Kärntner Institut für Seenforschung
Naturwissenschaftliches Forschungszentrum

Climate Change
Impact on Meromictic Lakes of Carinthia

Endbericht

silmas
alpine lakes network

Bearbeitung: Liselotte Schulz
Georg Santner
Roswitha Fresner
Gernot Winkler
Michael Schönhuber

Im Auftrag des Amts der Kärntner Landesregierung, Abteilung 8 (Kompetenzzentrum Umwelt, Wasser und Naturschutz),
Flatschacher Straße 70, 9020 Klagenfurt am Wörthersee

Klagenfurt am Wörthersee, im August 2012

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Flatschacher Straße 70,
9020 Klagenfurt am Wörthersee

Koordination: Kärntner Institut für Seenforschung
Kirchengasse 43,
9020 Klagenfurt am Wörthersee
Dr. Roswitha Fresner

Für den Inhalt verantwortlich: Dr. Liselotte Schulz

Bearbeitung: Dr. Liselotte Schulz
Mag. Georg Santner
Dr. Roswitha Fresner
Gernot Winkler
Mag. Michael Schönhuber, MSc.

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1 Zusammenfassung

Die klimabedingte Erwärmung verursacht Änderungen im Wasserhaushalt eines Sees, wie die Erwärmung des Wasser zu einem frühren Zeitpunkt im Frühling (Endoh et al. 1999), die Verlängerung der Periode in der der See mehr als 10°C aufweist (Jarvet 2000) und die Verkürzung der Periode mit Eisbedeckung und eine Abnahme der Eisdicke (Todd & Mackay 2003). Darüber hinaus zeigen die großen, tiefen Seen südlich der Alpen in jüngster Vergangenheit eine Änderung der Mischungsprozesse (holomiktisch, meromiktisch, monomiktisch, di- und polymiktisch). Das steht im engen Zusammenhang mit den klimatischen Bedingungen in den Wintermonaten der letzten 20 Jahre, die eine progressive Erwärmung der Atmosphäre und eine Abnahme der Windhäufigkeit und –Stärke zeigen. Magnusen et al. (2000) führen eine weiteren Beweis der systematischen Erderwärmung an. Sie konnten anhand von Aufzeichnungen (von 1846 bis 1995) entlang der nördlichen Hemisphäre an Gewässern eine später einsetzende Eislegung und eine früher auftretende Eisschmelze feststellen (durchschnittlich 12 Tage kürzer). Der Zeitpunkt des Eisbruchs ist aus ökologischer Sicht äußerst wichtig, weil mit dem Verschwinden der Eisdecke der See zu mischen beginnt.

Im Rahmen der routinemäßigen Gewässergütekontrollen des Landes Kärntens ist in letzter Zeit eine Änderung im Zirkulationsverhalten einiger meromiktischer (teilzirkulierender) Seen aufgefallen. Ein Sauerstoffvorkommen in der Tiefe, knapp über Grund, dieser Seen lassen eine Vollzirkulation vermuten. In den 1930er Jahren zirkulierte der Wörthersee bis in eine Tiefe von 40 Metern (Findenegg 1932, 1933). In den letzten 20 Jahren mischte der See mehrfach bis in eine Tiefe von 60 bis 70 m, was anhand von vorkommender Sauerstoff-Konzentration, geringere Ammonium-Konzentration sowie durch eine niedrigere Temperatur in der Tiefe während der Frühjahreszirkulation beobachtet wurde.

Im Mittelpunkt der vorliegenden Untersuchung steht der Einfluss des Klimawandels auf die Hydrologie, die Wassertemperatur und der Wasserzirkulation. Die Wasserzirkulation im See ist abhängig von verschiedenen Parametern wie: Wind, Niederschlag sowie hydrologische Bedingungen. Die treibende Kraft für die Zirkulation ist der Wind. Die Erderwärmung mit all ihren Auswirkungen bedingt folglich eine Veränderung der Eisbedeckung an Seen, eine Änderung der Schichtungs- und Zirkulationsphasen, besonders zum Zeitpunkt der Homothermie.

Die Wassertemperatur an der Oberfläche der drei untersuchten Seen: Wörthersee, Klopeiner See und Ossiacher See hat in den vergangen Jahrzehnten zugenommen. Im Mittel nahm die Wassertemperatur in den letzten 20 Jahren um 0,8 °C zu. Die stärkste Erwärmung war in allen drei Seen im Frühjahr (April) zu beobachten.

Im meromiktischen Wörthersee konnte eine Verschiebung der Grenze zwischen Mixo- und Monimolimnion von 40 bis 50 m auf 60 bis 70 m Tiefe beobachtet werden. Dadurch wird kaltes und sauerstoffreiches Wasser tiefer verfrachtet als in den 1930er Jahren. Die tiefer reichenden Zirkulationen im Frühjahr sind in 50 m Tiefe deutlich an der Zunahme der Sauerstoffkonzentration und einem Rückgang der hier vorherrschenden Temperaturen zu erkennen. Aufgrund der allgemein wärmeren Winter wird die Periode der Eisbedeckung kürzer und an manchen Seen auch seltener. Es kann daher angenommen werden, dass die Winterschichtung aufgrund der milderen Lufttemperatur weniger stabil ausgebildet wird und dass dadurch die Zirkulation über einen längeren Zeitraum begünstigt wird. Seit 1800 hat die Anzahl der Monate mit Temperaturen unter minus 4 °C signifikant abgenommen.

Der meromiktischen Klopeiner See hat keine nennenswerte Verschiebung der Grenze zwischen Monimo- und Mixolimnion seit 1932 gezeigt. Die Grenze zwischen dem stagnierenden Wasserkörper in der Tiefe und dem darüber zirkulierenden Wasserkörper liegt zwischen 20 und 30 m, dennoch war eine leichte Ausbreitung der sauerstofffreien Zone (Monimolimnion) zu erkennen. In den Jahren von 1971 bis 1997 wurde gelegentlich aber auch Sauerstoff in 30 m Tiefe gemessen. Das sich leicht ausbreitende Monimolimnion ist darauf zurückzuführen, dass der See jedes Jahr eine geschlossene Eisdecke von Ende Dezember bis Ende März aufweist. Der Zeitraum für die Zirkulationsphase im Frühjahr (Homothermie bei 4°C) zwischen Eisbruch und Erwärmung der Wassertemperatur wird aufgrund der zunehmenden Lufttemperatur kürzer. Folglich verkürzt sich die Zeit für die Mischungsphase im Frühjahr als Folge der raschen Erwärmung.

2 Abstract

Climate warming caused changes in the thermal regime of lake waters like the earlier water warming in spring (Gronskaya et al., 2001), the increase in water temperature both on the surface and at deeper levels in lakes (Endoh et al., 1999), the lengthening of the period in summer when lake water temperatures exceed 10°C (Jarvet, 2000) and the shortening of periods with ice cover and decrease in its thickness (Todd and Mackay, 2003). Moreover the recent history of deep lakes south of the Alps shows that the processes of holo- and meromixis as well as mono- and polymixis have alternated. This is due primarily to the winter climatic conditions of the last twenty years, which showed a progressive warming of the atmosphere and a reduction in wind. Magnuson et al. (2000) provided a further evidence for systematic global warming over the past 150 years (from 1846 to 1995) by demonstrating on rivers and lakes across the whole Northern Hemisphere a significant trends towards earlier break-up and later formation of ice cover. The timing of lake ice break-up is of ecological importance because the disappearance of ice cover affects the mixing of water body.

In the recent past, a change in circulation mode of some meromictic Carinthian lakes was recognised during the routine monitoring. Some normally meromictic (partly circulating) lakes recently made a total circulation according to oxygen measurements in the depth near the lake's sediment. In the 1930s the water body of Lake Wörthersee was mixing down to 40 m depth (Findenegg 1932, 1933). In the last twenty years, the water body was mixing several times down to 60 and 70 meters. This was demonstrated by higher oxygen concentration, lower ammonium concentration, as well as by lower temperature in the depth during spring circulation phase.

Within this study, the focus is laid on the impact of climate change and effects on hydrology, water temperature and water circulation. The circulation of lake water is influenced by various parameters like wind and precipitation as well as hydrological factors. The water mixing driving force is the wind. So climate changes will cause impacts on ice cover, lake stratification and mixing patterns of lake water, especially in seasons where the lakes are more sensitive (homotherme).

The water temperatures at the surface of the three studied lakes in Carinthia: Wörtersee, Ossiacher See and Klopeiner See have risen. In general, the temperature increased by a mean value of 0.8 °C within the last 20 years. In all three lakes, the strongest warming has been observed in spring (April).

In Lake Wörthersee, the boarder between mixolimnion and monimolimnion descended in the period since 1931 to 2011 from 40 to 50 m to 60 to 70 m. Cold and oxygen rich water from the surface gets now transported deeper than in the 1930s. The deeper circulations in spring time caused a decrease in temperature and an increase in oxygen concentration in 50

meters depth. According to the warmer winters, the periods with ice cover become shorter and rarer. We assume that the winter stratification is less developed and the time for the mixing process is prolonged due to the increasing air temperature in winter. The number of month with temperature < below 4 °C has declined significantly since 1800.

In the meromictic Lake Klopeiner See the extension of monimolimnion and mixolimnion didn't change noticeably since 1932. The boarder between the two water bodies is situated at a depth between 20 and 30 meters and the oxygen free water zone shows a slight extension. In the years between 1971 and 1997, occasional oxygen was recorded in 30 meters depth. In the last decades, the oxygen poor zone begins at a depth of 20 meter. The smooth increasing monimolimnion is reducible to the fact that this lake has every year a closed ice cover (end of December to end of March). The time period of mixing phase, homothermous temperature between ice break and warming in spring is getting shorter due to increasing air temperature in spring. The time for the mixing process gets shorter as a consequence to the quick warming in spring.

3 The SILMAS project

The SILMAS project (www.silmas.eu) forms part of the Alpine Space Programme, which in turn is part of the European Community's European Territorial Cooperation Programme. Category B programmes are aimed at encouraging harmonious, balanced development of Europe's territory. Under this framework, the SILMAS project (Sustainable Instruments for Lakes Management in the Alpine Space) is developed transnational co-operation between 5 countries: Germany, Austria, France, Italy and Slovenia. Transnational co-operation contributes to national cohesion and reinforces the Alpine Space as an attractive, powerful space for living and working in.

SILMAS is launched for a three year period (September 2009 to August 2012) and is managed by the Rhône-Alpes Region (France). The total budget is of € 3,260,993 and 76 % of it is financed by Europe (ERDF). SILMAS is a project for pooling experience and know-how in terms of the sustainable management of alpine lakes. Its goal is to produce concrete, sustainable tools for better management of alpine lakes and in order to raise the general public's awareness of the sustainable development stakes involved in the lakes. 15 partners from local bodies, environmental administrative authorities, research institutes and universities are involved and 22 lakes are subject of investigations.

SILMAS work priorities are:

- The probable effect of climate change on Alpine lakes and how to tackle them
- Managing water usage conflicts
- Education the public in sustainable development as it relates to Alpine lakes.

4 Introduction

"Climate change can result in significant changes in the variables and processes that affect water quality and biodiversity of alpine lakes. These include: physical changes such as increased water temperature, reduced ice cover, vertical stratification and mixing behaviour of deep lakes as well as changes in water discharge which affect water level and retention time (ETC Water Technical Report 1/2010 of the European Environment Agency, European Topic Centre of Water).

Recent studies show that the impact of regional effects of global climate change on aquatic ecosystem functions and services can be larger than that of local anthropogenic activity. A strong correlation to water temperatures to the climate and climatological indicators exists, even in the depth near the lake's sediment. Moreover the recent history of deep lakes south of the Alps shows that the processes of holo- and meromixis as well as mono- and polymixis have alternated. This is due primarily to the winter climatic conditions of the last twenty years, which showed a progressive warming of the atmosphere and a reduction in wind.

In the recent past, a change in circulation mode of some meromictic Carinthian lakes was recognised during the routine monitoring. Some normally meromictic (partly circulating) lakes recently made a total circulation according to oxygen measurements in the depth near the lake's sediment. In the 1930s the water body of Lake Wörthersee was mixing down to 40 m depth (Findenegg 1932, 1933). In the last twenty years, the water body was mixing several times down to 60 and 70 meters. This was demonstrated by higher oxygen concentration, lower ammonium concentration, as well as by lower temperature in the depth during spring circulation phase. The analysis of external influences like altering wind patterns, precipitation and increasing air temperature will help to understand if the changing circulation behaviour is a consequence of global warming. While slight changes in the most frequent wind direction may well be hidden by the effects of local topography, an overall increase (or decrease) in wind speed would have a notable impact on the mixing behaviour of alpine lakes. With a rise in winter mean temperature it can be assumed that the number of days with ice cover on the lakes will decrease within the next decades. Magnuson et al. (2000) indicated that ice cover has been occurring on average 5.8 days later per 100 years, while ice brake-up has been occurring on average 6.5 days earlier, implying an overall decrease in the duration of ice cover at a mean rate of 12 days per 100 years. Wind stress on the lake acts as long as the surface is still liquid water. Once there is an ice sheet covering the lake, vertical mixing due to wind ceases. Hence, a warmer climate favours mixing in winter time.

Also the monitoring of water temperature of Carinthian lakes showed an increase during the last decades. This corresponds to the study of Dokulil, which shows that the surface temperature during the bathing season will increase up to 2 °C until 2050.

The objective of the investigation done by the Carinthian Institute for Lake Research and by the Joanneum Research Centre was to find a correlation between global warming and water temperature of alpine lakes and the impact of climate change on mixing and stratification behaviour. The aim was to detect past and possible future changes of lake water balance, water temperature and circulation patterns. It is to be expected that increasing air temperatures, changing wind patterns and reduced precipitation will presumably modify variables such as water residence time, stratification and mixing patterns of lakes.

Located in the southern part of the Alps three Carinthian lakes, Wörthersee, Klopeiner See and Ossiacher See were investigated, concerning the following issues: water balance, water temperature and mixing behaviour of water bodies. These three lakes were chosen because of the availability of long term data on water temperature and physical-chemical parameters collected since 1930. Lake Wörthersee and Lake Klopeiner See are known as meromictic lakes. Meromictic lakes are characterized by a partly mixing water body during the circulation phases. Lake Ossiacher See, a holomictic (total circulating) lake, has been chosen as a reference lake.

The questions are: to which extent the phenomenon of mixing behaviour is climate change induced and which effect has a changing water balance on lakes' water quality by further global warming?

Within this study, the focus is laid on the impact of climate change and effects on hydrology, water temperature and circulation. The circulation of lake water is influenced by various parameters like wind and precipitation as well as hydrological factors. The water mixing driving force is the wind. So climate changes will cause impacts on ice cover, lake stratification and mixing patterns of lake water, especially in seasons where the lakes are more sensitive (homotherme).

5 Meromixis

Meromictic lakes are characterized by a partly mixing water body. In spring and autumn, when the temperature from bottom to the surface is homogenous, the wind energy is too low to mix up the whole water mass. This usually goes back to an unfavourable ratio between surface and depth, wind protected position and low flow rate. The deeper non-mixed water body, the water with the highest density at 4 °C, becomes enriched with sedimentation and degradation products. The microbial decomposition of dead organic material causes a lack of oxygen and an increase of nutrients in the depth. Because of partial circulation, the deep water is not reloaded with oxygen. The deep anaerobic and nutrient-rich water body is named monimolimnion. The seasonal circulating water body is called mixolimnion.

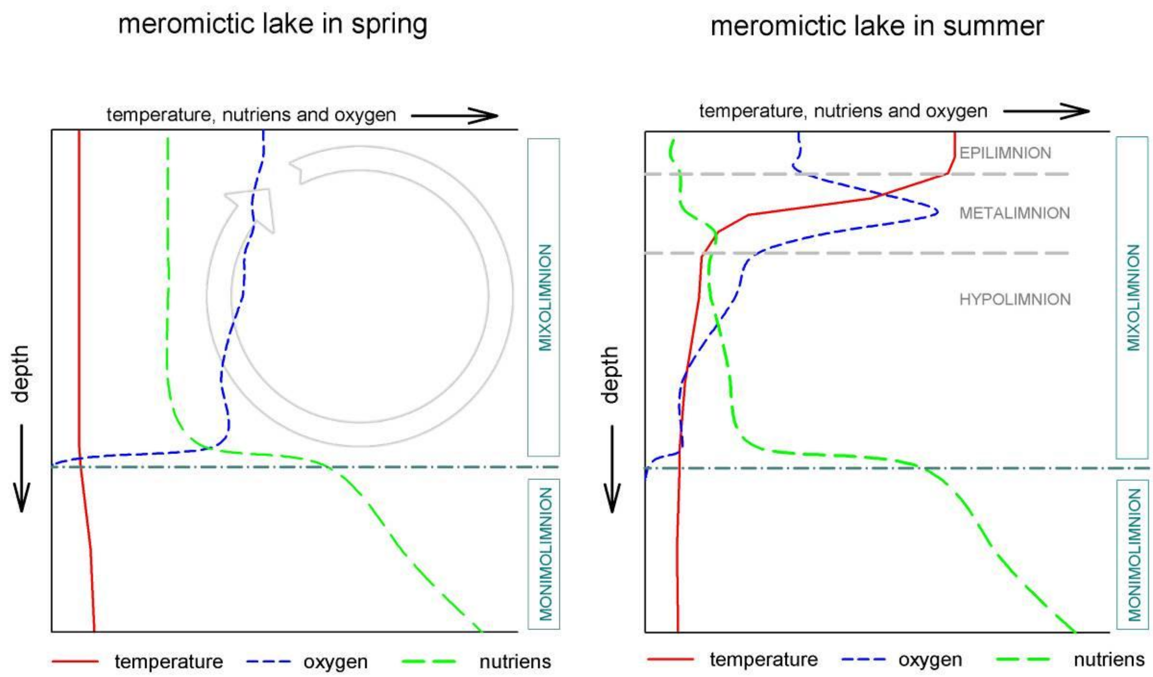


Fig. 1: Scheme of stratification of a meromictic lake during spring circulation and summer stagnation phase.

In spring temperature, nutrients and oxygen are homogeneous distributed along the mixolimnion (Fig. 1). The graphic indicates at the transition point between mixolimnion and monimolimnion a steep raise of nutrient concentration and a steep decrease of oxygen concentration, while the temperature is slightly increasing because no cold water from the surface enters the monimolimnion. During summer the mixolimnion shows the typical stratification of temperature, oxygen and nutrients, while the monimolimnion is stagnant.

6 Limnological characterisation of investigated lakes

The three investigated Carinthian lakes: Wörthersee, Klopeiner See and Ossiacher See are situated north of the Drau valley, close to the Slovenian border (Fig. 2).

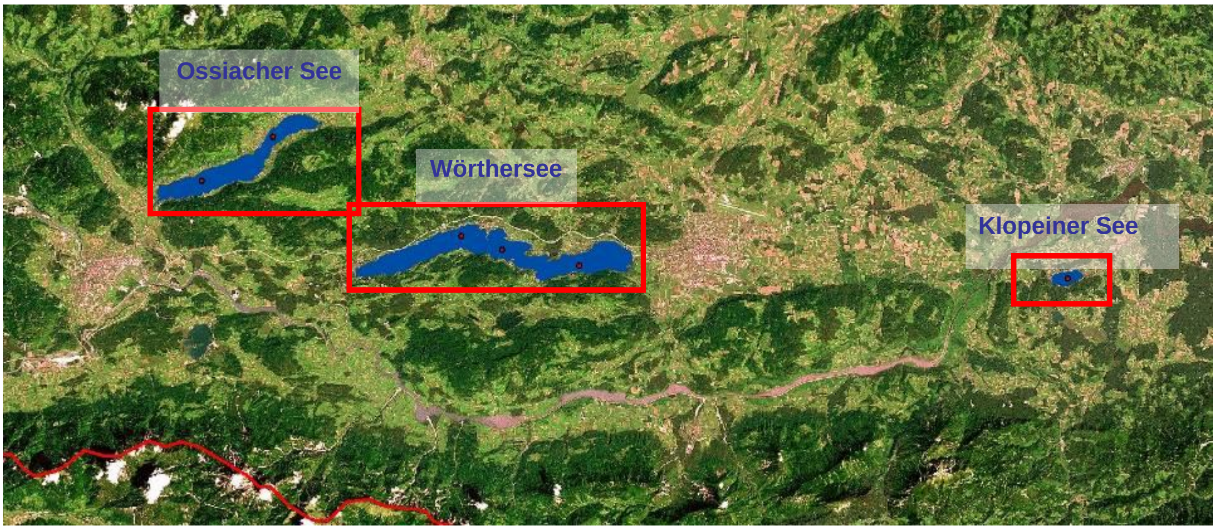


Fig. 2: Map of investigaed lakes in Carinthia (Austria): Ossiacher See, Wörthersee and Klopeiner See.

6.1 Wörthersee

Lake Wörthersee (Fig. 3) is with an area of 19,4 km² the largest lake of Carinthia. It is situated in a valley away from the main drainage line of the River Drau. The valley shows a tectonic disorder which was covered by the Drau glacier of the last ice age. The lake stretches from east to west and is structured by islands and peninsulas. Underwater dams divide the lake into three basins. The western one (7,9 km²) is the deepest (85,2 m), the middle one (3,5 km²) is 39,9 m deep and the eastern basin (8 km²) is the largest and has a depth of 73,2 m. The lake is mainly feed by small tributaries around the lake. The main inflow is the River Reifnitzbach with an average discharge of 630 liter per second. The outflow, the River Glanfurt leaves the lake at the east end and drains via River Glan and Gurk into the River Drau. The theoretical water renewal time is given as 10.5 years by an inflow of 2.460 liter per second. Because of this long time and its wind protected situation the water warms up very quickly and build a strong thermal stratification during summer. The metalimnion with temperatures between 12 and 5 °C is between 8 and 15 m depth. From about 15 meters to the ground the water has all over the year 4 to 5 °C. Ice coverage usually occur from end of January, but only in extremely cold winters there is a closed ice cover all over the lake. The ice can reach a thickness of 30 cm. The ice break up normally is in late March. Lake Wörthersee belongs to the meromictic type of lakes. The water circulates in spring and in autumn only goes down to a depth of 40 to 60 m. The deeper water layer is untouched by the circulation. This fact results out of the deep basins, the little water flow rate and the wind protected position. Because of this partial circulation of the lake the deep waters are not provided with oxygen. The microbial decomposition of dead organic material causes anaerobic conditions. The actual trophic status of Lake Wörthersee is weak mesotroph

Fig. 3: Wörthersee view to the eastern end where Klagenfurt is situated.

6.2 Klopeiner See

Lake Klopeiner See (Fig. 4) is the warmest bathing lake of Carinthia due to the fact that it has only few small tributaries and a very little runoff. The lake is a vestige of a former much larger after ice age lake that enclosed the whole region around the village of Kühnsdorf. The lake was filled up by the drift of the after ice age River Vellach and only left back the water surfaces of the Klopeiner See and the closed by Lake Kleinsee. The southern shore of the Klopeiner See follows a high plateau of conglomerate, the so called Rückersdorfer Platte. The other shores are framed by gravel fields, moraines and sediments of the former Kühnsdorfer See. The shores show their originality only in a few smaller sections. The lake is not fed only by small, surface tributaries but also by groundwater wells. The runoff leaves the lake in the west; it has an average flow rate of 35 liter per second and drains to the Drau in the end. It is one of the least through flown lakes of Carinthia. The Klopeiner See is meromictic, meaning that in spring and in autumn not the whole water body is circulating. The water body near the ground stagnates and stays free of oxygen. In the 1930s the circulation currents reached down to 32 m (Findenegg 1933). With the increasing load of nutrients (eutrophication) a rise of the line between mixolimnion and monimolimnion could be observed. The actual trophic status of Lake Klopeiner See is weak mesotroph.

Fig. 4: Klopeiner See; view to the north western shore.

6.3 Ossiacher See

Lake Ossiacher See (Fig. 5) is the third largest lake of Carinthia with an surface of 10,8 km². The lake is embedded between woody hills and its basin sunk in old crystalline rock bulk, which partly is covered by glacial gravel. The lake is characterized by two basins that are parted from each other by a dam in a depth of 10 meters. The eastern, smaller basin (3,9 km²) has a maximum depth of 11 meter and the larger (6,9 km²) western basin is 52 meters deep. It is a holomictic lake, meaning that the whole water body from the surface to the bottom is mixing during the circulation phases in spring and late autumn. During summer month the surface water warms up to more than 24 °C. The surface layer, the epilmnion, reaches a depth of about 6 meters. Deeper the water quickly gets colder and in a depth of 15 meter the temperature is about 4 to 5 °C. The ice cover can last only for few weeks from late December to Mid of March and in mild winters there is no ice cover at all. Its main tributary is the River Tiebel with 1.750 liter per second. The smaller tributaries from the hills of the Mountain Gerlitzen are unimportant. East of the lake there is a drained moor, “Bleistätter Moor (area: 6 km²) which is flown through by the River Tiebel. The trophic status of Lake Ossiacher See is weak mesotroph.

Fig. 5: Ossiacher See, view to east end of the lake.

7 Methodology

The description and interpretation of the past changes in the limnological conditions of the investigated lakes were carried out on the basis of long-term monitoring water data, homogenised long-term meteorological data (p.e. project HISTALP) and hydrological modelling of the changes of the inflows (surface water and groundwater) from the catchment areas to the lakes. Additionally, a monitoring on environmental meteorological data, water temperature, isotopes and quality parameters (mainly: oxygen content) was done over 2 years to get more detailed information concerning the actual mixing processes by using temperature recorders. Models for the description of the last 40 years are well understood and can be applied straight foreword. Based on the changes in the past and on the data collected during the project duration, an interdisciplinary prospective analysis of possible future trends of the lake ecosystems was carried out through the cooperation of Joanneum Research Institut and the Lake Research Institutes of Carinthia and of Langenargen.

To guarantee a serious data base for this report, the gauge data measured at the lake surface near the shore line were compared with water temperature of 0 m sampled over the deepest point of Lake Wörthersee (further on so called: limnological data). The mean difference between the water gauge data and the limnological data is only 0.5 °C. As the water gauge is situated in the shallow shore zone of the lake Wörthersee, the water temperature rises faster and reaches higher values in summer and lower values in winter as the wind exposed surface in the middle of the lake (Fig. 6). From 97 compared data 22 times the difference is higher than 1.0 °C. The maximum discrepancy was 1.6 °C and the standard deviation was 0.79 °C.

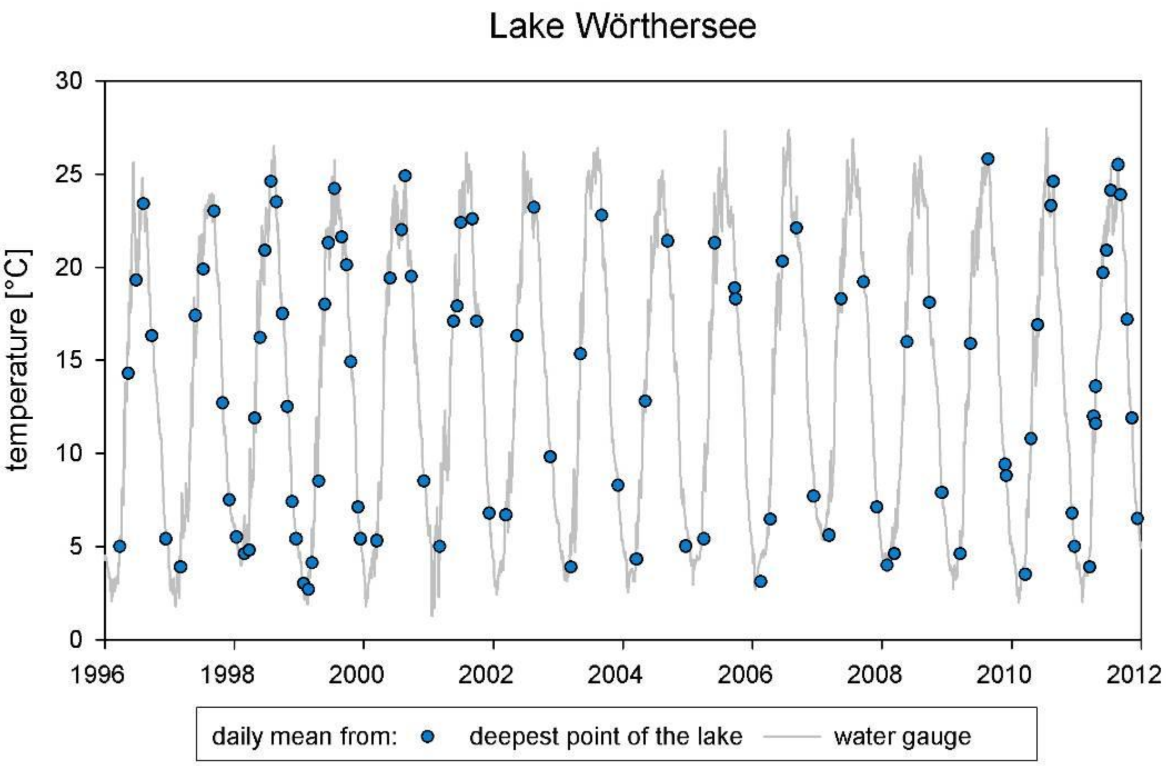


Fig. 6: Comparison of daily mean of surface water temperature from the gauge with the temperature of the limnological monitoring at the deepest point of Lake Wörthersee.

7.1 Long-term development of surface water temperature

To observe the variation of the water temperature over a long time period we used data from three water gauge stations (Hydrology Service of the Carinthian Government) established at Lake Wörthersee, Lake Klopeiner See and Lake Ossiacher See (Tab. 1).

Tab. 1: water gauge and recording period:

Lake	Water gauge	Start of recording period	Digitalised recorder
Wörthersee	Pörtschach am See	19.05.1931	01.01.1997
Klopeiner See	Unterburg	01.01.1994	01.10.2006
Ossiacher See	St. Andrä	01.01.1991	01.01.1998

Before the digital recorder gets used, the water temperature was generally recorded only one time a day. To document the long term aspect only data of the same day time (e.g.: 7:00 to 10:00 a.m.) were calculated. From the statistical point of view, the data were tested with the Mann Kendall trend test (monotonic trend in a time series z[t] based on the Kendall rank correlation of z[t] and t).

7.2 Annual lake stratification – based on recorded water temperature

To investigate the mixing behaviour and for the modelling (Joanneum Research Center and Institute for Lake Research of Langenargen) of the three project lakes, 40 digital thermographs were established in 6 units (Fig. 7). The measurements of temperature started in November 2009 on following locations:

Tab. 2: List of the established units.

Name of the sampling point	Depth of lake basin	Depth of exposed data logger
Wörthersee, Saag	85 m	3, 8, 15, 20, 30, 40, 50, 60, 70, 84 m
Wörthersee, Maria Wörth	40 m	3, 8, 15, 20, 30, 40 m
Wörthersee, Klagenfurter Bucht	73 m	3, 8, 15, 20, 30, 40, 50, 60, 71 m
Klopeiner See	45 m	3, 8, 15, 20, 30, 40, 45 m
Ossiacher See, Westbecken	48 m	3, 8, 15, 20, 30, 40, 47 m
Ossiacher See, Ostbecken	11 m	3, 8 m

The data loggers were disposed along a vertical profile from the surface to the bottom (Tab. 2). On the bottom was placed an anchor and at the lake surface a buoy. The accuracy of the data loggers is 0.0625 °C. The measuring interval was 3 hours.

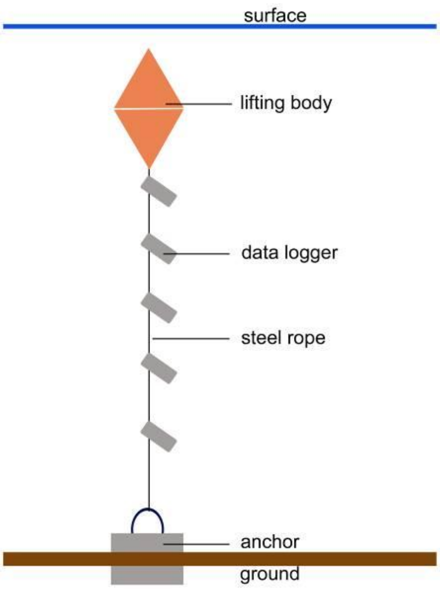


Fig. 7: Sketch of the monitoring unit.

The first control of the monitoring unit was in April 2010. Some units were moved by drifting ice and were placed back in position. All units worked well. Last summer 4 units were lost, probably due to boat traffic. Three new units were replaced. For safety reasons, all monitoring units were fixed with underwater buoys in three meter depth. Over the whole sampling period (winter 2009 to spring 2012) 180.000 data were recorded. For the contour graphs, the daily mean water temperature was calculated.

7.3 Limnological data

Since 1970, there is a regular limnological monitoring on Carinthian lakes done by the water authorities of the provincial government of Carinthia. The samples were collected over the deepest point of the lakes, 4 to 12 times a year. For the trend analysis, the data were tested with the Mann Kendall test. The chemical parameters used in this report were analysed by the accredited (EN 45001) environmental laboratory of Carinthia.

7.4 Climate - Air temperature

From 1760 to 2000, the air temperature in the Alps increased significantly. The global warming is about 1 °C and the warming in the alpine region amounts 2 °C (HISTALP data,). Remarkable is the steep rise of air temperature in the period from 1980 to 2000 (Fig. 8). In this comparative short time period, the air temperature in the alpine space increased by more than 1 °C.

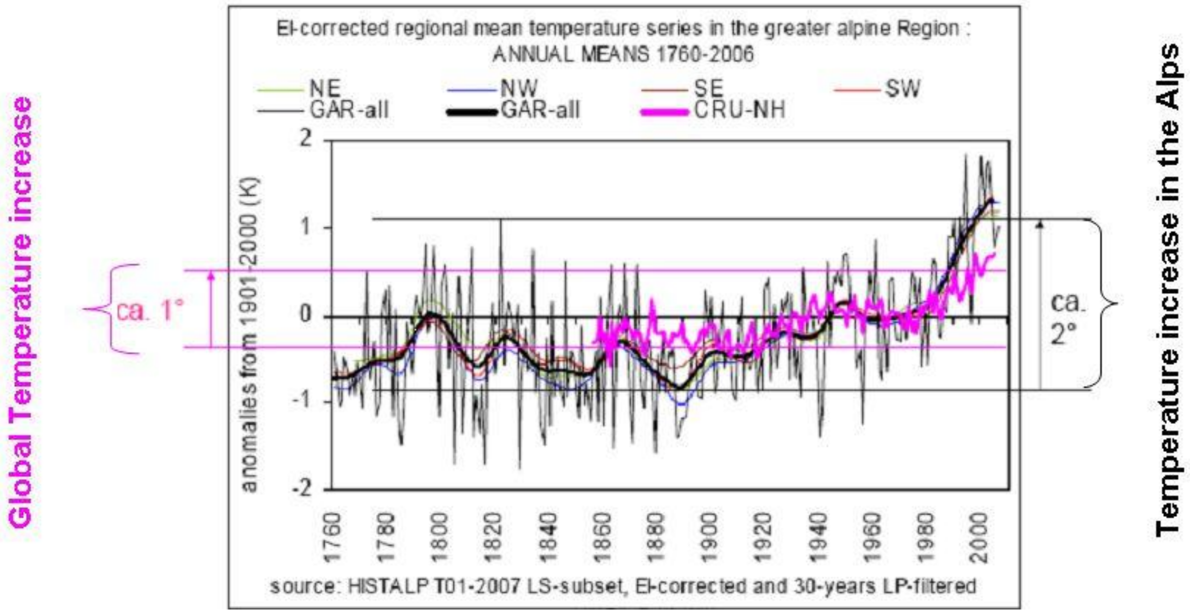


Fig. 8: Development of global air temperature and air temperature in the Alps.

Due to the fact that the circulation phases take place in winter time, the air temperature of the months from December to March, recorded by the HISTALP station in Klagenfurt, was of interest. The average month values show a clearly increasing trend of 1.5 °C. The number of month with a mean temperature of minus 4 °C is significantly decreasing (Fig. 9). This fits to the observation, that at the bigger Carinthian lakes the time period with closed ice cover becomes shorter or a closed ice cover is more often not developed.

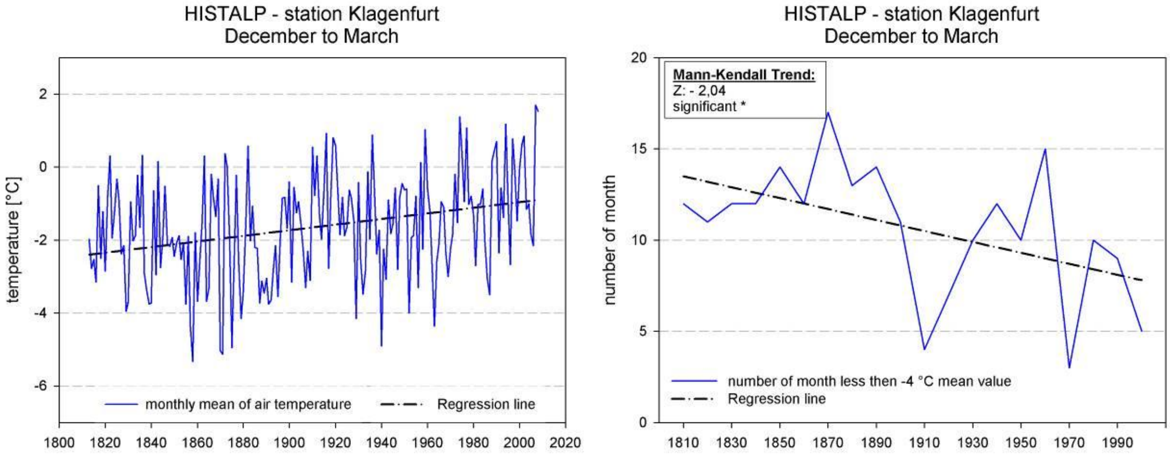


Fig. 9: Air temperature data from HISTALP station in Klagenfurt from December to March since 1800 to 2000: Left: monthly average value; Right Number of months with a monthly average value < minus 4 °C, calculated for decades.

8 Results

8.1 7.1 Long term development of surface water temperature

According to the development of air temperature in the Alps, the water temperature at the lake surface of all three investigated lakes increased more or less.

Two different ways of analysis were done to describe the long term changes of water temperature. The MANN-Kendall test was used to evaluate the dataset for trend calculation. In the following figures, selected months are presented to show the characteristic seasonal temperature situation of the investigated lakes over a time period of respectively 40 and 80 years. Some of them have a high significance according to the dataset. To describe the seasonal increase in water temperature, four representative months were selected and the monthly mean was calculated. The Tab. 3 represents the increasing temperature trend calculated on the base of the average value of ten year periods for winter (January), spring (April), summer (August) and autumn (November).

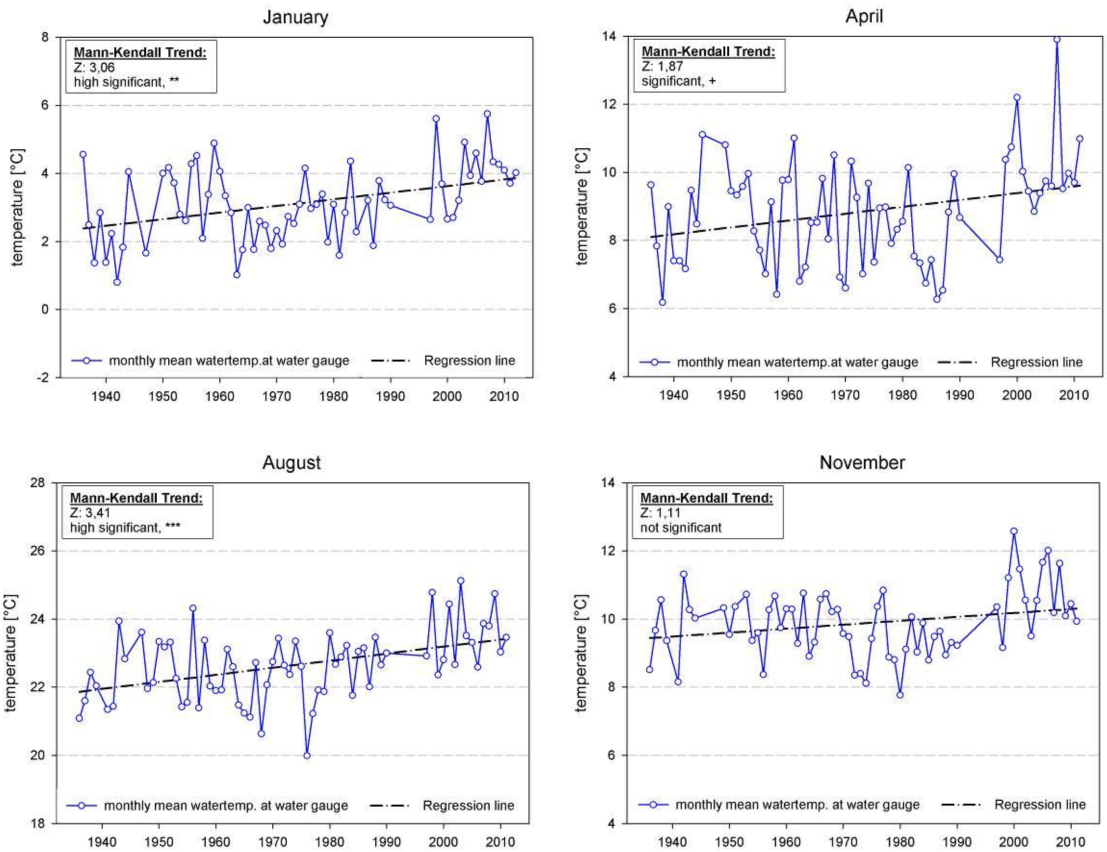


Fig. 10: Lake Wörthersee water temperature at the lake surface in January, April, August and November since 1940.

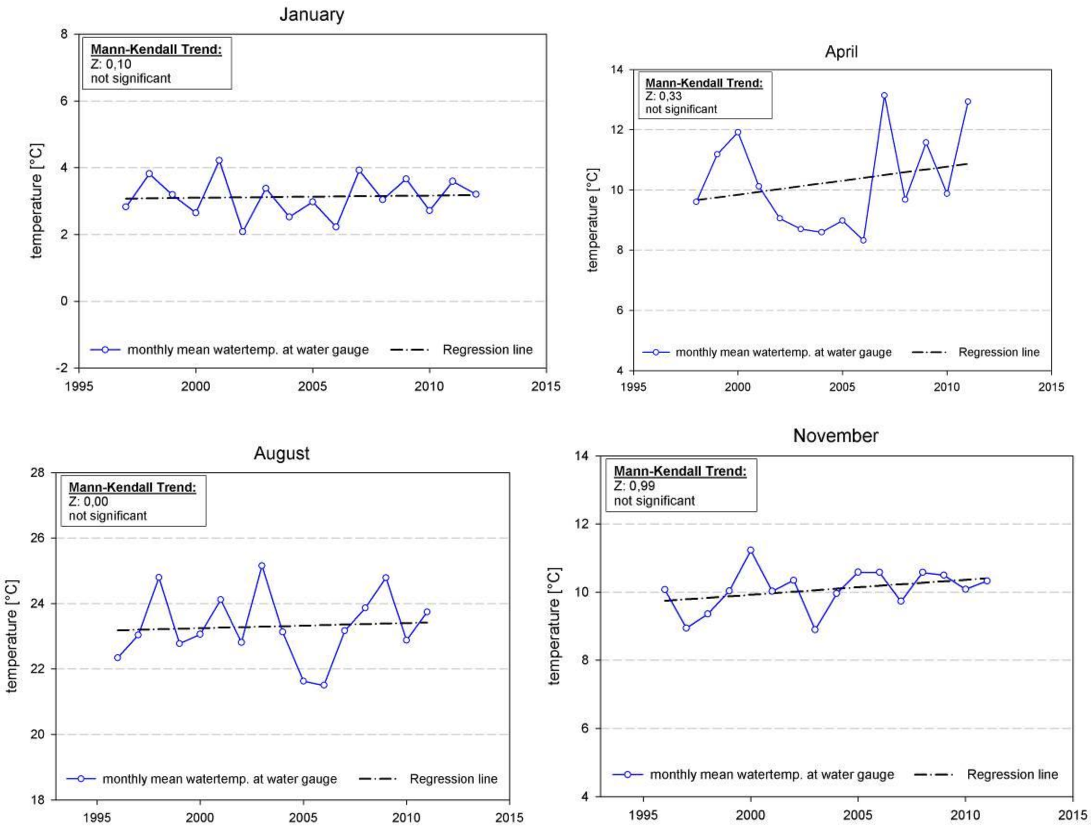


Fig. 11: Lake Klopeiner See water temperature at lake surface in January, April, August and November since 1990.

Temperature data recorded between 1940 and 2011 at the meromictic Lake Wörthersee demonstrate an increase in the presented month (Fig. 10) between 0.8 and 1.8 °C. The graphs show a high significant trend in January as well as in August. The strongest temperature rise was observed in spring (April).

Water temperature data of the surface are available for the meromictic Lake Klopeiner See since 1996. The water temperature increased not significantly in winter and significantly in summer (Fig. 11). The maximum temperature increase of 1.1 °C was observed in April.

The water temperature of the holomictic Lake Ossiacher See (Fig. 12) showed also an increasing trend since 1990. The development of the water temperature of Lake Ossiacher See is according to the Mann-Kendall test not significant. But an increasing trend is visible in January, April and November. In August, the temperature curve shows a decreasing trend since 1990. A possible explanation for the decrease of water temperature in August may be an increase in evaporation rate of the water from the lake surface due to higher air temperature.

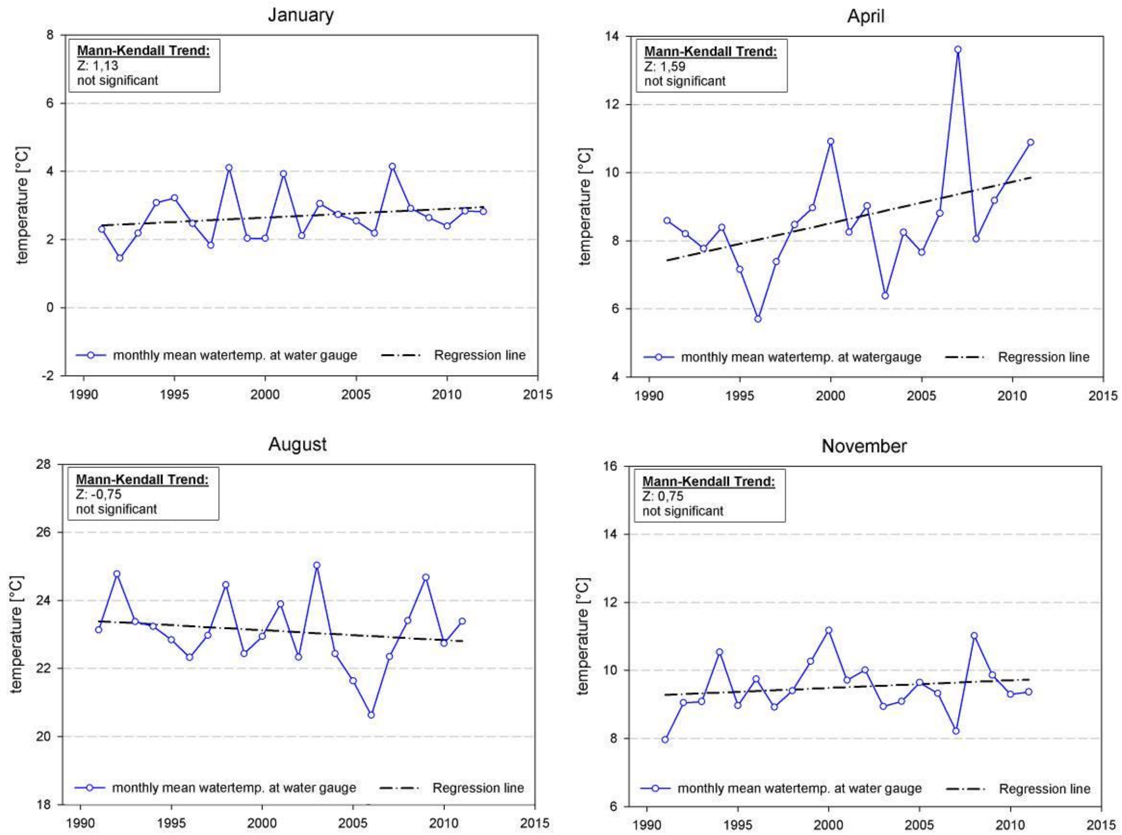


Fig. 12: Lake Ossiacher See water temperature at the lake surface in January, April, August and November since 1990.

The long time change of water temperature for different months calculated on the base of the average value of ten-year periods from 1940 to 2010 for Lake Wörthersee and from 1990 to 2010 for Lake Ossiacher See and from 1996 to 2010 for Lake Klopeiner See is presented in

Tab. 3. According to the Mann-Kandell test, the dataset of Lake Wörthersee has a high significance because of the large dataset. The datasets of the other lakes, because of the shorter monitoring period, show a lower or no significance. In general, the temperature increased in all three lakes in January and April that fit to the milder air temperature in winter and warmer temperature in spring. In the summer, the stronger evaporation due to higher air temperature works against the increase of surface water temperature. This could be clearly watched at Lake Ossiacher See, where the water temperature decreased in August (Tab. 3). In addition to evaporation effects, we also have to consider that changes in weather conditions like heavy precipitation and frequency of thunderstorms can also impact the water temperature.

Tab. 3: Development of surface water temperature of selected months on the base of monthly mean values.

Lake	January	April	August	November
Wörthersee 1930 -2010	+ 1,2 °C	+ 1,5 °C	+ 1,2 °C	+ 1,0 °C
Klopeiner See 1996-2010	+ 0,2 °C	+ 1,1 °C	+ 0,2 °C	+ 0,7 °C
Ossiacher See 1990 -2010	+ 0,4 °C	+ 2,5 °C	- 0,8 °C	+ 0,4 °C

8.2 Temperature stratification – based on recorded water temperature

The graphs (of Fig. 13, 14 & 15) show the results of the continuous temperature registration by the data logger exposed within the SILMAS project. Notable is the strong temperature stratification in summer, the high temperatures are indicated by yellow and red colours in the epilimnion (0 to 6 m of water depth). In all lakes, the water surface reaches temperatures between 24 and 26 °C. The metalimnion (water body that is characterized by a temperature decrease of 1 °C per meter of depth) goes from 7 to 20 respectively to 30 meters in late summer and below that depth the temperature is about 4 °C. The winter stratification is not so clear developed as in summer and temperature below 4 °C occurs in the period from January to March (purple and blue colours). In Winter 2009/2010 and 2010/2011 there was no complete ice cover on Lake Wörthersee and Lake Ossiacher See. Remarkable is the quick cooling of the water body and the immediate start of circulation in late December and the short but intensive warming up period in spring.

At the meromictic **Lake Wörthersee** (Fig. 13), the winter circulation in December 2009 and 2010 went down to a depth between 40 and 50 meters. The spring circulation in 2010 and 2011 went deeper, down to 50 and 60 meters. In this meromictic lake, oxygen is transported with the circulation processes only down to a depth of 40 to 60 m.

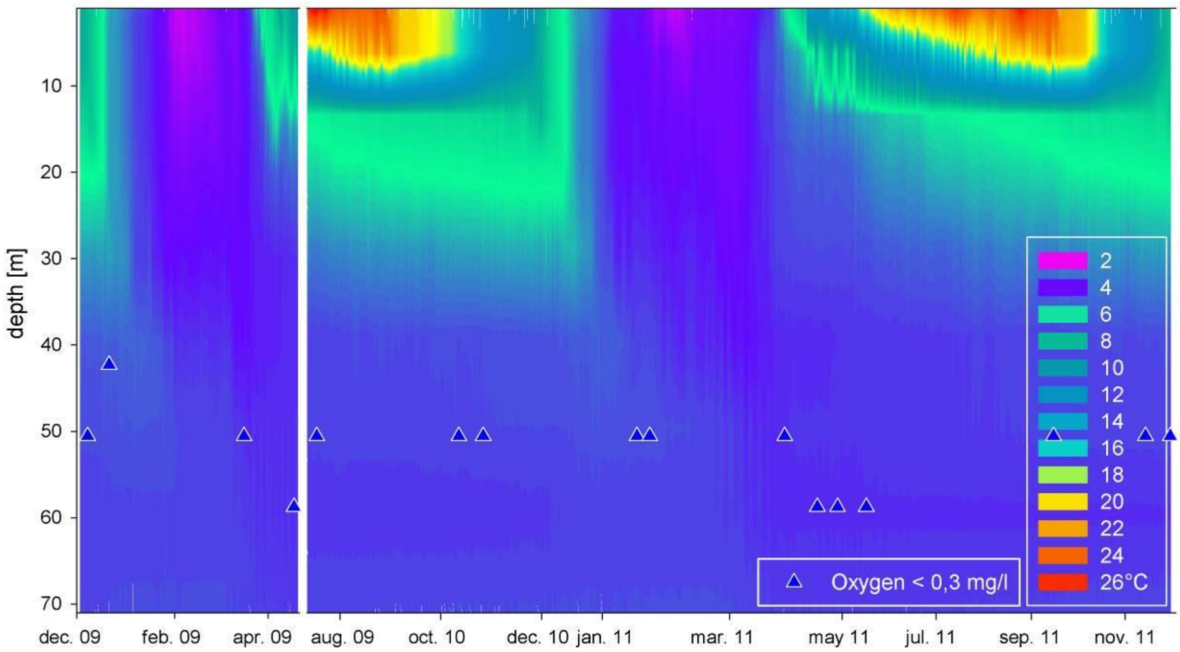


Fig. 13: Temperature stratification and circulation depth expressed by oxygen concentration (< 0,3 mg/l) of Lake Wörthersee from December 2009 to November 2011.

The meromictic Lake **Klopeiner See** (Fig. 14) has specific temperature stratification. The water body from the surface down to 30 m behaves similar to Lake Wörthersee. During summer period, a strong stratification is developed. The epilimnion (0-6 m) reaches temperatures up to 28 °C on the lake surface. The metalimnion is situated between 7 and 15 respectively 20 meters of depth in late summer. The border between mixolimnion and monimolimnion is known to be in 30 m depth. In this layer, temperatures of 4.0 to 4.5 °C were measured. Below this depth the water body is free of oxygen during the whole year, according to the meromictic character of the lake. in the deeper water layer the data logger registered higher temperatures, up to 5.5 °C. This phenomenon is caused by ground water inflow near the lake bottom as isotope studies proved (Joanneum Research Center). The occurrence of oxygen below a vertical depth of 30 meters is supposed to be an influence of oxygen loaded ground water inflow. The chemical density gradient is so strong that the incoming warmer groundwater does not mix immediately with the upper cooler water.

Lake **Ossiacher See** (Fig. 15) demonstrates the typical stratification behaviour of a holomictic lake by showing clear summer stratification. The epilimnion (0 – 6 m) reaches temperatures higher than 24 °C. The deep water temperatures warms up to nearly 6 °C at the beginning of the winter circulation. With the spring circulations, cold water is transported to the bottom where 3 to 4°C were registered. The recorded temperature data indicate that the lake was circulating nearly the whole winter 2010 and 2011. During these two winters, no closed ice cover was observed. In general this lake is more wind exposed than the other two investigated lakes.

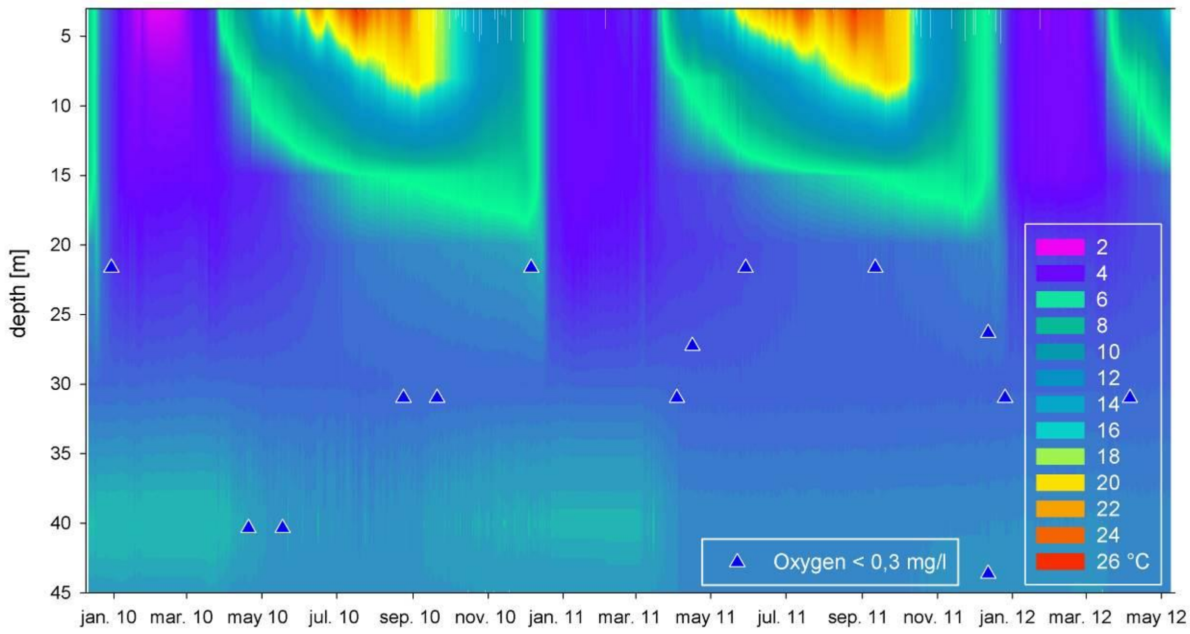


Fig. 14: Temperature stratification and circulation depth expressed by oxygen concentration (< 0,3 mg/l) of Lake Klopeiner See from December 2009 to November 2011.

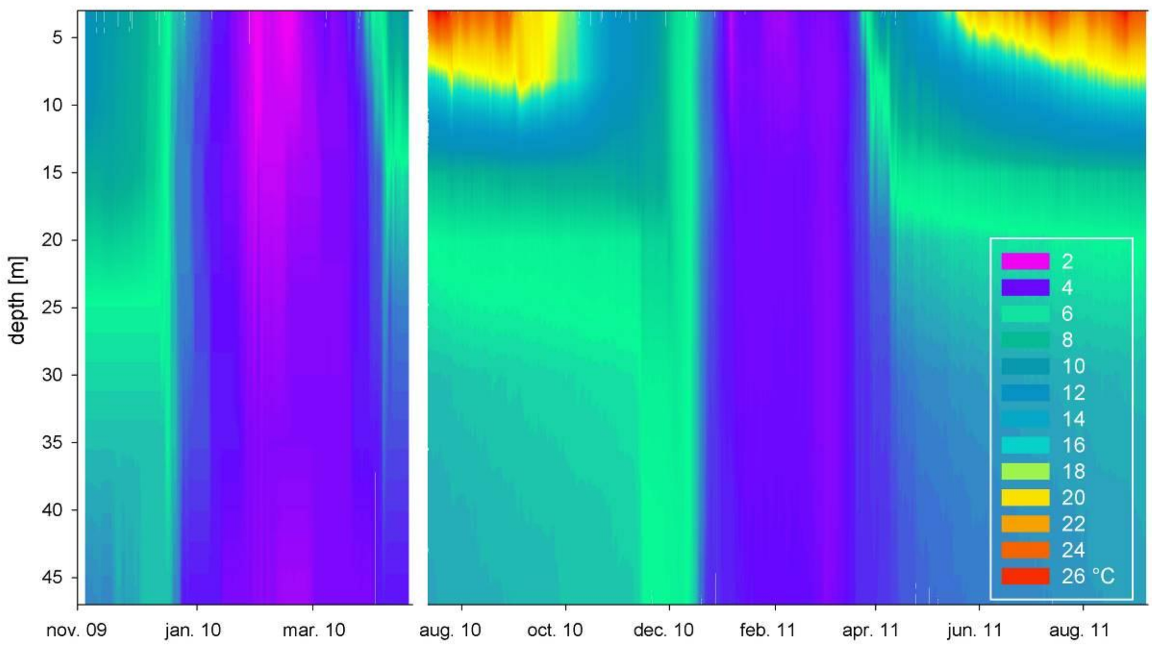


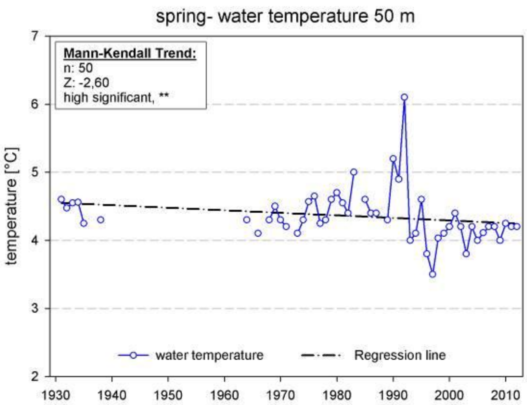
Fig. 15: Temperature stratification and circulation depth expressed by oxygen concentration (< 0,3 mg/l) of Lake Ossiacher See from December 2009 to November 2011.

8.3 Climate change input on mixing behaviour of meromictic lakes

A main focus of the SILMAS study was the question: is the mixing behaviour of the meromictic Lake Wörthersee and Lake Klopeiner See influenced by global warming? In this connection, the historical data of temperature, oxygen- and ammonium concentration were analysed. Depth profiles of these parameters with the focus on the border between mixolimnion and monimolimnion were evaluated.

First studies of meromictic circulation behaviour of Carinthian lakes were carried out by Findenegg in the years 1931 and 1932. Findenegg defined the border between mixolimnion and monimolimnion for Lake Wörthersee within the depth of 40 - 45 m and for Lake Klopeiner See within 30 m depth. The water body deeper than 50 m respectively 30 m was not touched by circulation processes at this time. The meromictic character of the lakes is caused by the shape of the basins with its steep slopes and the wind protected situation between mountain chains.

In the recent past at Lake Wörthersee, a deeper circulation had been observed, indicated by water temperature, oxygen and ammonium concentration at the end of the spring circulation phase. The Fig. 16 indicates the long term development of the parameters temperature and oxygen in the depth of 50 m. In the period between 1930 and 2010, the temperature shows a decreasing trend caused by deeper transport of cold water during spring circulation, correlated with higher oxygen transfer from the surface to the depth.



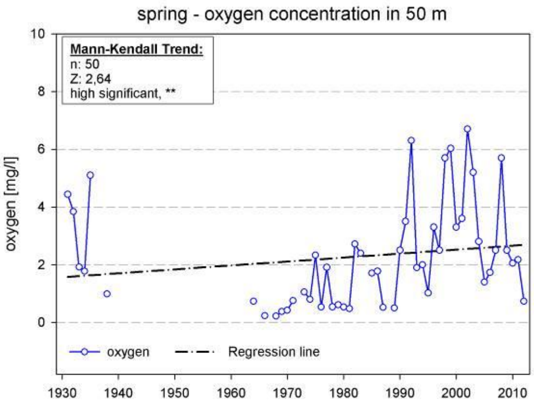


Fig. 16: Water temperature development in the depth of 50 m in Lake Wörthersee.

The deeper mixing in Lake Wörthersee can be shown by different depth profiles of the parameters temperature, oxygen and ammonium. In April 1970 and 1985, the Fig. 17 indicates a circulation depth between 40 and 50 m. Although the surface water already warmed up to 9 °C, the effect of cold water transport by spring circulation can be detected by lower temperature in the depth between 40 and 50 m. Below 50 m, the temperature slightly rises again to 4.4 °C. Only the water body from 0 to 50 m got enriched with oxygen and the oxygen concentration below 50 m was close to 0 mg/l. In this low-oxygen zone the ammonium concentration raised steeply. From 1982 to 2011 the turnover of lake water in spring reached from time to time depth until 70 m (Tab. 4).

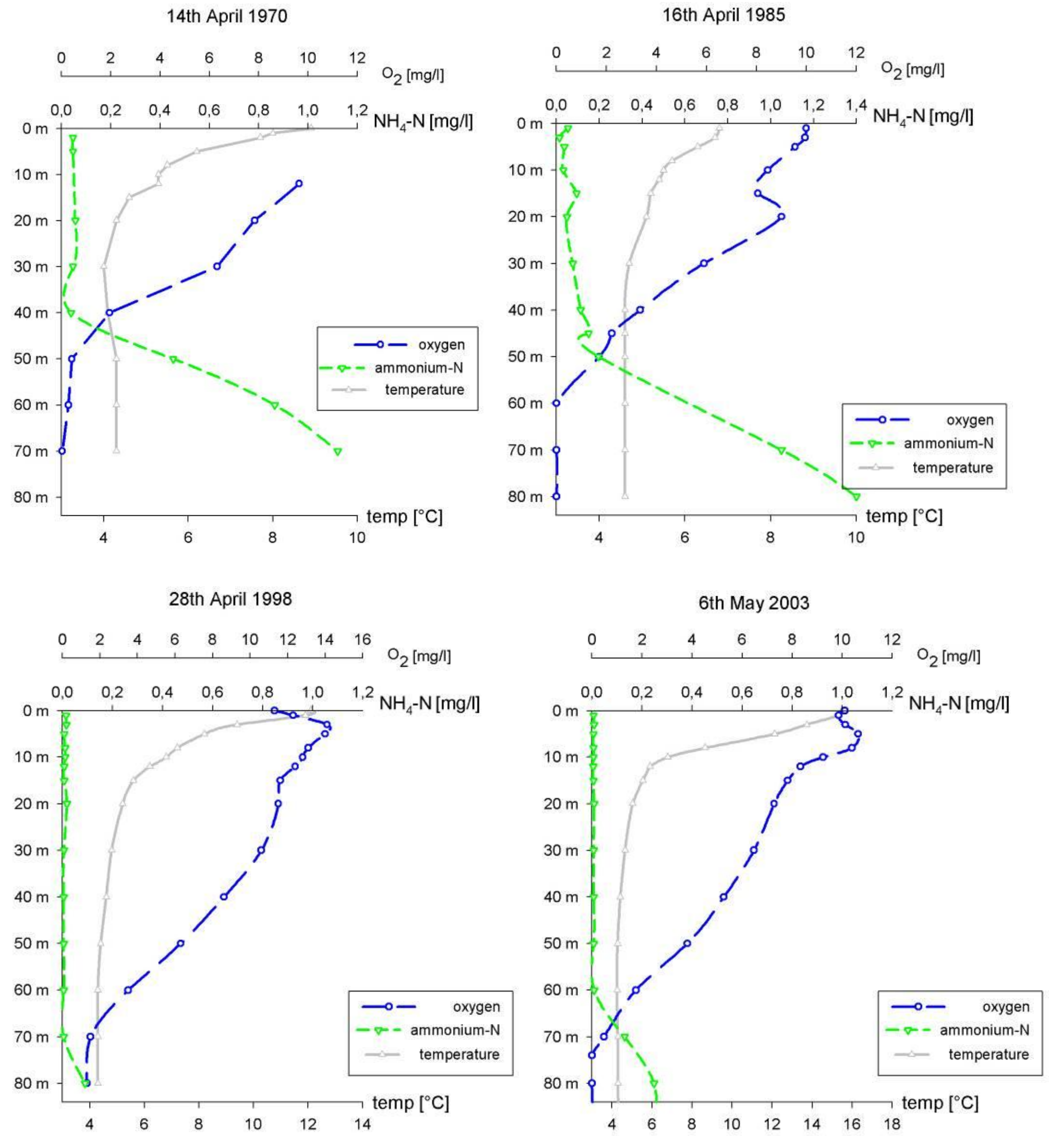


Fig. 17: Lake Wörthersee: depth profiles of temperature, oxygen- and ammonium-concentration at the end of spring circulation of different years.

Tab. 4: Extension of mixing water body during spring circulation in Lake Wörthersee (* Findenegg 1932 & 1933).

Year	Depth
1931*	40 – 45 m
1932*	40 – 45 m
1970	40 – 50 m
1985	50 - 60 m
1998	70 – 80 m
2003	60 – 70 m
2010	60 – 70 m
2011	60 – 70 m

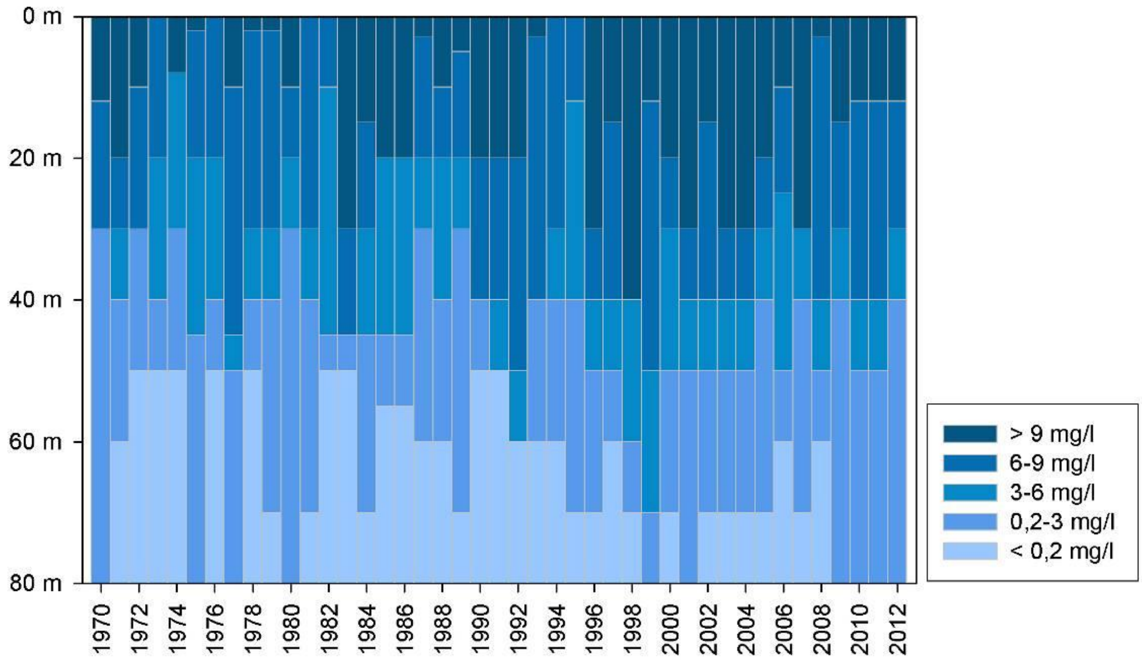


Fig. 18: Oxygen concentration at the end of the mixing period in spring in Lake Wörthersee.

The registered oxygen data indicate that since 1970 the concentration in the depth is increasing. The water body which contains no oxygen respectively < 0.2 mg/l (analytical limit) becomes smaller (Fig. 18). After spring circulation traces of oxygen (0,2 - 3 mg/l) at depths greater than 50 m could be measured more frequently in the last two decades. This observation is a clear indication that the boarder between mixolimnion and monimolimnion is increasingly shifting to deeper zones.

Following the temperature data continuously recorded by data logger in the frame of SILMAS project from 2010 and 2011 (Fig. 19), the instability of temperature stratification at the border between mixolimnion and monimolimnion in circulation phases is recognizable. In the depth of 40 m, the effect of circulation is clearly visible. After late autumn circulation, the temperature increases up to 4.9 °C, after spring circulation it decreases down to 3.9 °C. In the depth of 60 m, the temperature is nearly not affected by the circulation process and it is nearly constant (4.4 °C). The effect of the early winter circulation in 60 m depth leads to a maximum temperature of 4.6 °C and of spring circulation to a minimum of 4.2 °C.

It is suspected that the change in the circulation behaviour of the Lake Wörthersee can be an effect of global warming. According to the warmer winters, the periods with ice cover become shorter and rarer. We assume that the winter stratification is less developed and the time for the mixing processes is prolonged due to the increasing air temperature in winter. The number of month with temperature below 4 °C has declined significantly since 1800 (Fig. 9).

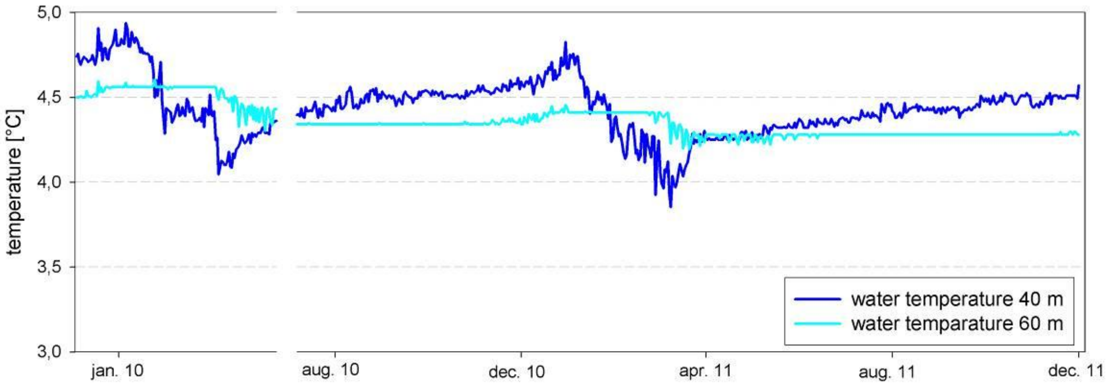


Fig. 19: Lake Wörthersee: temperature in 40 and 60 m depth form January 2010 to December 2011.

Lake Klopeiner See is known as a meromictic lake with a very strong thermal – chemical stratification. The border between mixolimnion and monimolimnion is situated at a depth between 20 and 30 m. Findenegg (1933) described the circulation behaviour of this lake already in the year 1932. At this time spring circulation reached a depth of 32 m. Recent investigations showed a similar behaviour with a slight trend of an upward movement of the oxygen free water body (Fig. 21).

Selected datasets of the period 1975 to 2011 show that there was nearly no change in the stratification of temperature, oxygen and ammonium at the end of spring circulation (Fig. 20).

In 1975, spring circulation touched the water layers down to a depth of 20 m. Although, at end of April the surface water already was warmed up to 11 °C. The effect of cold water transport by spring circulation can be detected by the temperature minimum at the depth of 15 m. Below this layer, the temperature slightly rised again to 4.5 °C. Only the water body from 0 to 20 m get enriched with oxygen, deeper zones were free of oxygen (measured concentration below the analytic limit). In the oxygen poor zone, the ammonium concentration raised steeply. The graphics of spring monitoring in 1979, 1986, 2002 and 2011 show a very similar stratification. The border between mixolimnion and monimolimnion moved at depths of 20 to 30 m (Tab. 5).

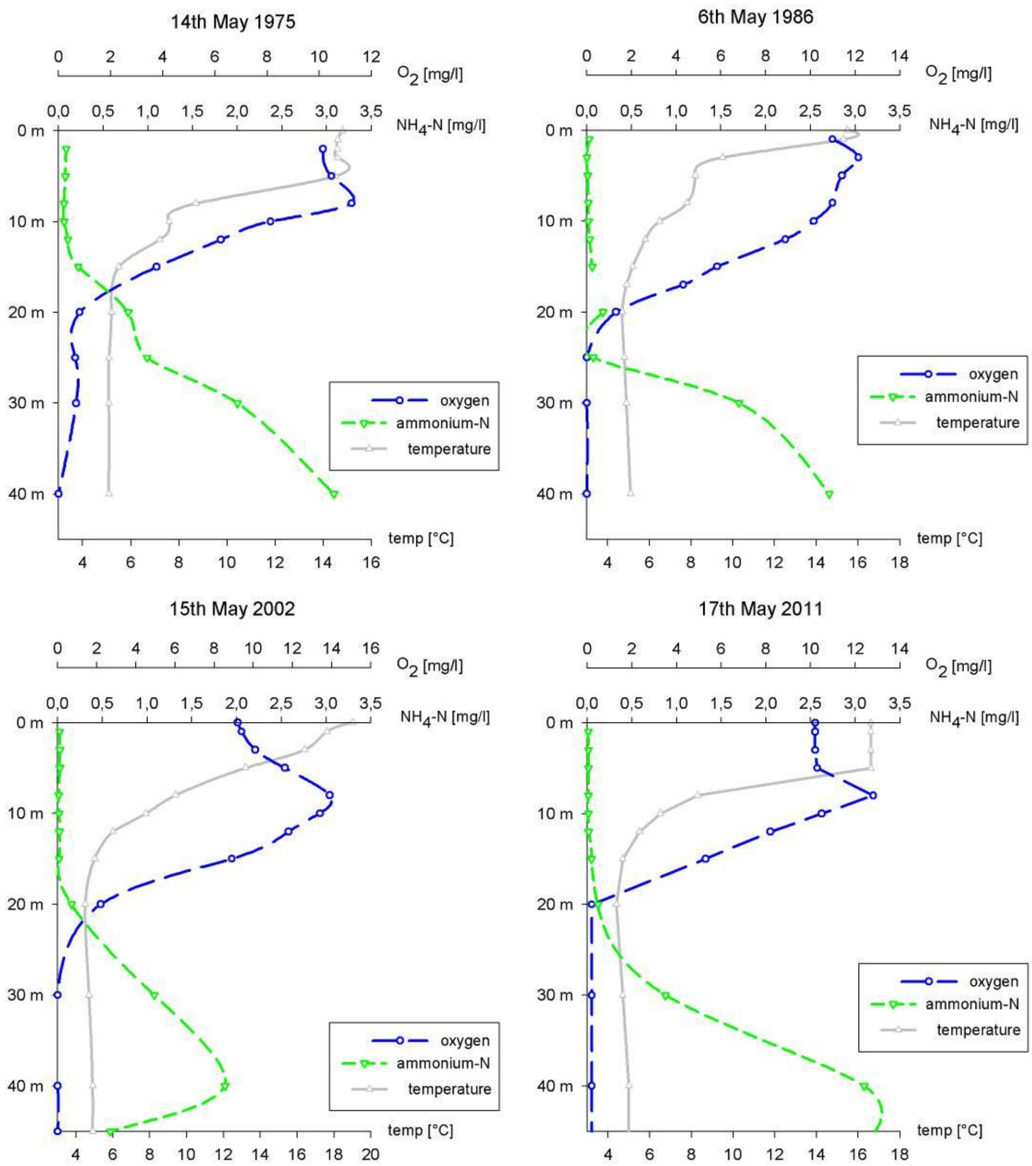


Fig. 20: Lake Klopeiner See: depth profiles of temperature-, oxygen- and ammonium-concentration at the end of spring circulation of different years.

Tab. 5: Extension of mixing water body during spring circulation in Lake Klopeiner See (* Findenegg 1933).

Year	Depth
1932 *	32 m
1979	20 m
1986	25 m
2002	20 - 30 m
2011	20 - 30 m

There is nearly no change in the mixing behaviour of Lake Klopeiner See as it is indicated by the deep profiles of the parameters temperature and ammonium and the development of the 4 °C temperature line (Fig. 22), recorded continuously by the data logger. But the parameter oxygen shows a slight trend to an extension of anaerobic water body within the last three decades. During this period, the layer deeper than 20 m was mostly free of oxygen (Fig. 21). The smooth increasing monimolimnion might be affected by the fact that this lake has every year a complete ice cover (end of December to end of March). The time period of mixing phase, homothermous temperature, between ice break and warming in spring, is getting shorter according to the earlier onset of air temperature warming. The time for the mixing process gets shorter as a consequence of the quick warming of air temperature in spring.

The temperature line in the depth of 20 m with amplitude of 3.9 to 5.6 °C indicates an influence of circulation processes in early winter respectively in spring. At the depth of 30 m no effect of circulation processes could be ascertained. The water temperature remains constantly at 4.9 °C. The stable conditions of the temperature at the beginning of the monimolimnion, compared with the situation at Lake Wörthersee, can be explained by the seasonal closed ice cover. The surface of the lake is totally covered with ice from end of December to end of March.

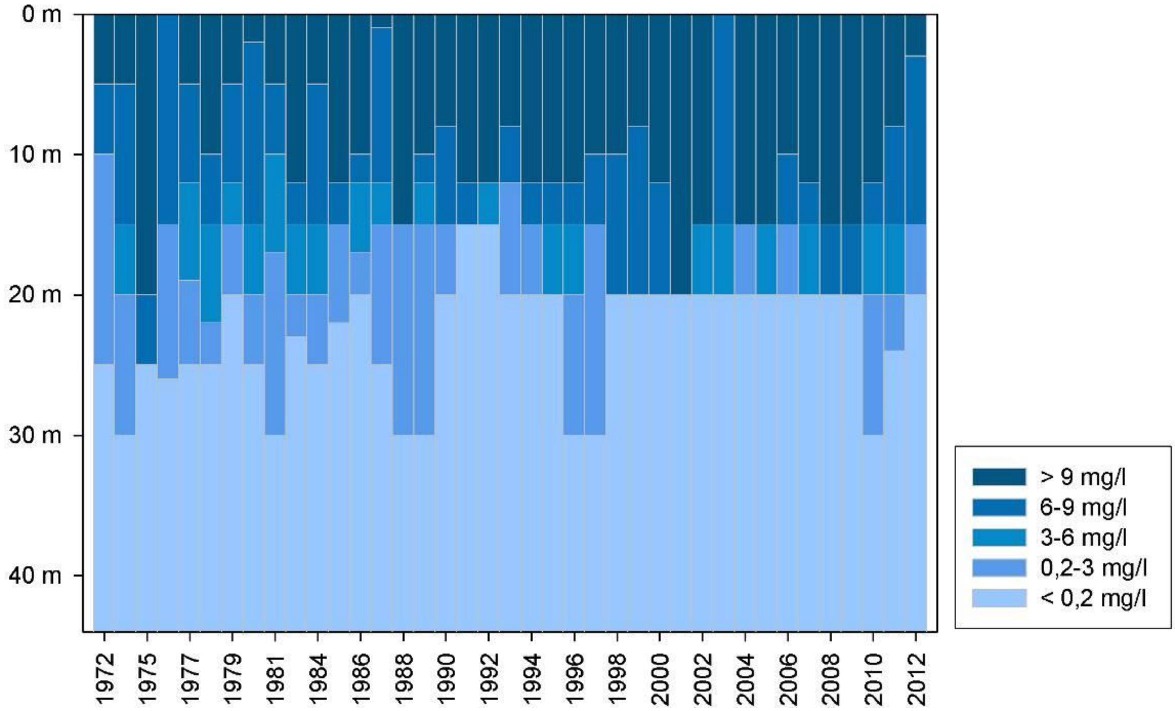


Fig. 21: Oxygen concentration at the end of the mixing period in spring in Lake Klopeiner See.

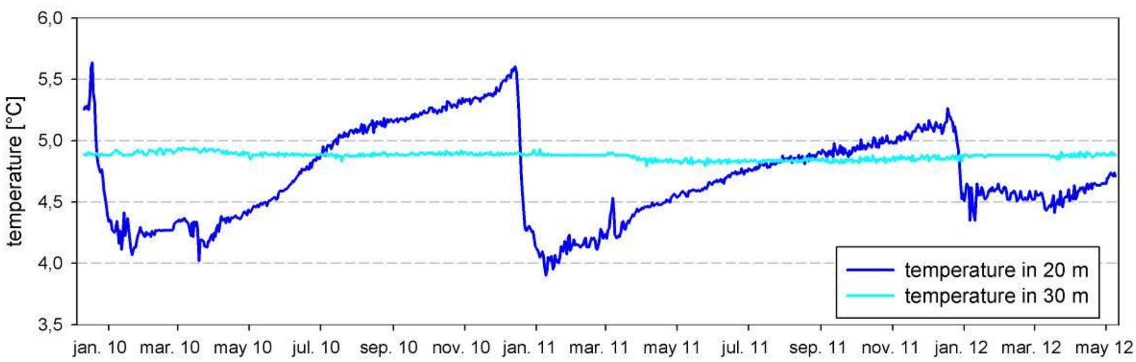


Fig. 22: Lake Klopeiner See: temperature in 20 and 30 m depth form December 2009 to April 2012.

9 Conclusions

The water temperatures at the surface of the three studied lakes in Carinthia have risen. In general, the temperature increased by a mean value of 0.8 °C within the last 20 years. In all three lakes, the strongest warming has been observed in spring (April).

Tab. 3: Development of surface water temperature of selected month on the base of monthly mean values.

Lake	January	April	August	November
Wörthersee 1930 -2010	+ 1,2 °C	+ 1,5 °C	+ 1,2 °C	+ 1,0 °C
Klopeiner See 1996-2010	+ 0,2 °C	+ 1,1 °C	+ 0,2 °C	+ 0,7 °C
Ossiacher See 1990 -2010	+ 0,4 °C	+ 2,5 °C	- 0,8 °C	+ 0,4 °C

In Lake Wörthersee, the boarder between mixolimnion and monimolimnion descended in the period since 1931 to 2011 from 40 to 50 m to 60 to 70 m. Cold and oxygen rich water from the surface gets now transported deeper than in the 1930s. The deeper circulations in spring time caused a decrease in temperature and an increase in oxygen concentration in 50 meters depth. According to the warmer winters, the periods with ice cover become shorter and rarer. We assume that the winter stratification is less developed and the time for the mixing process is prolonged due to the increasing air temperature in winter. The number of month with temperature < below 4 °C has declined significantly since 1800.

In the meromictic Lake Klopeiner See the extension of monimolimnion and mixolimnion didn't change noticeably since 1932. The boarder between the two water bodies is situated at a depth between 20 and 30 meters and the oxygen free water zone shows a slight extension. In the years between 1971 and 1997, occasional oxygen was recorded in 30 meters depth. In the last decades, the oxygen poor zone begins at a depth of 20 meter. The smooth increasing monimolimnion is reducible to the fact that this lake has every year a closed ice cover (end of December to end of March). The time period of mixing phase, homothermous temperature between ice break and warming in spring is getting shorter due to increasing air temperature in spring. The time for the mixing process gets shorter as a consequence to the quick warming in spring.

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Kärntner Institut für Seenforschung
Naturwissenschaftliches Forschungszentrum

Kirchengasse 43
9020 Klagenfurt am Wörthersee
Fax: [0043]-05-0536-57810
E-Mail: abt8.kis@ktn.gv.at
Tel.: [0043]-05-0536-57821

Besuchen Sie uns auf unserer Homepage: www.kis.ktn.gv.at