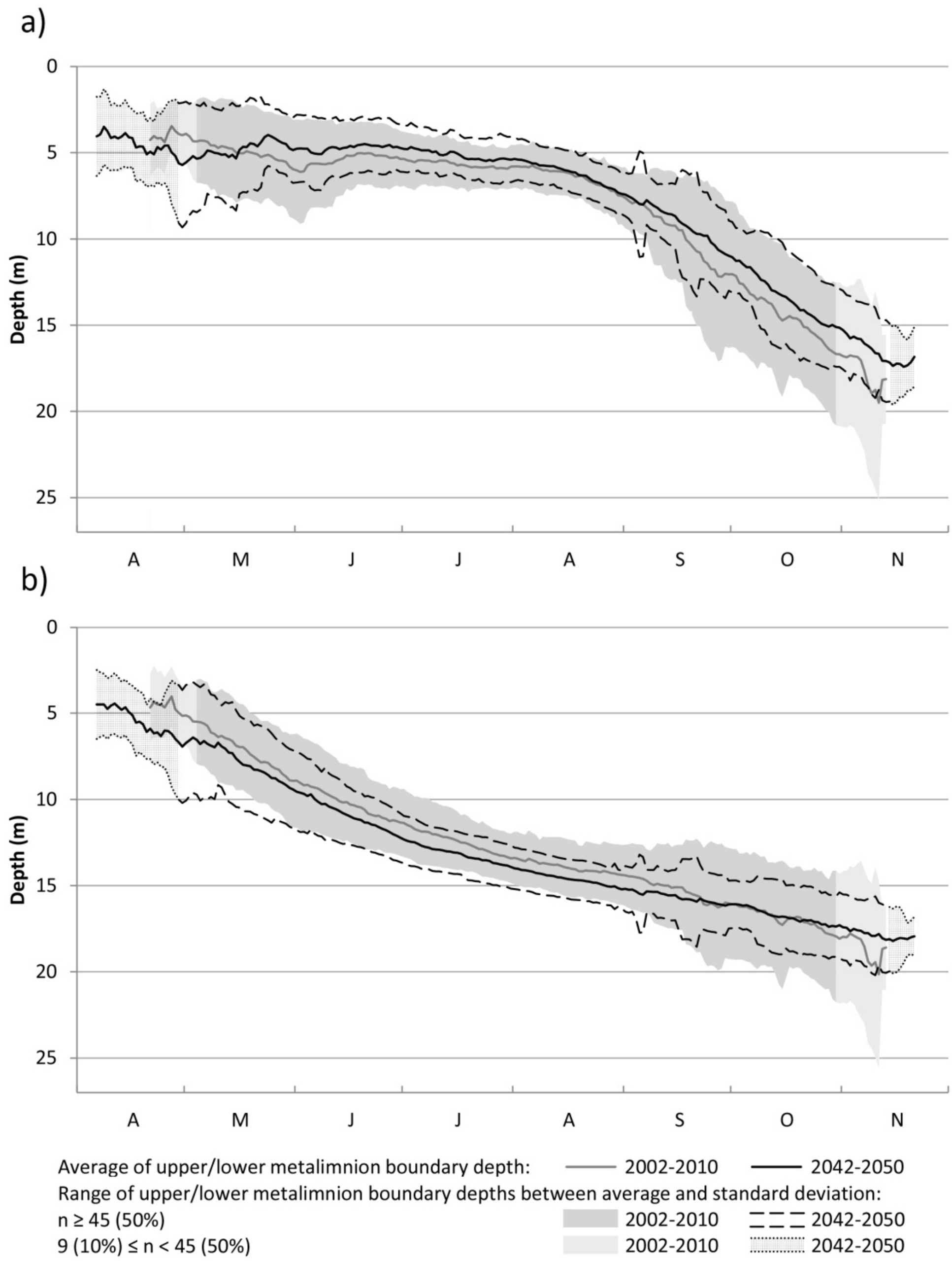

Fig. 5 Simulated depths of metalimnion layer boundaries (a upper, b lower) in the course of a year driven by WETTREG projection data for past (2002–2010) and future (2042–2050). The averages are displayed by *solid lines*. The standard deviations are represented by the edges of the illustrated polygons. The metalimnion boundaries are visualized for two percentage ranges of indication counts of all samples (n_{max} = 90): 10–50 % and ≥ 50 %. The percentage range of <10 % is not shown

2–3 m in both vertical directions was detected in the autumn months. Accordingly, depth variations in metalimnion boundaries in the late season were decreasing including extreme deviations from the average of the boundary depths.

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

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

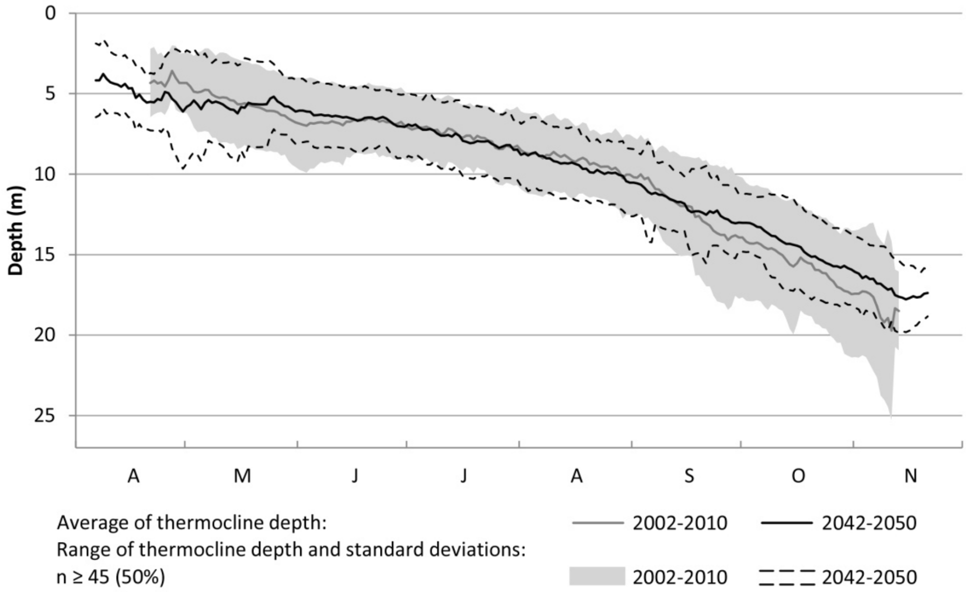

Fig. 6 Thermocline depths in the course of the year simulated for the past (2002–2010) and the future (2042–2050) forced by WETTREG projection data. The averages are displayed by *solid lines*. The standard deviations are represented by the edges of the illustrated polygons. Values are shown, if a metalimnion is indicated, in the water column for at least ≥ 50 % of the respective day of the year

5. Discussion

5.1. Past conditions

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

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

5.2. Estimation of future conditions

The differences, induced by changed climatic conditions, between the simulated past and future water temperatures point out clearly remarkable alterations for the future (Fig. 3). Since the air temperature shows the most intense difference (+1.6 K in average) of all meteorological input variables for the study area between past and future simulation periods, it must be named as the main reason for the altering water temperatures. Additional driving forces for this process are increasing global radiation (+8 Wm^{-2} on average), but also a slightly simulated reduction in wind speed (−0.1 ms^{-1} on average). The indicated differences in climatic variables are in accordance with the values calculated for all of Germany by Kreienkamp et al. (2010a). Warming in the upper layers (surface, epilimnion and upper metalimnion; 0–12 m) during the summer owing to changing climatic conditions was already investigated for past conditions of Lake Ammersee by Vetter and Sousa (2012), as well as for other northern pre-alpine lakes (Livingstone 2003; Adrian et al. 2009), and for lakes in other climatic zones (Coats et al. 2006; Austin and Colman 2007; Rimmer et al. 2011). Therefore, this reaction of the lake estimated by the WETTREG projections corresponds to the anticipated continuation of the process already initiated by a warming climate. Arvola et al. (2010) summarized a weak trend of rising winter water temperatures in lakes throughout Europe for the past few decades. Thus, the simulated higher future winter water temperatures throughout the entire water column of Lake Ammersee represent the ongoing nature of this process; however the values seem to be too high. The projected moderate warming of the complete water body during winter in this period is also in accordance with the specific mixing regime of Lake Ammersee. The influence of meteorological forcing on water temperatures of a dimictic lake during winter is normally interrupted by ice cover. The fact that Lake Ammersee rarely freezes completely (Bueche and Vetter 2014) causes an enhanced sensitivity of the lake to warming climatic conditions during winter. This makes the resulting magnitude of the increase in the future winter water temperatures of the WETTREG projections very plausible. The prediction of a decrease in metalimnetic and hypolimnetic water temperatures during the summer months at first seem to be contrary to a warming climate. But it can be assumed that this is a consequence of an earlier onset of the thermal stratification (Weinberger and Vetter 2014). Stratified conditions prevent the transport of heated surface water by mixing into deeper layers (Livingstone 2003; Straile et al. 2010) which induces warming of hypolimnion waters. As simulated for the future the period of vertical heat transport to the hypolimnion shortens due to an earlier onset of stratification and less heating takes place. This described phenomenon was also simulated by Hondzo and Stefan (1993) and observed by Tanentzap et al. (2008) for other sites.

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

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

The projected alterations in water temperature and stratification patterns could also have an impact on a lake's mixing behavior (Winder 2012). Due to the considerable extension of the stratification period (the prolongation is an increase of about 9 % to the simulated average period during the year of the past), time slots in spring and autumn for circulations will shorten. This could lead to a decrease in holomictic events or even induce a change in the mixing regime to a monomictic lake.

The lake chemistry and biology will also be affected by the simulated alterations of the limno-physical processes (Adrian et al. 2009; Wagner and Adrian 2009). The metalimnetic oxygen minima occurring during the summer stagnation in Lake Ammersee will intensify due to an earlier onset of stratification, which might have a great influence on fish population in the lake (Joehnk and Umlauf 2001). Another effect of incomplete mixing would be low oxygen concentrations in deep waters (Straile et al. 2003). A consequence of changes in stratification is also the strong impact on phytoplankton in the lake (Wagner and Adrian 2011). This could lead to a biomass increase by an earlier phytoplankton bloom due to an earlier onset of stratification, but also to a decrease in biomass due to reduced vertical mixing of nutrients (Bayer et al. 2013).

6. Conclusions

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

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

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Anhang C

Publikation III:

BUECHE T., VETTER M. (2014): Influence of groundwater inflow on water temperature simulations of Lake Ammersee using a one-dimensional hydrodynamic lake model. **Erdkunde**, 68(1): S. 19-31.

INFLUENCE OF GROUNDWATER INFLOW ON WATER TEMPERATURE SIMULATIONS OF LAKE AMMERSEE USING A ONE-DIMENSIONAL HYDRODYNAMIC LAKE MODEL

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With 5 figures and 1 table
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Summary: In this study we implemented groundwater inflow to the one-dimensional hydrodynamic simulation of lake water temperatures to improve the reproduction of the real water temperatures by the simulation results for Lake Ammersee, Southern Germany. As the hydro-geological conditions at Lake Ammersee have not yet been finally clarified, we created simulation scenarios for the hydrodynamic modeling with various characteristics of sub-terrestrial inflow. The scenarios were based on a review of the state of available information regarding the geology of the Ammersee basin. Analysis of the simulation results for each scenario revealed obvious alterations in the reproduction of real-temperature in comparison to those produced without accounting for subsurface inflows. For some inflow characteristics the implementation of groundwater inflow induced more accurate approximations of simulation results to real conditions for almost all depths and seasons. This implies that the hydrodynamic simulation of water temperatures at Lake Ammersee, including subsurface inflow, provides reliable results. Additionally it was possible to estimate roughly the potential conditions of groundwater inflow into the lake.

Zusammenfassung: In dieser Studie wurden Grundwasserzuströme bei der Modellierung der Wassertemperaturen des Ammersees (Süddeutschland) unter Verwendung eines eindimensionalen Wärmehaushaltsmodells berücksichtigt, um die Abbildung der realen Wassertemperaturen durch die Simulation zu verbessern. Da die hydrogeologischen Begebenheiten um den Ammersee noch nicht abschließend erforscht sind, wurden Szenarien mit verschiedenen Eigenschaften der unterirdischen Zuflüsse für die hydrodynamische Modellierung erstellt. Diese Szenarien basierten auf der Auswertung zu den verfügbaren Informationen über die Geologie des Ammerseebeckens. Im Vergleich zu den Simulationsergebnissen, welche nur oberirdische Zuflüsse berücksichtigten, ergaben sich für jedes Szenario deutliche Veränderungen in der Abbildung der realen Wassertemperaturverhältnisse. Die Studie zeigt, welche Ausprägungen der Grundwasserzuströme eine bessere Annäherung der Simulationsergebnisse an die realen Verhältnisse bewirkt. Daraus lässt sich folgern, dass die Wärmehaushaltsmodellierung am Ammersee durch die Berücksichtigung von unterirdischen Zuflüssen belastbare Ergebnisse erzielt und gleichzeitig eine grobe Abschätzung der potentiellen Verhältnisse der Grundwasserzuströme erfolgen kann.

Keywords: Lake Ammersee, hydro geology, hydrodynamic modeling, lake water temperatures, ground water

1 Introduction

As lakes can be considered to be sentinels of climate change (Adrian et al. 2009; Williamson et al. 2009), the simulation of future water temperatures using hydrodynamic models enables the evaluation of impact of changing climatic conditions on lakes. In order to carry out such simulations at Lake Ammersee, Southern Germany, the one-dimensional hydrodynamic lake model DYRESM (Dynamic Reservoir Simulation Model) was successfully calibrated for the site (Bueche and Vetter 2014). As applied in previous modeling studies of Lake Ammersee, e. g. by Joehnk and Umlauf (2001) or Danis et al. (2003), as well as in applications of DYRESM on natural lakes elsewhere, e. g. Gal et al. (2003), Tanentzap et al. (2007), Rinke et al. (2010) or Bayer et al. (2013), only surface inflows were considered. Lake-groundwater interactions have already been included in other hydrological studies, such as the simulation of catchment and lake water balances (Legesse et al. 2004; Niedda and Pirastru 2013) and the investigation of lake-stream networks (Woo and Mielko 2007). The conditions of the subsurface inflow to the lakes were either measured or assumed by previous studies (groundwater level, salinity, or inflow amount), but were not implemented in a hydrodynamic lake model, such as DYRESM, to simulate the influence on the water temperatures.

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It is to be assumed that the inclusion of groundwater inflow in DYRESM would have an impact on the simulation of the lake's water temperatures and heat budget. In order to achieve an improvement in the reproduction of real water temperature conditions compared to the simulation without groundwater inflows, in this study we implement subsurface inflow(s) to the input data of the lake model. So this is the first study simulating the heat budget of Lake Ammersee in consideration of potential subsurface inflows.

Investigations about the hydro-geological dynamics at Lake Ammersee which would enable the derivation of the subsurface inflow characteristics do not exist and measurement data are very rare for the entire wider lake environment and therefore are not representative. Hence scenarios of the characteristics of subsurface inflow are created based on a review of the available information regarding the hydro-geology of the Lake Ammersee basin and then adapted iteratively to improve the simulation results. Using scenarios instead of conduct field measurements enables an expeditious execution of this investigation. As a result of this modeling approach, the subsurface scenario characteristics, which induce the best approximation of the simulated to the real water temperatures, will help to receive a more detailed idea of the local hydro-geological conditions.

In sum, in the present study we want: (i) to show, that DYRESM provides reliable simulation results for the water temperatures of Lake Ammersee by the implementation of groundwater inflow, and (ii) to improve the reproduction of the real lake water temperature conditions in contrast to the simulations considering only surface inflows. In addition, this modeling approach allows a rough estimation of the characteristics of the inflows entering the lake sub-terrestrially.

2 Study site

Located 35 km south-west of Munich, in Southern Germany (47°59'N, 11°7'E) (see Fig. 1), the Lake Ammersee basin is glacial-morphological in origin and is considered to be typical of most pre-alpine lakes both locally and across the eastern part of the northern Alpine Foothills (Danis et al. 2004; Vetter and Sousa 2012). With a volume of 1.8 x 10^9 km³, a surface area of 46.6 km², a maximum depth of 83.7 m, and an average depth of 38.6 m the lake can be characterized as medium-sized. Lake Ammersee currently has a dimictic mixing regime. The occurrence of complete ice cover during winter is rare, last occurring in 2006 (Bueche and Vetter in revision). Under natural conditions the lake is potentially oligotrophic (Kucklentz 2001). After a period of eutrophism, especially before 1980, a process of reoligotrophication has set in as a result of water management activities which have led to an improvement in the lake's current trophic condition (Lenhart 1987; Vetter and Sousa 2012).

The residence time of the lake water is estimated to be around 2.7 years (Lenhart 1987; Dokulil et al. 2006), with the total catchment area covering 993 km² (Schaumburg 1996). The lake is drained by the Amper River in the north (long-term mean discharge: 21.1 ms^{-1}), the main tributary is the Ammer River entering from the south, which contributes about 80% of total annual lake runoff (long-term mean discharge: 16.6 ms^{-1}).

The whole tongue-shaped basin of Lake Ammersee was shaped into Tertiary and Quaternary sediments by the lobe of the Isar-Loisach-glacier (Alefs et al. 1996), which left the Alps to in the north during the Pleistocene. The resulting Tertiary surface has been investigated particularly, with the south mapped by Jerz (1993) and the eastern basin by Krause (2001) (see Fig. 2). After Wolf (2006), the pre-quaternary underground of the Ammer watershed can be considered as an aquiclude of sub-surface waters; however, the isohypses of the tertiary sediments indicate that the deepest point of the lake (449.3 m a.s.l.) lies above the tertiary rocks. The edges of the basin to the sides and to the north are built by late moraines (Würm) characterized by poor water permeability (Wolf 2006). In contrast, the southern part of the basin has been filled since the end of the last glacial by Holocene material including lake beds, alluvial and floodplain sediments of the Ammer River (Czymzik et al. 2010), and turf. The above-described hydro-geological conditions suggest that groundwater inflow largely enters Lake Ammersee from the south, with minor input from the east.

3 Methodology

3.1 Model description

In the present study, the one-dimensional hydrodynamic model DYRESM (v4.0.0-b2) was used to simulate the vertical distribution of lake water temperatures. The numerical model was developed by the Centre of Water Research (CWR) at

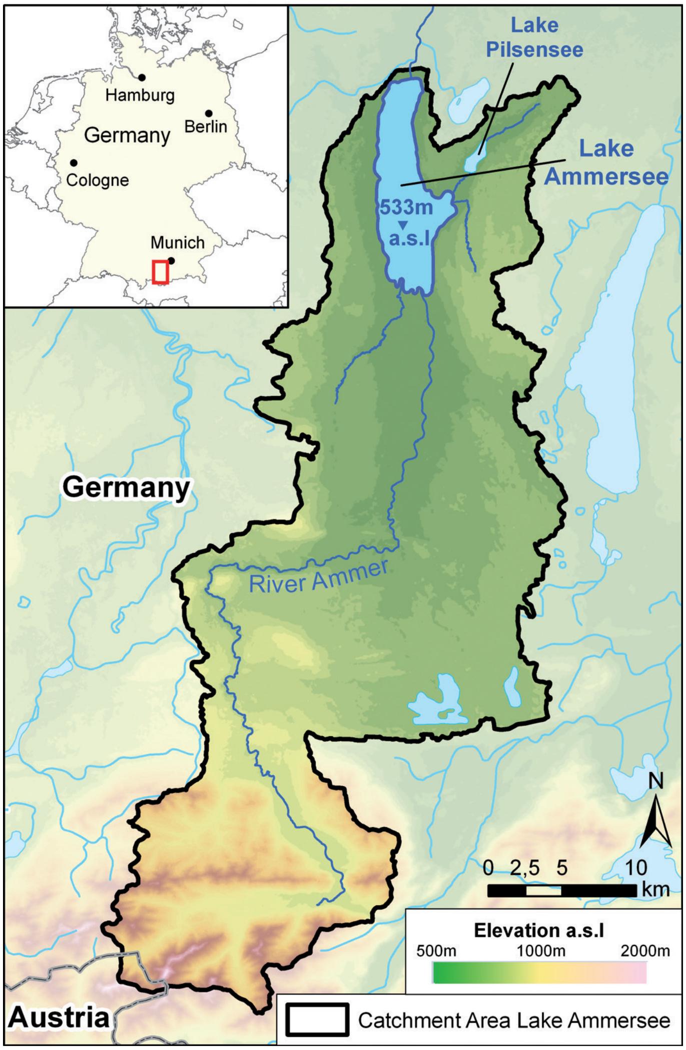

Fig. 1: Catchment area and elevation of Lake Ammersee (Source: Elevation data from ASTER GDEM, a product of METI and NASA)

the University of Western Australia (Imberger et al. 1978; Imberger and Patterson 1981). The model uses the Lagrangian approach of splitting and merging horizontal layers of uniform properties (temperature, salinity and density) (Imerito 2007). The limits of layer thicknesses are user-defined. The model output is the vertical distribution of lake water temperatures in the water column at the deepest point of the lake (83.7 m). The model requires meteorological (air temperature, precipitation, solar radiation, vapor pressure, cloud cover, and wind speed) and hydrological input data (see below) in daily resolution and information about the bathymetry. The model outputs are simulated water temperature profiles in a spatial resolution of < 1 m and temporally in daily resolution, too. Further details regarding the model in general, the process scheme and the input files can be found in our previous papers: Weinberger and Vetter (2012), Bueche and Vetter (2014), Bueche and Vetter (in revision), and Weinberger and Vetter (2014). Antenucci and Imerito (2003) provide a precise description of the variable model parameters stored in the input files, as well as the equations used for the model calculations.

In this investigation, only additional subsurface inflows were implemented; all other hydrological and meteorological input data as well as the simulation period (2002–2007) were not modified from the final settings of the model calibration. Hydrological inflow characteristics are described in DYRESM in terms of discharge (volume), temperature, and salinity; inflows can also be further defined either as surface inflow, which always enters

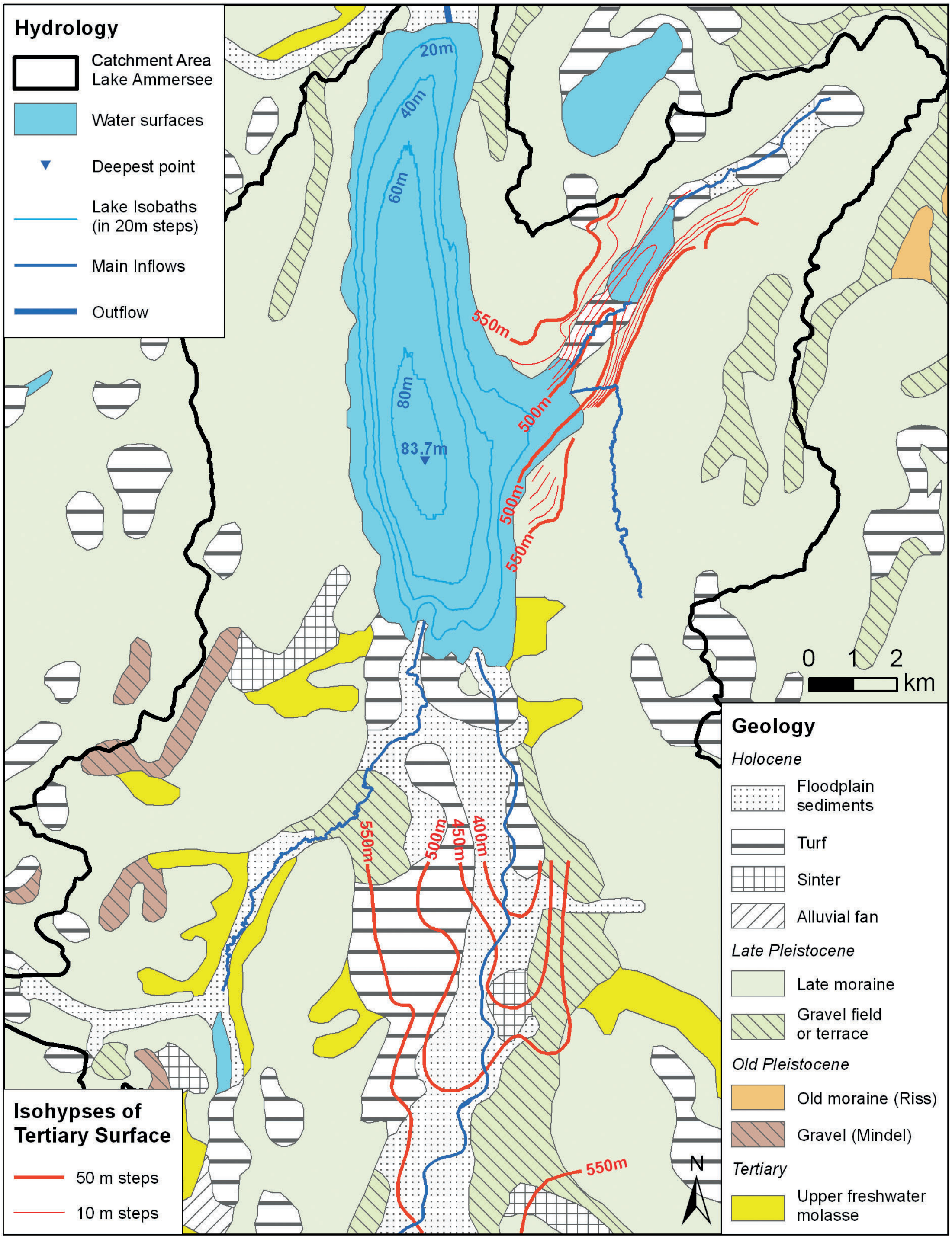

Fig. 2: Geology of the study area showing the major surface inflows to Lake Ammersee and the contour lines of the Tertiary surface (Source geo-data: Bavarian Surveying Authority/Bavarian Soil Information System)

the lake at the varying level of the surface height, or as sub-terrestrial inflow at a fixed height above the lake bottom.

Following limitations have to be considered when simulating lake water temperatures with DYRESM. The use of a constant light-extinction coefficient for the entire simulation period can result in an inaccurate projection of metalimnion temperatures (Gal et al. 2003; Bayer et al. 2013). This may induce an error in the simulation of hypolimnetic temperatures, especially during the summer stratification period (Bueche and Vetter 2014). Furthermore, shortages of the model are the limited capabilities of data post-processing and visualization.

3.2 Simulation scenarios

The present investigation was conducted assuming that the final settings resulting from the model calibration process deliver the optimal reproduction of real water temperatures when considering only surface inflow. A decrease in the error between the simulated and the real conditions in comparison to the results derived from calibration implementing various subsurface inflows could indicate an approximation to the real characteristics of all inflows. Scenarios were therefore created for the characteristics of the sub-terrestrial inflows and the settings improved iteratively. In total, 36 simulation runs were conducted in 6 succeeding groups and analyzed.

Groundwater temperature is roughly equivalent to annual average air temperature (Boehrer and Schultze 2008). In this investigation we assumed a constant water temperature for all sub-terrestrial inflow, which is not subject to change. Hence, all simulation runs were forced by the same water temperature for all subsurface inflows derived from the long-term average air temperature. To this end, the analysis of data series recorded at a meteorological station within the catchment area (1986–2010) and two stations (2002–2010) near the lake shore revealed a value of 8.65 °C.

For the other three variables the scenarios were created, a selection of which can be seen in table 1. The first digit in the scenario numbering system represents the group of simulation runs; the second number after the decimal point serves only to differentiate the scenarios within each group. The shown scenarios cover the variety of the inflow characteristics. The heights of the groundwater inflows are expressed in terms of depth (m) under the surface height of the initial profile (83.7 m), while salinity input data were either assumed to be equal to the observed surface inflow values or were set as constant values for the whole simulation period. The maximum volume of groundwater inflow was defined in advance by the execution of a water balance analysis in our previous calibration study (Bueche and Vetter 2014). The missing amount of total runoff was identified by subtracting all water influxes to the lake (the known inflow and precipitation) from all water effluxes (outflow and evaporation). During this analysis, ca. 257,000 m³ of unaccounted daily runoff for the lake outflow was identified to ensure a stable water balance. This amount represents both unknown smaller tributaries on the surface inflows and the total sub-terrestrial inflow. Hence, we assumed the volume of daily groundwater inflow to be a percentage of this amount and to be constant during the simulation period.

3.3 Statistical analysis

In-situ measurements of water temperatures in the vertical lake profile at the deepest point were available for the depths of 0–10 m in 2-m steps, for 10–20 m in 3-m steps, and for 20–80 in 10-m steps (in total 15 depths). The temporal resolution

Tab. 1: Selection of groundwater inflow scenarios

Scenario	2.1	3.1	3.5	4.5	4.7	4.8	4.9	5.2	6.1	6.2	6.3
Depth (m)	5	5	5/20	3	6	7	4/6	6/30	6	6	6
Volume (%)	50	50	50/20	70	70	70	35/35	70/5	70	65	75
Salinity	c	c	c/c	c	c	c	c/c	c/c	surf	c	c
[value] (PSU)	0.200	0.250	0.233	0.233	0.233	0.233	0.233	0.233	var	0.233	0.233

c = constant; surf = similar to surface inflow; var = variable of the field data is biweekly or monthly. For each date of the simulation period and depth the discrepancy between model-predicted and observed water temperatures – also known as bias error (BE) after Willmott and Matsuura (2005) – could be calculated. It can be assumed that the reproduction of real conditions via the model simulation is improved, when the magnitude of BE decreases. In order to quantify the alterations made between the simulation results of the final calibration run and those of the scenario runs, the difference in BE magnitude was calculated and summarized for each depth (Sum of magnitude differences of BE; SMD). Negative SMD values therefore represent an improvement in the reproduction of real conditions in relation to the results of the final calibration run. In addition the non-negative statistic root mean square error (RMSE) was calculated for each simulation run; larger RMSE values indicate a higher variability of the distribution of error magnitudes (Legates and McCabe 1999; Willmott and Matsuura 2005).

4 Results

In comparison to the simulations produced after the final calibration without subsurface inflow data (hereafter: calibration), the greatest decrease in error when simulating lake water temperatures was attained by the application of scenario 4.7, which involves one groundwater inflow at a depth of 6 m, with a constant salinity of 0.233, and a volume representing 70% of total unknown lake inflow. SMD and RMSE values, as well as the differences in RMSE values with respect to the calibration for 15 depths and the volume weighted total for the entire water column, are shown in figure 3. The same scenarios are specified as in table 1. In order to simplify the interpretation of the statistics, negative SMD values indicating an improvement in the reproduction of real conditions are colored green, with positive SMD values indicating the opposite displayed in red. Differences in RMSE values are colored in a similar way; the more intense the shade, the greater is the deviation in the simulation results. As

Scenario	Cal	2.1	3.1	3.5	4.5	4.7	4.8	4.9	5.2	6.1	6.2	6.3
SMD (K)												
Depth (m) 0m		1.98	3.56	3.51	0.67	-1.16	-0.64	1.18	1.21	0.76	0.03	0.46
2m		1.59	5.25	5.73	2.46	-0.57	0.89	0.74	3.23	0.36	1.31	1.61
4m		3.54	5.35	3.42	1.65	-0.01	-0.61	-0.18	3.96	0.19	2.06	1.31
6m		-1.87	7.55	0.78	1.18	-1.08	-0.37	-4.50	2.92	1.06	3.49	2.43
8m		-2.57	-2.53	-2.32	0.64	-3.16	-3.97	-4.99	-1.16	-1.77	-2.62	-0.84
10m		-0.74	4.74	3.45	-1.07	-4.27	-8.76	-3.60	-4.16	-0.74	-8.74	0.15
13m		-1.80	-8.32	4.07	-0.90	-2.78	-1.97	-3.29	-5.37	-0.72	-3.11	0.68
16m		-1.41	-5.76	-2.64	-6.02	-0.19	-2.63	-3.26	-3.90	-0.17	0.27	-1.28
20m		0.36	5.60	2.12	2.39	0.52	-2.98	2.15	0.48	1.79	0.51	-0.95
30m		0.05	0.96	0.23	-2.14	-2.10	-1.03	-0.89	-1.87	2.72	0.59	-1.79
40m		-0.67	0.69	-0.20	-1.77	-1.52	0.00	-1.24	0.28	0.78	1.15	0.58
50m		-0.80	0.66	-0.39	-0.45	-0.66	-0.20	-0.94	0.05	1.08	1.22	0.65
60m		-0.68	0.57	-0.38	-0.63	-0.60	-0.14	-0.70	-0.21	1.13	1.02	0.40
70m		-0.30	0.41	0.01	-0.26	-0.65	-0.14	-0.70	0.16	1.41	1.12	0.61
80m		-0.20	0.38	0.21	-0.04	-0.70	0.58	-0.12	0.32	1.65	1.23	0.99
total		**-4.55**	**19.44**	**13.83**	**-7.28**	**-17.99**	**-21.51**	**-16.37**	**-7.07**	**13.98**	**2.34**	**0.44**

RMSE (K)	Cal RMSE	2.1 RMSE	Δ	3.1 RMSE	Δ	3.5 RMSE	Δ	4.5 RMSE	Δ	4.7 RMSE	Δ	4.8 RMSE	Δ	4.9 RMSE	Δ	5.2 RMSE	Δ	6.1 RMSE	Δ	6.2 RMSE	Δ	6.3 RMSE	Δ
Depth (m) 0m	1.14	1.19	0.05	1.22	0.08	1.18	0.04	1.16	0.02	1.13	-0.01	1.14	0.01	1.16	0.02	1.17	0.04	1.17	0.03	1.15	0.01	1.14	0.00
2m	1.00	1.05	0.05	1.09	0.10	1.06	0.07	1.04	0.04	0.97	-0.02	1.01	0.01	1.02	0.03	1.05	0.06	1.02	0.03	1.02	0.02	1.04	0.04
4m	0.89	0.94	0.05	0.97	0.08	0.90	0.01	0.91	0.02	0.86	-0.03	0.86	-0.03	0.88	-0.01	0.92	0.03	0.89	0.00	0.92	0.03	0.89	0.00
6m	1.07	1.01	-0.05	1.10	0.03	0.95	-0.12	1.06	-0.01	1.05	-0.02	1.02	-0.05	0.95	-0.11	1.12	0.06	0.98	-0.09	1.02	-0.05	1.01	-0.05
8m	1.53	1.34	-0.19	1.36	-0.16	1.24	-0.29	1.46	-0.07	1.31	-0.21	1.30	-0.22	1.28	-0.24	1.16	-0.37	1.42	-0.10	1.32	-0.21	1.36	-0.16
10m	1.40	1.24	-0.16	1.39	-0.01	1.35	-0.05	1.33	-0.07	1.23	-0.17	1.17	-0.23	1.25	-0.16	1.21	-0.19	1.13	-0.27	1.18	-0.22	1.23	-0.17
13m	1.79	1.78	-0.01	1.44	-0.34	1.66	-0.13	1.84	0.05	1.72	-0.06	1.73	-0.05	1.65	-0.13	1.52	-0.27	1.80	0.01	1.72	-0.06	1.80	0.01
16m	1.42	1.34	-0.08	1.03	-0.39	1.19	-0.23	1.18	-0.24	1.38	-0.04	1.28	-0.14	1.29	-0.13	1.18	-0.24	1.38	-0.04	1.41	-0.01	1.28	-0.14
20m	1.12	1.10	-0.03	1.18	0.06	1.13	0.01	1.11	-0.02	1.11	-0.02	1.03	-0.10	1.07	-0.06	1.07	-0.05	1.10	-0.03	1.11	-0.02	1.04	-0.08
30m	0.99	0.99	0.00	0.99	0.00	0.99	0.00	0.95	-0.04	0.96	-0.03	0.97	-0.02	0.96	-0.03	0.95	-0.04	1.04	0.05	1.00	0.01	0.95	-0.04
40m	0.78	0.76	-0.02	0.79	0.00	0.77	-0.01	0.75	-0.03	0.75	-0.03	0.78	-0.01	0.75	-0.03	0.78	0.00	0.79	0.00	0.79	0.01	0.79	0.00
50m	0.66	0.64	-0.02	0.67	0.01	0.64	-0.01	0.63	-0.02	0.63	-0.02	0.65	-0.01	0.64	-0.02	0.65	-0.01	0.67	0.02	0.67	0.01	0.66	0.00
60m	0.64	0.62	-0.02	0.65	0.01	0.63	-0.01	0.62	-0.02	0.62	-0.02	0.63	-0.01	0.63	-0.02	0.63	-0.01	0.66	0.02	0.65	0.01	0.64	0.00
70m	0.61	0.59	-0.02	0.62	0.00	0.59	-0.02	0.58	-0.03	0.59	-0.02	0.60	-0.01	0.60	-0.01	0.60	-0.02	0.62	0.01	0.61	0.00	0.61	-0.01
80m	0.62	0.60	-0.03	0.62	0.00	0.60	-0.02	0.59	-0.03	0.61	-0.02	0.61	-0.01	0.60	-0.02	0.60	-0.02	0.63	0.00	0.62	-0.01	0.62	-0.01
total	**1.01**	**0.98**	**-0.03**	**0.98**	**-0.03**	**0.97**	**-0.04**	**0.98**	**-0.03**	**0.97**	**-0.04**	**0.96**	**-0.05**	**0.96**	**-0.06**	**0.95**	**-0.06**	**1.00**	**-0.01**	**0.99**	**-0.02**	**0.97**	**-0.04**

Scale of RMSE (K): 0 – 1.5 – 3

Fig. 3: SMD, RMSE and differences in RMSE values for simulation results of a selection of scenarios for the groundwater inflow characteristic (specified in Tab. 1). The statistics are given for 15 depths and the volume weighted mean of the total water column

the figure shows, scenario (sc.) 4.7 yields negative SMD values for the entire lake profile with the exception of a small positive value for a depth of 20 m. Moreover, this simulation setting resulted in a reduction in the RMSE at all depths. The simulation results for all other scenarios exhibit at least for some depths, either positive SMD or higher RMSE values, or even both.

The constant salinity value of 0.233 represents the average for the observed surface inflow during the simulation period. Varying salinity input values equal to those of observed surface inflow (e. g. sc. 6.1) induced no better reproduction, as demonstrated by the mainly positive SMD values in the water column. For water temperatures simulated using a higher constant salinity value of 0.25 (sc. 3.1), although the highest RMSE values at depths of 8–16 m were reduced, very high positive SMD values occurred at the epilimnion and for the total value. Smaller constant salinity values (e.g. sc. 2.1: 0.20) resulted in mostly negative SMD values, but high positive values at depths of 0–4 m indicate no improvement in the reproduction by the simulation.

The statistics calculated for deep inflows at over 10 m depth (data not shown) revealed degradation in reproduction quality. For shallower depths of groundwater inflow (< 10 m), the use of a depth of 6 m, which is equivalent to a height of 77 m above the lake bottom, resulted in the best improvement (compare to sc. 4.5 and 4.8). Scenarios involving two different inflow depths (sc. 3.5, 5.2), one shallow and one under the thermocline (deeper than 20 m (Bueche and Vetter in revision)) respectively, also led to a particularly significant degradation of the simulation results. This is especially true at depths of 0–6 m, represented by high positive SMD values. Scenario 4.9, whose two subsurface inflows at shallow depths (4 m and 6 m) are supposed to represent the fact that such flows probably enter the water body across a whole layer and not at single one point, is associated with a noticeable improvement in reproduction accuracy within the depth range of 6–16 m (layer which nearly falls entirely within the metalimnion), with SMD values smaller than -3.20 K and a decrease in RMSE values by more than 0.1 K. However, relative to that of scenario 4.7 the quality of reproduction at the lake surface is degraded.

The scenarios simulating less (sc. 6.2: 65%) or more (sc. 6.3: 75%) than 70% of the unknown inflow amount resulted in distinct decreases in the accuracy of water temperature reproduction, with positive SMD values observed down almost the entire water profile. The same result was the case when an even lower (< 65%) or greater (> 75%) inflow volume was simulated (not shown).

The degree of alteration of the three varied inflow variables (volume, depth, and salinity) can hardly be quantified due to their different value ranges and units. Hence, no separate sensitivity analysis is performed for the simulation of water temperatures. Nevertheless, the simulation results attest a high sensitivity for all three parameters. As discussed above on the scenarios 6.2 and 6.3, a modified groundwater inflow of 5% induces significant deviations in the simulation results. The same applies to the salinity of the inflow (compare sc. 2.1 and 3.1) and the depth (e.g. sc 4.7 and 4.8).

Detailed differences between the simulated water temperatures produced by the calibration runs and scenario 4.7 and those derived from in-situ measurement are displayed in figure 4 for each date of observation during the simulation period. Regarding surface (0 m) temperatures, only slight deviations (improved and decreased accuracy) from the two simulations were induced by the application of sc. 4.7., although higher divergences (> 0.5 K) are always associated with a reduction in bias, e.g. for the summers of 2006 and 2007. At a depth of 8 m, peak differences in the simulated water temperatures, which occur during the summer months, were distinctively reduced, with a maximum deviation decrease of around 2 K (2004). The highest RMSE value for the entire water column was calculated for the calibration at 13 m depth. After applying scenario 4.7, although the maximum RMSE was again observed at 13 m, the graph of temperature differences reveals only moderate deviations from in-situ measurements, both increasing and decreasing almost in balance. Regarding hypolimnion temperatures, represented by the 40 m line in figure 4, only slight deviations were induced by implementing groundwater inflow, with a constant error reduction observed for the period 2005–2007.

The spatial pattern of water body temperature alterations after the implementation of sc. 4.7 is presented in figure 5. Figure 5a illustrates the discrepancy (i.e. error) between calibration and in-situ data. An analysis of this figure reveals an overestimation of upper water body temperatures (0–20 m) for the months June-October, with a maximum in September. For the rest of the year and within the hypolimnion (20 m to bottom) in general, this simulation yields an underestimation. Figures 5a and b, the latter of which displays the differences between simulated and calibration water temperatures, to-

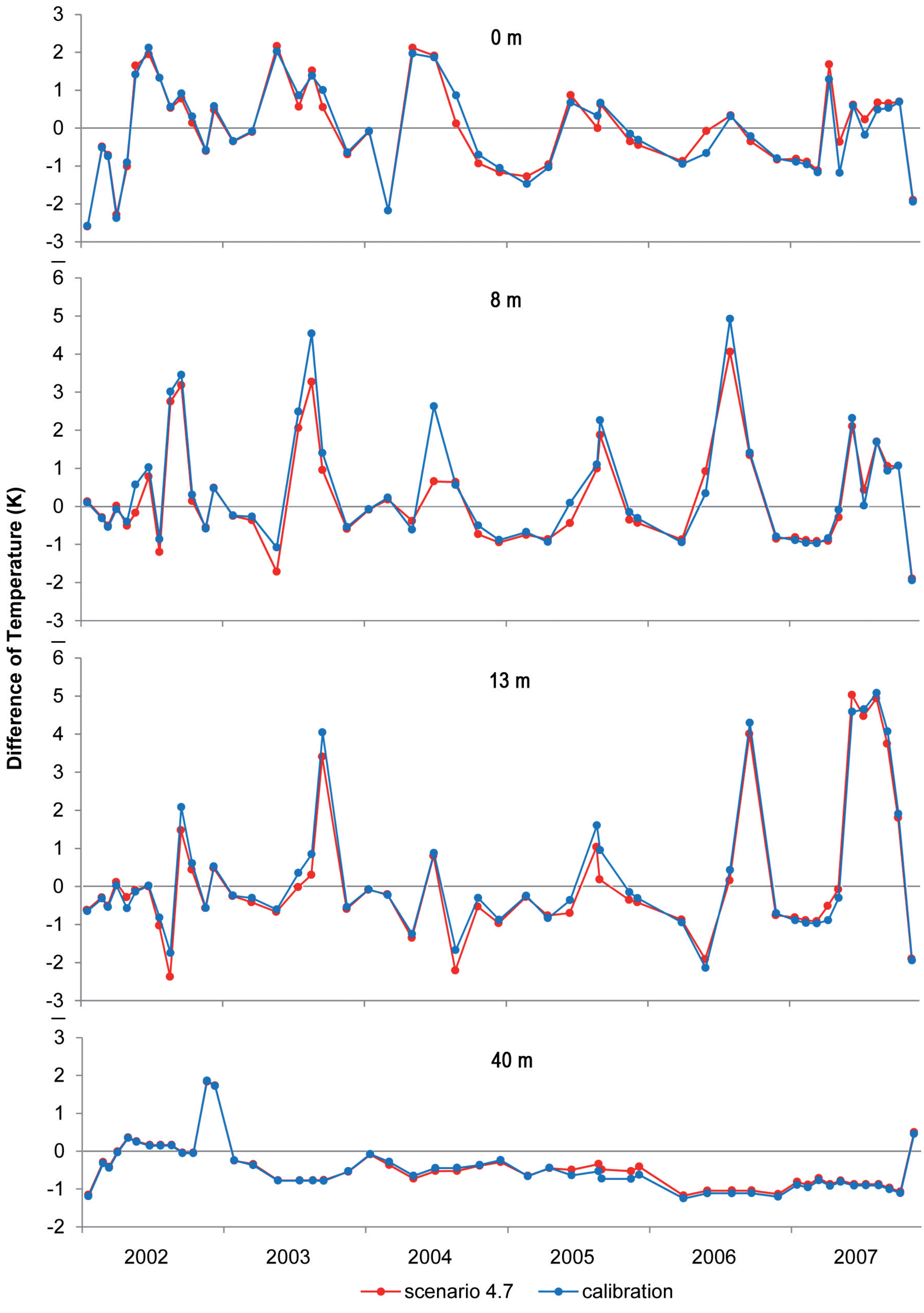

Fig. 4: Deviation of simulated water temperatures (calibration and scenario 4.7) from in-situ measurements for depths of 0, 8, 13, and 40 m

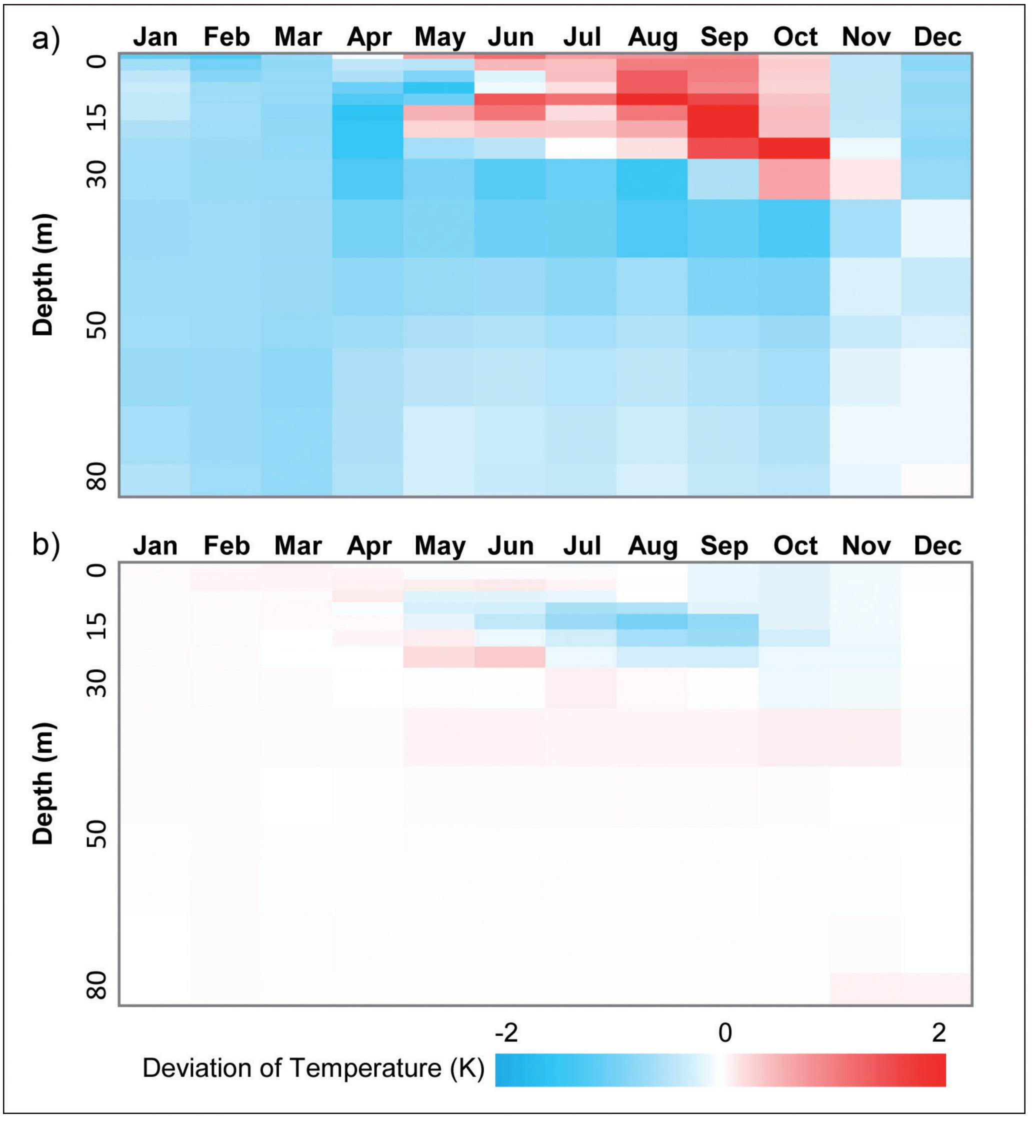

Fig. 5: (a) Monthly deviation averages of simulated (calibration) water temperatures and (b) the alterations induced by scenario 4.7

gether indicate that the reduction in deviations observed after the simulation of water temperatures is not only considerable (up to 1 K), but that it also occurs in a converse spatial pattern, i.e. a reduction in overestimated periods and layers, and an increase in underestimated water temperatures.

5 Discussion and conclusion

The inclusion of subsurface inflow in the one-dimensional hydrodynamic simulation of Lake Ammersee (see also Fig. 1) led to a considerably improvement in the reproduction of observed water temperatures in comparison to the simulation considering only surface inflows. This shows that DYRESM provides reliable simulation results considering groundwater inflows. Furthermore, the diverging modeling results for the applied scenarios attest a sensitivity of the model to varying groundwater inflow characteristics (Fig. 3).

The best error reduction in the reproduction of the water temperatures was identified in the simulation results for the groundwater inflow characteristics of scenario 4.7. Applying this scenario, a reduction in simulation deviation for almost all depths was achieved, represented by negative SMD values (with the exception of 20 m depth), a decrease in RSME values for the whole simulation period at all depths (Fig. 3), as well as alterations in the monthly averaged deviations as depicted in figure 5. The high degree of this improvement is reaffirmed by the reduction in error within the metalimnion during the summer stratification period. According to Perroud et al. (2009), this particular error can be ascribed to the fact that DYRESM tends to simulate the vertical position of the thermocline at too great depth, especially for the late season. Such an effect could have been reduced by the input of colder water during summer via subsurface inflow, resulting in a shallower thermocline. In comparison to the decrease in error for this depth and season, the slight increase in temperature overestimation for near-surface layers in May and June and the intensified underestimation for a depth of around 10 m during May is slight and not significant. Regarding the general error reduction, the induced decrease in the underestimation of water temperatures in the hypolimnion and throughout the entire water column during winter is not negligible. As a result of the almost constant winter water temperature of around 4 °C, these latter alterations, albeit slight, can be considered a considerable improvement in simulation, especially as this improvement is almost consistent for the mentioned depths/months.

The total SMD value of 4.8 is even smaller than that of 4.7. However, the statistics show two positive values (2 m, 80 m), one more and both higher than SMD values for sc. 4.7. The simulation results produced using the settings of sc. 4.7 providing a better reproduction of observed water temperatures.

The achieved notable improvement is not only represented by the averages of error values, but especially by the spatial and temporal pattern in the annual cycle of errors in the simulated water temperatures (Fig. 5). The implementation of groundwater inflow (sc. 4.7) induced a smoothing of the deviations of the calibration with only very rare and slight exceptions. Although yielding also a high reduction in SMD values, the results of scenario 4.9 show exceptions of smoothing for more data and depths (monthly resolution, data not shown), e.g. an increase of error at the surface, a weaker improvement in the hypolimnion layers and an enhanced underestimation of metalimnion temperatures.

As mentioned in section 2 and as shown in figure 2, the sediments found along the pathways designated for groundwater inflow to the south and east of the lake, including in the region around the Lake Pilsensee draining tributary, are Holocene floodplain sediments and lacustrine clays, which are generally considered as aquicludes due to the very small pore space (Krause 2001). Close to the lake shore, these sediments are mainly covered by turf and moorland, confirming their impermeability. The identified inflow depth of 6 m thus correlates with such hydro-geological conditions in which inflow at higher depths can be seen as negligible. The sc. 4.9 and 4.8 differ to sc. 4.7 only in the depth of inflow (see Tab. 1) varying in a moderate range around 6 m (+1 m for sc. 4.8, -2 m for the half of the inflow amount for sc. 4.9). The only slight improvement of the corresponding simulation results validates an inflow depth of about 6 m.

The best improvement in simulation results was achieved using a constant salinity value throughout the entire simulation period. One explanation for this could be that the time-variable parameter of nutrient input (here represented by salinity) can be projected only via the salinity of surface runoff. The salinity of subsurface inflows is buffered to the long-term average due to the longer retention period of water in the ground, as represented in the simulation input value used in scenario 4.7. However, the precision (three decimals) of the identified salinity value of 0.233 (sc. 4.7) results from averaging the surface inflow data and can only be considered as an approximation.

The result of using a discharge of 70% of unknown runoff during the simulation period cannot be verified by other references in the context of the present investigation. But the remaining 30% of unknown runoff for smaller surface inflows seems to be a realistic assumption. Furthermore it can be assumed that the input of a daily constant discharge is highly applicable to subsurface inflows. Long term variations are not projected in this approach, but intense fluctuations of subsurface discharge are hardly expected in the humid climate of the study area (Kunstmann et al. 2005).

The one-dimensionality of DYRESM is a simplified approach of processes in a lake, but it is very appropriate for the simulation of the vertical distribution of lake water temperatures (Joehnk and Umlauf 2001), especially for lakes with a simple bathymetry such as Lake Ammersee. The preparation of semi-automatic output data processing and visualizing tools enabled a rapid and expedient analysis of the simulation results for this study.

The inclusion of groundwater inflow in the simulation of water temperatures using DYRESM represents a simplified reproduction of real conditions. The identified characteristics of subsurface inflow are therefore only a preliminary approximation and cannot replace detailed hydro-geological investigation. Nevertheless, the results can provide a reliable basic idea of site conditions which have not previously been described in the literature. This simulation approach enables an economical and expeditiously investigation without any measurement campaign of groundwater data. Moreover, such a method is adequate for use in 1-D simulations, as the direction from which subsurface inflows enter the lake is not relevant to this type of modeling approach.

In the present study, an improvement in the reproduction of real-temperature conditions was obtained via the inclusion of subsurface inflow in hydrodynamic modeling using DYRESM. These results thus demonstrate that the latter model can be employed to simulate lake water temperatures when considering groundwater inflow.

It was also possible to roughly estimate the characteristics of groundwater inflows into Lake Ammersee by identifying the most accurate simulation results of those produced by different sub-terrestrial inflow scenarios. In combination with a review of currently available information regarding the geology of the Ammersee basin, obtaining an idea of actual subsurface inflow into the lake should provide a sound basis for further detailed investigation. The next step should be the validation of the characteristics of groundwater fluxes, which were obtained by this simulation approach, with field measurements to involve then the results to a simulation of the chemo-dynamics of Lake Ammersee, e.g. by applying the General Lake Model – Framework for Aquatic Biochemical Models (GLM-FABM).

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