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# The mixing regime of Lake Ammersee

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Abstract

Climate change affects the circulation of lakes and has already induced mixing regime shifts for several sites on the globe. The pre-alpine Lake Ammersee, Germany, is usually dimictic, but exhibits rarely a complete ice cover. Furthermore, it has potentially shown some monomictic years in the past. Based on vertical profile data of water temperatures (WT) and dissolved oxygen (DO) the mixing behavior of the lake was analyzed for the period of 1984-2016. To bridge periods of lacking limnological field data meteorological observations were taken into account and a decision tree was developed to standardize the detection of mixing events and stagnation periods for the study site. The classification of the lake mixing yielded 24 dimictic years and eight monomictic years, which approves the assumption of occasional monomixis in the lake. No evidence of a significant shift in mixing pattern was found. By examining holistic vertical mixing events using the vertical DO distribution, one year without complete overturn (meromictic) was detected. The results indicate that the circulation behavior of Lake Ammersee is marginal between dimictic and monomictic, but no shift in the mixing regime has set in for Lake Ammersee so far.

*Zusammenfassung*

*Der Klimawandel wirkt sich auf das Zirkulationsverhalten von Seen aus und hat bereits in einigen Fällen in verschiedenen Teilen der Erde Änderungen in deren Durchmischungsregimen induziert. Der Ammersee im bayerischen Alpenvorland besitzt normalerweise ein dimikitsches Zirkulationsverhalten. Allerdings ist die Eisdecke auf der Seeoberfläche selten geschlossen, und der See hat möglicherweise bereits in der Vergangenheit in einigen Jahren ein monomiktisches Zirkulationsmuster aufgewiesen. Auf Basis von Messungen der Wassertemperatur (WT) und des gelösten Sauerstoff (DO) im vertikalen Profil des Sees wurde das Durchmischungsverhalten des Sees für den Zeitraum 1984-2016 analysiert. Zur Überbrückung von Zeiträumen ohne limnologische Felddaten wurden meteorologische Messdaten herangezogen. Um den Prozess der Differenzierung von Durchmischungsereignissen und Stagnationsphasen für das Untersuchungsgebiet zu standardisieren, wurde ein Entscheidungsbaum erstellt. Die Klassifizierung der jeweiligen Jahre ergab 24 dimiktische und acht monomiktische Jahre, welches die Annahme eines gelegentlichen monomiktischen Zirkulationsverhaltens belegt. Dabei konnte kein signifikanter Trend für eine generelle Veränderung im Durchmischungsverhalten gefunden werden. Die ebenfalls aus den Daten des DO abgeleiteten Durchmischungstiefen zeigen zudem auch ein Jahr ohne komplette Zirkulation (Meromixis). Die Ergebnisse lassen daraus schließen, dass das Durchmischungsverhalten des Ammersees im Übergangsbereich zwischen dimiktisch und monomiktisch einzuordnen ist, jedoch bis 2016 keine grundsätzliche Veränderung des Durchmischungsregimes stattgefunden hat.*

**Keywords** Lake mixing, Lake Ammersee, physical limnology, dimictic, meromictic

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## 1. Introduction

Vertical mixing is one of the key processes in seasonally stratified lakes (*Kerimoglu* and *Rinke* 2013). As circulation regulates the flux of oxygen and nutrients in aquatic systems to and from hypolimnetic layers (*Modiri-Gharehveran* et al. 2014, *Peeters* et al. 2002), mixing "can have major physical, chemical and biological effects, on the whole lake ecosystem" (*Ambrosetti* and *Barbanti* 2005, p.1). Vertical transport in lakes is strongly affected by meteorological forcing and therefore changes in climatic conditions can be responsible for a lake's mixing regime (*Adrian* et al. 2009, *Butcher* et al. 2015, *Dokulil* 2016, *Hetherington* et al. 2015) shifting from polymictic to dimictic, as predicted for Müggelsee (*Hupfer* and *Nixdorf* 2011), dimictic to monomictic (*Shatwell* et al. 2013), or monomictic to oligomictic, as shown for Lower Lake Zurich (*Livingstone* 2003).

The pre-alpine Lake Ammersee in Southeast Germany is mostly defined as dimictic (*Ernst* et al. 2009, *Hofmann* and *Peeters* 2013, *Joehnk* and *Umlauf* 2001, *Nixdorf* et al. 2004, *Vetter* and *Sousa* 2012). Since a complete ice cover occurs rarely (*Bueche* and *Vetter* 2015) the lake cannot be classified as strictly-dimictic. Referring to *Von Grafenstein* et al. (1994) and *Alefs* and *Muller* (1999) Lake Ammersee has also occasionally shown a monomictic circulation pattern in the past. This presumes that the lake is naturally between a dimictic and monomictic mixing class. Such "margial" lakes are susceptible for mixing regime shifts due to changing climate or anthropogenic influence (*Shatwell* et al. 2016). For Lake Ammersee, *Danis* et al. (2004) simulated a future mixing regime shift from dimictic to monomictic based on the periods of homotherm conditions in the vertical water column.

In this study the mixing behavior of Lake Ammersee is analyzed for the period 1984-2016, particularly in respect to any trend of mixing regime shift has already set in. Based on vertical profile data of WT and DO periods of either holomixis, partial overturn (including the mixing depth), or stagnation (inverse stratification or ice cover) are identified. Subsequently, years are classified as either monomictic or dimictic. The resulting time series of mixing is analyzed to assess whether a significant trend of decreasing dimictic years can be found.

## 2. Study site and Methodology

### 2.1. Study site and data

Lake Ammersee, located in the Bavarian Alpine Foreland, has a glacial-morphological origin (*Kucklentz* et al. 2001). With a surface of 46.6 km$^2$, a maximum and mean depth of 83 m (Fig. 1) and 37.5 m (*Nixdorf* et al. 2004), respectively, the lake can be characterized as medium-sized (*Bueche* and *Vetter* 2014). The theoretical water renewal time is calculated as 2.7 years. The average lake surface level is 533 m asl.

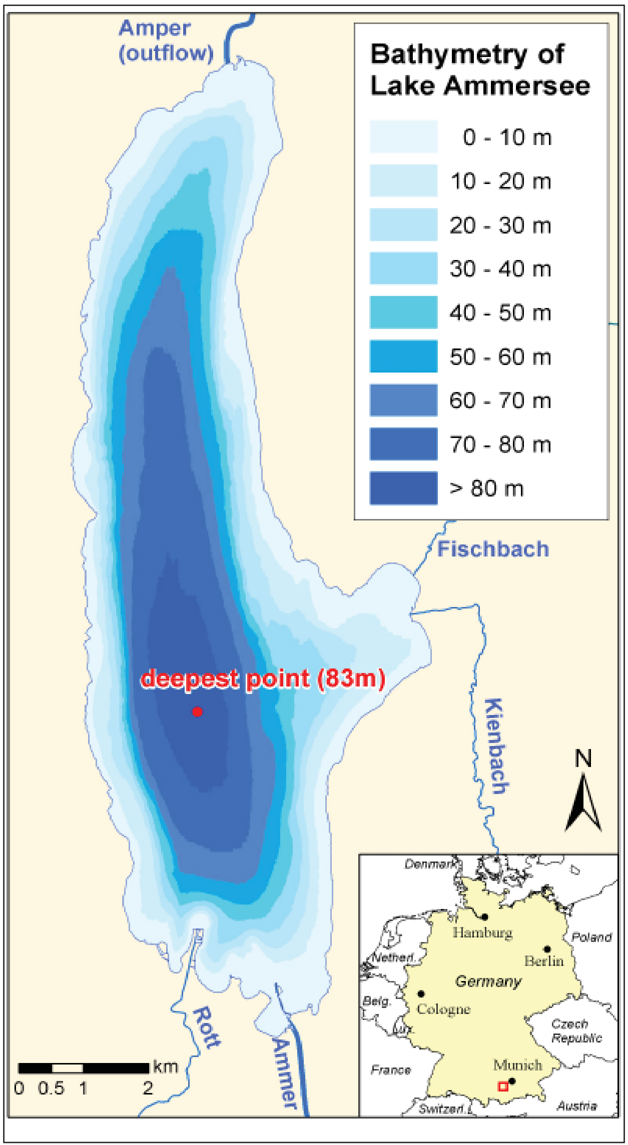

*Fig. 1* *Bathymetry, inflows, and outflow of Lake Ammersee. The main inflow (River Ammer) is marked as thick blue line, other inflows as thin blue lines (Data source: Geobasisdaten © Bayerische Vermessungsverwaltung, www.geodaten.bayern.de)*

The analyzed WT and DO data were sampled by the Water Management Agency Weilheim at the deepest point of the lake (Fig. 1) for the period 1986 to 2016 at biweekly or monthly temporal resolution. The data were taken in 15 depths (surface to 10 m in steps of 2 m, 10 to 20 m in steps of 3 m, 20 to bottom in steps of 10 m) to reproduce the vertical profile of the lake. Due to the simple bathymetry of the lake, these profile data can be seen as representative for the entire water body. Daily data of air temperature and wind speed were available for two meteorological stations in a distance of 7.5 km and 12.9 km to the deepest lake point, which lies exactly between the two stations.

The distribution of DO in the vertical profile of Lake Ammersee is usually very heterogeneous during the stratification period, which is distinctive for this site. In the end of the stratification period the surface mixed layer normally shows oxygen concentrations of > 10 mg $l^{-1}$ whereas low values of < 5 mg $l^{-1}$ beneath the thermocline (metalimnetic oxygen minimum) and of 2 mg $l^{-1}$ and less are found in the bottom layer. The latter two layers with low DO values are separated by the upper hypolimnion with relatively high DO concentrations (*Joehnk* and *Umlauf* 2001). A complete overturn after the cessation of the thermal stratification will result in a homogeneous DO distribution within the vertical profile.

## 2.2 Data analysis

For each year of the period 1986-2016 the circulation pattern of the lake was analyzed. Conditions were classified into partial overturn, complete overturn, inverse stratification and ice cover, using the profile data of WT and DO. For periods without limnological field data daily averages of air temperature (AT) and wind speed (WS) were used to estimate the circulation conditions. The classification for each two-week period was conducted chronologically applying a developed decision tree presented in Fig. 2.

The decision tree is subdivided into 4 sections. The first section applies to two-week periods of available lake profile data (Q1.1) deriving mixing conditions from the gradients of WT ($\Delta_{WT}$) and DO ($\Delta_{DO}$) within the entire water profile. A complete overturn in the lake requires homotherm conditions in the vertical water column, usually around 4 °C for deeper lakes in temperate regions. Therefore periods of potential mixing were identified when $\Delta_{WT}$ ranges between -0.2 and 0.2 °C (Q1.2). A $\Delta_{WT} < 0.2$ °C indicated an inverse stratification, a $\Delta_{WT} > 0.2$ °C was determined as partial overturn. However water masses in lakes are not inevitably to mix completely during homothermy. The distribution of DO concentrations within the vertical profile provides a natural tracer of mixing in lakes (*Holzner* et al. 2009, *Rempfer* et al. 2010, *Straile* et al. 2003). It was also used in this investigation to identify mixing events. As complete overturn will result in a homogeneous DO within the vertical profile, this will be indicated by a small $\Delta_{DO}$. This enables the identification of a holistic mixing process even when data are sampled with a delay after the mixing event. In this study periods of potential complete mixing were identified when $t\Delta_{DO}$ did not exceed 2.5 mg $l^{-1}$ (Q1.3). In the sections 2-4 mixing conditions are classified for two-week periods without available water profile data. Periods of ice cover (Q2) are not derived from field data but from observations (*Büche* 2009, *Lenhart* 1987). In Section 3 two-week periods are classified, which are followed by a period with available field data (Q3.1). In this case $\Delta_{DO}$ can also be used as a tracer to identify complete overturns within the water column by exhibiting small values. However this applies only if the water profile was unmixed at both times before and after (Q3.2), to subsequently be able to attribute the mixing event precisely to the examined two-week period. Additionally, to exclude the effect of a potential increase of $\Delta_{DO}$ induced by DO-consumption after a mixing event, the maximum duration to the next date with available field data has to be limited. Therefore this period is determined to be at least one two-week period (Q3.1). On these terms complete mixing can be excluded by the application of the same threshold for $t\Delta_{DO}$ (Q3.3) as used in Q1.3. A circulation event involving the entire water column is also marked by a significant reduction of $\Delta_{DO}$, even if the value had been below 2.5 mg $l^{-1}$ before. A reduction by at least 1.0 mg $l^{-1}$ (Q3.4.1) identifies a complete overturn within the two-week period. If the questions in section 3 result in unmixed conditions, AT is used to distinguish between inverse stratification and partial overturn (stratified conditions with a positive $\Delta_{WT}$). An inverse stratification is indicated if a period with the duration of at least 10 days with an average of AT ($AT_{avg}$) ≤ -3.0 °C exists. In Section 4 only AT and WS data are used to determine the circulation pattern. Warm conditions will keep or reheat the surface strong enough to prevent complete mixing in the lake and the threshold of $AT_{avg} > 6.0$ °C (Q4.1) is applied to indicate these conditions of a partial overturn. Inverse stratification is identified in Q4.2.1 similarly to Q3.4.2. Complete overturns can be induced by strong

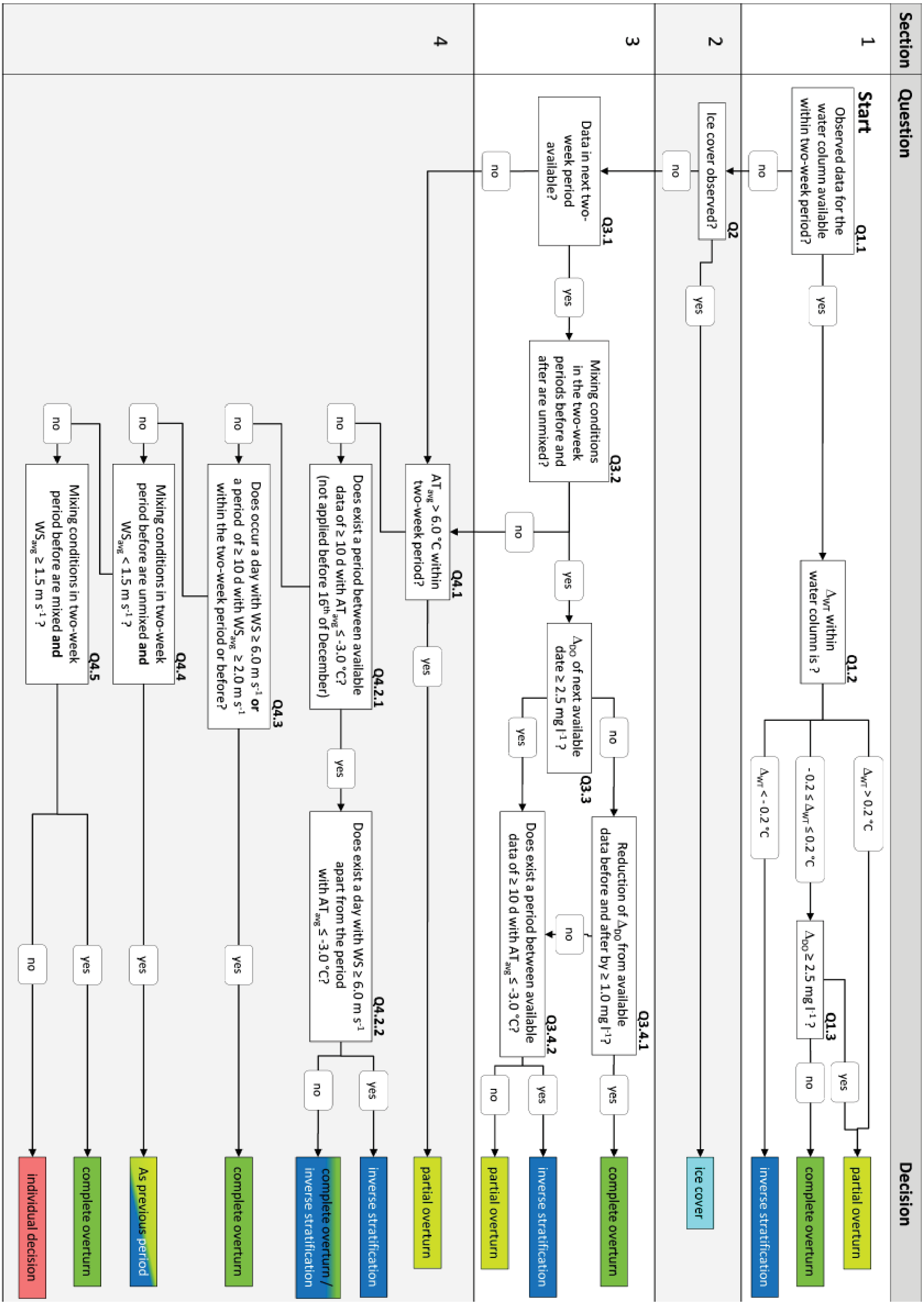

*Fig. 2 Schematic decision tree. Questions (Q) are contained by rectangles and answers by rounded text boxes. Decision classes are colored in the same way as depicted in Fig. 3.*

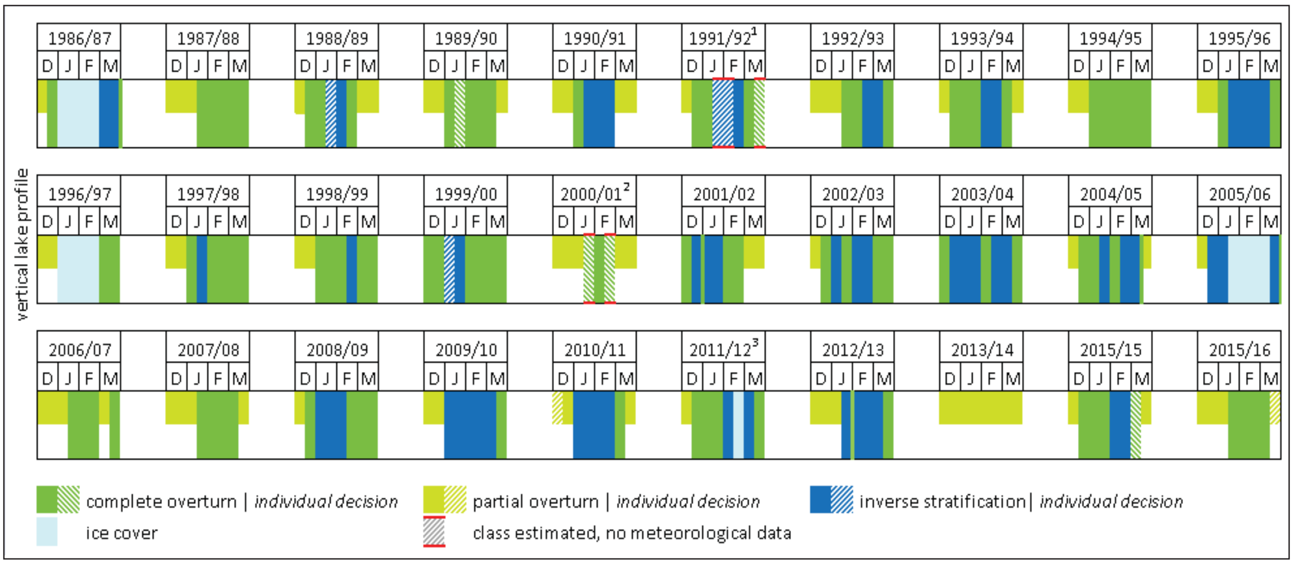

*Fig. 3 Classification for the potential months of mixing (December to March) subdivided in eight two-week periods. The vertical lake profile is colorized entirely for the periods of complete overturn, inverse stratification, and ice cover. Partial overturns are displayed by a schematic colorization of the profiles only halfway from the surface. Small green bars indicate mixing events in the class complete overturn/inverse stratification, if the adjacent period is not a complete overturn either. $^1$No meteorological data available for January – March 1992. $^2$No wind speed data available for January and February 2001. $^3$Lake ice was not observed to cover the surface completely but nearly in February 2012 and is pictured as ice cover in this graph.*

but short events of high wind speeds. These short events can occur within the same two-week period right before an inverse stratification is developing or even by that time, which subsequently leads to the cessation of it. To mark both the event of complete mixing and the occurrence of an inverse stratification, a two-week period is indicated as a combination of both classes if a day with WS of ≥ 6.0 m $s^{-1}$ exists apart from the period of AT ≤ -3.0 °C in the same time slot (Q4.2.2). The same threshold for WS of a single day value is applied in Q4.3 to indicate a complete overturn. Having already excluded intense warm and cold conditions by Q4.1 and Q4.2 in the decision tree before, WS is also considered to mark a holistic circulation event when a period of longer enhanced average WS ($WS_{avg}$) was observed. A threshold of $WS_{avg}$ ≥ 2.0 m $s^{-1}$ over a period of minimum 10 days is applied. By reaching Q4.4 the occurrence of distinctive meteorological events are precluded (Q4.1/Q4.2/Q4.3). Calm wind conditions will not be able to break up a partial overturn or inverse stratification and a value of $WS_{avg}$ ≤ 1.5 m $s^{-1}$ is determined to trace the continuity of the pre-condition (Q4.4). In contrary, values of $WS_{avg}$ > 1.5 m $s^{-1}$ mark the persistence of holistic mixing conditions (Q4.5), as the required wind energy to induce mixing is low when the water body was already mixing completely before. If no condition applies to the examined two-week period the classification has to be implemented by individual decision. This was mainly based on meteorological data but also on expert knowledge. For periods of lacking data, observations of a weather station with in a distance of 22 km were taken into account.

After the application of the decision tree each year was classified either to be dimictic or monomictic. According to *Schwoerbel* and *Brendelberger* (2005) a dimictic mixing regime is characterized by two periods of stagnation and circulation per year, respectively, including at least one complete overturn (holomixis). In this study, a year was defined as dimictic when any period of inverse stratification or even ice cover occurred. Otherwise the year was classified as monomictic. Years without a complete overturn are called meromictic (*Boehrer* and *Schultze* 2008) but have also either a dimictic or monomictic circulation pattern and were classified, too.

As the mixing season for Lake Ammersee was detected not to exceed the time window of December to March, the results are displayed only these four months (see Fig. 3). In accordance with the temporal resolution of the available lake profile data, the lake conditions were defined for eight time slots of two weeks, respectively, each year.

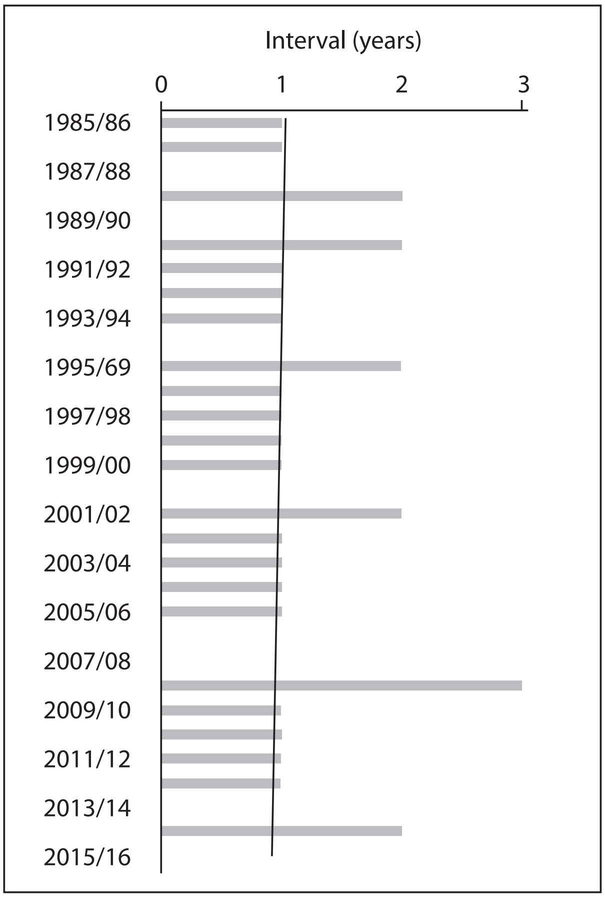

*Fig. 4 Time series of intervals between dimictic years. Annual labels representing the second year of the season, respectively. The line shows the linear trend.*

2.3. Statistical analysis

To detect a monotonic decrease (or increase) of dimictic years the nonparametric Mann-Kendall test is used. Therefore the intervals between the occurrences of dimictic years were calculated. Monomictic years have the value 0 in this time series. The test is applicable for time series with sample sizes > 10 (*Hennemuth* et al. 2013, *Salmi* et al. 2002). Since a complete ice cover was observed in the years 1984/85 and 1985/86 (*Lenhart* 1987) the time series could be extended by two more years to yield n = 31 years. Naturally the interval of the first year (1984/85) could not be calculated and was excluded from the analysis.

## 3. Results

The identified periods of mixing and interrupted circulation, as a result of the application of the decision tree, are presented in Fig. 3. Within the examined three decades occurred years with and without inverse stratification or ice cover. In total, eight monomictic and 22 dimictic years (plus two representing 1984/85 and 1985/86, not shown in Fig. 3) were classified (Table 1). Additionally one meromictic year was found in 2013/14. The lack of a complete overturn in this season results in low DO contents in the bottom near layers throughout the following summer and stratification period. A DO content of 5.8 mg $l^{-1}$ was observed in the depth 70 m in August 2014, which is the lowest value measured in that layer within the whole period (1986-2016) and the only below 6.0 mg $l^{-1}$.

*Table 1 Classification of the mixing pattern in Lake Ammersee*

| Year | Mixing | Year | Mixing | Year | Mixing |
|---|---|---|---|---|---|
| 1984/85 | dimictic* | 1995/96 | dimictic | 2006/07 | monomictic |
| 1985/86 | dimictic* | 1996/97 | dimictic | 2007/08 | monomictic |
| 1986/87 | dimictic | 1997/98 | dimictic | 2008/09 | dimictic |
| 1987/88 | monomictic | 1998/99 | dimictic | 2009/10 | dimictic |
| 1988/89 | dimictic | 1999/00 | dimictic | 2010/11 | dimictic |
| 1989/90 | monomictic | 2000/01 | monomictic | 2011/12 | dimictic |
| 1990/91 | dimictic | 2001/02 | dimictic | 2012/13 | dimictic |
| 1991/92 | dimictic | 2002/03 | dimictic | 2013/14 | monomictic (meromictic) |
| 1992/93 | dimictic | 2003/04 | dimictic | 2014/15 | dimictic |
| 1993/94 | dimictic | 2004/05 | dimictic | 2015/16 | monomictic |
| 1994/95 | monomictic | 2005/06 | dimictic | | |

** derived from observed ice cover only (Lenhart 1987)*

The Fig. 4 shows the intervals between dimictic years. The linear trend suggests a slight decrease of the average interval between dimictic years. The Mann-Kendall test however shows that this trend is not significantly different from a random outcome ($p > 0.1$). Monomictic years emerge as value 0 in this graph and scatter over the examined period.

## 4. Discussion

The analysis of the available WT and DO data combines the investigation of temporal mixing behavior and spatial (vertical) circulation pattern. The total gradients of WT and DO of the vertical profiles are reliable indicators to identify events of complete mixing on the on hand, and periods of stagnation on the other hand. The usage of AT and WS data complements the presented decision tree to a consistent classification tool bridging the periods of missing limnological data. The application of the decision tree enables simultaneously the indication of both short term events of complete mixing and longer phases of prevented overturn.

The individual decision implemented in the decision tree as "last resort" had to be applied only for 11 of 240 two-week periods (4.6 %). The process of the individual decision was relied on meteorological data as well if available, but no thresholds are defined. The lack of meteorological data was the reason for the need of an individual decision in five of these 11 cases. In no case the individual decision had an impact on the classification of the mixing pattern of the season (monomictic or dimictic).

The insignificant trend for the intervals between dimictic seasons is not in accordance to a potential regime shift of dimictic lakes to a monomictic pattern suggested by *Shatwell* et al. (2013) due to climate change. Considering the result of a slight decreasing trend it has to be taken into account, that the time series ends with a monomictic year. Subsequently the next value for a dimictic year is going to be 2 or more, which will lead to an increasing trend, but this effect is expected to remain rather weak. The occurrence of monomictic years scattered over the whole time window and additionally several seasons with only short inverse stratification periods confirming the marginal mixing class of Lake Ammersee. However, the analysis yields also that the lake has not undergone a mixing regime shift yet. Despite increasing summer surface temperatures of Lake Ammersee related to raising air temperatures in the last 3 decades (*Vetter* and *Sousa* 2012) the circulation pattern has been resilient to climate change impact. A stronger impact might result from warmer winter water temperatures, like those simulated for the future by *Bueche* and *Vetter* (2015), which subsequently could induce a regime shift to more monomictic years.

One year without a complete overturn in 2013/14 gives evidence for the occasional occurrence of meromictic conditions in Lake Ammersee. The DO content in deep layers during the entire following year was found to be below the values during the heat wave 2003 in Europe (*Jankowski* et al. 2006), which was associated with a very high stability of thermal stratification in Lake Ammersee. A more frequent occurrence of years without holistic lake mixing can have severe consequences for the lake ecosystem including the vertical distribution and composition of the biota (*Adrian* et al. 2009, *Ito* and *Momii* 2015).

## 5. Conclusion

In this study the mixing behavior of Lake Ammersee of 1984 to 2016 was investigated. Using gradients of water temperature and dissolved oxygen in combination with meteorological observations provides a reliable approach to define dimictic or monomictic years. The presented decision tree can be used as a basis to analyze the mixing behavior of other lakes, however this would require the adaption of the site-specific thresholds of the used tracers. It is found, that Lake Ammersee showed dimictic and monomictic years in the past three decades, which confirms the marginal mixing class of the lake. However, no significant change is detected for the mixing regime of Lake Ammersee in the last three decades. The occurrence of one year without complete overturn recently induced the lowest values of dissolved oxygen content in near-bottom layers ever observed. Hence it is of great interest to find out, if the meromictic seasons 2013/14 will remain a rare event for Lake Ammersee in the future or wheter meromictic years will become more frequent, which would be accompanied by negative impacts on the lake ecosystem (*Dokulil* 2016). Estimations about this and the consequences for its oxygen budget could be provided by simulations using an ecological lake model, e.g. the model framework General Lake Model – Aquatic Ecodynamics Model Library (GLM-AED, *Hipsey* et al. 2013). But such modeling studies require first investigations about the conditions of the past and present, as presented in this study.

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