UPPSALA UNIVERSITET

SLU

UPTEC W 17030
Examensarbete 30 hp
Oktober 2017

A modeling study of the impact of climate change on temperature and oxygen profiles in three Swedish lakes

Ida Eriksson

Abstract

A modeling study of the impact of climate change on temperature and oxygen profiles in three Swedish lakes
Ida Eriksson

Climate change is one the greatest environmental challenges of our time, both due to direct effects such as global warming but also due to the potential of the climate acting as a driver for other environmental problems. This thesis aims to evaluate the impact of climate change on thermal properties and the content and distribution of dissolved oxygen in boreal lakes. By calibrating the one-dimensional, process based model MyLake with data from three, long-time monitored lakes in Sweden, vertical profiles of temperature and oxygen could be studied over time.

Changes in air temperature, precipitation and discharge showed to have a great impact on the thermal properties of the lakes. Simulations 30 and 80 years in the future with high impact climate scenarios indicated an overall increase in lake water temperature and reduced duration of ice cover. The increase in lake water temperature decreased with depth, indicating enhanced thermal stratification.

Climate change also had a profound impact on the content and distribution of dissolved oxygen, DO, in the lakes. Climate-induced increases in dissolved organic carbon, DOC, had an overall negative impact on the DO content in the water column. The impact of changes in air temperature, precipitation and discharge however had an overall positive impact on lake water DO, most likely due to increased oxygen supply during the winter months due to the shorter duration of ice cover. The risk of summer anoxia increased due to the combined effect of increased air temperatures and elevated DOC concentrations.

In conclusion, the impact of climate change will, directly or indirectly, have a profound impact on both the thermal conditions and the content and distribution of oxygen in lakes. This may drastically change future lake water quality as well as the living conditions for the aquatic life.

Keywords: climate change, lake modeling, MyLake, temperature, oxygen, boreal lakes, DOC, water quality, anoxia

Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Science.
Lennart Hjelms väg 9, P.O. Box 7050, SE-75007 Uppsala, Sweden ISSN1401-5765.

Referat

En modelleringsstudie av klimatförändringarnas påverkan på temperatur- och syrgasprofiler i tre svenska sjöar
Ida Eriksson

De pågående klimatförändringarna är ett av vår tids mest utmanade miljöhot, dels på grund av direkta effekter såsom global uppvärmning men också på grund av klimatets potential att agera som en drivande faktor i många miljösammanhang. Målet med denna studie var att undersöka hur klimatförändringarna påverkar temperatur- och syrgasgasförhållanden i sjöar. Genom att kalibrera den en−dimensionella, processbaserade modellen MyLake, med data från tre svenska sjöar, kunde vertikala temperatur- och syrgasprofiler undersökas över tid.

Förändringar i lufttemperatur, nederbörd och flöde, baserade på vedertagna klimatscenarier med hög klimatpåverkan, visade sig ha en tydlig påverkan på sjörnas temperaturförhållanden. Simuleringar 30 och 80 år fram i tiden resulterade i förhöjda vattentemperaturer i hela vattenkolumnen samt förändringar i tidpunkt för isbildning och smältning. Vattentemperaturen ökade för samtliga undersökta djup, men ökningshastigheten minskade med ökat djup. Detta tyder på starkare skiktning av vattenkolumnen i framtiden.

Förändringar i klimatet visade sig också ha en stor inverkan på sjöarnas syrgasförhållanden. Ökande halter av löst organiskt kol, orsakade av klimatförändringar, hade negativ inverkan på sjöarnas syrgasförhållanden. Förändringar i lufttemperatur, nederbörd och flöde hade däremot en överlag positiv inverkan på sjöarnas syrgasförhållanden. Detta beror troligtvis på att tillflödet av syrgas ökar i och med att tiden då sjön är täckt av is förkortas. Risken för syrefattiga förhållanden under sommarmånaderna ökade dock, på grund av den kombinerade effekten av förhöjd lufttemperatur och ökande DOC halter.

Sammanfattningsvis förväntas klimatförändringar ha en tydlig effekt på både temperatur- och syrgasförhållanden i sjöar. Detta riskerar att avsevärt försämra både sjöarnas vattenkvalitet och levnadsförhållanden för vattenlevande organismer.

Nyckelord: Klimatförändringar, modellering, MyLake, temperatur, syre, DOC, vattenkvalitet, syrebrist

Institutionen för vatten och miljö, Sveriges lantbruksuniversitet. Lennart Hjelms väg 9, P.O. Box 7050, SE-75007 Uppsala, Sverige ISSN1401-5765.

Preface

This Master's thesis, corresponding to 30 credits, marks the final part of the M.Sc. in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Science. Supervisor for this project has been Martyn Futter and subject reviewer Brian Huser, both from the Department of Aquatic Sciences and Assessment at the Swedish University of Agricultural Science.

The last months I've spent working on this project has been challenging, fun and extremely educational. I would like to thank Martyn and Brian for giving me the opportunity to do this project and for all help, support and useful input along the way. I would also like to send a big thanks to Raoul-Marie Couture at the Norwegian Institute for Water Research for giving me access to the evolved version of the MyLake model and for helping me get through many miles of code and countless model errors.

I would also like to thank friends and family for love and support during this intense period, with a special shout out to the lunch crew at SLU. Last, but not least, thank you Max for all your support, encouragement and, of course, your mean programming skills, I would not have been able to do this without you.

Ida Eriksson
Stockholm, 2017

 UPTEC W 17 030, ISSN 1401-5765. Published digitally at the Department of Earth Sciences, Uppsala University, Uppsala 2017.

Populärvetenskaplig sammanfattning

En modelleringsstudie av klimatförändringarnas påverkan på temperatur- och syrgasprofiler i tre svenska sjöar
Ida Eriksson

De pågående klimatförändringarna är ett av vår tids mest utmanade miljöhot. I framtiden förväntas bland annat lufttemperaturen att öka och nederbördsmönster förändras. Klimatförändringar förväntas också bidra med en ökad tillförsel av löst organiskt kol (eng. dissolved organic carbon), DOC. I denna studie har klimatförändringarnas inverkan på temperatur och syrgashalter i sjöar undersökts.

Klimatförändringar förväntas öka vattentemperaturen i sjöar men också påverka hur temperaturen fördelas i sjön. I Sverige är många sjöar dimiktiska vilket innebär att hela vattenkolumnen blandas om två gånger per år, en gång på hösten och en gång på våren. Under tiden mellan omblandningarna säger man att sjön är skiktad. En skiktad sjö består av ett övre vattenlager, *epilimnion*, och ett undre vattenlager, *hypolimnion*. Denna skiktning uppkommer på grund av att temperaturskillnader i epilimnion och hypolimnion leder till skillnader i densitet vilket gör att vattenmassan i epilimnion flyter ovanpå hypolimnion. Om klimatet förändras är det troligt att temperaturskillnaderna mellan epilimnion och hypolimnion ökar vilket kommer förstärka sjöarnas skiktning.

När en sjö är skiktad innebär det att lösta ämnen inte fördelas jämnt i vattenkolumnen. Halten och fördelningen av syrgas i en sjö är något som påverkas kraftig av sjöns skiktningsmönster. När sjön är skiktad når inte syrgas från luften ner till de lägre nivåerna i sjön. Då en stor del av syrgasförbrukningen i en sjö sker i bottenvattnet kan långa perioder av skiktning leda till syrefattiga förhållanden, speciellt i bottenvattnet. Om syrgashalterna i en sjö blir låga finns det risk att vattenlevande organismer kan påverkas eller till och med dö. Det finns också stor risk att vattenkvaliteten försämras.

För att förstå vilken inverkan klimatet kan komma att ha på temperatur- och syrgasförhållanden i sjöar användes en modell för att simulera hur sjöarnas temperatur- och syrgasprofiler i sjöar, alltså fördelningen av temperatur respektive syrgas genom vattenkolumnen, förändras över tid. Modellen kalibrerades med data från tre svenska sjöar, utspridda runt om i landet. För att simulera framtida klimat skapades tre klimatscenarier. Det första scenariet, *climate*, var endast baserat på förändringar i lufttemperatur, nederbörd och flöde i sjön. Det andra scenariet, *DOC*, var endast baserat på ökande halter av löst organiskt kol och det sista, *climate+DOC* var baserat på den kombinerade effekten av förändringar i klimat och DOC halter.

Förändringar i lufttemperatur, nederbörd och flöde, baserade på vedertagna klimatscenarier med hög klimatpåverkan, visade sig ha en tydlig påverkan på sjörnas temperaturförhållanden. Simuleringar 30 och 80 år fram i tiden resulterade i förhöjda vattentemperaturer genom vattenkolumnen och också förändringar i tidpunkt för isbildning och smältning. Vattentemperaturen ökade för samtliga djup, men ökningshastigheten minskade med ökat djup. Detta tyder på starkare skiktning av vattenkolumnen i framtiden.

Förändringar i klimatet visade sig också ha en stor inverkan på sjöarnas syrgasförhållanden. Ökande halter av löst organiskt kol hade negativ inverkan på sjöarnas syrgasförhållanden. Förändringar i lufttemperatur, nederbörd och flöde hade däremot en överlag positiv inverkan på sjöarnas syrgasförhållanden. Detta beror troligtvis på att tillflödet av syrgas ökar i och med att tiden då sjön är täckt av is förkortas. Risken för syrefattiga förhållanden under sommarmånaderna ökade dock, på grund av den kombinerade effekten av förhöjd lufttemperatur och ökande DOC halter.

Sammanfattningsvis kommer klimatförändringar ha en tydlig effekt på både temperatur- och syrgasförhållanden i sjöar. Detta riskerar att avsevärt försämra både sjöarnas vattenkvalitet och levnadsförhållanden för vattenlevande organismer.

Table of Contents

1 INTRODUCTION

1.1 OBJECTIVE

Climate change is one of the most challenging environmental issues of our time. Changes in climate does not only lead do direct effects such as global warming but the climate also has a great potential to act as a driver for other environmental problems. The aim of this study is to investigate the impact of climate change on boreal lakes by studying the changes in temperature and oxygen profiles for some Swedish lakes. By implementing data from long-time monitored lakes in the one-dimensional, process based model MyLake, the distribution of temperature and dissolved oxygen over time and depth can be studied. The goal is to investigate both individual and combined effects of different factors influencing the distribution of temperature and dissolved oxygen. To do this, different future scenarios will be created based on existing climate scenario data with a high climatic impact.

1.2 HYPOTHESES

The following hypothesises were to be evaluated to investigate the impact of climate change on temperature and oxygen profiles

- Increased air temperatures will lead to longer and intensified periods of stratification and altered ice phenology.
- Changed stratification patterns will reduce the oxygen content in the water column and lead to more frequent events of hypoxia or anoxia.
- The concentration of dissolved organic carbon is dependent on climatic factors and will increase in the future. This will result in both intensified thermal stratification and reduced oxygen content.

1.3 DELIMITATIONS

This study has been limited to only include three lakes, with no extreme morphometric, chemical or biological features. All lakes are located in Sweden.

The study is also limited to only focus on the impact of climate change on temperature and oxygen, the impact on other variables and the possible interactions between different variables are neglected.

The calibration of the model was done manually by altering parameters thought to have an impact on the temperature and oxygen distribution. Due to time restriction, no uncertainty or sensitivity analysis was performed on the model parameters.

When evaluating the impact of climate change, only changes in air temperature, precipitation, inflow and concentration of dissolved organic carbon are considered. The study only include climate scenarios with a high climatic impact.

2 BACKGROUND

2.1 THERMAL STRATIFICATION

The vertical temperature distribution in lakes is usually not uniform but varies with depth in the water column. The lake is then said to be stratified. When a lake is stratified it is divided into an upper layer, the *epilimnion*, and a lower layer, the *hypolimnion* (Figure 1). The two layers are separated by the *thermocline*, which is the surface layer with the maximum vertical temperature gradient. The vertical temperature distribution, and thus the thermal stratification, is strongly affected by the surrounding climate and often has seasonal variations (Hutter et al., 2011).

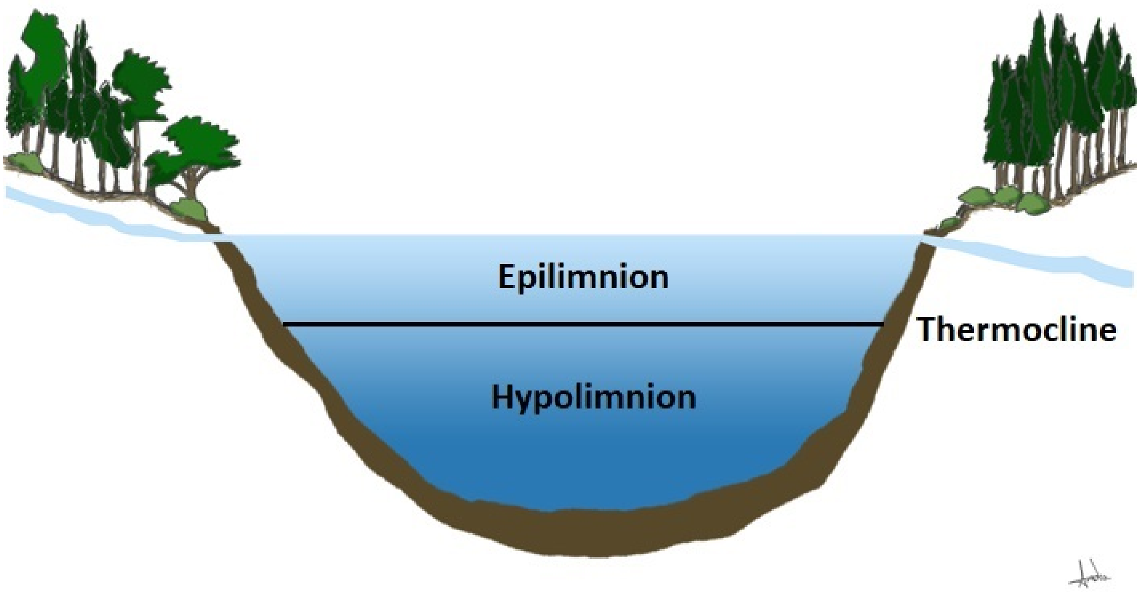


Figure 1 A stratified lake with epilimnion and hypolimnion, divided by the thermocline.

The concept of stratification emerges from the fact that the density of water changes with temperature. Since the water temperature in a lake usually not is uniform, water bodies will sink or float depending on the temperature, and thus the density, of the surrounding water bodies. The maximum density of water is at 4°C. Temperatures above or below 4°C will result in lower density, though the density does not decrease linearly. The density of water is also influenced by the salinity of the water and the concentration of suspended solids (Zhen-Gang, 2008).

Thermal stratification develops due to seasonal changes in temperature. During summer months the upper layer of the lake starts to warm up due to higher air temperatures and increased solar radiation, making the water less dense. The surface water warms up faster than the bottom water, separating the water column into a warmer, less dense water layer, the epilimnion, and a colder, more dense bottom layer, the hypolimnion. This creates a stable density profile throughout the water column, which means that the water gets colder and heavier with increasing depth. As the heating of the surface layer continues during the summer months the stratification intensifies (Hutter et al., 2011).

In the autumn, the surface water begins to cool off due to colder air temperatures. As the temperature of the surface water decreases, the water gets heavier and starts to sink, mixing the water column. Increased wind activity is often characteristic for the season and the mixing processes are therefore increased by wind-induced mixing. The mixed layer grows with time until the entire water column is mixed. When the mixing reaches the bottom water it is called *winter homothermy*. As the air temperature gets cooler the entire water column cools down until it reaches 4°C, the temperature when the density of the water is at its maximum. Further cooling of the water column from the surface makes the upper layer of the lake cooler and therefore lighter than the lower layers. This again creates a, often weaker, thermal stratification of the water column. If ice is formed on the lake, that will block any wind-induced energy from reaching the water column (Hutter et al., 2011).

In the spring, increasing air temperature melts potential ice and heats up the surface water. The warmer, and therefore heavier, surface water then mixes with the underlying layers until the entire water column is at maximum density at 4°C. As the season goes towards summer the air temperature increases and the summer stratification starts over (Hutter et al., 2011).

The above mentioned processes are typical for *holomictic* lakes where the entire water column is mixed once or several times each year, especially for *dimictic* lakes, which mixes twice per year. *Meromictic* lakes are lakes that do not mix entirely, but only to a certain depth. Those lakes are usually deep, with an increasing salinity at the lower layers of the lake which increase the density of the bottom water. Lakes that never mix are called *amictic lakes.* Local climate, especially air temperature and exposure to wind are important factors controlling the thermal stratification of lakes. Location, inflow and outflow of water and lake morphometry are also factors influencing the development of stratification in lakes (Hutter et al., 2011).

2.1.1 Stability of the water column

The stability of a lake, or the potential of the lake to turn over, is physically controlled by the incoming energy from solar radiation and wind. Solar radiation is the main driver for thermal stratification and the stronger the stratification is the higher the stability gets. Wind stress at the surface can import turbulent activity to the lake, which plays an important role for the stability of the water column. The influence from wind and therefore the turbulent activity attenuates with increasing depth. The *turbocline* is the maximum depth to which turbulence can penetrate. (Hutter et al., 2011).

The Schmidt stability is a way to describe the overall stability of the water column in a lake. The Schmidt stability constant can be calculated as

$$S = \frac{1}{A_0} \sum_{z=0}^{z_{max}} (z - z_*)(\rho(z) - \rho_*)A(z)\Delta z \tag{1}$$

where A_0 is the lake surface area, z is the depth, varying by $\Delta z = 1m$ from 0 at the lake surface to z_{max} at the maximal depth of the lake. $\rho(z)$ and $A(z)$ are the density and area at depth level z and z_* and ρ_* are the volumetric mean depth respectively mean density, both defined equivalent as

$$\alpha_* = \frac{1}{V} \sum_{\alpha=0}^{\alpha_{max}} \alpha A(\alpha)\Delta\alpha \tag{2}$$

The Schmidt stability depends on both the density differences due to temperature gradients and the temperature change, both leading to increased stability (Schwefel et al., 2016).

2.2 DISSOLVED OXYGEN

The concentration of dissolved oxygen in lakes is one of the most important factors determining the water quality (Ptak and Nowak, 2016). Dissolved oxygen acts both as an indicator and a driver for water quality and has great impacts on both the chemical and the biological process in lakes (Snortheim et al., 2017).

A main supply source of oxygen to lakes is the atmospheric flux of oxygen through the water-air interface, oxygenating the surface water. By diffusion and mixing of the water column, the atmosphere supplies not only the surface water but also the lower layers of the water column with oxygen. In thermally stratified lakes the atmospheric exchange result in higher DO content in the epilimnion of the lakes and lower DO in the hypolimnion. Another supply source of oxygen is through photosynthetic production (Golosov et al., 2012). The concentration of dissolved oxygen is also in close relation with the water temperature. Due to decreasing solubility, increasing water temperature leads to a decrease in the content of dissolved oxygen (Ptak and Nowak, 2016). Wind speed and relative humidity are other meteorological drivers affecting the content and distribution of dissolved oxygen (Snortheim et al., 2017). In more shallow parts of a lake, the content of dissolved oxygen is mainly controlled by the water temperature. Along the thermal profile, especially in deeper parts of a lake, the distribution of dissolved oxygen in thermal profiles is more complex and is, to a larger extent, controlled by mineralization processes occurring at the bottom and of processes reducing the supply of oxygen from the surface water (Ptak and Nowak, 2016).

In the hypolimnion, the primary mechanism for oxygen depletion is associated with decomposition of organic matter. Oxygen can also be consumed by respiration or through uptake of the sediment. The oxygen consumed by processes occurring in the sediment is called the sediment oxygen demand, SOD. SOD, is often primarily controlled by inorganic chemical reactions with iron and sulfide (Lee and Jones-Lee, 1999). The thickness of the hypolimnion has appeared to be an important factor driving the rate of oxygen depletion. For deep lakes with a thick hypolimnetic layer, the total oxygen depletion is mostly controlled by the hypolimnetic oxygen demand. For shallow basins, oxygen depletion is strongly controlled by the sediment oxygen demand (Bouffard et al., 2013).

Oxygen depletion and reduced oxygen supply may decrease the oxygen content of a lake, sometimes to an extent where the oxygen concentration is lower than the minimum concentration required to sustain the life of fishes and invertebrates. For most animals, the minimum oxygen concentration for surviving in water is 2 mg O_2 L^{-1}. When the oxygen concentration reaches below this limit the condition is called *hypoxia*. The complete absence of oxygen is called *anoxia*. Both hypoxia and anoxia are serious environmental issues with the ability to severely decrease water quality and have a devastating impact on the aqautic life of lakes (Diaz, 2001).

2.3 THE IMPACT OF CLIMATE CHANGE

A changing climate has the ability to alter many of the processes occurring in lakes, both physical, chemical and biological. This is likely to have a great impact on the future water quality of lakes.

2.3.1 Changes in temperature distribution

Warmer air temperatures will affect the water temperatures of lakes and the global warming of the world is predicted to cause the overall water temperature of lakes to increase (Fang and Stefan, 2009; Saloranta et al., 2009; Schwefel et al., 2016). The temperature of the surface water is directly dependent on the air temperature, but the warming trends are usually more distinct for surface water temperatures than for air temperatures (Soja et al., 2014). Depending on the lake type, the water temperature is affected in different ways. *Polymictic* lakes are lakes that mixes several times a year. In these lakes, the entire water column responds directly to changes in air temperatures. In stratified lakes, changes in air temperature will mainly affect the epilimnion, until the water column is mixed (Saloranta et al., 2009). The water temperature in the epilimnion is often directly dependent on the air temperature (Ptak and Nowak, 2016). During stratified periods, the hypolimnetic water temperature will increase constantly but at a much lower rate than in the epilimnion (Schwefel et al., 2016). In deeper parts of thermally stratified lakes, during periods without mixing of the water column, the temperature distribution is more complex and the water temperature is controlled by a combination of factors such as morphometric parameters and ground water supply (Ptak and Nowak, 2016).

Since increases in air temperature affect the epilimnion to a larger extent than the hypolimnion, climate changes are predicted to increase both the duration and the strength of stratification in stratified lakes. For dimictic lakes, the onset of thermal stratification is predicted earlier in the spring while the mixing in the fall is predicted later, extending the duration of the stratified period (Foley et al., 2012; Bouffard et al., 2013; Holmberg et al., 2014; Palmer et al., 2014).

2.3.2 Changes in ice phenology

A warmer climate will also alter the ice phenology. Later formation of ice cover and earlier ice break up has been observed, decreasing the duration of ice cover. Also later first appearance of ice cover along the shore and reduced thickness of ice has been observed (Choiński et al., 2015). There are indications that the trends of reduced ice cover began as early as in the 16th century (Magnuson et al., 2000). Different types of lakes respond, in terms of changes in ice phenology, in different ways to increasing air temperatures. Important factors explaining differences in lake ice dynamics are geographic location and altitude of a lake as well as average depth and total lake volume (Choiński et al., 2015).

2.3.3 Effects of changed thermal stratification and ice phenology on dissolved oxygen content

Changes in thermal stratification and ice phenology have proven to have a great impact on the content and distribution of dissolved oxygen in lakes (Golosov et al., 2012,). The length of the ice-covered period, the heat content of bottom sediments and the amount of organic matter stored in bottom layers and sediment surface are also factors shown to control the extent of anoxic zones (Terzhevik et al., 2009).

Increased thermal stability due to changes in the climate leads to longer periods of stratification. In stratified lakes, the hypolimnion will not be reoxygenated until the water column is mixed. During periods without mixing the oxygen supply to the hypolimnion is therefore low and since a lot of oxygen is consumed by microbial respiration and oxygen flux to the sediment the hypolimnetic oxygen concentrations may decrease drastically (Bouffard et al., 2013). The longer stratified periods therefore increase the risk of hypoxic or anoxic conditions in the hypolimnion and bottom layer of lakes (Foley et al., 2012; Bouffard et al., 2013; Palmer et al., 2014; Schwefel et al., 2016).

During periods of ice cover the atmospheric gas exchange at the air-water interface is excluded, eliminating the main supply source of dissolved oxygen to the lakes (Golosov et al., 2012). In many lakes winter anoxia during periods of ice cover is projected to shorten due to shorter duration of ice cover while summer anoxia is projected to lengthen due to longer periods of thermal stratification (Fang & Stefan, 2009; Couture et al., 2015).

2.3.4 The effect of browning

Changes in climate are also predicted to increase the amount of dissolved organic matter in lakes, increasing the colouration and decreasing the water clarity. The phenomenon is called browning and has the potential to alter lake water quality by changing physical, chemical or biological properties. Browning has been observed in many lakes in the northern hemisphere (Evans et al., 1988; Haaland et al., 2010; Ekström et al., 2011). Positive trends for organic carbon have shown to remain relatively constant across both climatic gradients and catchment sizes, indicating that browning occurs in many different types of lakes. The largest positive trends in organic carbon have been observed in regions with a strong reduction in sulfur deposition. In dry regions, precipitation has shown to be a strong, positive driver for organic carbon, due to increased mobilization of organic carbon in the catchment area. As the climate continues to change, the browning trend is predicted to keep increasing, affecting the water quality of lakes around the world (de Wit et al., 2016).

Browning of lakes has the potential to affect temperature distribution and thermal stratification has been shown to depend strongly on water clarity (Persson and Jones, 2008; Heiskanen et al., 2015). Water clarity is a measurement of how deep the incoming solar radiation can penetrate the water column and is connected to the color of the water and the amount of suspended particles. The color of water mainly consists of colored dissolved organic matter, CDOM. CDOM is tightly connected to dissolved organic carbon, DOC (Pace and Cole, 2002) and is usually part of the allochthonous DOC that originates from the watershed (Findlay and Sinsabaugh, 2003; Kritzberg et al., 2004). A measurement of water clarity is the light extinction coefficient, a factor shown to have a great impact on the temperature distribution of lakes (Persson and Jones, 2008; Heiskanen et al., 2015). Large light extinction coefficients increase the absorption of solar radiation in the upper layer of lakes, enhancing the warming of the surface water. Because most solar radiation is absorbed in the epilimnion, warming of the hypolimnion will decrease, making for a greater temperature gradient between the epilimnion and the hypolimnion and thus stronger lake stratification (Persson and Jones, 2008). This effect is more visible in smaller than in larger lakes (Saloranta et al., 2009). DOC content also affects the mixing depth. Large increases in the DOC content lead to a greater increased temperature and a reduction in thickness of the epilimnion (Palmer et al., 2014).

High DOC content may also affect primary production in lakes. If the light reaching the bottom layers of a lake is reduced this will diminish or even eliminate the primary production in this areas, eliminating the oxygen supply from photosynthesis. This may cause greater depletion of oxygen in the bottom layers, and in worst case cause anoxic or hypoxic conditions in the bottom water

(Brothers et al., 2014). Apart from negatively affecting the water quality and the living conditons for aquatic organisms, anoxic conditions may also lead to the release of DOC, phosphorous and other substances from the sediment. This causes a negative loop which increases the effect of brownification and may further reduce the oxygen content of the lake (Brothers et al., 2014).

3 MATERIALS AND METHODS

3.1 STUDY SITES

Three swedish lakes were chosen as case studies (Figure 2), Remmarsjön in the north-east (Figure 2:1), Härsvatten in the mid-west (Figure 2:2) and Fiolen in the south-east (Figure 2:3) of Sweden. The selection of study sites were based on location, to make for a large spatial spread, on physical and chemical features of the lakes and on the amount of data available.

1. Remmarsjön
Remmarsjön is located in Västernorrland region in the north of Sweden. The lake is 1.37 km^2 and located at an altitude of 234 m above sea level (Lantmäteriet, 2017). The mean depth is 5.2 m and maximum depth is 14.4 m. The catchment area of the lake is 124.4 km^2 (Persson, 1996a).

2. Härsvatten
Härsvatten is located in Västra Götaland region in the south-west of Sweden. The lake is 0.19 km^2 and located at an altitude of 128 m above sea level (Lantmäteriet, 2017). The mean depth is 5.7 m and maximum depth is 26.2 m. The catchment area of the lake is 2.21 km^2 (Persson, 1996b).

3. Fiolen
Fiolen is located in Kronoberg region in the south of Sweden. The lake is 1.65 km^2 and located at an altitude of 226 m above sea level (Lantmäteriet, 2017). The mean depth is 3.8 m and maximum depth is 10.5 m. The catchment area of the lake is 5.46 km^2 (Persson, 1996c).

Figure 2 A map of Sweden showing the location of the three lakes chosen as study sites. Remmarsjön (1) in the north and Härsvatten (2) and Fiolen (3) in the south of Sweden.

3.2 THE MYLAKE MODEL

To study the impact on temperature and oxygen profiles data from the three study sites were implemented in the MyLake model, a one-dimensional process-based model code developed by Tuomo M. Saloranta and Tom Andersen. MyLake is an open source model available for public access on GitHub (Github, 2016). The following description is based on the manual for MyLake (v 1.2) developed by Saloranta & Andersen (2007).

MyLake stands for Multi-year simulation model for Lake thermal- and phytoplankton dynamics and the model is used to simulate the vertical distribution of lake water temperature, the formation of seasonal ice and snow coverage and phosphorus-phytoplankton dynamics. The light attenuation is possible to calculate from light absorption by water molecules, phytoplankton and colored DOC, light scattering and shading.

As input data, the model uses time series of meteorological variables and inflow properties, lake morphometry and initial profiles and model parameter values. The model time step is one day (24 h) and therefore daily resolution of the time series is required. Missing values are automatically estimated in MyLake by linear interpolation. The vertical resolution of the simulations was set to

10 cm.

3.2.1 Modeling of lake thermodynamics

In the MyLake model, lakes are assumed to be horizontally homogeneous and the vertical profile is divided into a number of layers for which calculations are made to create a one-dimensional profile over the lake.

Temperature distribution in the water column
Temperature distribution in the water column is controlled by diffusive mixing and local heating processes. The present temperature distribution, $FT_i(t)$, in each layer, i, can be computed as

$$FT_i(t) = T_i(t - \Delta t) + \Delta T_i(t) \tag{3}$$

where $T_i(t-\Delta t)$ is the temperature in layer i at the previous time step and ΔT_i is the local heating in the layer during the last time step. The local heating during open water periods can, for the surface layer, be computed by

$$\Delta T_1 = (Q_{WS\_norm\_1} + Q_{turb} + Q_{lv} + Q_{sw\_abs\_1})A_1/\rho_w C_p V_1 \tag{4}$$

where $Q_{WS\_norm\_1}$ is the heat flux from the sediment, Q_{turb} is the turbulent heat flux, Q_{lv} the net longwave radiation flux, $Q_{sw\_abs\_1}$ is the incoming solar radiation flux absorbed in the layer, A_1 and V_1 are the area and volume of the first layer (the surface) and ρ_w and C_p are the density and specific heat capacity of the water. The local heating of subsurface layers is calculated in the same way except that the turbulent heat flux and the net longwave radiation flux is excluded. During periods of ice-coverage only sediment-water heat flux and shortwave radiation. MyLake uses the MATLAB Air-Sea toolbox to calculate some of the radiative and turbulent heat fluxes, surface wind stress and astronomical variables. Some algorithms, e.g. for calculation of shortwave radiation, are contained directly in the code for the MyLake model.

3.2.2 Heat flux from the sediment

To calculate the heat flux between sediment and water the temperature profile is solved for a 10 m thick sediment layer. At depths deeper than 10 m the heat flux in the sediment is assumed to vanish. The temperature at the top of the sediment layer is assumed to be the same as in the bottom of the water column and the sediment temperature profile is then solved in a similar way as for the water column, depending on the heat diffusion rate and the density and specific heat capacity of the sediment.

3.2.3 Solar radiation flux

Incoming light is divided in two wavelength bands, photosynthetically active radiation, PAR light ($\lambda = 400 - 700nm$), and non-PAR light($\lambda < 400 or \lambda > 700nm$). Non-PAR light, especially the longer wavelengths are rapidly attenuated in the upper layers of the water column. The incoming solar radiation flux can be calculated

$$\begin{aligned} Q_{sw\_abs} = Q_{sw}(1-\alpha)\{f_{PAR}[\,exp(-\bar{\epsilon}_{i-1}z_i) - exp(-\bar{\epsilon}_i z_{i+1})\frac{A_{i+1}}{A_i}] \\ [+(i - f_{PAR})\,exp(-\bar{\hat{\epsilon}}_{i-1}z_i) - exp(-\bar{\hat{\epsilon}}_i z_{i+1})\frac{A_{i+1}}{A_i}]\,\} \end{aligned} \tag{5}$$

where α is the average daily albedo, f_{PAR} is the PAR fraction of the total incoming radiation and $\bar{\epsilon}$ and $\bar{\hat{\epsilon}}$ is the PAR and non-PAR light extinction coefficients at each layer. $\bar{\epsilon}$ and $\bar{\hat{\epsilon}}$ takes both chlorophyll and non-chlorophyll related attenuation into account. During periods of snow or ice cover, the light is strongly attenuated before reaching the surface layer.

3.2.4 Mixing of the water column

Mixing of the water column can be wind-induced or due to an unstable density profile. In every iteration MyLake search for water masses below the freezing point, if found ice formation is initiated. For layers with temperatures above freezing point, density is calculated. Unstable density profiles induce convective mixing. Layers with unstable vertical density profiles are mixed with the first stable layer underneath until the entire water column is stable or neutral.

During open water periods mixing of the water column can also be forced by wind. Total kinetic energy, TKE, accumulated over one time step can be calculated as

$$TKE = W_{str} A_s \sqrt{\frac{\tau^3}{\rho}} \Delta t \tag{6}$$

where τ is wind stress, calculated with the *Air-Sea Toolbox*, ρ is water density, Δt is the time step,A_s is the surface area and W_{str} is the wind sheltering coefficient. TKE is compared with the potential energy, PE, required to mix the epilimnion with the first layer below. If TKE is larger than PE the layers will continue to mix with the epilimnion until TKE is smaller than PE. During periods of ice cover, no wind-induced mixing can occur and TKE is defined as zero.

3.2.5 Modeling of ice and snow cover

Ice formation occurs when the water temperatures reach below zero. T_f denotes the freezing point. Simplified processes for ice formation are applied. When the air temperature, T_a, is above T_{f_ice} melting can occur. Snow melts before ice. Energy used for melting is calculated from total heat flux at the surface, where the shortwave radiation is assumed to be absorbed in the snow/ice layer. When the lake is covered with ice the temperature of the surface water is set to T_f.

3.2.6 Modeling of dissolved and particulate matter and phytoplankton

MyLake uses a simple approach to model phytoplankton dynamics, containing only two state variables, phytoplankton biomass, C (measured as chlorophyll a) and dissolved inorganic phosphorus, P. By assuming fixed composition C and P are related by a constant yield coefficient y_c. As opposed to phosphorus chlorophyll both attenuates light and is subject to sinking losses, leading to following partial differential equations for P and C

$$A\frac{\delta P}{\delta t} = \frac{\delta}{\delta z}[KA\frac{\delta P}{\delta z}] - Ay_c^{-1}rC \tag{7}$$

$$A\frac{\delta C}{\delta t} = \frac{\delta}{\delta z}[KA\frac{\delta C}{\delta z}] - A\frac{\delta(wC)}{\delta z} + A(rC + S_{Csed}) \tag{8}$$

where K is the vertical diffusion coefficient, A the area of the layer, w the sinking velocity for chlorophyll, r the specific rate of change for chlorophyll and S_{Csed} is the resuspension rate from the sediment.

3.2.7 Modeling of DO dynamics

The original version of MyLake does not include modeling of DO dynamics, though providing a suitable basis by handling ice dynamics, primary productivity, DOC degradation and light attenuation. In addition to the current model Couture et al. (2015) developed an oxygen module based on the physical exchange of DO between air and water, production of DO by photosynthesis and consumption of DO by respiring organisms. MyLake with the DO module included will be referred to as Mylake v.2.

The balance of DO can be described as

$$S_{DO} = (P - R - S_{OM}) - F_{DO} \tag{9}$$

where P is the photosynthetic production of DO, R and S_{OM} are the DO consumption due to respiration and microbial decay of organic matter and F_{DO} the flux of oxygen between the atmosphere and the surface.

Air-water exchanges of DO
The flux of oxygen at the surface is calculated according to

$$F_{O2} = k_{O2}([O_2]_{sur} - [O_2]_{eq}) \tag{10}$$

where k_{O2} is the transfer velocity of oxygen, $[O_2]_{sur}$ the concentration of oxygen in the surface water and $[O_2]_{eq}$ is the concentration of oxygen at equilibrium. The transfer velocity of oxygen is affected by the wind speed and the temperature of the surface water.

Production and consumption of DO
The production of DO during photosynthesis is proportional to the concentration of chlorophyll-a and can be described as

$$P(z,t) = s_{Chl}\mu P_{Chl} \tag{11}$$

where μ is the specific growth rate of algal biomass and S_{Chl} the yield coefficient between oxygen and chlorophyll-a. The specific growth rate is controlled by the temperature and the available amount of light and phosphate.

The consumption of DO due to respiration is also proportional to the chlorophyll-a concentration and can be calculated as

$$R(z,t) = s_{Chl} m P_{Chl} \tag{12}$$

where m is the mineralization rate of phytoplankton, a term mainly controlled by the temperature.

Consumption of DO due to degradation of organic matter, OM, is strongly dependent on the OM concentration and can be described as

$$S_{OM} = k_{OM}\Theta_{OM}^{T-20} OM \tag{13}$$

where k_{OM} is the organic decomposition rate, Θ_{OM} a temperature adjustment coefficient and OM includes DOC and non-chlorophyll related detritus.

3.2.8 Strenghts and limitations of MyLake

MyLake is a robust model that only uses the most significant physical, chemical and biological processes, though in a well-balanced way making the model suitable both as an investigating tool as well as for making predictions. The relatively simple model structure allows easy setup and short runtimes which make the model suitable for making long-term predictions or simulation of a large number of lakes. Since the model includes the formation of snow and ice it is especially useful for lakes in colder climates. MyLake is an open source code, allowing for easy public access and the possibility to change and modify the code after own preferences.

The model has been tested and proven useful for a number of applications, though it comes with certain limitations. The model time step is fixed to 24 hours, which can make some applications impossible. The model also neglects lateral heterogeneity which makes it only suitable for lakes where a one-dimensional assumption is reasonable. Complex processes such as saline or groundwater intrusions, food web processes, detailed water-sediment nutrient feedback etc. are not included in the model making it too simple for some applications.

3.2.9 Model setup and run

To run the MyLake model the following data needed to be provided; an input file containing daily meteorological and hydrological measurements, an initial file containing information of lake morphometry and initial profiles of lake substances, and a parameter file containing the model parameters.

Meteorological and hydrological input data
The input file consists of daily measurements of meteorological and hydrological variables. The meteorological variables includes global radiation, cloud cover, air temperature, relative humidity,

air pressure, wind speed and precipitation. The hydrological variables includes inflow and inflow temperature and constant values of incoming carbon, sulfate, total and dissolved phosphorus, chlorophyll-a, DOC, etc.

The meteorological data was collected from the SMHI (sv. *Sveriges Meteorologiska och Hydrologiska Institut*) site for meteorological observations (SMHI, 2017a). Measurements were collected from the station closest to the lake with as much data as possible available (Appendix A, Table 13). No data before 2008 was used due to the lack of global radiation measurements.

Hydrological inflow data was collected from SMHI (SMHI, 2017b) based on modeled data for the catchment areas of the lakes. For Härsvatten inflow data was only available for a larger sub catchment area. To estimate the inflow to Härsvatten the inflow for the entire catchment was multiplied by the ratio between the catchment area and the specific area of the Härsvatten basin.

The inflow of oxygen was estimated from the temperature of the incoming water according to Fondriest Environmental (2013). Zero salinity was assumed.

The inflow of DOC was estimated as the mean DOC concentration for each lake over the entire time period.

Initial data
The initial file contains data of lake morphometry, in terms of chosen depth levels and lake area at these levels, and initial profiles of temperature, carbon, sulfate, total and dissolved organic phosphorus, chlorophyll-a, dissolved organic carbon, etc. The initial profiles were all set to constant values and no initial snow or ice was assumed.

Parameter values
The parameter file contains most of the model parameters, both physical and chemical. Initially, all parameters were set to the default values coming with the model, except for longitude and latitude which were specified for each lake.

3.2.10 CALIBRATION OF THE MODEL

To calibrate the model, data of observed temperature and oxygen profiles for the three lakes were used. The depth levels chosen for each lake were based on the availability of observation data. The model was calibrated manually for each lake respectively by changing values in the parameter file. To evaluate the fit between modeled and observed values the mean squared error, MSE, was calculated according to

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2 \tag{14}$$

where $\hat{Y}_i$ is the modeled value, Y_i the observed value and n the number of observations.

The physical aspects of the model were calibrated using the observed temperature profiles. Diffusion coefficients and shelter coefficient were parameters varied to improve the fit between modeled and observed values of temperature and to minimize the MSE. The model was then calibrated based on observed profiles of dissolved oxygen. The rate of decomposition and the sediment oxygen demand were parameters varied to improve the fit between modeled and observed oxygen and minimize the MSE.

To simplify the calibration, the sediment module included in MyLake v.2 was deactivated. To calculate the sediment oxygen demand a simpler structure, already implemented in the model code, was used.

3.3 SIMULATING FUTURE SCENARIOS

To investigate the impact of climate change and to predict future changes in temperature and dissolved oxygen profiles, three different scenario data sets were created. The first scenario was based purely on climatic changes, in terms of changing air temperature and precipitation. This scenario will be referred to as *climate 30* and *climate 80*, for simulations 30 and 80 years in the future. The second scenario was based on only changing DOC values and will be referred to as *DOC 30* and *DOC 80.* The third and final scenario was based on the combined effect of both climate change and changing DOC. This scenario will be referred to as *climate+DOC 30* and *climate+DOC 80.* These scenarios were chosen to evaluate the individual impact of a changing climate and changing DOC values as well as the more realistic scenario, where changes in climate also leads to changes in DOC.

For comparison between present and future conditions a base scenario was created. The base scenario was based on the measurement data used for calibration, with the exception that modeled inflow, simulated with the HBV model, was used.

3.3.1 Air temperature and precipitation

Predictions of future air temperature and precipitation were based on climate scenarios from SMHI (SMHI, 2017c). The climate scenarios contains information about predicted changes in seasonal mean values of temperature and precipitation. This information was given as a number in $^{\circ}C$ for temperature and in % for precipitation. Specific values for each season, each year were available. The predicted changes were in relation to the long term mean value for the time period 1961-1990. Three different scenarios were available, $RCP_{8,5}$, $RCP_{4,5}$, $RCP_{2,6}$ corresponding to high, medium and low climate impact. In this study, only the scenario with the highest climatic impact, $RCP_{8,5}$, was used.

To create future scenario data sets of air temperature and precipitation, the predicted changes for each season was added to the corresponding quarter for each year of the existing data sets of air temperature and precipitation used for calibration. The entire data set used during the calibration was used. To eliminate the dependency of the time period $1961-1990$, the mean value of the difference for the present time period was subtracted from the two periods 30 and 80 years in the future.

3.3.2 Simulating future disharge with the HBV model

Future discharge was simulated using the HBV model in the software HBV light. The model was calibrated with the data of discharge used for calibration of MyLake. Future discharge was simulated using the predicted future time series of air temperature and precipitation. The following description of the HBV model is based on the manual for HBV light version 2 (Seibert, 2005),

The HBV-model (Bergström, 1976) is a hydrological model developed by the Swedish Meteorological and Hydrological Institute, SMHI, and is used to simulate runoff. The model has since then been widely used and applied in different types of projects in more than 30 different countries (Siebert, 2005). HBV light is a software based on the concept of the HBV model, version HBV-6 (Bergström, 1992). Slight changes have been made to the original model to provide a model suitable for Windows and easy to apply in research and education. The HBV-model simulate discharge, with daily resolution, using temperature, precipitation and potential evapotranspiration as input. Model parameters include for example information about the water retaining capacity of the soil, the percolation rate of groundwater and interactions between rain and snow.

Input and Model Run
To run the HBV model in the software HBV light, files containing measurements of air temperature, precipitation, discharge and estimated potential evapotranspiration for the catchment area needed to be provided. The daily measurements of temperature, precipitation, and discharge, used as input to the MyLake model, were used directly and stored in the file PTQ.dat.

To be able to run HBV light the input data in PTQ.dat could not contain any gaps. Measurement data from 2012 was extracted since no measurement was missing for this year for any of the lakes. Potential evapotranspiration could be introduced to the model as monthly or daily mean values or daily measurements. Since no daily measurements were available, potential monthly evapotranspiration was calculated according to the Thornthwaite method (Palmer and Havens, 1958). The method calculates monthly potential evapotranspiration based on monthly mean temperature as

$$PET_i(L) = KPET_i(0) \tag{15}$$

where $PET_i(0)$ is the potential evapotranspiration at 0° and K is a correction factor based on the location of the catchment area. $PET_i(0)$ can be computed as

$$PET_i(0) = 1.6(\frac{10T_i}{J})^c \tag{16}$$

where the exponent c can be computed as

$$c = 0.000000675J^3 - 0.0000771J^2 + 0.01792J + 0.49239 \tag{17}$$

J is the annual temperature efficiency index, computed as

$$J = \sum_{i=1}^{12} I_i \tag{18}$$

where I is the heat index based on the mean monthly temperature T_i

$$I_i = (\frac{T_i}{5})^{1.514} \tag{19}$$

Since the equations were not able to handle negative values of monthly mean temperature, all temperatures below zero were set to zero. The calculated monthly mean potential evapotranspiration was stored in the file EVAP.dat.

The files PTQ.dat and EVAP.dat were used as input to HBV light to simulate discharge in the area. Measurements of discharge, from PTQ.dat, were used to calibrate the model. The model was automatically calibrated using 5000 Monte Carlo runs. The simulations were evaluated based on the efficiency coefficient, R_{eff} and the mean difference, $mean_{diff}$. The parameter set for the run with the highest R_{eff} and lowest $mean_{diff}$ was chosen for each lake respectively.

3.3.3 DOC trends

Future DOC values were estimated according to de Wit et al. (2016) by linear relations between DOC concentration and median annual precipitation. Future DOC concentrations were calculated as

$$DOC = slope * MAP \tag{20}$$

where MAP is the median annual precipitation in mm and *slope* where determined by the amount of precipitation at the study site (Table 1). The value of r^2 and p indicates the accuracy of the linear relation. High r^2 indicates a strong relation and a low p-value indicates a high significance of the relation. If the p-value is > 0.05 the relation is non-significant and therefore not reliable.

Table 1 Slopes for the linear relations between median annual precipitation, MAP, and DOC concentration, with r^2 and p describing the strength and significance of the relation.

MAP [mm]	Slope	r^2	p
MAP < 700	0.055	0.80	< 0.0001
700 <= MAP > 800	0.082	0.37	< 0.005
800 <= MAP > 1100	0.0029	0.37	< 0.005
1100 <= MAP > 1400	0.0003	0.02	> 0.5
MAP >= 1400	-0.0004	0.22	<0.05

The median annual precipitation at each study site was used to calculate DOC concentrations 30 and 80 years in the future (Table 2). The median annual precipitation for Härsvatten is in the span 1100 <= MAP > 1400 where the relation between MAP and DOC is non-significant.

Table 2 Median annual precipitation, corresponding DOC slope, present DOC concentration and resulting DOC 30 and 80 years in the future for all three lakes.

	Remmarsjön	**Härsvatten**	**Fiolen**
Prec [mm/year]	534	1123	736
DOC now [mg/l]	10.323	4.254	8.606
DOC 30 [mg/l]	13.509	4.278	10.801
DOC 80 [mg/l]	17.064	4.294	12.782

3.4 ANALYSIS OF LAKE PROFILES

3.4.1 Temperature

Temperature profiles were evaluated for the base scenario and the future scenarios. The mean temperature difference between the base scenario and the future scenario was calculated for each depth level. The extent of thermal stratification was evaluated and possible thermocline depth, TD, was set to the depth where the density gradient in the water column were at its maximum. By assuming low salinity in the lakes (<0.6 psu) and neglecting the difference between in situ and potential temperature the density of the water at each depth could be calculated as

$$\rho = \rho(S, T_{pot}) = \sum_{i=0}^{6} a_i T_{pot}^i + S \sum_{i=0}^{2} b_i T_{pot}^i = \sum_{i=0}^{6} a_i T^i + S \sum_{i=0}^{2} b_i T^i \qquad (21)$$

where T is the temperature at the given depth, S is the lake salinity and a_i and b_i are coefficients given by

$$\begin{aligned} a_i = [&999.8395;\ 6.7914 * 10^{-2};\ -9.0894 * 10^{-3};\ 1.0171 * 10^{-4}; \\ &-1.2846 * 10^{-6};\ 1.1592 * 10^{-8};\ -5.0125 * 10^{-11}] \\ b_i = [&0.8181;\ -3.85 * 10^{-3};\ 4.96 * 10^{-5}] \end{aligned}$$

3.4.2 Dissolved oxygen

Changes in oxygen profiles for the base scenario and the future scenarios were evaluated by the percentage of the water column with a DO concentration below a certain critical level and the number of days with oxygen levels below the critical level anywhere in the water column. Critical DO concentrations were chosen as 2 mg/l and 4 mg/l.

4 RESULTS

4.1 CALIBRATION OF THE MYLAKE MODEL

The parameters longitude, latitude, Kz_ak and C_shelter were used to calibrate the modeled temperature. To calibrate dissolved oxygen the parameters K_bod and K_sod were used. Specific parameter values for each lake are shown in Table 3. Parameter values for C_shelter indicates that Remmarsjön is the lake with highest wind exposure and Härsvatten the most sheltered lake. The high values of K_bod and K_sod for Fiolen indicates that this lake has a high consumption of oxygen, both from high degradation rate of organic material and a high sediment oxygen demand.

Table 3 Parameter values used for calibration of lake water temperature and dissolved oxygen.

	Remmarsjön	**Härsvatten**	**Fiolen**	**Function**
Longitude [deg]	63.87	58.02	57.08	*geographic location*
Latitude [deg]	18.26	12.03	14.53	*geographic location*
Kz_ak [-]	0.02	0.0007	0.01	*diffusion koeff*
C_shelter [-]	0.8	0.135	0.3	*exposure to wind*
K_bod [mg/kg]	0.001	0.0005	0.01	*rate of degradation*
K_sod [mg/m^2]	350	250	900	*sediment oxygen demand*

4.1.1 Temperature

The model captures the temperature well in both surface and bottom water for all lakes (Figure 3−5). For complete temperature profiles, see Appendix B. To avoid spin up effects the first year of data has been cut off. The temperature in the surface water varies more than in the bottom water, resulting in slightly higher MSE (Table 4). When visually inspecting the figures it is however clear that the surface water temperature is being captured with a higher accuracy than the temperature in the bottom water. The spikes in bottom water temperature, especially visible for Härsvatten (Figure 4 b), are likely due to mixing of the water column in the autumn.

a) **b)**

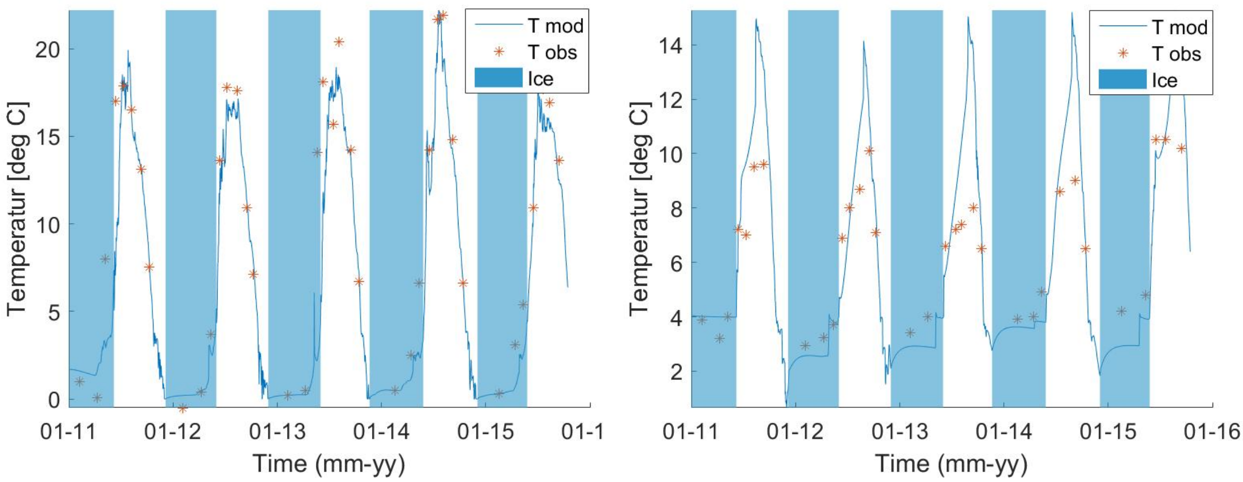


Figure 3 Modeled and observed temperature in surface (a, 0.5m) and bottom (b, 13m) water for Remmarsjön.

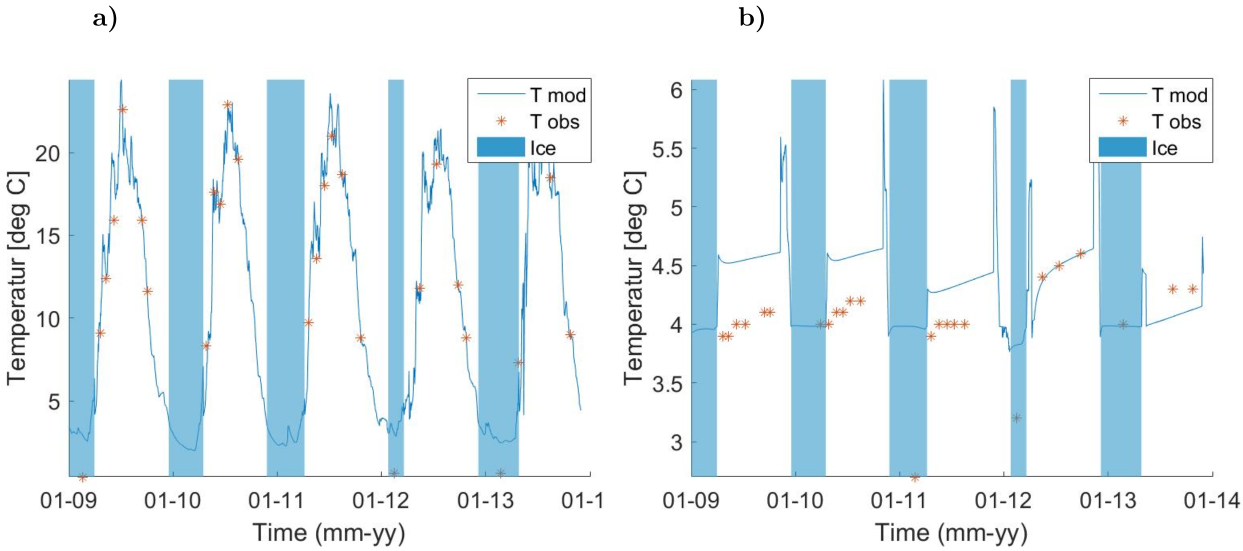


Figure 4 Modeled and observed temperature in surface (a, 0.5m) and bottom (b, 24m) water for Härsvatten.

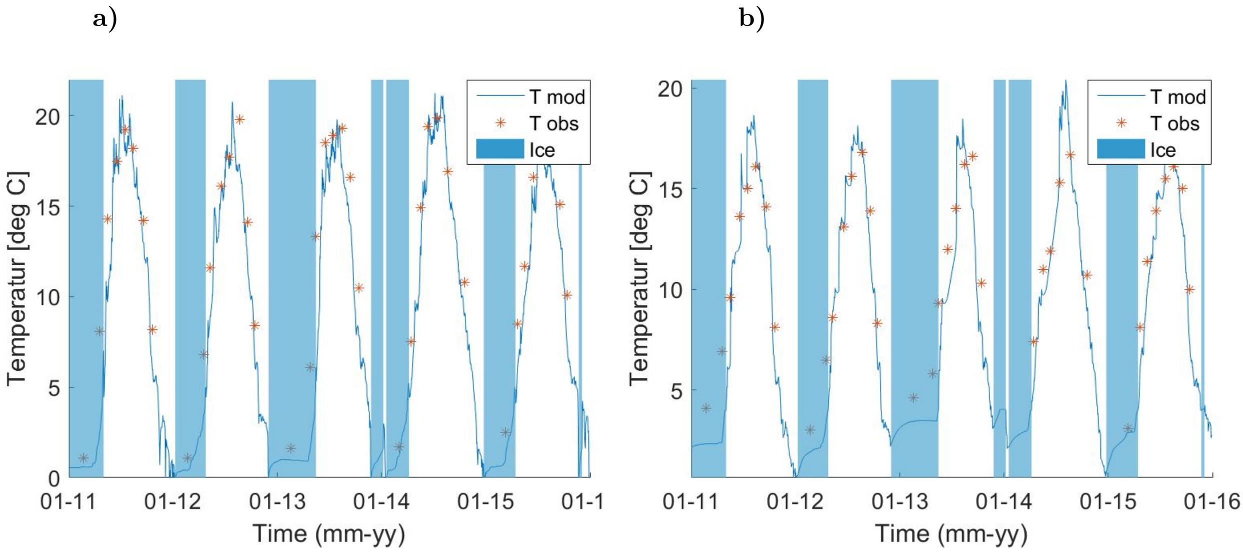


Figure 5 Modeled and observed temperature in surface (a, 0.5m) and bottom (b, 8m) water for Fiolen.

Table 4 Mean squarred error, MSE, between observed and modeled temperature for the three lakes

	Surface [m]	Bottom [m]	MSE surface	n	MSE bottom	n
Remmarsjön	0.5	13	9.78	39	3.48	39
Härsvatten	0.5	24	1.90	27	0.22	27
Fiolen	0.5	8	6.80	39	4.66	39

4.1.2 Dissolved oxygen

The model is also able to capture most of the variations in dissolved oxygen concentrations in both surface and bottom water for all three lakes (Figure 6−8), however not with as high accuracy as the modeled temperature. For complete oxygen profiles, see Appendix C. The oxygen concentration decrease during the summer when the water temperature reaches its maximum, both in surface and bottom waters. The temperature in the surface water starts to increase as the surface water cools off in the autumn. In the bottom water the oxygen levels gets low during to summer and peaks during autumn mixing. During periods with ice cover the oxygen levels decrease drastically, especially for Fiolen (Figure 8) and Remmarsjön (Figure 6)where the oxygen consumption is high. Periods of ice are followed by reoxygenation in the spring, affecting both surface and bottom temperature. For Härsvatten, there are a sudden drop in the oxygen concentration during 2009 (Figure 7a). This is most likely due to model instabilities. MSE between modeled and observed oxygen in Table 5.

a) **b)**

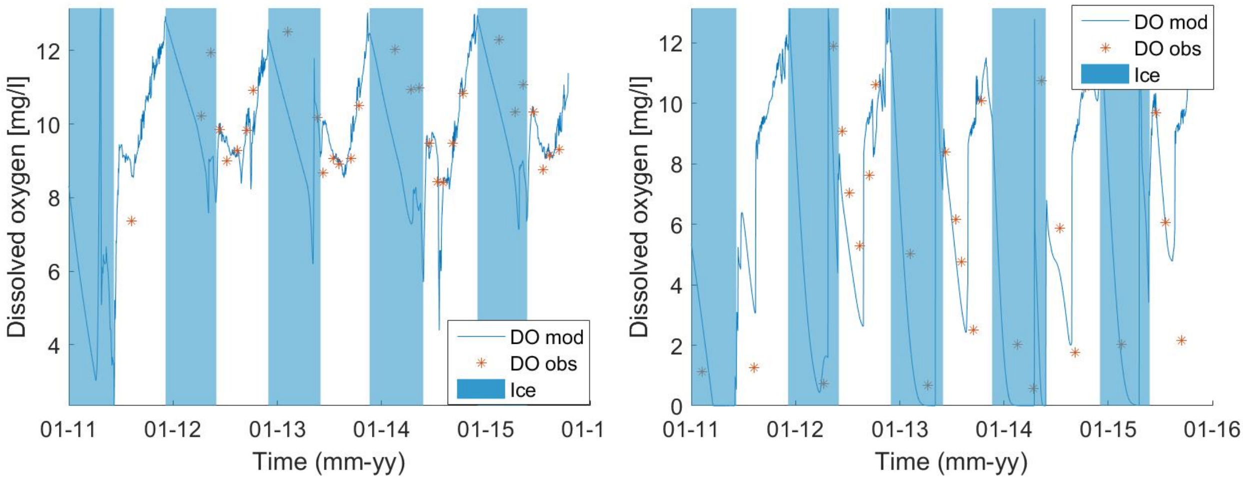


Figure 6 Modeled and observed dissolved oxygen at the surface (left, 0.5m) and bottom (right, 13m) for Remmarsjön.

a) **b)**

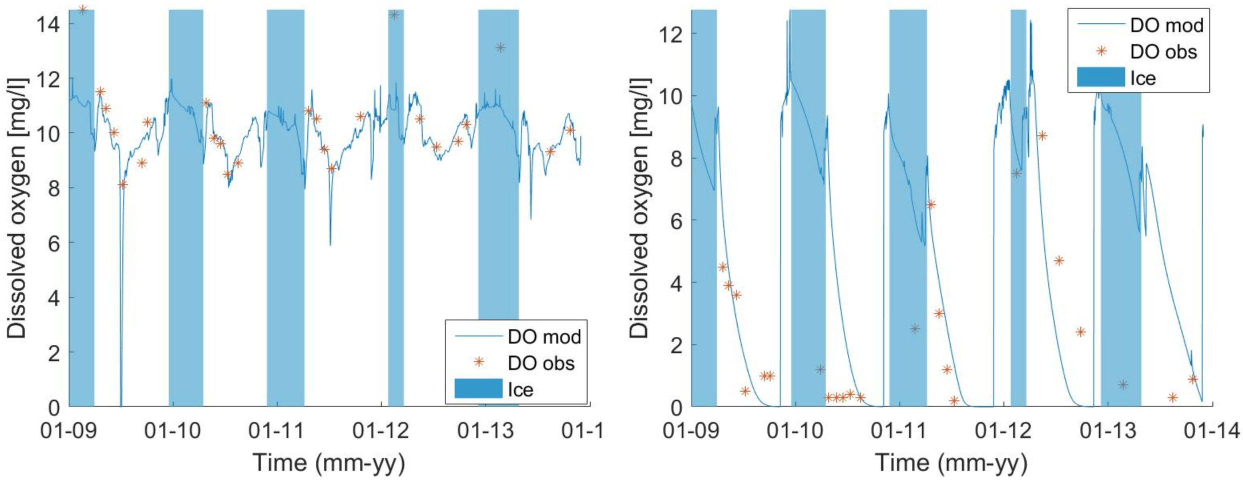


Figure 7 Modeled and observed dissolved oxygen at the surface (left, 0.5m) and bottom (right, 24m) for Härsvatten.

a) b)

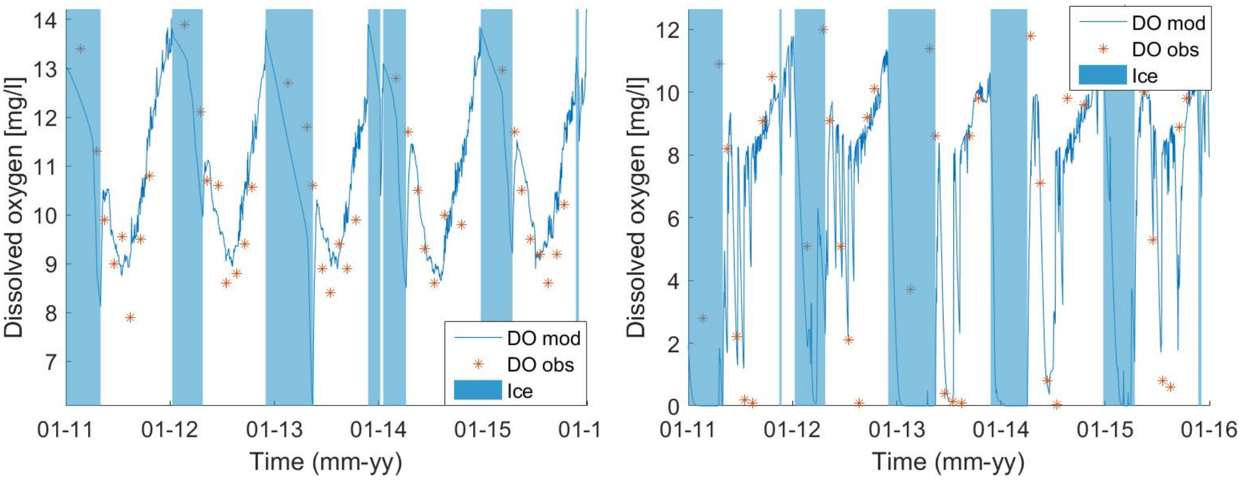


Figure 8 Modeled and observed dissolved oxygen at the surface (left, 0.5m) and bottom (right, 8m) for Fiolen.

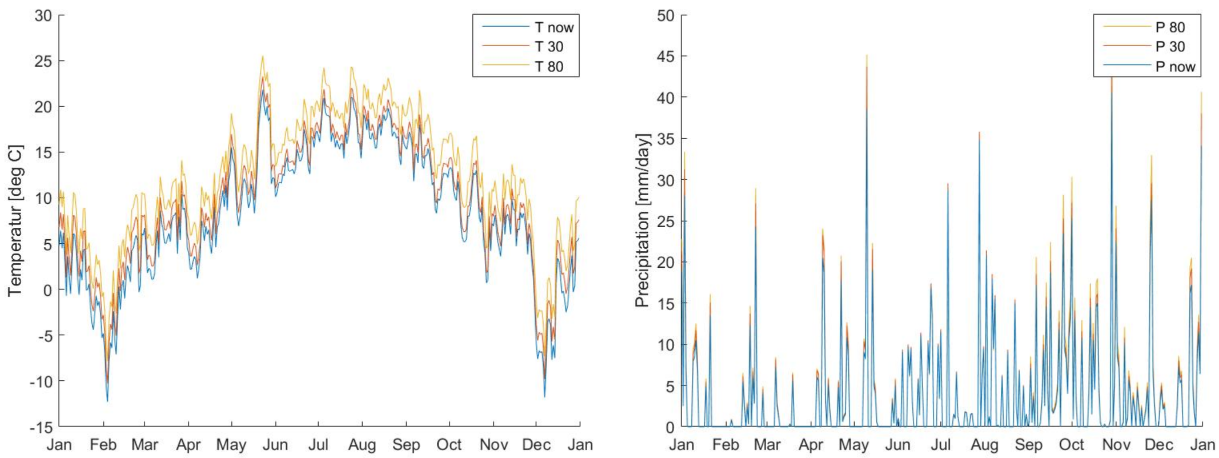
Table 5 Mean squarred error, MSE, between observed and modeled oxygen concentrations for the three lakes

	Surface [m]	**Bottom [m]**	**MSE surface**	**n**	**MSE bottom**	**n**
Remmarsjön	0.5	13	1.66e-6	39	11.87	30
Härsvatten	0.5	24	1.84e-6	27	9.82	24
Fiolen	0.5	8	1.38e-6	39	27.20	38

4.2 SCENARIO DATA

Simulated data sets of air temperature, precipitation and inflow for Härsvatten indicated that all variables will increase in the future (Figure 9). To increase the visibility, only one year of simulated data is shown in the figure. The results were similar for both Remmarsjön and Fiolen.

a) b)



c)

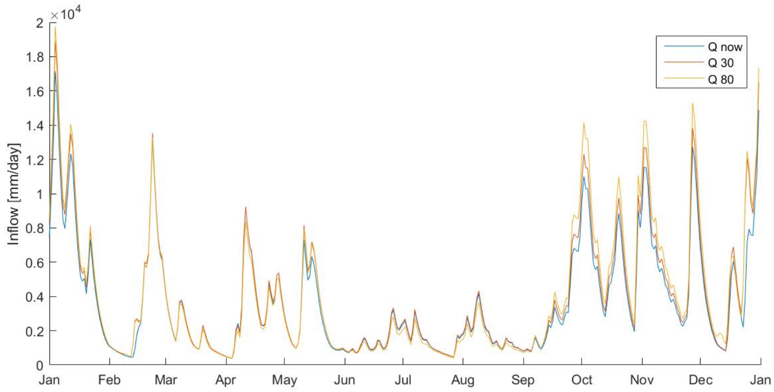


Figure 9 Simulated air temperature (a), precipitation (b) and inflow (c) for 2012 and 30 and 80 years in the future for Härsvatten.

Table 6 shows the predicted seasonal change in air temperature and precipitation at each study site. The temperature increased at all study site, both 30 and 80 years in the future. The increase in temperature was most distinct during the winter. The amount of precipitation also increased in most cases, though in a more variable way than the temperature.

Table 6 Predicted changes in air temperature and precipitation 30 and 80 years in the future. Mean values for the entire time period for respective lake.

		Remmarsjön		Härsvatten		Fiolen	
Years in the future		*30*	*80*	*30*	*80*	*30*	*80*
T spring	[°C]	1.60	4.77	1.44	3.72	0.95	3.22
T summer	[°C]	0.90	3.26	0.95	3.30	0.71	3.07
T autumn	[°C]	1.14	4.12	1.10	3.77	0.87	3.27
T winter	[°C]	2.14	5.47	2.01	4.48	1.45	3.57
P spring	[%]	15.50	29.74	13.48	17.25	3.89	13.90
P summer	[%]	12.03	22.20	2.88	-2.06	3.47	-3.71
P autumn	[%]	4.82	21.08	7.50	19.81	-0.81	6.53
P winter	[%]	13.81	21.13	11.55	19.17	8.21	17.09

4.3 SCENARIO RUNS

Two scenarios, *climate 80* and *climate+DOC 80* for Härsvatten, are not displayed in the following results, due to a model error.

4.3.1 Temperature

Temperature profiles for the present and future time period, simulated with the scenario *climate+DOC*, indicated an overall increase in water temperatures for all studied lakes (Remmarsjön, Figure 10; Härsvatten, Figure 12; Fiolen, Figure 14). The increase in temperature decreased with depth for all lakes (Remmarsjön, Figure 11; Härsvatten, Figure 13; Fiolen, Figure 15)

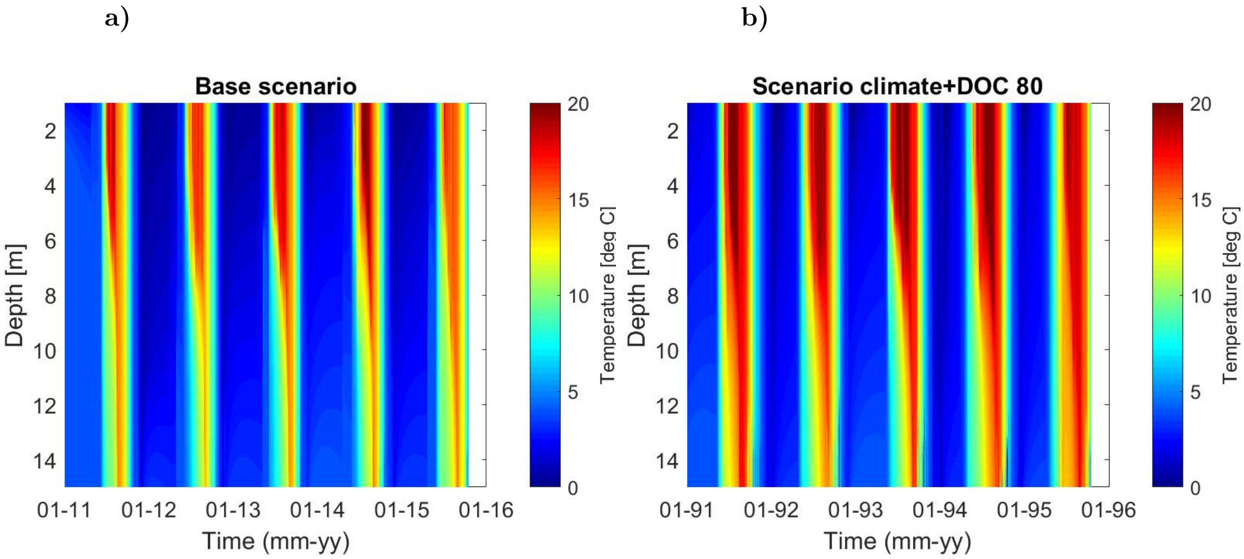


Figure 10 Simulated temperature profile for Remmarsjön for the base scenario (a) and 80 years in the future with the scenario *climate+DOC* (b).

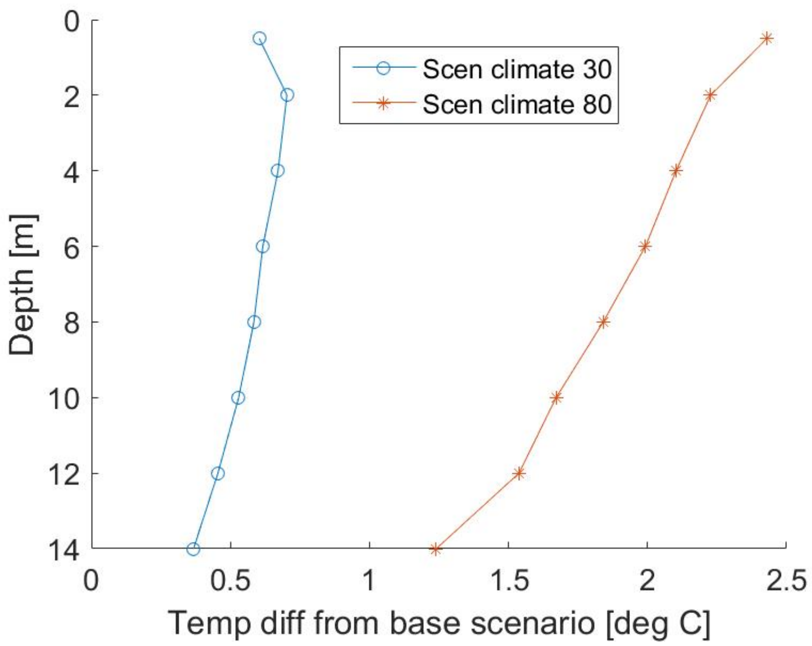


Figure 11 Temperature differentiation between base scenario and simulations 30 and 80 years in the future with the scenario *climate* for Remmarsjön.

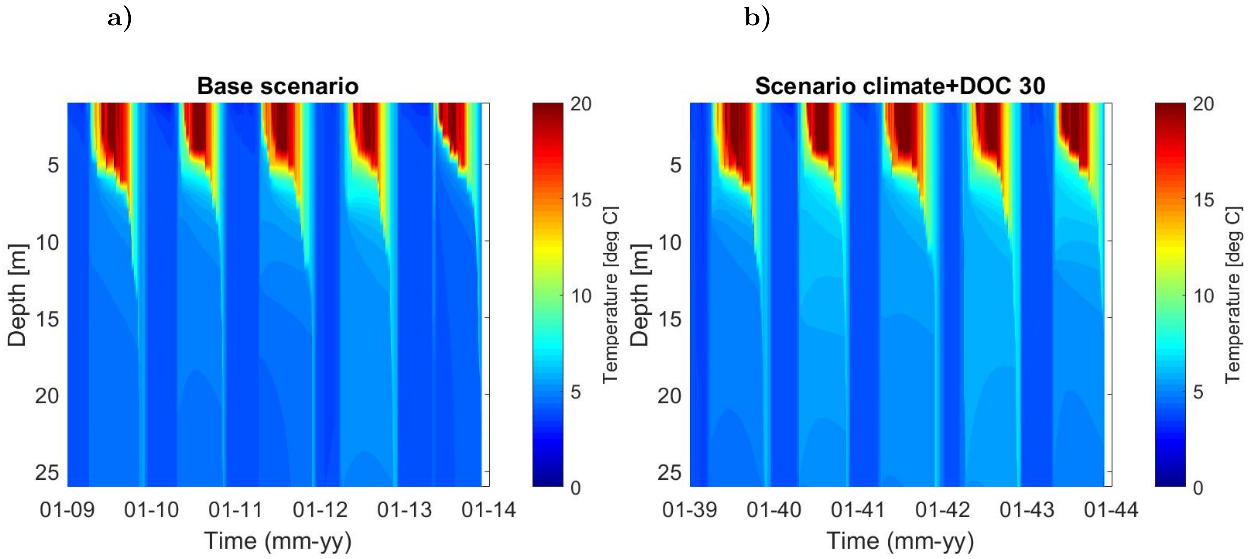


Figure 12 Simulated temperature profile for Härsvatten for the base scenario (a) and 30 years in the future with the scenario *climate+DOC* (b).

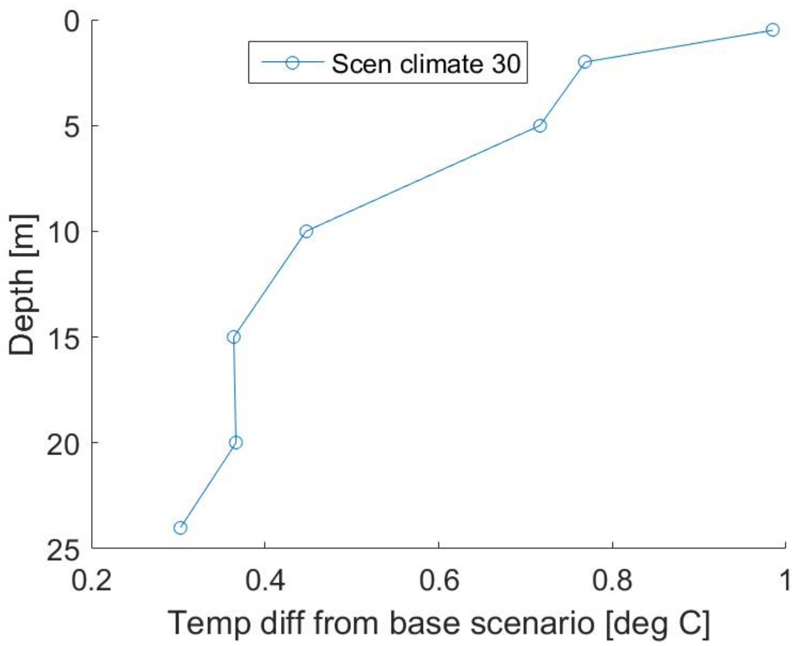


Figure 13 Temperature differentiation between base scenario and simulation 30 years in the future with the scenario *climate* for Härsvatten.

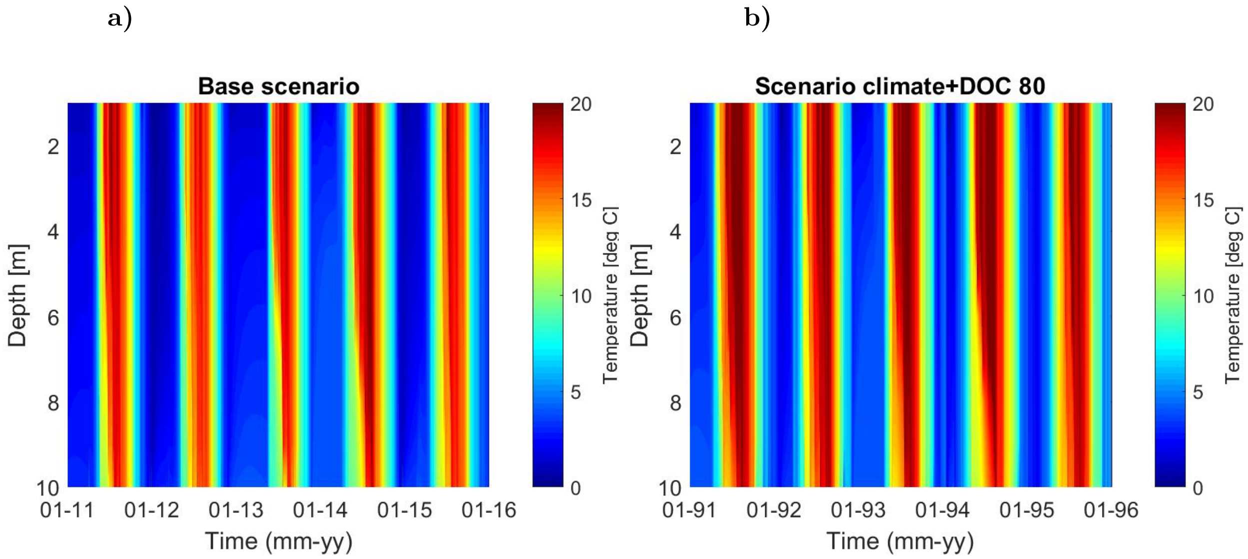


Figure 14 Simulated temperature profile for Fiolen for the base scenario (a) and 80 years in the future with the scenario *climate+DOC* (b).

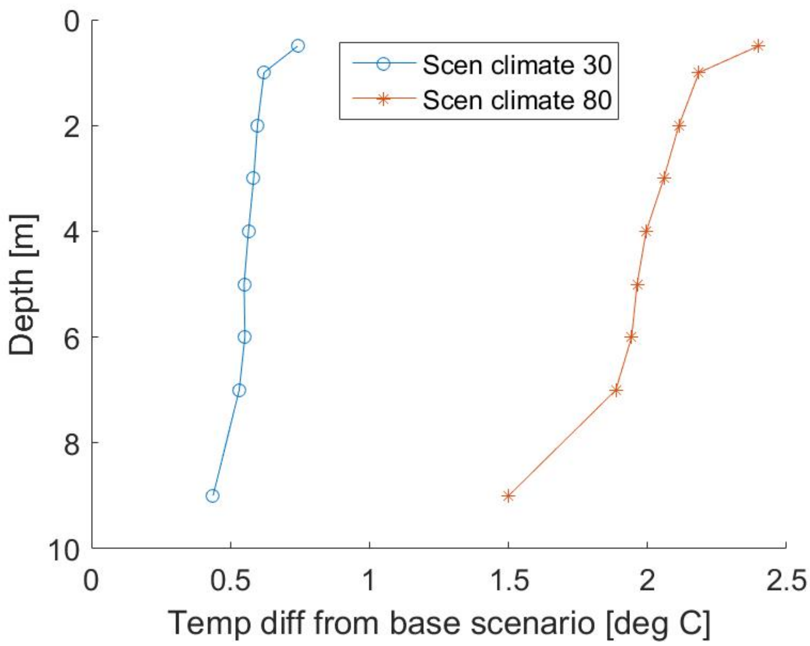


Figure 15 Temperature differentiation between base scenario and simulations 30 and 80 years in the future with the scenario *climate* for Fiolen.

The *climate* and *climate+DOC* scenario also had a visible impact on the ice phenology of the lakes (Remmarsjön, Table 7; Härsvatten, Table 8; Fiolen, Table 9). For these runs, the first ice formation occurred later, the ice break up occurred earlier and the total length of the ice covered period was shorter than for the present time period. The results were identical for *climate* and *climate+DOC*. For the *DOC* scenario, no visible changes in ice phenology were observed for any of the lakes.

Table 7 REMMARSJÖN. Total length of ice covered period, first ice formation and ice break up dates simulated 30 and 80 years in the future with the scenarios *climate*, *DOC* and *climate+DOC* and compared with the base scenario.

(yellow) = no change (red) = negative change

	Base	Climate_30	Climate_80	DOC_30	DOC_80	Climate_DOC_30	Climate_DOC_80
	Total length of ice covered period						
2011/2012	178	162	105	178	178	162	105
2012/2013	183	178	162	183	183	178	162
2013/2014	188	179	96	188	188	179	96
2014/2015	174	155	109	174	174	155	109
Diff [days]	**mean**	**-12**	**-63**	**0**	**0**	**-12**	**-63**
Diff [days]	**median**	**-12**	**-72**	**0**	**0**	**-12**	**-72**
	Ice ON dates						
2011/2012	06-dec	12-dec	13-jan	06-dec	06-dec	12-dec	13-jan
2012/2013	30-nov	30-nov	04-dec	30-nov	30-nov	30-nov	04-dec
2013/2014	20-nov	21-nov	09-dec	20-nov	20-nov	21-nov	09-dec
2014/2015	03-dec	09-dec	13-jan	03-dec	03-dec	09-dec	13-jan
Diff [days]	**mean**	**+3**	**+26**	**0**	**0**	**+3**	**+26**
Diff [days]	**median**	**+4**	**+29**	**0**	**0**	**+4**	**+29**
	Ice OFF dates						
2011/2012	01-jun	22-maj	27-apr	01-jun	01-jun	22-maj	27-apr
2012/2013	01-jun	27-maj	15-maj	01-jun	01-jun	27-maj	15-maj
2013/2014	27-maj	19-maj	16-apr	27-maj	27-maj	19-maj	16-apr
2014/2015	26-maj	13-maj	12-apr	26-maj	26-maj	13-maj	12-apr
Diff [days]	**mean**	**-9**	**-34**	**0**	**0**	**-9**	**-34**
Diff [days]	**median**	**-9**	**-38**	**0**	**0**	**-9**	**-38**

Table 8 HÄRSVATTEN. Total length of ice covered period, first ice formation and ice break up dates simulated 30 and 80 years in the future with the scenarios *climate*, *DOC* and *climate+DOC* and compared with the base scenario.

(light yellow) = no change; (red) = negative change

	Base	**Climate_30**	**Climate_80**	**DOC_30**	**DOC_80**	**Climate_DOC_30**	**Climate_DOC_80**
	Total length of ice covered period						
2009/2010	121	107	error	121	121	107	error
2010/2011	133	116	error	133	133	116	error
2011/2012	61	61	error	61	61	61	error
2012/2013	144	88	error	144	144	88	error
Diff [days]	**mean**	**-22**	**-**	**0**	**0**	**-22**	**0**
Diff [days]	**median**	**-30**	**-**	**0**	**0**	**-30**	**0**
	Ice ON dates						
2009/2010	17-dec	21-dec	error	17-dec	17-dec	21-dec	error
2010/2011	26-nov	27-nov	error	26-nov	26-nov	27-nov	error
2011/2012	24-dec	31-jan	error	24-dec	24-dec	31-jan	error
2012/2013	05-dec	08-dec	error	05-dec	05-dec	08-dec	error
Diff [days]	**mean**	**+12**	**-**	**0**	**0**	**+12**	**0**
Diff [days]	**median**	**+4**	**-**	**0**	**0**	**+4**	**0**
	Ice OFF dates						
2009/2010	17-apr	07-apr	error	17-apr	17-apr	07-apr	error
2010/2011	08-apr	23-mar	error	08-apr	08-apr	23-mar	error
2011/2012	21-mar	09-mar	error	21-mar	21-mar	09-mar	error
2012/2013	28-apr	16-apr	error	28-apr	28-apr	16-apr	error
Diff [days]	**mean**	**-13**	**-**	**0**	**0**	**-13**	**0**
Diff [days]	**median**	**-12**	**-**	**0**	**0**	**-12**	**0**

Table 9 FIOLEN. Total length of ice covered period, first ice formation and ice break up dates simulated 30 and 80 years in the future with the scenarios *climate*, *DOC* and *climate+DOC* and compared with the base scenario.

= no change = negative change

	Base	Climate_30	Climate_80	DOC_30	DOC_80	Climate_DOC_30	Climate_DOC_80
	Total length of ice covered period						
2011/2012	115	79	50	115	115	79	50
2012/2013	166	158	133	166	166	158	133
2013/2014	129	81	27	129	129	81	27
2014/2015	110	75	8	110	110	75	8
Diff [days]	**mean**	**-32**	**-76**	**0**	**0**	**-32**	**-76**
Diff [days]	**median**	**-42**	**-84**	**0**	**0**	**-42**	**-84**
	Ice ON dates						
2011/2012	16-nov	24-jan	30-jan	16-nov	16-nov	24-jan	30-jan
2012/2013	01-dec	01-dec	07-dec	01-dec	01-dec	01-dec	07-dec
2013/2014	25-nov	26-nov	22-jan	25-nov	25-nov	26-nov	22-jan
2014/2015	25-dec	25-dec	26-dec	25-dec	25-dec	25-dec	26-dec
Diff [days]	**mean**	**+18**	**+35**	**0**	**0**	**+18**	**+35**
Diff [days]	**median**	**+1**	**+32**	**0**	**0**	**+1**	**+32**
	Ice OFF dates						
2011/2012	25-apr	12-apr	20-mar	25-apr	25-apr	12-apr	20-mar
2012/2013	16-maj	08-maj	19-apr	16-maj	16-maj	08-maj	19-apr
2013/2014	03-apr	19-mar	18-feb	03-apr	03-apr	19-mar	18-feb
2014/2015	14-apr	10-mar	03-jan	14-apr	14-apr	10-mar	03-jan
Diff [days]	**mean**	**-18**	**-52**	**0**	**0**	**-18**	**-52**
Diff [days]	**median**	**-14**	**-40**	**0**	**0**	**-14**	**-40**

4.3.2 Dissolved Oxygen

All three scenarios had visible impact on the dissolved oxygen content for all lakes. For Remmarsjön, the DO content decreased in almost all cases for *DOC 30* and *80* and for *climate 30* (Table 10). For *climate 80* and *climate+DOC 80* the DO content increased in all cases. The DO content in the bottom water (Figure 16) indicated a similar behavior as for Härsvatten, with stronger DO depletion during the summer months and slightly higher DO content during the winter.

Table 10 Remmarsjön. Percentage of the water column with DO levels below 2 or 4 mg/l and the total number of days with DO levels below the limits anywhere in the water column. Results for the present time period and for the simulated scenarios climate, DOC and climate+DOC 30 and 80 years in the future.

= positive change = no change = negative change

	now	Climate_30	Climate_80	DOC_30	DOC_80	Climate_DOC_30	Climate_DOC_80
% <2 mg/l	0.1048	0.1083	0.0733	0.1178	0.1337	0.2170	0.0913
nr <2 mg/l	842	838	754	888	936	882	814
% <4 mg/l	0.1659	0.1729	0.1200	0.1835	0.205	0.1925	0.1445
nr <4 mg/l	1128	1149	979	1172	1216	1182	1036

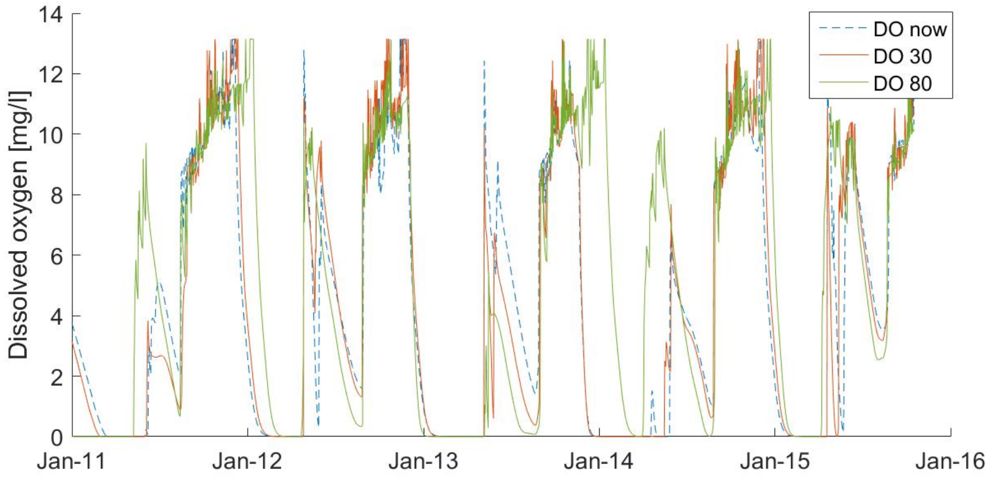


Figure 16 Dissolved oxygen for bottom water (13 m) in Remmarsjön. For the present time period and 30 respectively 80 years in the future for the scenario climate+DOC.

For Härsvatten the DO content decreased in most cases (Table 11), though slightly increasing for two cases during the *climate 30* run. For four cases during the *DOC* runs there were no visible changes. When comparing the DO content of the bottom water for the the *climate+DOC 30* run with the base scenario, the DO was slightly higher during winter months but with stronger DO depletion during summer months (Figure 17).

Table 11 Härsvatten. Percentage of the water column with DO levels below 2 or 4 mg/l and the total number of days with DO levels below the limits anywhere in the water column. Results for the present time period and for the simulated scenarios climate, DOC and climate+DOC 30 and 80 years in the future.

= positive change = no change = negative change

	now	Climate_30	Climate_80	DOC_30	DOC_80	Climate_DOC_30	Climate_DOC_80
% <2 mg/l	0.0660	0.0678	error	0.0662	0.0662	0.0679	error
nr <2 mg/l	872	1041	error	872	872	1041	error
% <4 mg/l	0.1227	0.1124	error	0.1228	0.1228	0.1125	error
nr <4 mg/l	1079	1210	error	1079	1079	1210	error

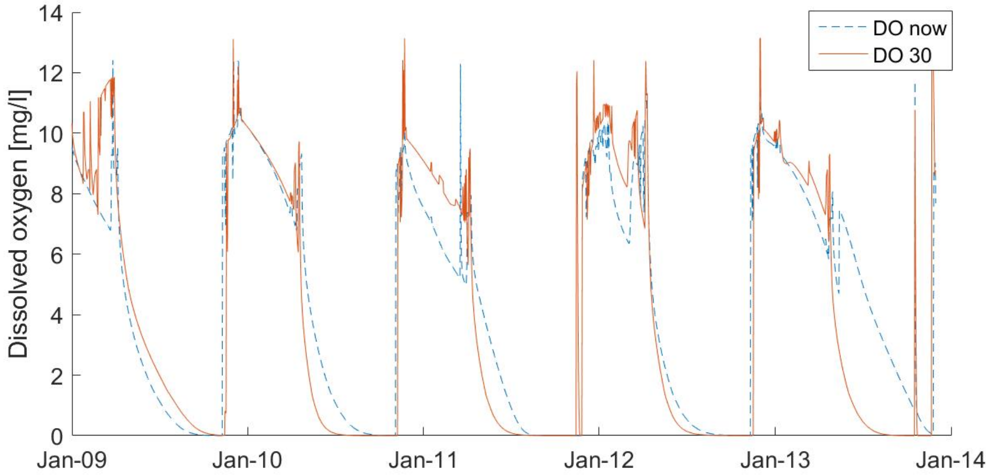


Figure 17 Dissolved oxygen for bottom water (13 m) in Remmarsjön. For the present time period and 30 respectively 80 years in the future for the scenario climate+DOC.

For Fiolen, the DO content increased in all cases for all scenarios including climate (Table 12). For the scenarios *DOC 30* and *80* the DO content decreased in all cases. The DO content in the bottom water (Figure 18) is highly fluctuating making seasonal changes hard to evaluate.

Table 12 Fiolen. Percentage of the water column with DO levels below 2 or 4 mg/l and the total number of days with DO levels below the limits anywhere in the water column. Results for the present time period and for the simulated scenarios climate, DOC and climate+DOC 30 and 80 years in the future.

= positive change = no change = negative change

	now	Climate_30	Climate_80	DOC_30	DOC_80	Climate_DOC_30	Climate_DOC_80
% <2 mg/l	0.1562	0.1194	0.1089	0.1604	0.1645	0.1206	0.1125
nr <2 mg/l	875	752	660	878	882	754	661
% <4 mg/l	0.2137	0.1552	0.1407	0.2185	0.2227	0.1565	0.1438
nr <4 mg/l	1005	877	768	1006	1007	878	771

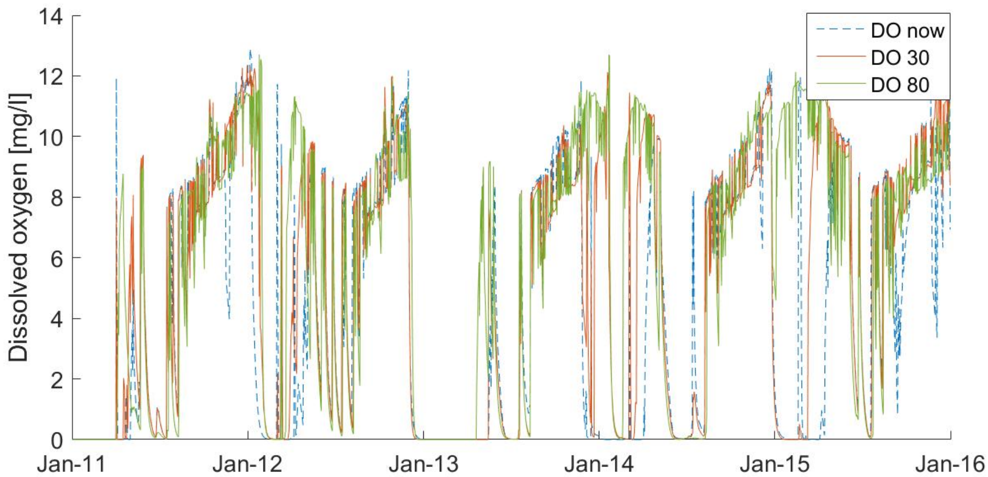


Figure 18 Dissolved oxygen for bottom water (13 m) in Remmarsjön. For the present time period and 30 respectively 80 years in the future for the scenario climate+DOC.

5 DISCUSSION

5.1 MODELING WITH MYLAKE

5.1.1 Temperature and oxygen profiles

The simulated temperature and oxygen profiles for the three lakes showed that the MyLake model was able to well capture the behavior of both temperature and dissolved oxygen throughout the water column.

The surface water temperature is modeled with a high accuracy for all three lakes. The temperature is also captured reasonably well throughout the rest of the water columns as well as in the bottom waters of the lakes. The high accuracy of the model is clear when visually inspecting the observed and modeled temperature, but it is not always reflected in the MSE. Since the temperature changes quite rapidly, delayed or premature predictions of temperature may result in a large distance between modeled and observed values and a disproportionately high MSE.

Härsvatten is the deepest of the three lakes and the only lake with a clear distinction between epilimnion and hypolimnion. The thermocline for Härsvatten is usually located at approximately five meters depth, explaining the difficulties to simulate the temperature at this level (Appendix B, *Simulated and observed temperature at 5 m*). Stratification also happens in Remmarsjön and Fiolen but since these lakes are quite shallow the density differences between epilimnion and hypolimnion are much lower. This will lead to weak stratification that may only last a short period, maybe in terms of weeks or even hours.

Since the content and distribution of dissolved oxygen in a lake is controlled by many different drivers, physical, chemical and biological, it is a complicated variable to model. In the surface water, the oxygen levels are mainly controlled by atmospheric gas exchange, which is being well captured by the model. Deeper down in the water column, the processes controlling the oxygen distribution gets more complicated, but the model is still able to capture most of the variations in DO. The typical seasonal behaviour of total mixing, and reoxygenation, of the water column in the autumn is being captured for all lakes as well as the typical decline in DO during the summer months and during periods of ice cover. For Härsvatten, the lake appears to not mix entirely during the period 2012/2013. This is visible for the observed measurements of bottom water DO but it is not being captured by the model (Figure 7).

The DO in the bottom water for Remmarsjön and Fiolen is fluctuating more than for Härsvatten. This is probably because these lakes are quite shallow and therefore being more directly affected by processes occurring in the surface water. Wind induced mixing or cut off oxygen supply due to ice cover may therefore be directly reflected in the bottom water. The DO content in the bottom water is quickly reduced during periods of ice cover for both Remmarsjön and Fiolen, indicating that the bottom water is highly dependent on the surface water for oxygen supply.

5.1.2 Model evaluation

MyLake has proven suitable and useful for the given problem. By changing only a few model parameters it was possible to reasonably well describe variations in both temperature and dissolved oxygen concentrations for three, rather different lakes. There are of course limitations to this type of calibration, with the main problem being the time aspect. The model consist of many parameters and to achieve a higher model accuracy would be extremely time consuming with manual calibration. Since the model is process-based it was possible to make assumptions about which parameters that were reasonable to change to match the conditions at each study site. A well functioning automatic calibration would probably have improved the calibration further but would be too complicated the implement given the extent of this project.

To simplify the calibration process, the sediment module included in MyLake v.2 was deactivated. The sediment oxygen demand was included by a simple set of equations, but other processes occurring in the sediment was being left out. This may have affected the result to some extent, since some of these process might affect bottom water DO.

Working with the MyLake model comes with certain limitations. The biggest issue was probably the requirement of high quality, daily resolution data of several meteorological and hydrological variables. By using interpolation, the model was able to handle small gaps in the data sets. However, the model was still sensitive for missing measurements and larger gaps in the data set could easily cause the model to break. The project in itself has therefore, by some means, been limited by the amount and quality of the available data.

5.2 SIMULATION OF FUTURE SCENARIOS

5.2.1 Scenario data

The three scenarios, *climate*, *DOC* and *climate+DOC*, were chosen to be able to study the individual impact of a changing climate and changing DOC content, as well as the, more realistic, combined effect of the two.

The scenario data were based on the existing meteorological patterns in the data used for calibration. This is not ideal since the meteorological patterns will change for each year. However, since future scenario data are not available on a daily resolution basis this method was chosen as most suitable. The created scenario data only takes changes in the four variables, air temperature, precipitation, inflow and DOC, into account. In reality, all variables used as input to MyLake will likely change in the future. The future simulations do not include the changes in extreme events patterns, such as droughts or extreme amounts of precipitation.

Future simulations of inflow are based on simulations with the HBV model. Because the simulations are based on simulated values of air temperature and precipitation this may lead to increased model insecurities.

Future changes of DOC were calculated by the mean annual changes in precipitation, according to de Wit et al. (2016). This is a simple, linear model that does not include all processes affecting DOC values. The relations used for Remmarsjön and Fiolen were both significant, and therefore more likely to predict future DOC values with a high accuracy. The relation between DOC and precipitation for Härsvatten was not significant, making the predictions for future DOC values at this site unreliable.

5.2.2 Scenario runs

Mylake was able to run all scenarios except two, *climate 80* and *climate+DOC 80* for Härsvatten. All scenarios including climate had a significant impact on the ice phenology of the lakes. In most cases, the predicted climate change resulted in shorter periods of ice cover due to later formation of ice and earlier ice break up. The results were identical for the scenarios *climate* and *climate+DOC* as well as between the base scenario and the DOC scenario. This indicates that the effect of increasing DOC on the thermal properties of the lakes was not captured by the model. It is likely though that the DOC content still has an impact on the thermal regime of the lakes, but not in ways and to an extent that can be captured by the model.

All scenarios had a visible impact on the DO content of the lakes. The *DOC* scenario had a negative impact on the DO content in all cases. For Härsvatten these changes were slight or not visible, probably due to the low, predicted increase in DOC for this study site. However, since the DOC trend in this site is not definite, the impact of increased DOC values on the DO content in Härsvatten is uncertain. For Remmarsjön and Fiolen the increasing DOC content visibly reduced the overall DO content in the water column.

Scenarios including climate had somewhat of the opposite effect on DO concentrations. This was especially visible for Fiolen, were climate change actually caused the DO content to increase. This is most likely due to the decrease in the duration of the ice covered period, reducing the risk of winter anoxia. Reduced winter anoxia will increase the overall DO content, seen to an entire year. For Fiolen, the combined scenario climate+DOC resulted in decreased DO content compared to the scenario climate but increased DO content compared to the scenario DOC. This indicates that

DOC and climate counteract each other when it comes to the effect on the DO content. This effect is also visible for Remmarsjön, but first after 80 years. The effect was somewhat diminished by the high DOC content at this study site.

The effect of climate change and increased DOC was also visible in the bottom water DO for all lakes. For Härsvatten (Figure 17) the scenario climate+DOC resulted in higher bottom water DO during the winter months followed by a more rapid decrease in DO during the summer months. This effect is also visible for Remmarsjön (Figure 16). For Fiolen, the figure (Figure 18) is difficult to read due to the large fluctuations of the bottom water DO. These results, with decreasing winter anoxia and lengthened periods of summer anoxia are in line with earlier studies (Fang and Stefan, 2009; Couture et al., 2015). Couture et al. (2015) also concluded that DOC and air temperature were antagonistic when it comes to DO content and that DOC most likely is a stronger driver for DO consumption than air temperature. According to Couture et al. (2015) DOC is likely to be the main driver controlling the DO content of lakes in the future. Since the DOC content in lakes is mainly controlled by climatic impact (Holmberg et al., 2014; de Wit et al., 2016), climate change will play an important role for lake DO but in a more indirect way by controlling DOC content.

5.2.3 Implications of changing temperature and oxygen profiles

The identified changes in temperature and oxygen profiles are likely to alter future physical, chemical and biological conditions in lakes. Oxygen is a critical variable in many lake processes and changes in the oxygen regime will therefore have a great impact on lake water quality and the living conditions for aquatic life (Diaz, 2001).

Even if the content of dissolved oxygen are somewhat increasing seen to the entire studied period it is more important to look at the seasonal changes. The growing season is a critical period for aquatic ecosystems and decreasing oxygen content during this time may have a negative impact on lake biota. The living conditions for the aquatic life are defined by the worst reigning conditions, and even if the oxygen levels increase during the winter, this will not recover biota loss happening during the summer.

During periods of low oxygen levels there are also an increased risk of substances leaching from the sediment. This may include DOC, nutrients as well as other substances. Leaching of DOC and nutrients may increase the browning effect in lakes as well as increase the risk of eutrophication (Brothers et al., 2014).

5.3 RECOMMENDATIONS FOR FUTURE STUDIES

The study of temperature and oxygen profiles are important to increase the understanding of how physical, chemical and biological conditions of lakes will change in the future. To further investigate how lakes at different location and of different types are likely to behave in the future it would be interesting to include more lakes in the study, with a larger geographical spread. Improvement of the calibration, preferably by automatic calibration, and inclusion of the sediment module in the MyLake model, would be to recommend to fine-tune the model and include the complex processes occurring in the sediment.

To increase the understanding of the impact of climate change, further development of the future scenario data would be necessary. One important thing to add to the scenarios would be extreme events such as floods and droughts. It would also be interesting to include possible changes in wind, especially at extreme weather events, since this may lead to wind-induced mixing of the water column. The frequency and intensity of extreme events are predicted to increase in the future (Cheng et al., 2012). This will have a significant impact on the incoming DOC to the lakes, something that may have a drastic impact on future DO content.

In this study, only the climate scenario with the highest climatic impact was used. In future studies it would be interesting to also include scenarios with lower climatic impact, such as $RCP_{2.8}$ and $RCP_{4.5}$. When using climate scenarios with a lower climatic impact, the positive effect on lake water DO due to reduced ice cover is likely to be less significant.

6 CONCLUSIONS

Both climatic factors, simulated with a high climatic impact, and changes in DOC concentrations were shown to have a great impact on both the temperature and the oxygen profiles of the studied lakes. Based on the evaluated hypotheses, the following conclusions were made

- Air temperature will increase in the future and this will increase the overall water temperature, intensify the thermal stratification and reduce the length of the ice covered period. The shorter ice period will decrease the risk of winter anoxia, resulting in climate change actually increasing the overall oxygen content seen to the entire water column and the entire time time period.
- During summer months, the combined effect of climate change and increased DOC concentrations had a negative impact on the oxygen content. The DOC concentration seamed however to have a stronger negative impact on the DO content.
- Climatic factors and changes in DOC concentrations plays different roles when it comes to the impact on temperature and oxygen profiles. DOC seams to be a stronger the driver controlling oxygen depletion. Climate change is an important indirect controller, since the DOC concentration is highly dependant on climatic factors.

It is clear that climate change will, directly or indirectly, have a profound impact on both the thermal conditions and the content and distribution of oxygen in lakes. In the future there is a high risk of drastic changes in lake water quality as well as the living conditions for all aquatic life.

7 REFERENCES

7.1 Litterature

Bergström, S. (1976). Development and application of a conceptual runoff model for Scandin SMHI, Reports RHO, No. 7, Norrköping.

Bergström, S., and Forsman, A. (1973) Development of a conceptual deterministic rainfall-ruHydrology, Vol. 4, No. 3. 147-170.

Bouffard, D., Ackerman, J.D., Boegman, L., (2013). Factors affecting the development and dynamics of hypoxia in a large shallow stratified lake: Hourly to seasonal patterns. Water Resour. Res. 49, 2380–2394. doi:10.1002/wrcr.20241

Brothers, S., Köhler, J., Attermeyer, K., Grossart, H.P., Mehner, T., Meyer, N., Scharnweber, K., Hilt, S., (2014). A feedback loop links brownification and anoxia in a temperate, shallow lake. Limnol. Oceanogr. 59, 1388–1398. doi:10.4319/lo.2014.59.4.1388

Cheng, C.S., Auld, H., Li, Q., Li, G., (2012). Possible impacts of climate change on extreme weather events at local scale in south-central Canada. Climatic Change 112, 963–979. doi:10.1007/s10584-011-0252-0

Choiński, A., Ptak, M., Skowron, R., Strzelczak, A., (2015). Changes in ice phenology on polish lakes from 1961 to 2010 related to location and morphometry. Limnologica 53, 42–49. doi:10.1016/j.limno.2015.05.005

Couture, R.-M., de Wit, H.A., Tominaga, K., Kiuru, P., Markelov, I., (2015). Oxygen dynamics in a boreal lake responds to long-term changes in climate, ice phenology, and DOC inputs. J. Geophys. Res. Biogeosci. 120, 2015JG003065. doi:10.1002/2015JG003065

de Wit, H.A., Valinia, S., Weyhenmeyer, G.A., Futter, M.N., Kortelainen, P., Austnes, K., Hessen, D.O., Räike, A., Laudon, H., Vuorenmaa, J., (2016). Current Browning of Surface Waters Will Be Further Promoted by Wetter Climate. Environ. Sci. Technol. Lett. 3, 430–435. doi:10.1021/acs.estlett.6b00396

Diaz, R.J., (2001). Overview of Hypoxia around the World. Journal of Environmental Quality 30, 275–281. doi:10.2134/jeq2001.302275x

Ekström, S.M., Kritzberg, E.S., Kleja, D.B., Larsson, N., Nilsson, P.A., Graneli, W., Bergkvist, B., (2011). Effect of acid deposition on quantity and quality of dissolved organic matter in soil-water. Environ. Sci. Technol. 45, 4733–4739. doi:10.1021/es104126f

Evans, A., Zelazny, L.W., Zipper, C.E., (1988). Solution Parameters Influencing Dissolved Organic Carbon Levels in Three Forest Soils. Soil Sci. Soc. Am. J. 52, 1789–1792. doi:10.2136/sssaj1988.03615995005200060049x

Fang, X., Stefan, H.G., (2009). Simulations of climate effects on water temperature, dissolved oxygen, and ice and snow covers in lakes of the contiguous U.S. under past and future climate scenarios. Limnol. Oceanogr. 54, 2359–2370. doi:10.4319/lo.2009.54.6_part_2.2359

Findlay, S.E.G., Sinsabaugh, R.L., (2003). Aquatic Ecosystems: Interactivity of Dissolved Organic Matter. Elsevier Inc.

Foley, B., Jones, I.D., Maberly, S.C., Rippey, B., (2012). Long-term changes in oxygen depletion in a small temperate lake: Effects of climate change and eutrophication. Freshw. Biol. 57, 278–289. doi:10.1111/j.1365-2427.2011.02662.x

Fondriest Environmental, (2013). Inc. "Dissolved Oxygen." Fundamentals of Environmental Measurements. Web.

http://www.fondriest.com/environmental-measurements/parameters/water-quality/dissolved-oxygen/

Golosov, S., Terzhevik, A., Zverev, I., Kirillin, G., Engelhardt, C., (2012). Climate change impact on thermal and oxygen regime of shallow lakes. Tellus Dyn. Meteorol. Oceanogr. 64, 17264. doi:10.3402/tellusa.v64i0.17264

Haaland, S., Hongve, D., Laudon, H., Riise, G., Vogt, R.D., (2010). Quantifying the Drivers of the Increasing Colored Organic Matter in Boreal Surface Waters. Environ. Sci. Technol. 44, 2975–2980. doi:10.1021/es903179j

Heiskanen, J.J., Mammarella, I., Ojala, A., Stepanenko, V., Erkkilä, K.-M., Miettinen, H., Sandström, H., Eugster, W., Leppäranta, M., Järvinen, H., Vesala, T., Nordbo, A., (2015). Effects of water clarity on lake stratification and lake-atmosphere heat exchange. J. Geophys. Res. Atmospheres 120, 7412–7428. doi:10.1002/2014JD022938

Holmberg, M., Futter, M.N., Kotamaki, N., Fronzek, S., Forsius, M., Kiuru, P., Pirttioja, N., Rasmus, K., Starr, M., Vuorenmaa, J., (2014). Effects of changing climate on the hydrology of a boreal catchment and lake DOC - probabilistic assessment of a dynamic model chain.

Hutter, K., Wang, Y., Chubarenko, I.P., (2011). Physics of Lakes. Volume 1: Foundation of the Mathematical and Physical Background, Physics of Lakes. Springer.

Kritzberg, E.S., Cole, J.J., Pace, M.L., Granéli, W., Bade, D.L., (2004). Autochthonous versus allochthonous carbon sources of bacteria: Results from whole-lake 13C addition experiments. Limnol. Oceanogr. 49, 588–596.
doi:10.4319/lo.2004.49.2.0588

Lee, F.G., Jones-Lee, A., (1999). Mechansims of the Deoxygenation of the Hypolimnia of Lakes.

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Stewart, K.M., Vuglinski, V.S., (2000). Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science 289, 1743–1746. doi:10.1126/science.289.5485.1743

Nash, J.E. and Sutcliffe, J.V. (1970). River flow forecasting through conceptual models part Iprinciples. Journal of Hydrology 10: 282–290.

Pace, M.L., Cole, J.J., (2002). Synchronous variation of dissolved organic carbon and color in lakes. Limnol. Oceanogr. 47, 333–342.
doi:10.4319/lo.2002.47.2.0333

Palmer, W.C., Havens, V.A., (1958). A Graphical Technique for Determining Evapotranspiration by the Thornthwaite Method.
Available http://onlinehydro.sdsu.edu/onlinethornthwaitereference.pdf [2017-08-09]

Palmer, M.E., Yan, N.D., Somers, K.M., (2014). Climate change drives coherent trends in physics and oxygen content in North American lakes. Clim. Change 124, 285–299. doi:10.1007/s10584-014-1085-4

Persson, I., Jones, I.D., (2008). The effect of water colour on lake hydrodynamics: a modelling study. Freshw. Biol. 53, 2345–2355. doi:10.1111/j.1365-2427.2008.02049.x

Ptak, M., Nowak, B., (2016). Variability of Oxygen-Thermal Conditions in Selected Lakes in Poland. Ecol. Chem. Eng. S 23, 639–650. doi:10.1515/eces-2016-0045

Saloranta, T.M., Andersen, T., (2007). MyLake—A multi-year lake simulation model code suitable for uncertainty and sensitivity analysis simulations (PDF Download Available). ResearchGate.
doi:http://dx.doi.org/10.1016/j.ecolmodel.2007.03.018

Saloranta, T.M., Forsius, M., Järvinen, M., Arvola, L., (2009). Impacts of projected climate change on thermodynamics of a shallow and deep lake in Finland: model simulations and Bayesian uncertainty analysis. doi:10.2166/nh.2009.030

Schwefel, R., Gaudard, A., Wüest, A., Bouffard, D., (2016). Effects of climate change on deepwater oxygen and winter mixing in a deep lake (Lake Geneva): Comparing observational findings and modeling. Water Resour. Res. 52, 8811–8826. doi:10.1002/2016WR019194

Seibert, J., (2005). HBV light version 2, User's Manual.
Available https://www.geo.uzh.ch/dam/jcr:c8afa73c-ac90-478e-a8c7-929eed7b1 b62/HBV_manual_2005.pdf [2017-08-09]

Simčič, T., Germ, M., (2010). Increased temperature due to global warming alters the respiratory potential in aquatic organisms from an Oligotrophic Lake. Int. Rev. Hydrobiol. 95, 370–382. doi:10.1002/iroh.201011213

Snortheim, C.A., Hanson, P.C., McMahon, K.D., Read, J.S., Carey, C.C., Dugan, H.A., (2017). Meteorological drivers of hypolimnetic anoxia in a eutrophic, north temperate lake. Ecol. Model. 343, 39–53.
doi:10.1016/j.ecolmodel.2016.10.014

Soja, A.-M., Kutics, K., Maracek, K., Molnár, G., Soja, G., (2014). Changes in ice phenology characteristics of two Central European steppe lakes from 1926 to 2012 - influences of local weather and large scale oscillation patterns. Clim. Change 126. doi:10.1007/s10584-014-1199-8

Terzhevik, A., Golosov, S., Palshin, N., Mitrokhov, A., Zdorovennov, R., Zdorovennova, G., Kirillin, G., Shipunova, E., Zverev, I., (2009). Some features of the thermal and dissolved oxygen structure in boreal, shallow ice-covered Lake Vendyurskoe, Russia. Aquat. Ecol. 43, 617–627. doi:10.1007/s10452-009-9288-x

Zhen-Gang, J., (2008). Hydrodynamics and Water Quality: Modeling Rivers, Lakes and Estuaries. John Wiley & Sons.

7.2 Data, program and map material

Github, 2016. biogeochemistry/MyLake_public: MyLake version 1.2.
Available: https://github.com/biogeochemistry/MyLake_public

Lantmäteriet, 2017. Kartsök och ortnamn-
Available: https://kso.etjanster.lantmateriet.se/#

Persson, G., 1996 (a). 26 svenska referenssjöar 1989 - 1993, en kemisk-biologisk statusbeskrivning: Remmarsjön, Västernorrlands län. Institutionen för miljöanalys, SLU, Uppsala.
Available: http://info1.ma.slu.se/gp/REMMAR.WWW/PG1.HTML

Persson, G., 1996 (b). 26 svenska referenssjöar 1989 - 1993, en kemisk-biologisk statusbeskrivning: Härsvatten, Göteborgs och Bohus län. Institutionen för miljöanalys, SLU, Uppsala.
Available: http://info1.ma.slu.se/gp/HAERSVAT.WWW/PG1.HTML

Persson, G., 1996 (c). 26 svenska referenssjöar 1989 - 1993, en kemisk-biologisk statusbeskrivning: Fiolen, Kronobergs län. Institutionen för miljöanalys, SLU, Uppsala.
Available: http://info1.ma.slu.se/gp/FIOLEN.WWW/PG1.HTML

SMHI, 2017a. Öppna data, meteorologiska observationer.
Available https://opendata-download-metobs.smhi.se/explore/?parameter=0

SMHI, 2017b. Klimatscenarier.
Available https://www.smhi.se/klimat/framtidens-klimat/klimatscenarier?area=avr&var=t&sc=rcp85&seas=ar&dnr=0&sp=sv&sx=0&sy=163

SMHI, 2017c. Vattenwebb, modelldata per område.
Available: https://vattenwebb.smhi.se/modelarea/

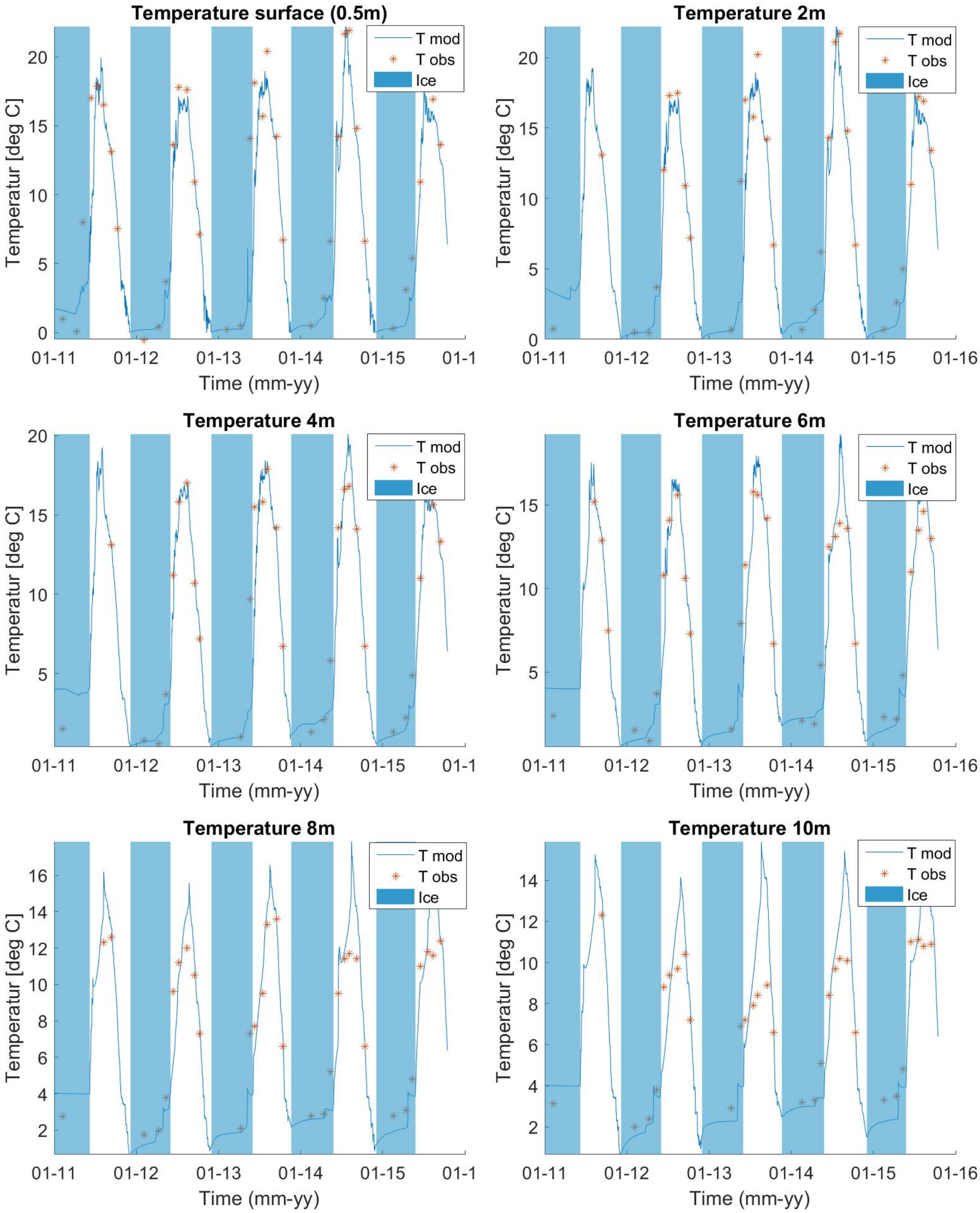
Appendix A Meteorological data

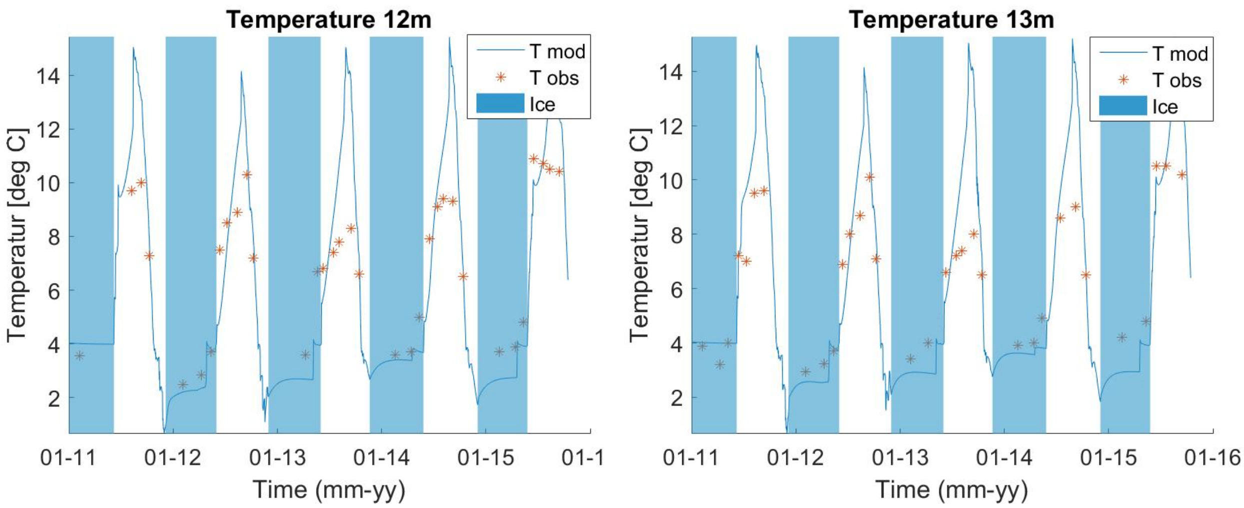
Table 13 Measurement stations and information about the data for all three lakes. All data collected from SMHI opendata.

	Sjö:Härsvatten Station (number)	**Sjö: Remmarsjön Station (number)**	**Sjö: Fiolen Station (number)**	**Info**
Global radiation	Göteborg sol (71415)	Umeå sol (140615)	Växsjö sol (64565)	sum of hourly measurements
Cloud cover	Såtenäs (71470)	Fredrika (148050)	Hagshult Mo(74180)	measurement 12:00 PM
Air temperature	Göteborg A (71420)	Fredrika (148050)	Berg (74080)	daily measurement
Relative humidity	Göteborg A (71420)	Fredrika A (148040)	Växsjö A (64510)	12:00 PM
Air pressure	Göteborg A (71420)	Hemling A (138390)	Växsjö A (64510)	12:00 PM
Wind speed	Göteborg A (71420)	Fredrika (7148050)	Växsjö A (64510)	12:00 PM
Precipitation	Komperöd (82040)	Fredrika A (148040)	Berg (74080)	daily

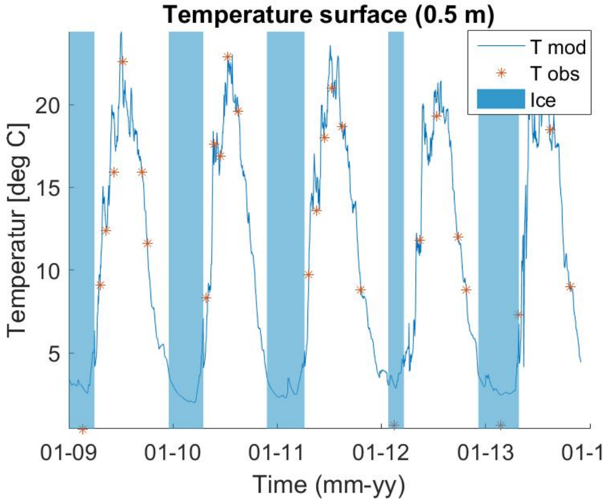
Appendix B Temperature profiles

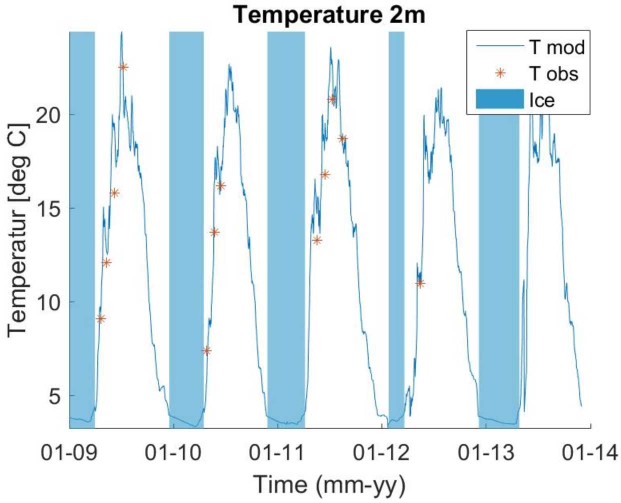
B.1 Remmarsjön

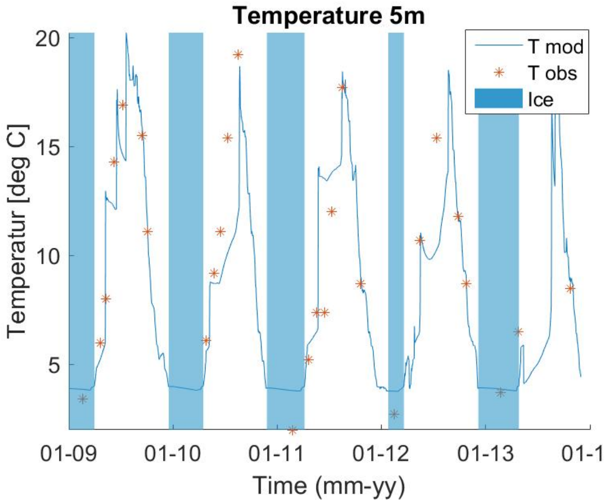


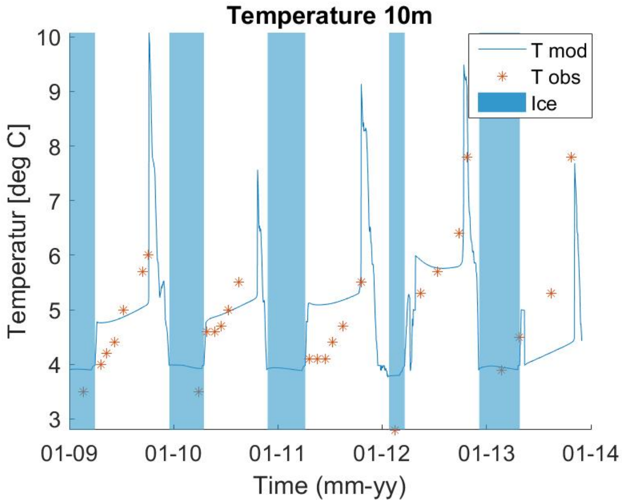

Temperature 12m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)
01-11
01-12
01-13
01-14
01-15
01-1
Temperature 13m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)
01-11
01-12
01-13
01-14
01-15
01-16

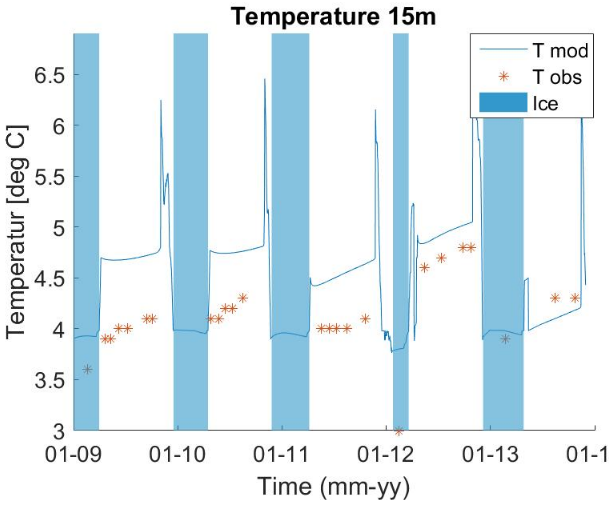
B.2 Härsvatten

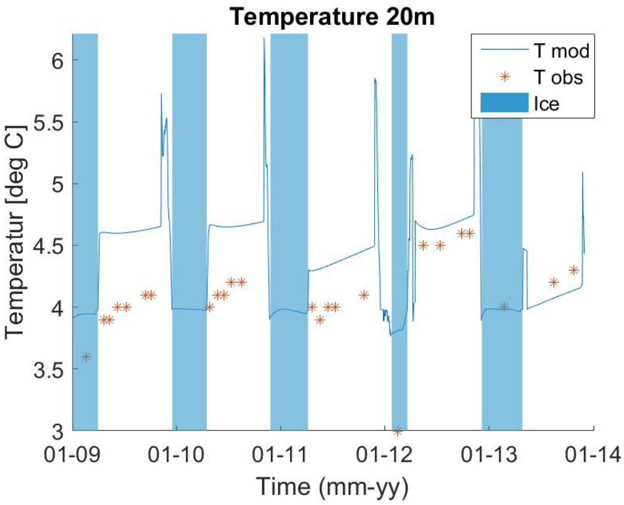


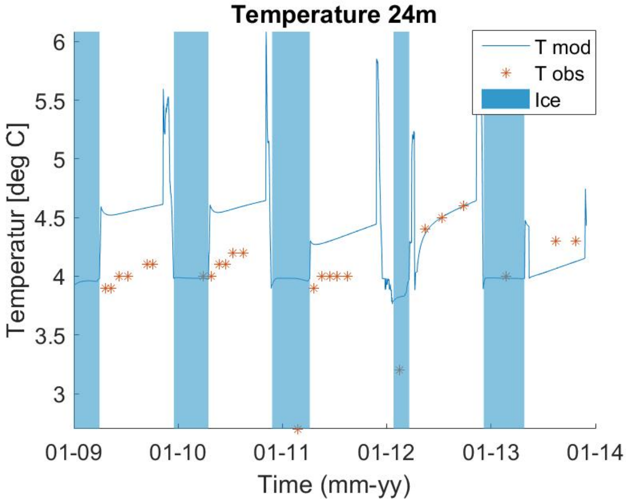






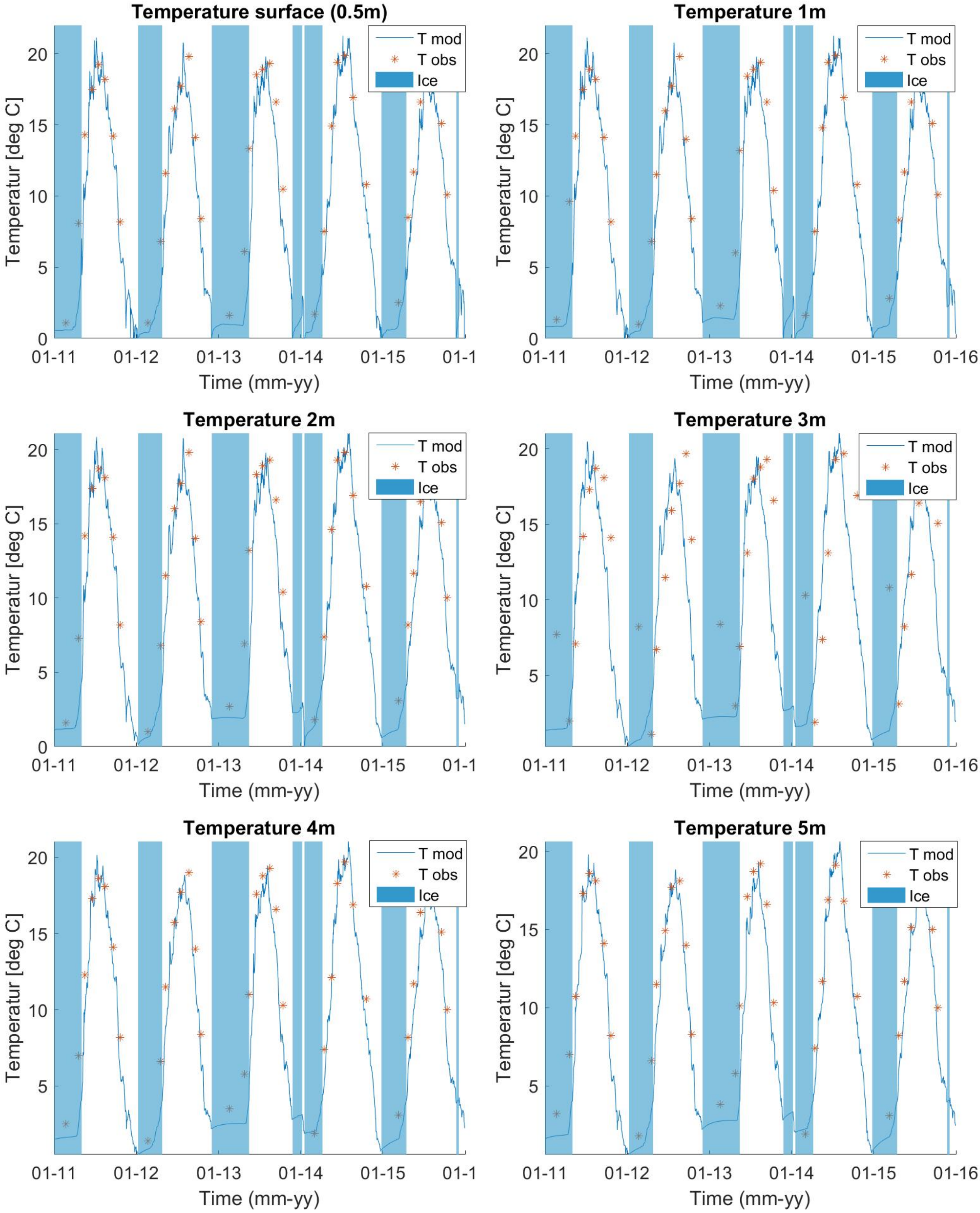


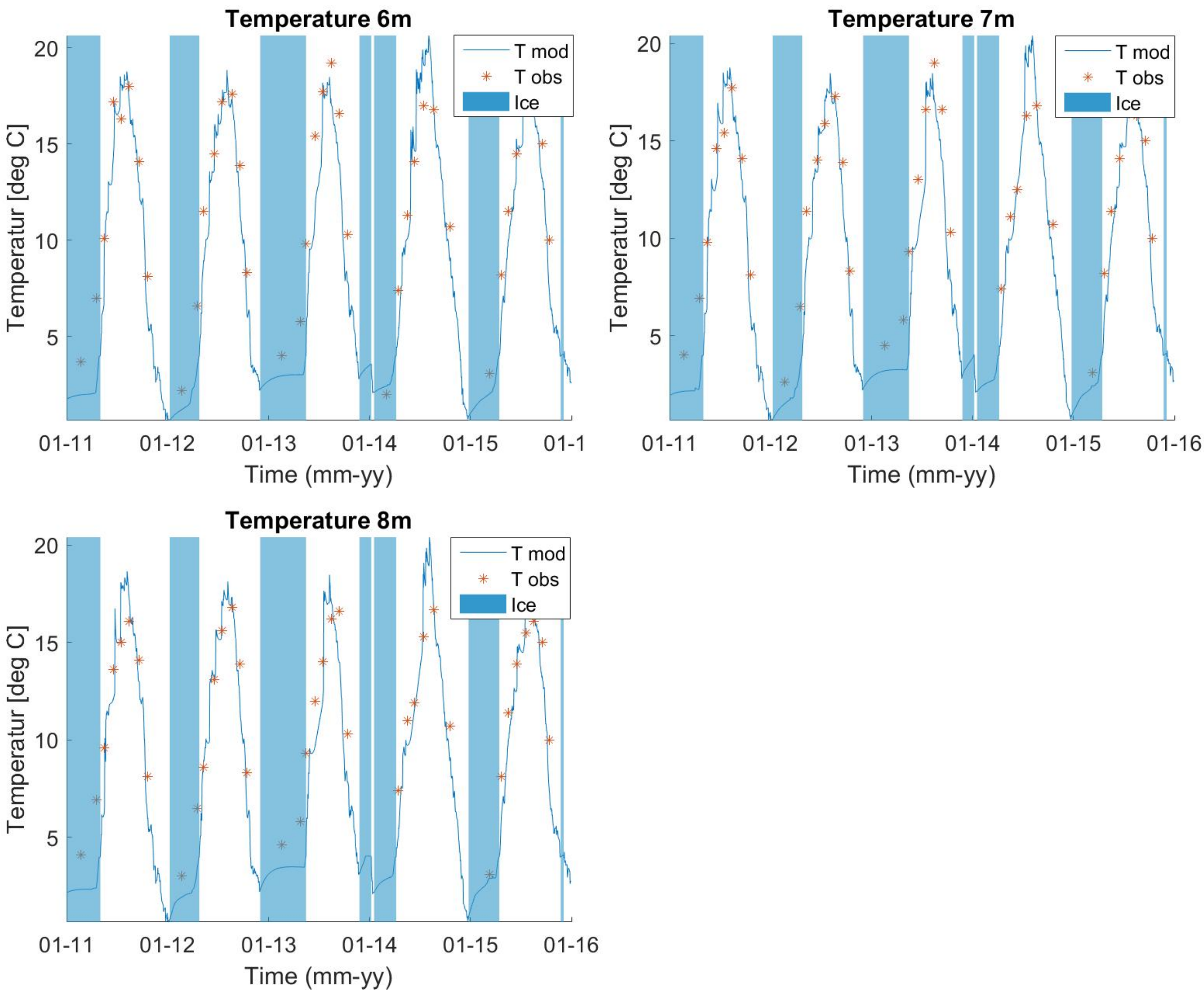




Temperature 24m
T mod
T obs
Ice
Temperatur [deg C]
6
5.5
5
4.5
4
3.5
3
01-09
01-10
01-11
01-12
01-13
01-14
Time (mm-yy)

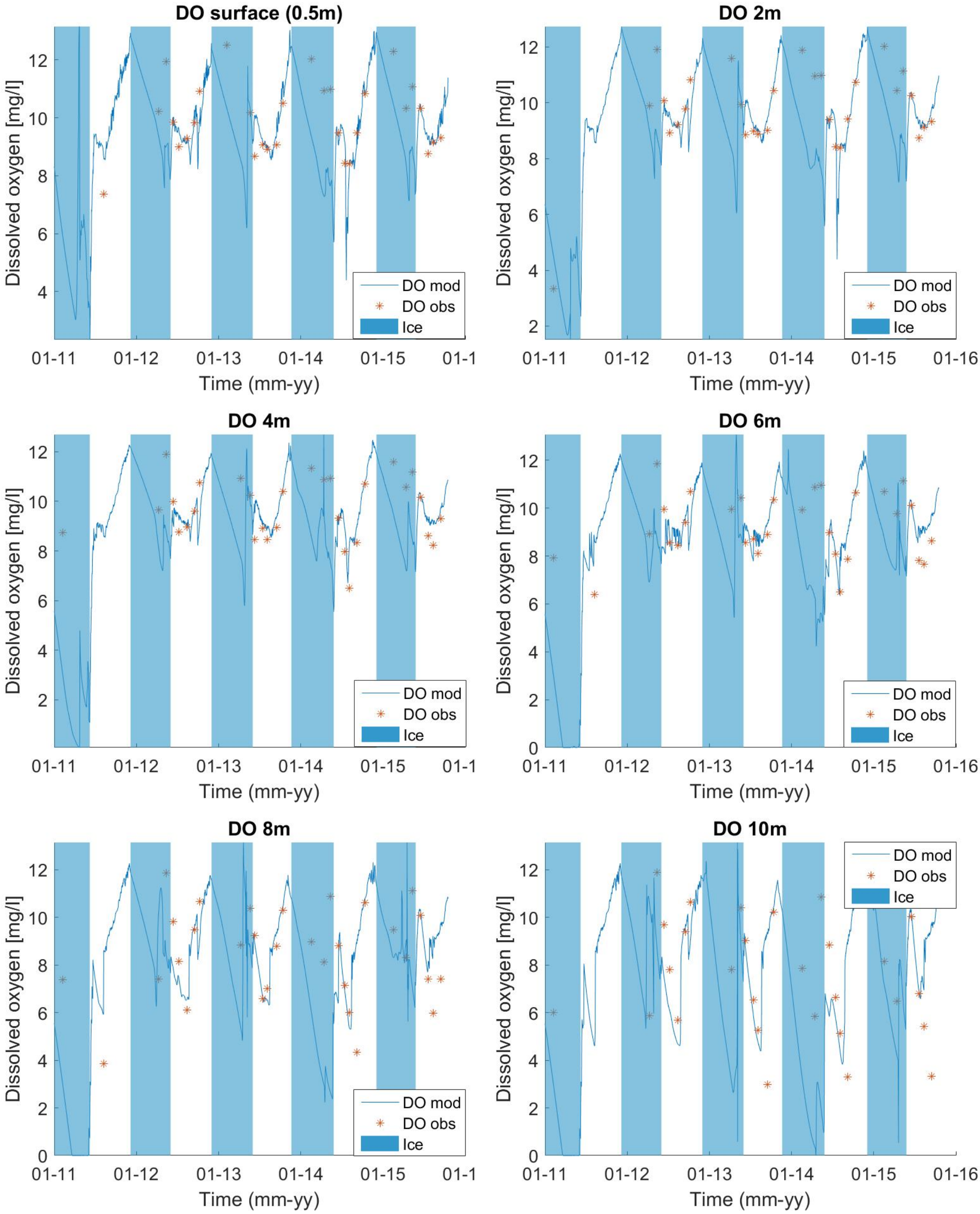
B.3 Fiolen

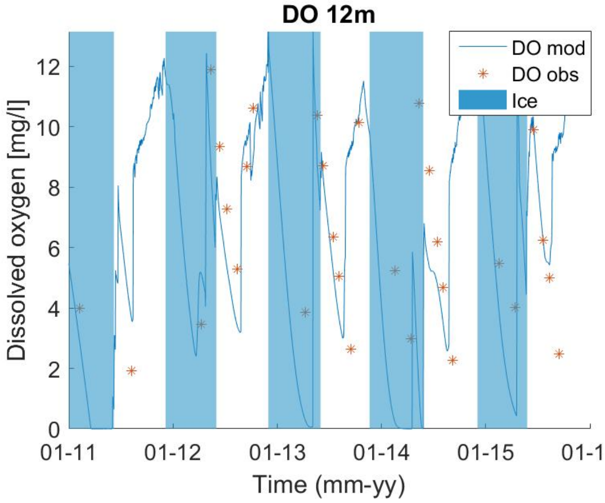

Temperature surface (0.5m)
Temperature 1m
Temperature 2m
Temperature 3m
Temperature 4m
Temperature 5m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)
01-11
01-12
01-13
01-14
01-15
01-16


Temperature 6m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)
Temperature 7m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)
Temperature 8m
T mod
T obs
Ice
Temperatur [deg C]
Time (mm-yy)

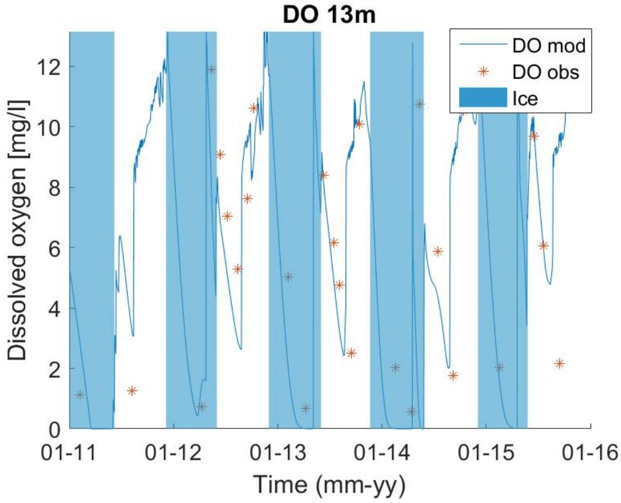
Appendix C Dissolved oxygen profiles

C.1 Remmarsjön



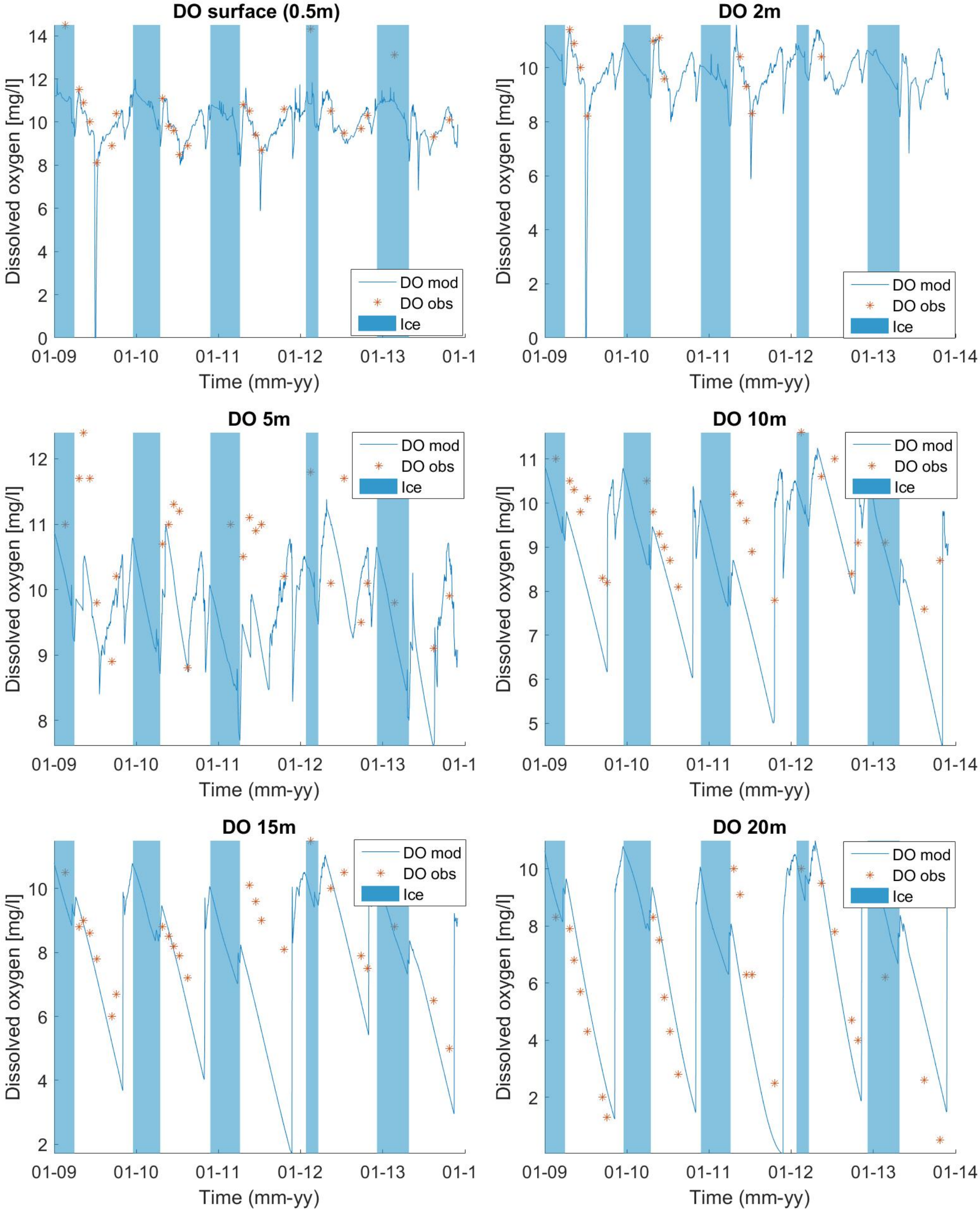


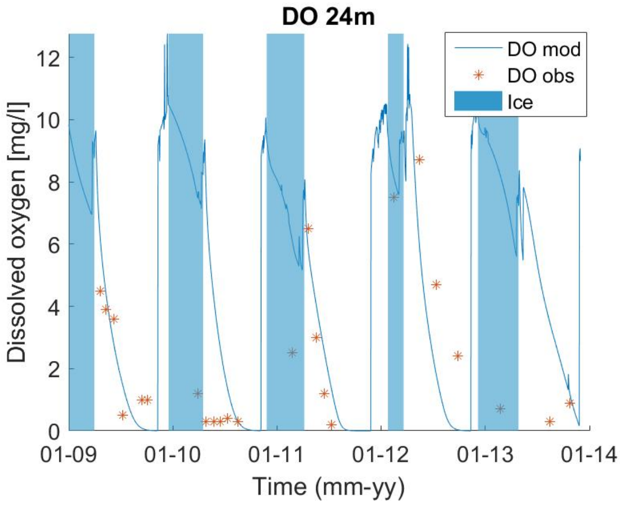
DO 12m
DO mod
DO obs
Ice
Dissolved oxygen [mg/l]
Time (mm-yy)
0
2
4
6
8
10
12
01-11
01-12
01-13
01-14
01-15
01-1



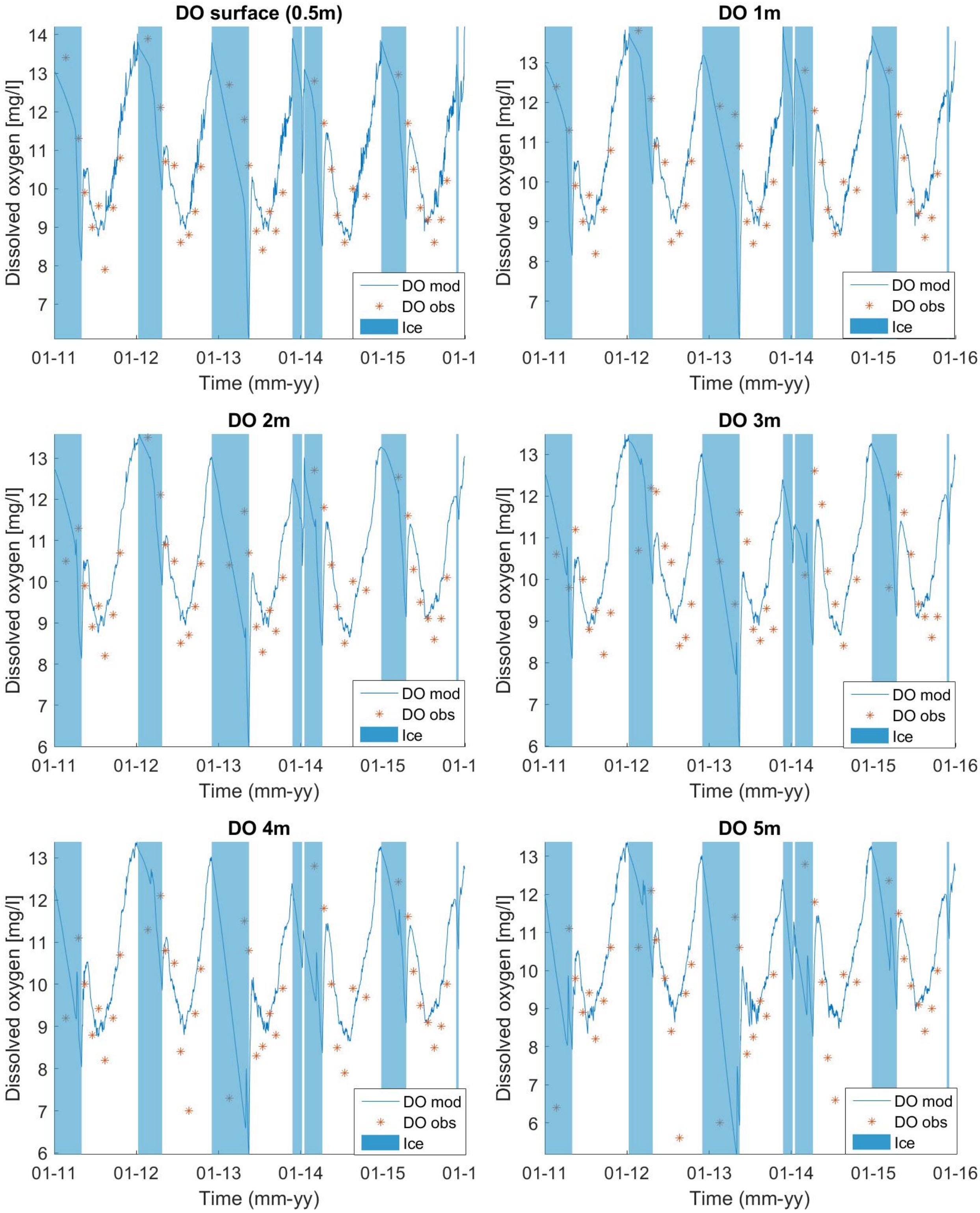
DO 13m
DO mod
DO obs
Ice
Dissolved oxygen [mg/l]
Time (mm-yy)
0
2
4
6
8
10
12
01-11
01-12
01-13
01-14
01-15
01-16

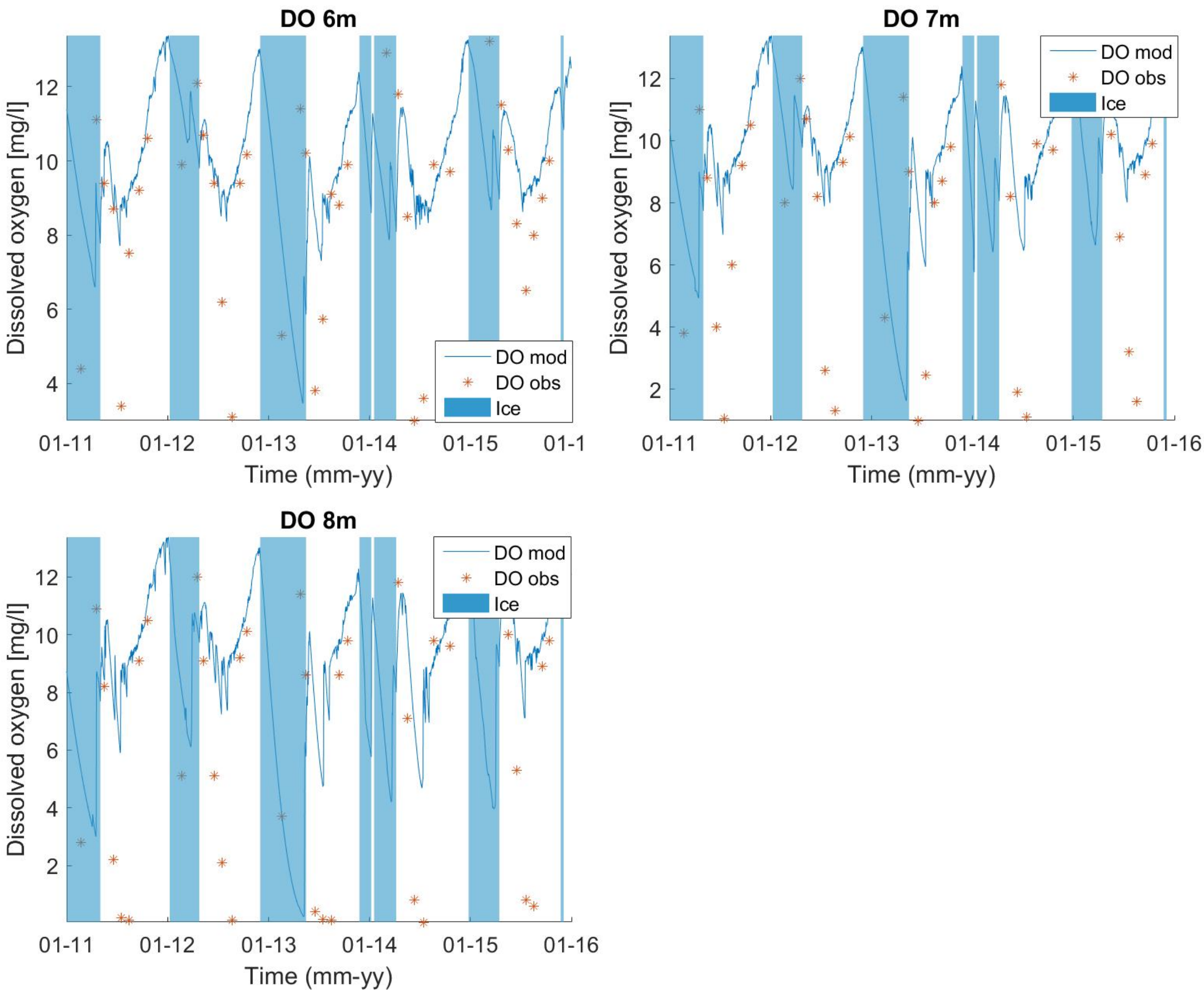
C.2 Härsvatten




DO 24m
DO mod
DO obs
Ice
Dissolved oxygen [mg/l]
0
2
4
6
8
10
12
01-09
01-10
01-11
01-12
01-13
01-14
Time (mm-yy)

C.3 Fiolen


DO surface (0.5m)
DO 1m
DO 2m
DO 3m
DO 4m
DO 5m
Dissolved oxygen [mg/l]
Time (mm-yy)
01-11
01-12
01-13
01-14
01-15
01-16
DO mod
DO obs
Ice


DO 6m
DO 7m
DO 8m
Dissolved oxygen [mg/l]
Time (mm-yy)
01-11
01-12
01-13
01-14
01-15
01-16
DO mod
DO obs
Ice