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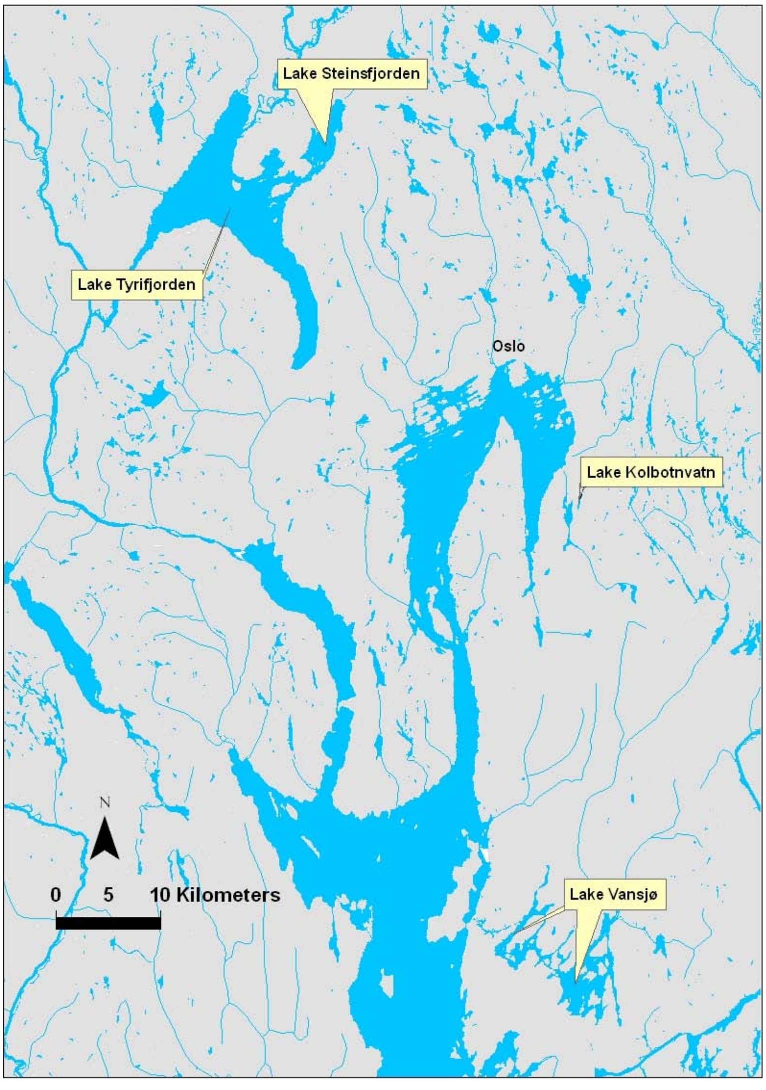
Simulated effects on hydrophysics and water quality in lakes due to climate changes



Norwegian Institute for Water Research
– an institute in the Environmental Research Alliance of Norway

REPORT

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Abstract

The objective of the studies was to quantify effects on water quality in lakes due to a future climate change. This was done by using climatic scenarios for the climate of today and in the future as input to the water quality model CE-QUAL-W2 for three Norwegian lakes. The results of the simulations were focused on water temperature, ice cover, oxygen, nutrients and algae.

A future warmer climate leads to:

- Increase in water temperature especially at the surface
- Periods with ice cover become shorter and less frequent
- Prolonging of summer stagnation period and more frequent circulation during winter
- Less oxygen during summer and more during winter
- Prolonging of growth season leads to more cyanobacteria

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Preface

The project is part of the Strategic Institute Program (SIP) for 2006-2009 named Integrated environmental modelling for river basin management (Model-SIP). The work is funded by the Research Council of Norway).

This report mainly concerns simulation of future climatic effects of water quality in three lakes. For two of the lakes, Lake Tyrifjorden and Lake Kolbotnvatn, the model was allready calibrated and the results reported. For the the third lake, Lake Vansjø, the calibration and making of various scenarios was funded by both the Model-SIP and and NOrth sea regional and Local IMPlementation of the Water Framework Directive (NOLIMP) funded by the project partners and the European Regional Development Fund INTERREG IIIB.

Oslo, 1. March 2008

Torulv Tjomsland

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Summary

Introduction

The objective of the study was to quantify effects on water quality in lakes due to a future climate change. Scenarios for the climate of today and in the future were used as input to the water quality model CE-QUAL-W2. The results of the simulations were focused on changes in water temperature, ice cover, oxygen, nutrients and algae due to climatic changes.

Daily values of climate variables from scenarios for the 1961-1990 and 2071-2100 periods were used as input. Indirect climatic effects on water flow, nutrient transport, organic matter etc. from the drainage catchments to the lakes were not included.

The lakes in the study are Lake Tyriforden and Lake Steinsfjorden, Lake Kolbotnvatn and the two main basins of Lake Vansjø (Storefjorden and Vanemfjorden). The lakes are localized in the South Eastern part of Norway**.** The surface areas of the lakes were between 0.3 km^2 and 64 km^2, maximum depth between 19 m to 295 m and the water quality were of oligotrophic- to eutrophic nature.

The model was calibrated against observed data for each of the lakes for a period of three to five years. Generally the simulated temperatures seldom deviated more then a one degree Celsius from measured values. There were good accordance between simulated oxygen and nutrients values, and observations. The model showed the main variation of the development of algae.

When running the climate scenarios the calibrated coefficients were used.

Results

The future climate in the scenarios became warmer then to day. The yearly mean air temperature increased from 5.9 ^{o}C to 9.5 ^{o}C from period 1961-1990 to 2071-2100. The temperature increased throughout the year. Median daily temperature became higher than 0 ^{o}C during the winter. The 10% lowest temperatures in the future got about the same magnitude as the median (50%) values of today. There were no clear changes of cloud cover and wind velocities

The yearly mean temperatures in the layer 0-10 meter in the lakes increased from about 7^{o}C with about 2^{o}C from the 1961-1990 period to the 2071-2100 period. On the surface the increase was close to 2.5 ^{o}C. At 15 meter depth the increase was below 1^{o}C. In Tyrifjorden an increase of 0.1^{o}C was found on both 100 meter and 250 meter.

In the scenarios reflecting the present situation the lakes were covered by ice from 44 to 88 days in a mean year. In the future scenarios all of the lakes were without ice cover throughout the winter. Only in cold winters we can expect ice cover. For cold winters (10 percentile), days with ice cover for the lakes were reduced from between 99 to 146 days in the today scenarios to between 68 to 107 days in the future scenarios.

The future temperatures were higher than the today temperatures throughout the year. On the surface, the median temperatures of the future scenarios were of the same magnitude or even higher then the 90% highest temperatures of the today scenarios. The future lowest temperatures (10%) were about the same as the median temperatures of today from January to August. The rest of the year these future low temperatures were higher then the 90% highest of the today temperatures.

Under median condition in the future scenarios the temperatures reached 4^{o}C about two weeks earlier in the spring and one month later in the autumn. The circulation period for the lake in the spring started earlier and the circulation period in the autumn started later. The duration of the summer conditions with a warmer and more stable top layer between these circulations periods increased. Future ice free condition reduced the stable conditions during the winter with following increased duration of the circulation period through the winter

Climate changes had minor influence on the mean values of the oxygen concentrations in our scenarios. The differences became greater when we studied the changes through the year. In the today scenario for a median year in bottom layer of Lake Kolbotnvatn the oxygen saturations were zero during the summer from the middle of May to the middle of October and in the winter from late December to the middle of March. In the future scenario the deficit period during the summer was extended by about two weeks in the spring and one month in the autumn. During the winter the future saturation values increased. For ten percent of the years (10%) the period with summer deficit increased with over a month and the winter condition still showed saturation values equal zero. Oxygen problems to some extent also existed in Steinsfjorden and Vansjø-Storefjorden. The same phenomena clearly took place also there. For the other lakes no oxygen problems existed.

The future scenarios lead to reduced oxygen saturation during the summer and increased values during the winter. This reason relates to the temperature conditions and the following changes of circulation periods. Warmer and normally ice free winters in the future scenarios lead to earlier increase of the temperature in the spring with resulting warm epilimnion and stable water column. Further the warmer future climate lead to later cooling and later start of the autumn circulation in the lakes. Degradation of algae and other organic material reduced the oxygen in the water body. Longer stable summer conditions combined with prolonged algal growth lead to future lower oxygen values during the summer. When the circulation starts in the autumn, the water column become mixed and the bottom layer gets oxygen from layer above, which leads to better oxygen conditions during the autumn and winter. In some cases the circulations continued until the rise of temperature in the spring.

The changes in the vertical circulation of the lakes also will influence other water quality constituents. A water work intake near bottom will in the future be better protected from pollution entered on the surface of the lake during the prolonged summer stagnation period. The prolonged circulation period during the winter, especially due to increased period with ice free condition, will have the opposite effect and lead to increased influence of pollutions on the surface.

The predicted changes in mixing patterns, water temperature, and oxygen saturation will have little consequences for the total amount of phytoplankton biomass as long as nutrient loading remains constant. Phytoplankton growth in spring will start 1-2 weeks earlier as compared with present conditions. The maximum density will also be reached earlier. In addition, the growth season may be prolonged. According to model predictions, cyanobacteria will benefit from climate change, which may induce a shift in phytoplankton composition towards potentially toxic cyanobacteria. This would have serious consequences for recreation and drinking water production. Lake Kolbotnvatn and Lake Vansjø are affected by the occurrence of toxic cyanobacterial blooms to day. This problem is likely to increase in the future.

Conclusions

A future warmer climate may lead to:

- Increase in water temperature especially at the surface
- Periods with ice cover become shorter and less frequent
- Prolonging of summer stagnation period and more frequent circulation during winter
- Less oxygen during summer and more during winter
- Prolonging of growth season and more cyanobacteria

1. Materials and methods

1.1 Objective

The objective of the study was to quantify effects on water quality in lakes due to a future climate. The method was using climatic scenarios for the climate of today and in the future as input to a water quality model. The simulations were focused on water temperature, ice cover, oxygen, nutrients and algae.

1.2 Climate scenarios

Climate scenarios for the lakes were based on dynamically-downscaled daily mean data from the Rossby Centre Regional Climate Model (RCAO) provided by the EU FP6 project PRUDENCE (http://prudence.dmi.dk). The RCAO simulations were based on two global climate models, HadAM3 (Hadley) run with the scenario of greenhouse gas (GHG) emissions, A2 (IPCC 2000). The model use 1961-1990 as control period and 2071-2100 as scenario period. The downscaled data from RCAO are allocated to a 50x50 km grid. The scenario for grid cell rlat 58 and rlat 49 was chosen. This is localized between Lake Vansjo and Lake Kolbotnvatn and represented all of the lakes.

The daily mean values of the following variables were used in the model: Air temperature, dew point temperature, wind 10 m above surface, wind direction and cloud percent. For the scenarios these were the only climatic effects that were taken into consideration.

Indirect climatic effects on water flow, nutrient transport, organic matter etc. from the drainage catchments to the lakes were not included.

1.3 Description of the lakes

The lakes in the study are Lake Tyriforden and Lake Steinsfjorden, Lake Kolbotnvatn and the two basins of Lake Vansjø: Storefjorden and Vanemfjorden. The lakes are localized in the South Eastern part of Norway**, Figure 1.** Typical data from the lakes are shown in **Table 1.**

Lake Tyrifjorden and Lake Steinsfjorden

Lake Steinsfjorden is connected to Lake Tyrifjorden through a narrow and shallow sound of about 30 m wide and 3 m deep. The surface area of Lake Steinsfjorden is 13.9 km^2 and the local drainage area is 63.7 km^2. Maximum and mean depths are 24 m and 10 m respectively. The lake is surrounded by agriculture land with a marked run off of nutrients. The lake is of mesotrophic character. The most common algae species was the cyanobacteria *Planktothrix*. During the summer the oxygen deficit was common in the deepest parts of the lake.

The drainage area of Tyrifjorden inclusive Steinsfjorden is 9952 km^2. Mean and maximum depths are 114 m and 295 m respectively. The water quality is of oligtrophic nature.

Lake Kolbotnvatn

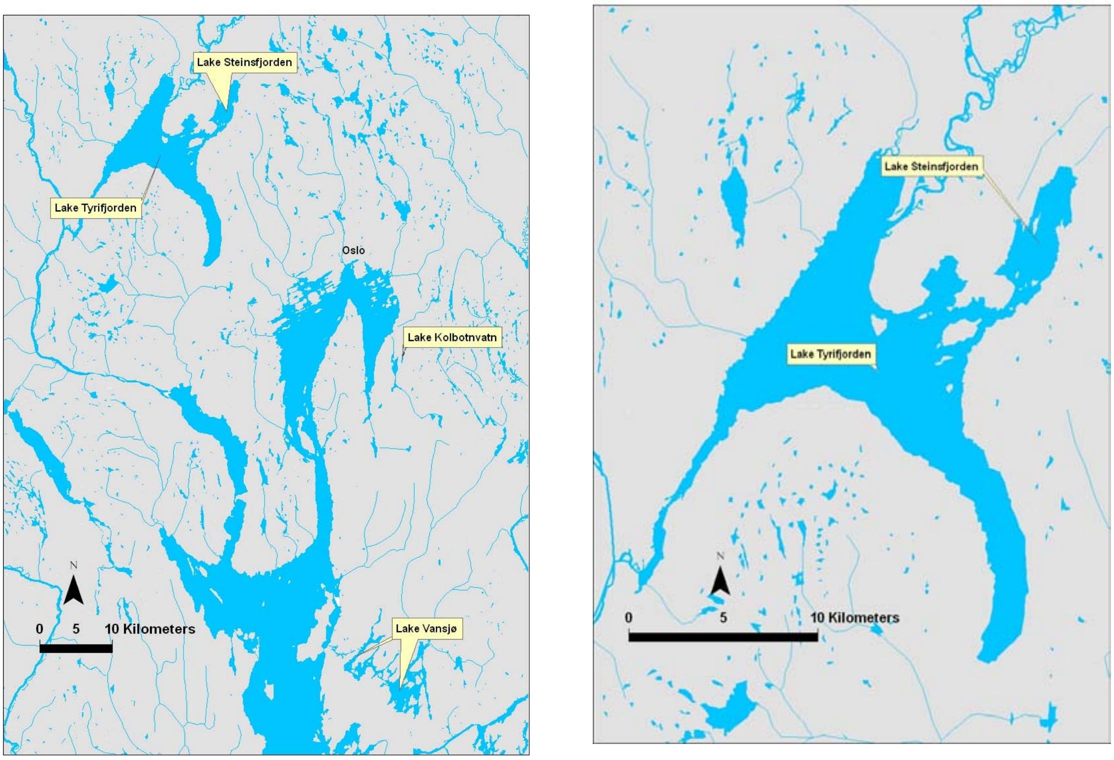
The drainage area is 3 km^2. The area of the lake is 0.3 km^2. Maximum and mean depths are 19 m and 10 m respectively. The lake is surrounded by populated area. This leads to great loads of nutrient and eutrophic conditions. The lake is eutrophic with regular blooms of toxic blue-green planktonic algae. The dominating algae species is the cyanobacteria *Planktrothrix agardhii*. During the summer oxygen deficit is common in the deepest parts of the lake.

Lake Vansjø

The watershed of Lake Vansjø is 689 km^2. The surface area of the lake is 36 km^2. Mean and maximum depth is 7 and 41 meter. Mean discharge is 11 m^3/s. The watershed have 40 000 inhabitants. More than 2000 households have little or no treatment of waste water. The lake is surrounded with agriculture land. Lake Vansjø suffers from severe eutrophication with regular blooms of toxic blue-green planktonic algae. The main sources for nutrient loading to the lake are discharges from the population and agriculture. The lake morphology is rather complex with a shallow western part (Vanemfjorden) and deeper eastern part (Storefjorden).

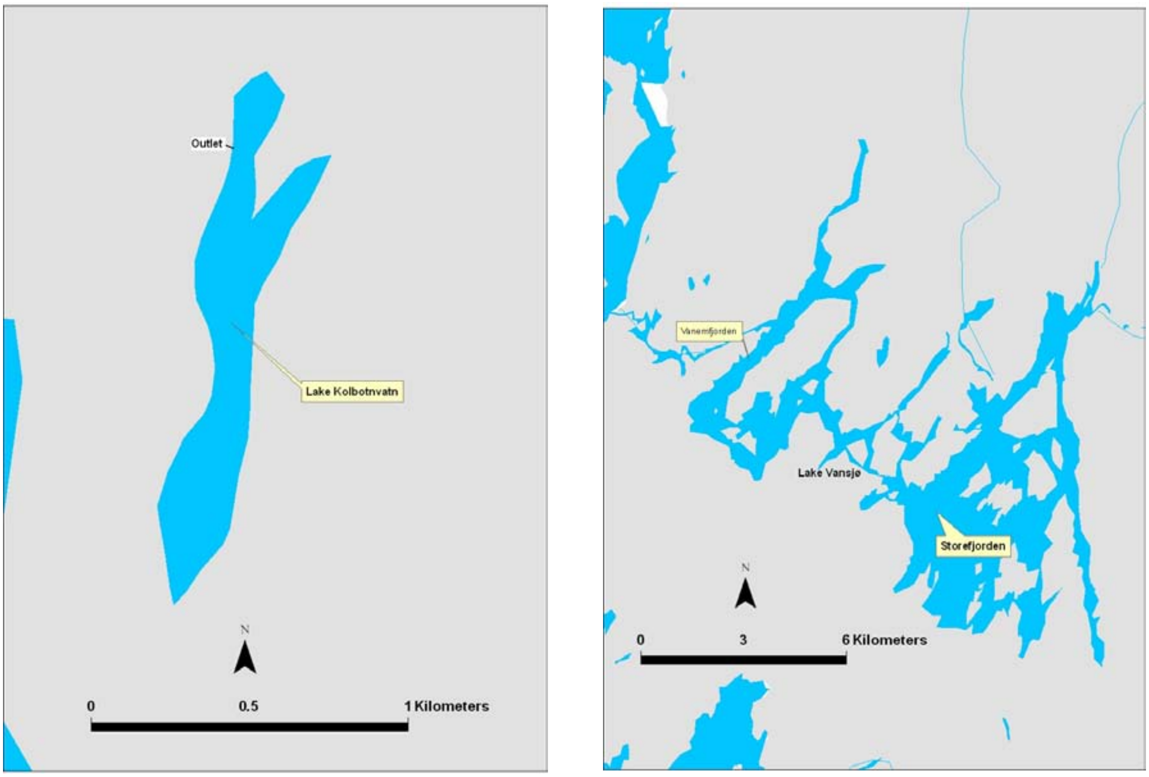
Table 1. Characteristic data of the lakes

Variable	Unit	Steinsfjorden	Tyrifjorden	Kolbotnvatn	Vansjø
Drainage area	km2	64	9952	3	689
Lake area	km2	14	121	0.3	36
Mean depth	m	10	114	10	7
Maximum depth	m	24	295	19	41
Heigh above sea	m	63	63	95	25
Mean water discharge	m3/s	1	165	0.07	11



The lakes are localized in the SE of Norway

Lake Tyrifjorden and Lake Steinsfjorden



Lake Kolbotnvatn

Lake Vansjø with basins Storefjorden and Vanemfjorden

Figure **1.** Lake overview

1.4 The model

CE-QUAL-W2, is developed by US army Corps of Engineers and University of Portland, (http://www.ce.pdx.edu/w2). The model calculates hydrodynamic and water quality variables of rivers, lakes and estuaries. The model is a two-dimensional (longitudinal/vertical). However several 2-dimentional segments may be cobbled and simulated simultaneously. The model therefore is quasi 3-dimentional and may handle dendritic lakes, **Figure 2**. The model calculates in lake processes as interactions between algae, nutrients, organic matter and sediments. The response is a function of climate, water flow and water quality of the inflowing water. The results are calculated forwards in time with step of some minutes for each of the cells.

Variables: Water surface level, vertical and horizontal velocities, temperatures, ice thickness, conservative and non conservative groups, water age/residence time, inorganic suspended solids, particulate organic matters, dissolved organic matters, BOD, phosphorus, nitrogen, silica, iron, oxygen, alkalinity, organic sediments, bacteria, algae groups, zooplankton groups, epiphyton groups, macrophytes groups, 60 derived variables among them ph, TOC, organic phosphorus, particular phosphorus.

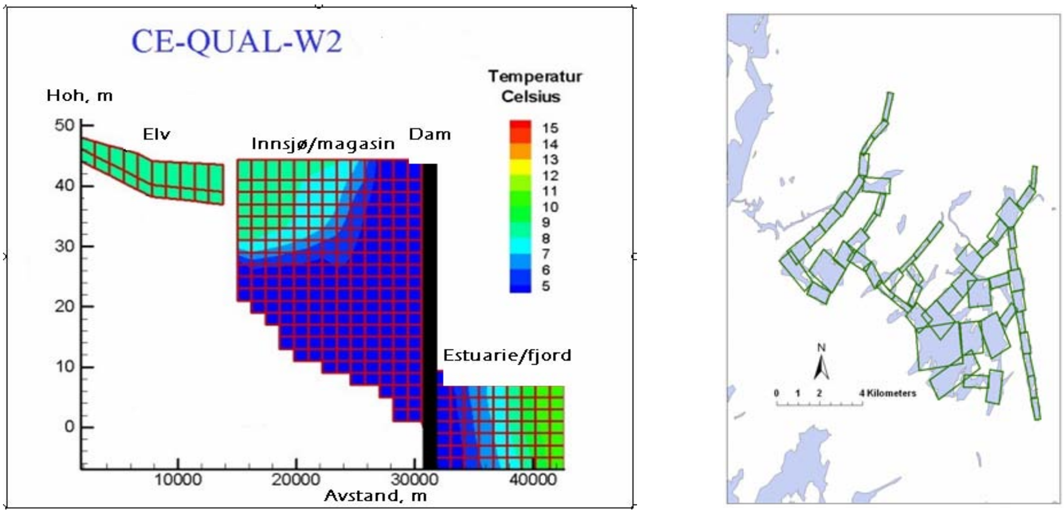


Figure 3. The model handles rivers, lakes and estuaries. The model is 2-dimentional (length-depth). 2-dimentional segments may be cobbled. The model therefore is quasi 3-dimentional as shown for LakeVansjø.

2. Calibrations

The model was calibrated against observed values. These studies are reported separately and only some main results are presented here, see Oredalen, Rohrlack and Tjomsland 2006, Tjomsland, Berge, Halstvedt and Rohrlack 2006.

2.1.1 Lake Tyrifjorden and Lake Steinsfjorden

The lake is regulated between 62 and 63 meter above sea level, **Figure 4**. A fast increase of the level took place during the snow melting period in the spring. In that period there were high net flows of water from Tyrifjorden into Steinsfjorden. In the period November/December – March the lake was covered by ice. The observed and simulated temperature showed good accordance. The model predicted the low oxygen saturation values in the bottom layer in the late summer. Simulated nutrients and algae concentrations match reasonably well with observed values. Both phosphate phosphorus and nitrate nitrogen had values near zero and were in periods limiting nutrient for algal growth. We simulated two algal groups: The cyanobacteria *Plantothrix* and “Other algae”. Planktothrix was the dominating group, especially on deep water. “Other algae” were most common near the surface.

Due to the great depths of Lake Tyrifjorden, the ice did not covered the lake before January, **Figure 5**. Phosphate phosphorus was the limiting nutrient for algal growth. The simulations showed good accordance with the few observations that existed. The algae content was low. *Planktothrix,* that was the dominating group in Steinsfjorden, was nearly absent.

2.1.2 Lake Kolbotnvatn

The water level was stable around 95 meters above sea level, **Figure 6**. The lake was covered by ice from about November to March. The deviations between simulated and observed temperatures were seldom more then 1 ^{o}C. Both phosphate phosphorus and nitrate nitrogen were periodical limiting nutrient for algal growth. The model handled the oxygen deficit in the bottom layers during the summer. The simulations showed the main variations of the algal development, **Figure 7**. ” *Planktothrix agardhii* was the dominating group, especially on deep water. “Other algae” were most common in near the surface.

2.1.3 Lake Vansjø

The simulated results showed rather good accordance with the observed data in the surface layer of the lake for the most important variables that concern eutrophication. In the model we used two algal groups. The results presented are only the total algae content.

Lake Vansjø-Storefjorden

The lake froze in December and broke up in Mars, **Figure 8**. The oxygen saturation decreased during the summer; however there were no lack of oxygen. Simulated values of total phosphorus and total nitrogen showed rather good accordance with the observations. Phosphorus was the limited nutrient for algal growth. Algae/chlorophyll values were probably too high in early spring and late summer. Else the simulated values mainly were of the same magnitude as the observations.

Vansjø – Vanemfjorden

The lake froze in December and broke up in Mars, **Figure 9**. There was good accordance between observed and simulated temperatures. Both phosphorus and nitrate may be limiting nutrient. The simulated algae/chlorophyll values were mainly of the same magnitude as the observations.

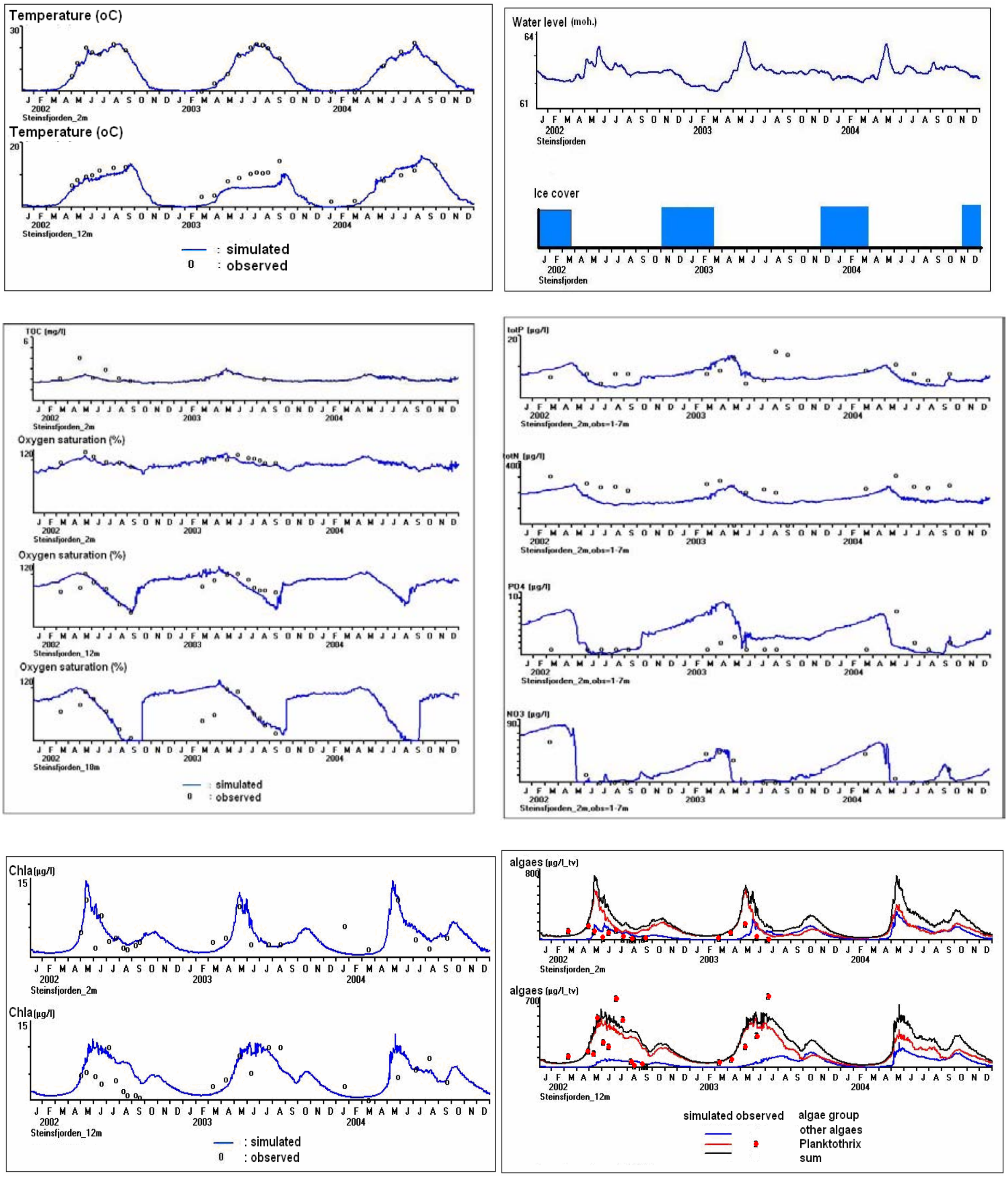


Figure 4. Lake Steinsfjorden. The simulated and observed concentrations of temperature, water level, ice cover, total organic matter, oxygen saturation, nutrients chlorophyll and algae.

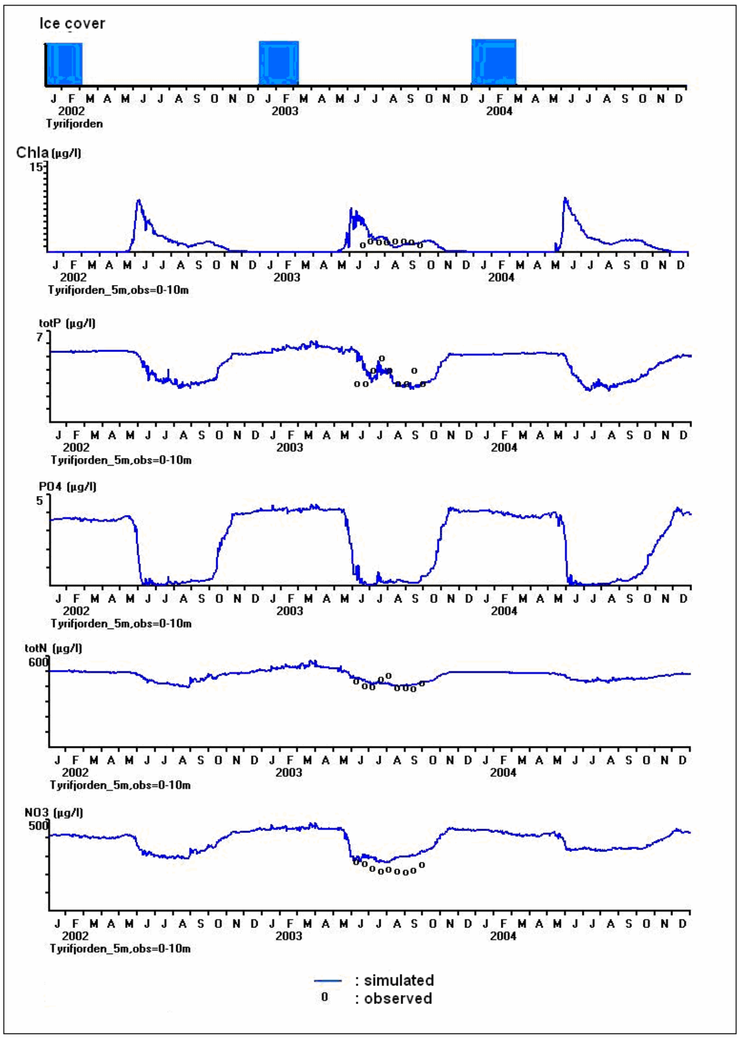


Figure 5. Lake Tyriforden. The simulated concentrations showed rather good accordance with observed values of nutrients and algae measured as chlorophyll a.

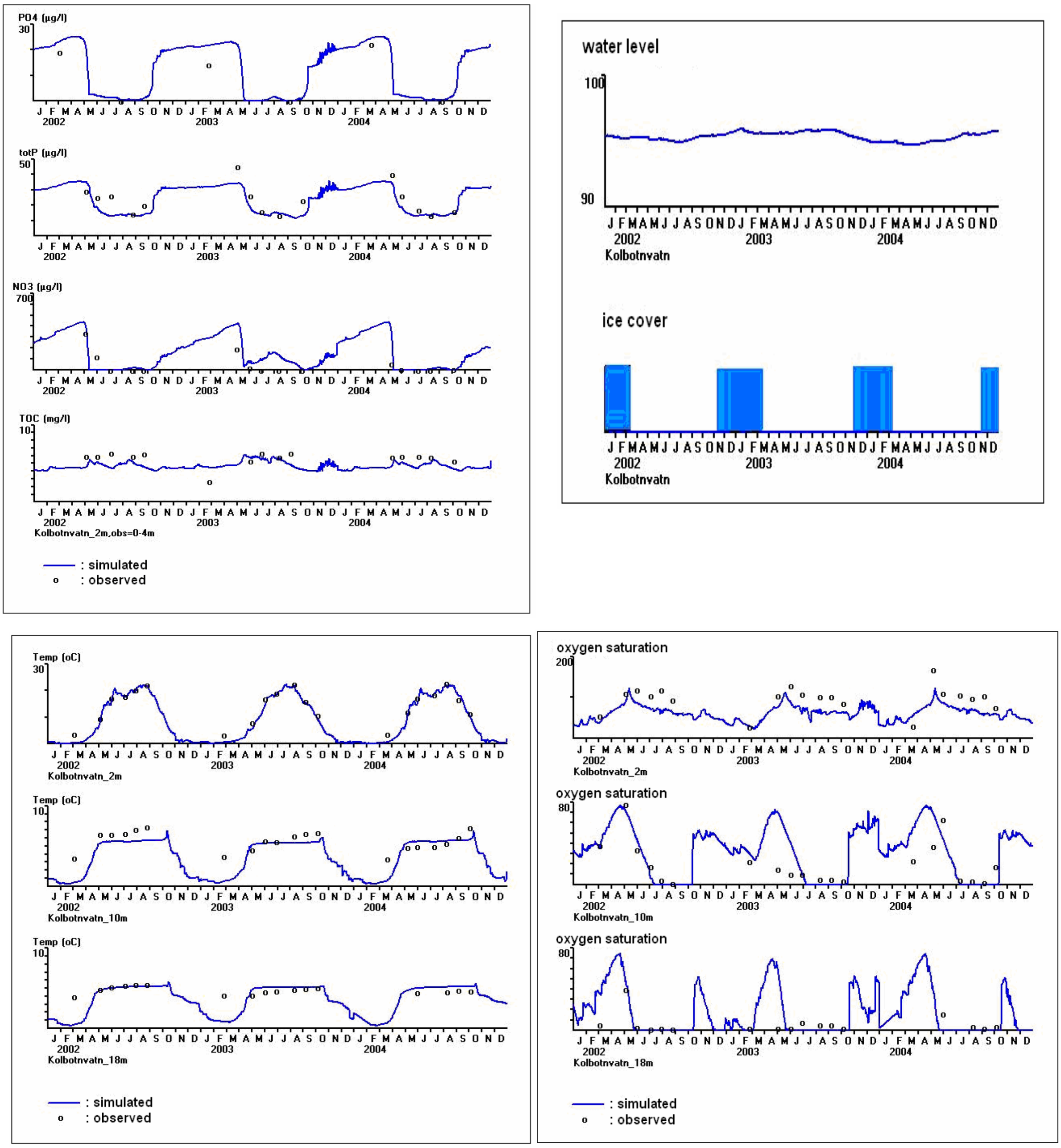


Figure 6. Lake Kolbotnvatn. Simulated values of nutrients, temperatures and oxygen showed good accordance with observations.

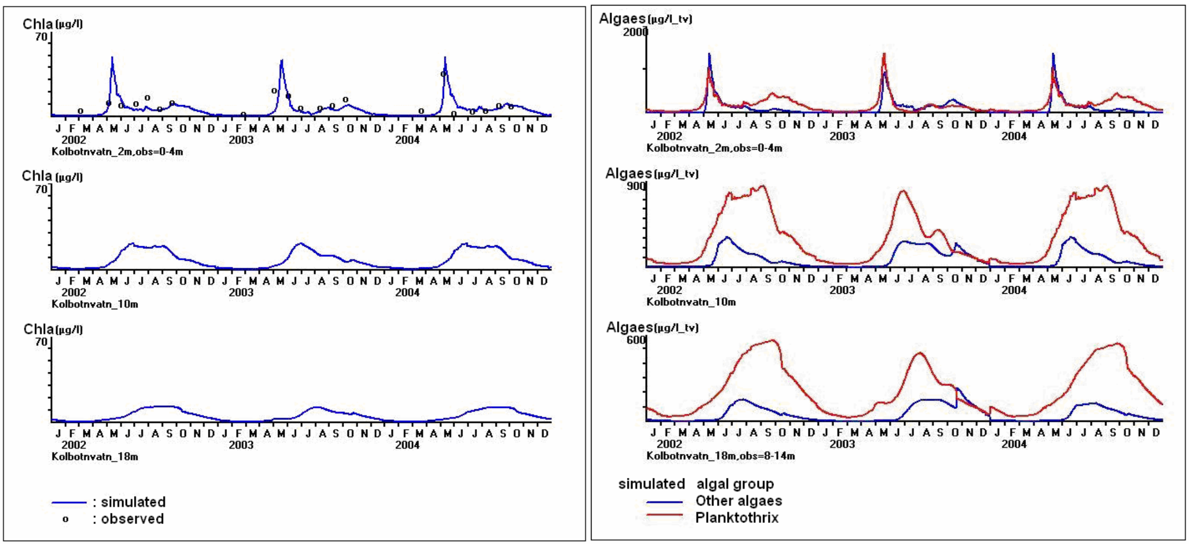


Figure 7. Lake Kolbotnvatn. Observed and simulated consentrations of algae.

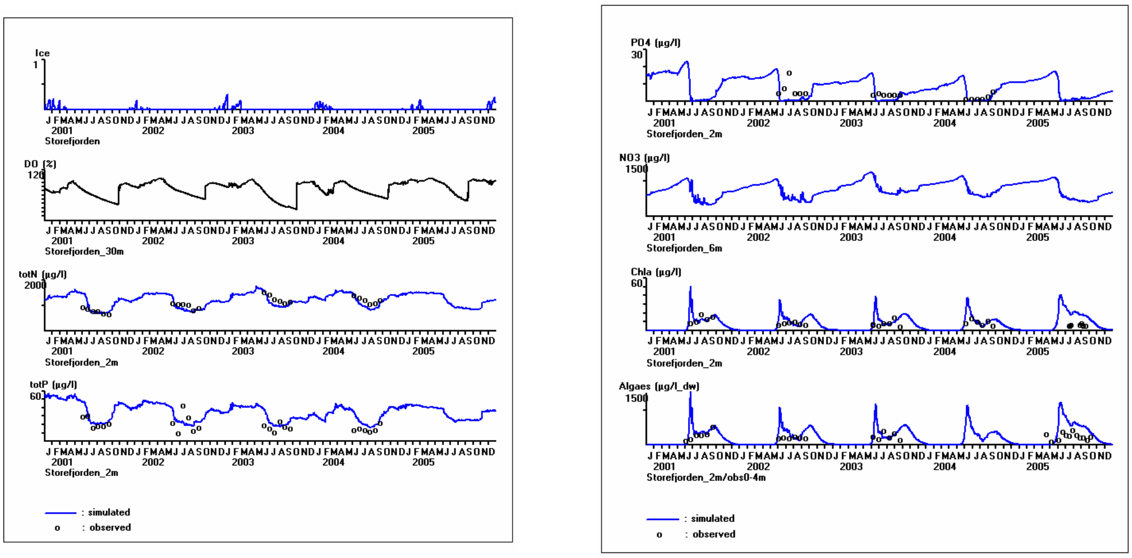


Figure 8. Lake Vansjø – Storefjorden. Observed and simulated values of ice, oxygen saturation, nutrients and algae.

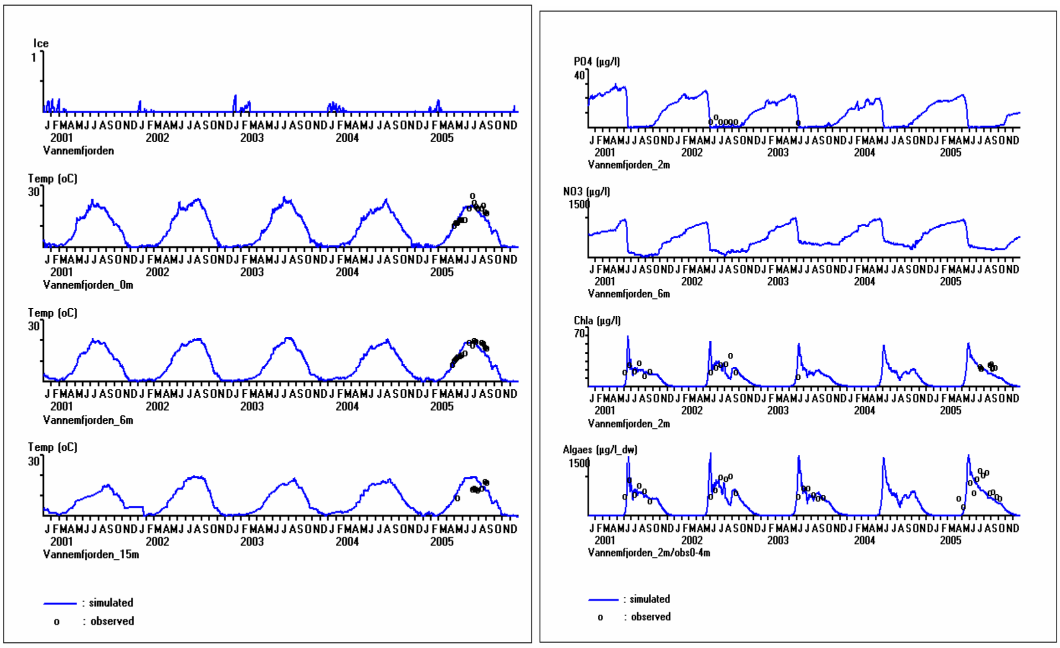


Figure 9. Lake Vansjø – Vanemfjorden. Observed and simulated values of ice, oxygen saturation, nutrients and algae.

3. Results and discussion

Daily values of climate variables from the scenarios for the 1961-1990 and 2071-2100 periods were used as input. Other inputs as inflow and outflow of water and the quality of the inflowing water were kept unchanged. For each lake such data from the calibrated period were cyclic reused to fill a 30-year period. The model was used with calibrated coefficients for each of the lakes.

3.1.1 Climate

The future climate in the scenarios became warmer than today. The annual mean air temperature increased from 5.9 ^{o}C to 9.5 ^{o}C from period 1961-1990 to 2071-2100, **Table 2**. The temperature increased throughout the year. Median diurual temperature became higher then 0 ^{o}C during the winter. The 10% coldest temperatures in the future got about the same magnitude as the median (50%) values of today, **Figure 10**.

The mean values of cloud cover and wind velocity were almost equal. During the year there were differences in the wind velocities between the two periods; however the velocities were of the same magnitude with no obvious systematic seasonal differences, **Figure 11**.

Table 2. Mean values of climate variables

Variables	Mean values 1961-1990	 2071-2100
Temperature oC	5.9	9.5
Dew point temp., oC	2.7	6.1
Cloud cover, %	69	70
Wind, m/s	3.2	3.2

3.1.2 Temperature and ice

The annual mean temperatures in the layer 0-10 meter in the lakes increased from about 7^{o}C with about 2^{o}C from the 1961-1990 period to the 2071-2100 period. The temperature increase on the surface was close to 2.5 ^{o}C. The effect was reduced downwards in the water column. In the levels around 15 meters the increases were below 1^{o}C. In Tyrifjorden an increase of 0.1^{o}C was found on both 100 meter and 250 meter, **Table 3** and **Table 4**.

In the today scenarios the lakes were covered by ice from 44 to 88 days in a mean year. In the future scenarios all of the lakes were without ice cover throughout winter. We can expect ice cover only in cold winters. For cold winters (10 percentile), days with ice cover for the lakes were reduced from between 99 to 146 days in the today scenarios to between 68 to 107 days in the future scenarios.

The future temperatures were higher then the today temperatures during the year, **Figure 12**-**Figure 16**. On the surface the median temperatures of the future scenarios were very much the same as the 90% highest temperatures of the today scenarios from January to August, and the rest of the year these median temperatures were higher. The future lowest temperatures (10%) were about the same as the median temperatures of today from January to August. The rest of the year these future low temperatures were higher then the 90% highest of the today temperatures.

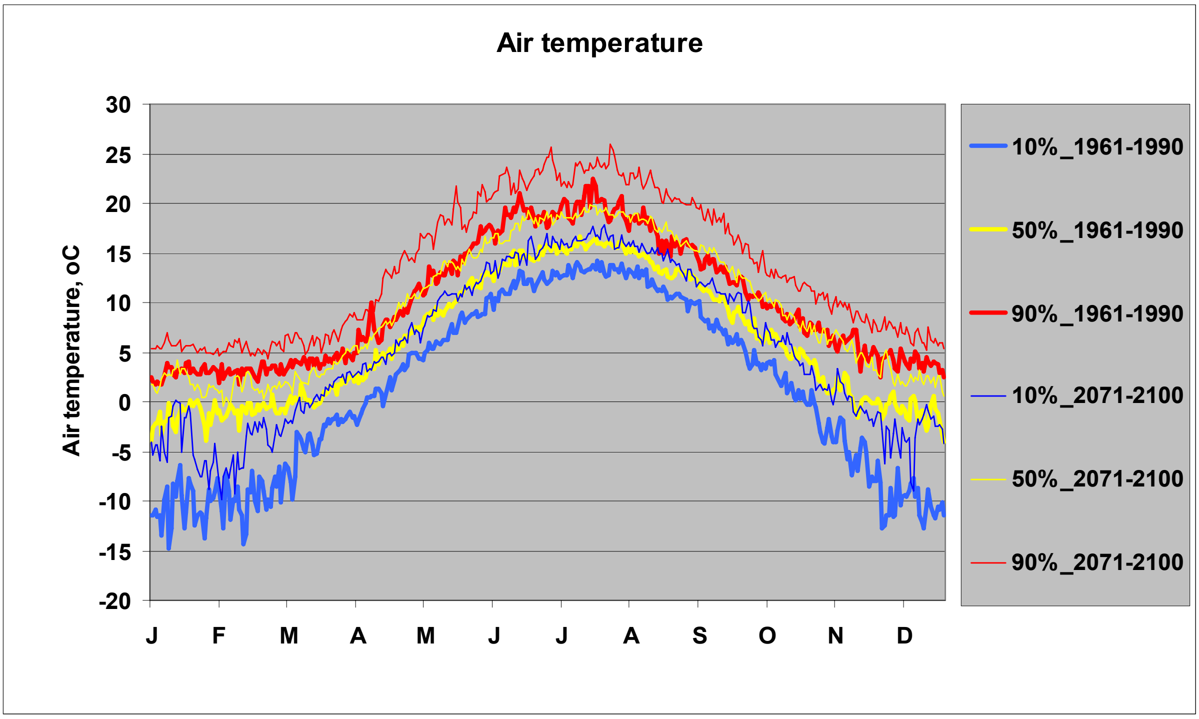


Figure 10. Percentiles of air temperatures. The temperature increased from 1971-1990 to 2071-2100. Future median daily temperature became over 0 ^{o}C during the winter.

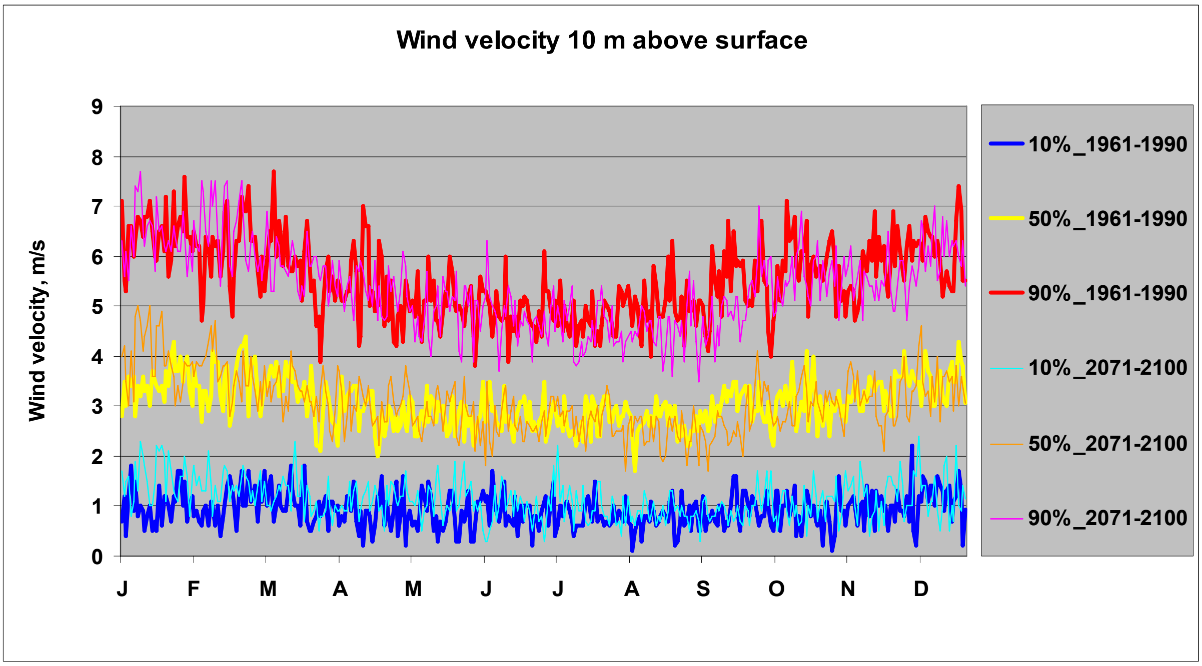


Figure 11. Percentiles of wind velocities. The velocities in both periods were of the same magnitude during the year.

The water has its greatest density on 4°C. This temperature is important for the circulation of the water column in the lake spring and autumn/winter. Under median condition in the future scenarios reached 4°C about two weeks earlier in the spring and one month later in the autumn. This means that the circulation period in the spring will start earlier and the circulation period in the autumn will start later. The duration of the summer condition, with a warmer and more stable top layer between these circulations periods, will increase. Future ice free condition reduced the stable conditions during the winter with following increased duration of the circulation period through the winter. Periodic warmer surface temperatures beetween 0 - 4 °C increase the density with resulting circulation. This may sometime lead to colder water than today on greater depths as shown for Kolbotnvatn and Vansjø-Vanemfjorden on depth 15m, and Tyrifjorden at 100 m in the late winter.

3.1.3 Oxygen

In the surface layers (0-10 m) the annual mean oxygen saturation of the today scenarios were between 56% and 95%. In the bottom layer the oxygen saturation of Kolbotnvatn was 12%, for the other lakes over 50%. Climate changes had minor influence on these mean values, **Table 3** and **Table 4**.

The differences became greater when we studied the changes through the year, **Figure 17**-**Figure 19**. In the today scenario for a median year in bottom layer of Kolbotnvatn the oxygen saturations were zero during the summer from the middle of May to the middle of October and in the winter from late December to the middle of March. In the future scenario the deficit period during the summer was extended by about two weeks in the spring and one month in the autumn. During the winter the saturation values became positive. For ten percent of the years (10%) the period with summer deficit increased with over a month and the winter condition still showed saturation values equal to zero. Oxygen problems to some extent also existed in Steinsfjorden and Vansjø-Storefjorden. The same phenomena clearly took place also there. For the other lakes no oxygen problems existed.

The future scenarios lead to reduced oxygen saturation during the summer and increased values during the winter. The reason relates to the temperature conditions and the following changes of circulation periods. Warmer and normally ice free winters in the future scenarios lead to earlier increase of the temperature in the spring with resulting warm epilimnion and stable water column. Further the warmer future climate lead to later cooling and later start of the autumn circulation in the lakes. Degradation of algae and other organic material reduced the oxygen in the water body. Longer stable summer conditions combined with prolonged algal growth lead to future lower oxygen values during the summer. When the circulation starts in the autumn, the water column become mixed and the bottom layer gets oxygen from layer above. In the figures this is shown by a rapid increase of oxygen during a few days. The future climate lead to increased duration of the circulating period, which lead to better oxygen conditions during the autumn and winter. In some cases the circulations continued until the rise of temperature in the spring as in Kolbotnvatn, look at **Figure 17** (90 percentil).

The changes in the vertical circulation of the lakes also will influence other water quality constituents. A water work intake near bottom will in the future be better protected from pollution entered on the surface of the lake during the prolonged summer stagnation period The prolonged circulation period during the winter, especially due to increased period with ice free condition, will have the opposite effect and lead to increased influence of pollution discharges on the surface.

Table 3. Mean values 0-10 meter below surface

		Steinsfjorden		Tyrifjorden		Kolbotnvatn		Vansjø_Storefjorden		Vansjø_Vanemfjorden	
Variable	Unit	1961-1990	2071-2100	1961-1990	2071-2100	1961-1990	2071-2100	1961-1990	2071-2100	1961-1990	2071-2100
Temperature	oC	6.8	9.0	6.8	9.0	5.6	7.2	6.8	8.6	7.1	9.0
Chlorophyll a	µg/l	3.0	3.2	1.0	1.0	7.0	7.6	6.7	11.4	11.0	14.5
Sum algae	µg dw/l	150	160	51	50	349	378	499	855	824	1091
Cyanobacteria	µg dw/l	97	149	7	14	167	302	2	790	6	1012
Othe algaes	µg dw/l	53	11	44	36	183	77	497	65	818	79
Oxygen saturation	%	92	92	87	88	56	56	88	87	95	95
TOC	mg/l	2	2	1	1	5	5	2	2	2	2
totP	µg/l	5	6	4	4	41	41	37	43	43	51
totN	µg/l	5167	4290	7813	7859	536	493	1335	1225	1019	906
PO4	µg/l	2	3	2	2	28	28	14	19	20	28
NO3	µg/l	5039	4175	7730	7776	235	206	881	719	548	407

Table 4. Mean values depths of ice cover, temperature and oxygen saturation

Lake	Maximum depth m	Depth m	Ice cover		Temperature		Oxygen saturation	
			1961-1990 days/year	2071-2100 days/year	1961-1990 oC	2071-2100 oC	1961-1990 %	2071-2100 %
Steinsfjorden	20	0	86	0	7.5	10.0	94	94
		12			4.6	5.7	86	84
		18			3.8	4.7	77	70
Tyrifjorden	270	0	46	0	7.4	9.8	88	90
		100			3.8	3.9	72	77
		250			3.9	4.0	70	76
Kolbotnvatn	19	0	88	0	8.0	10.4	73	75
		6			4.4	5.8	50	50
		16			3.8	3.9	12	17
Vansjø_Storefjorden	36	0	44	0	8.1	10.6	93	96
		15			4.1	4.9	77	73
		35			4.7	5.0	67	68
Vansjø_Vanemfjorden	17	0	56	0	8.0	10.4	100	103
		15			4.8	5.2	79	73

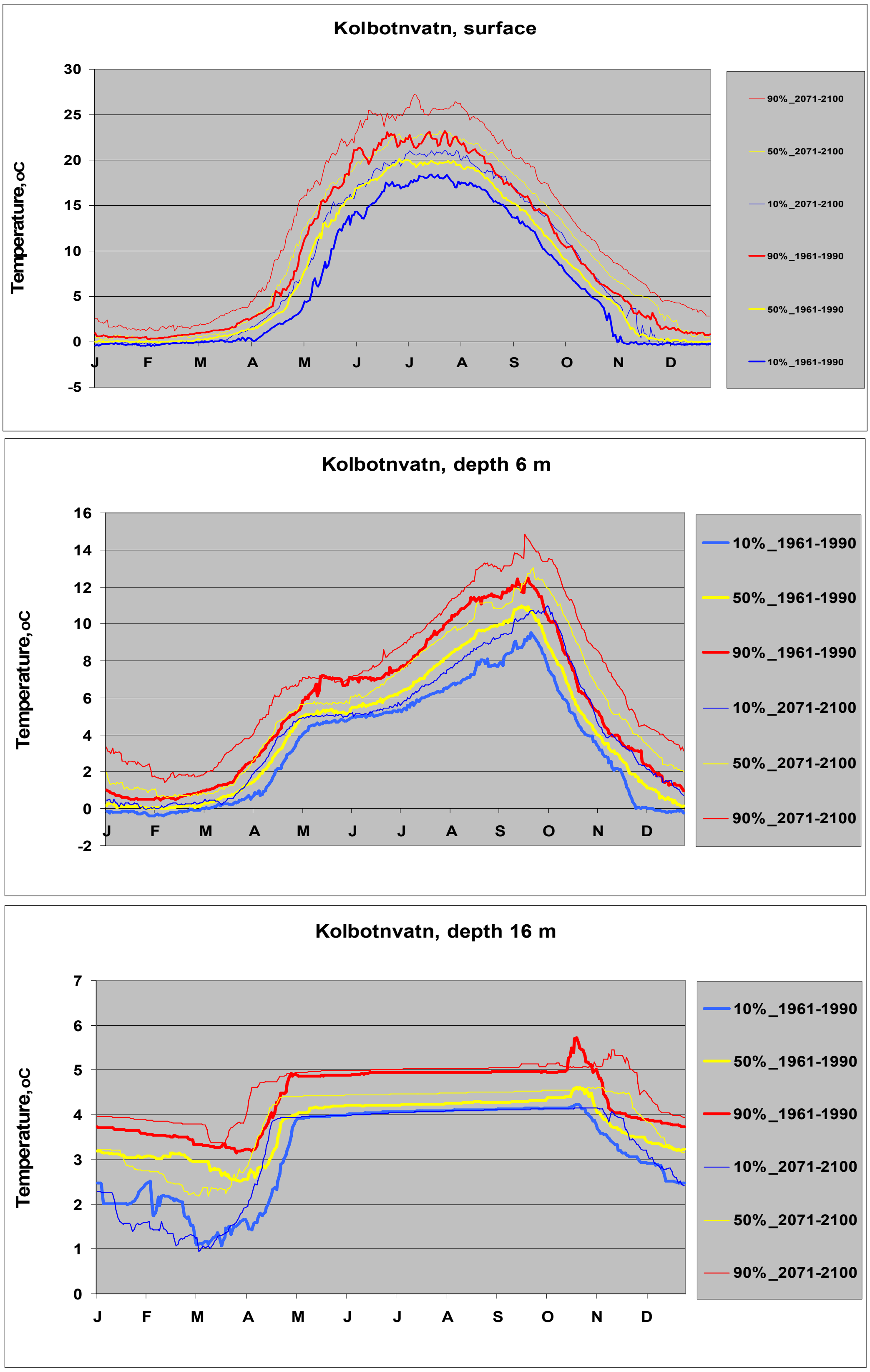


Figure 12. Lake Kolbotnvatn. Percentiles of temperatures at 0, 6 and 16 meter below surface.

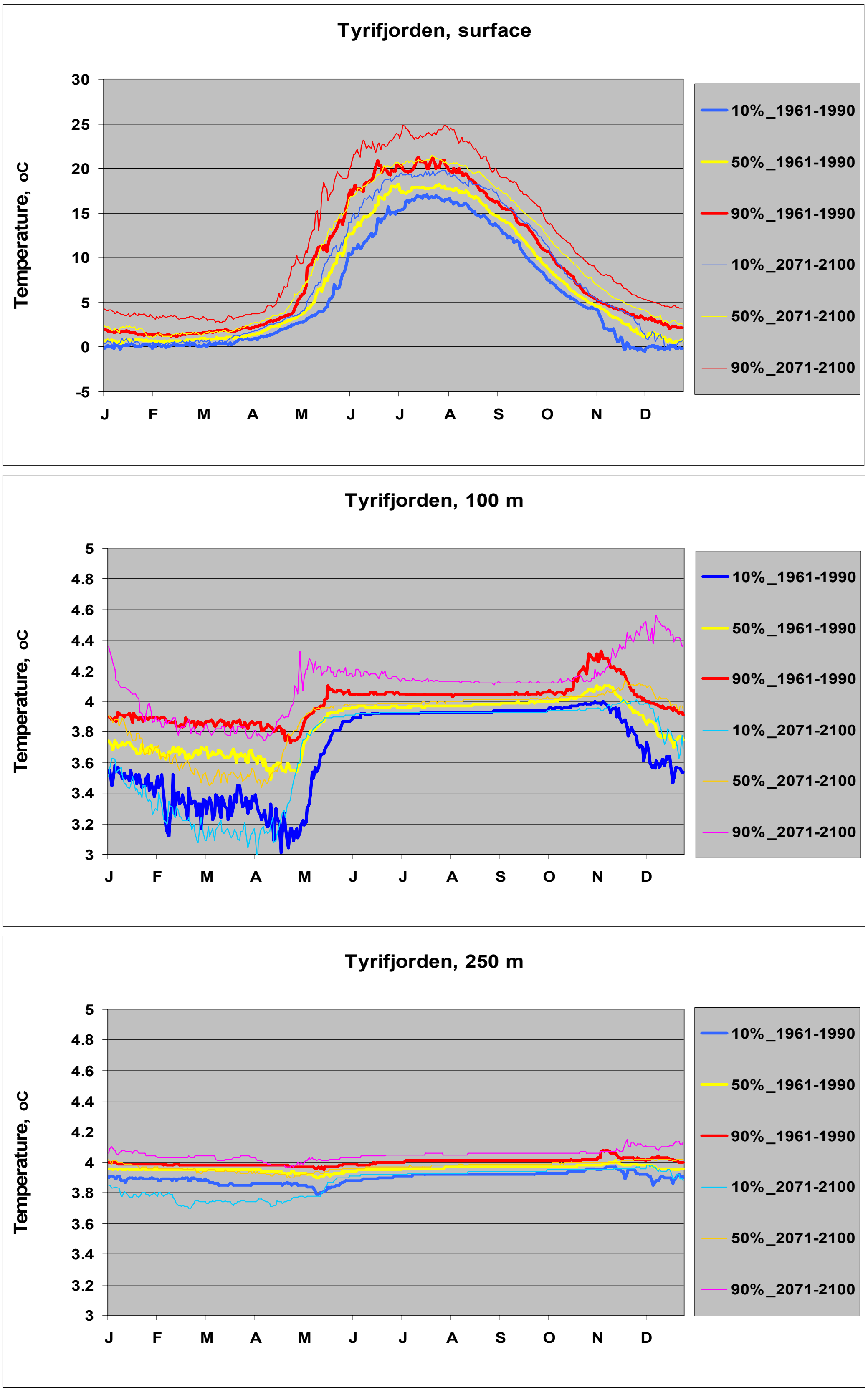


Figure 13. Lake Tyrifjorden. Percentiles of temperatures at 0, 100 and 250 m below surface.

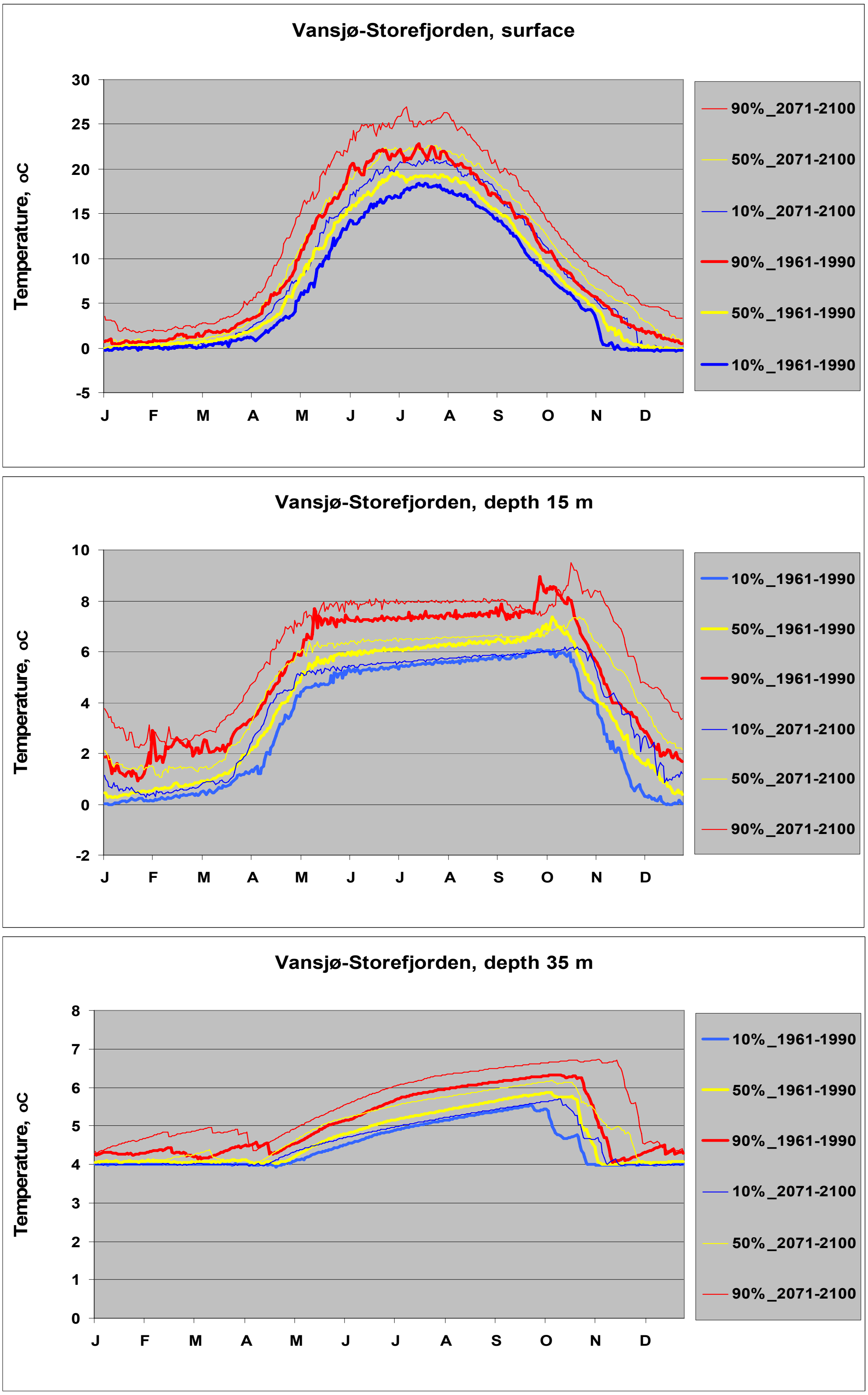


Figure 14. Lake Vansjø_Storefjorden. Percentiles of temperatures at 0, 15 and 35 meter below surface.

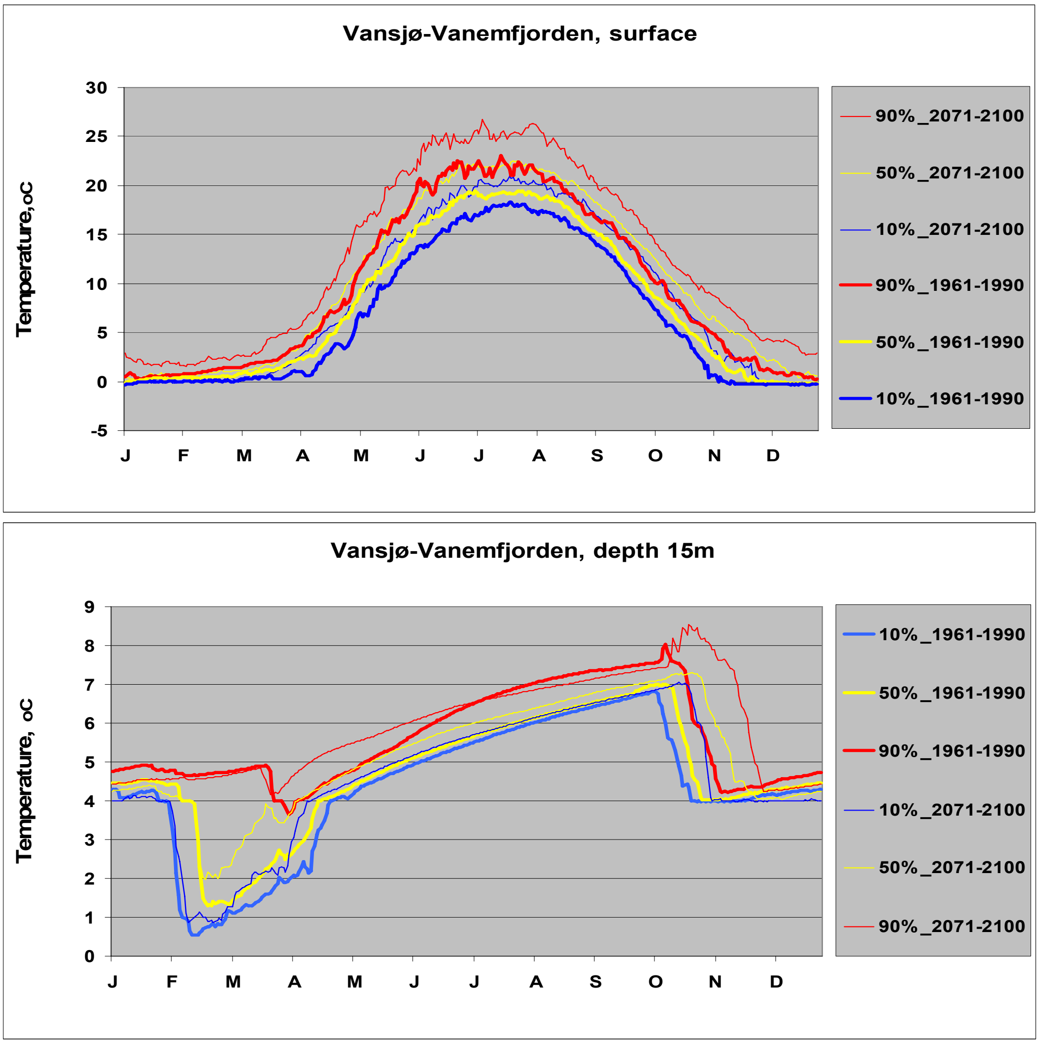


Figure 15. Lake Vansjø-Vanemfjorden. Percentiles of temperature at 0 and 15 meter below surface.

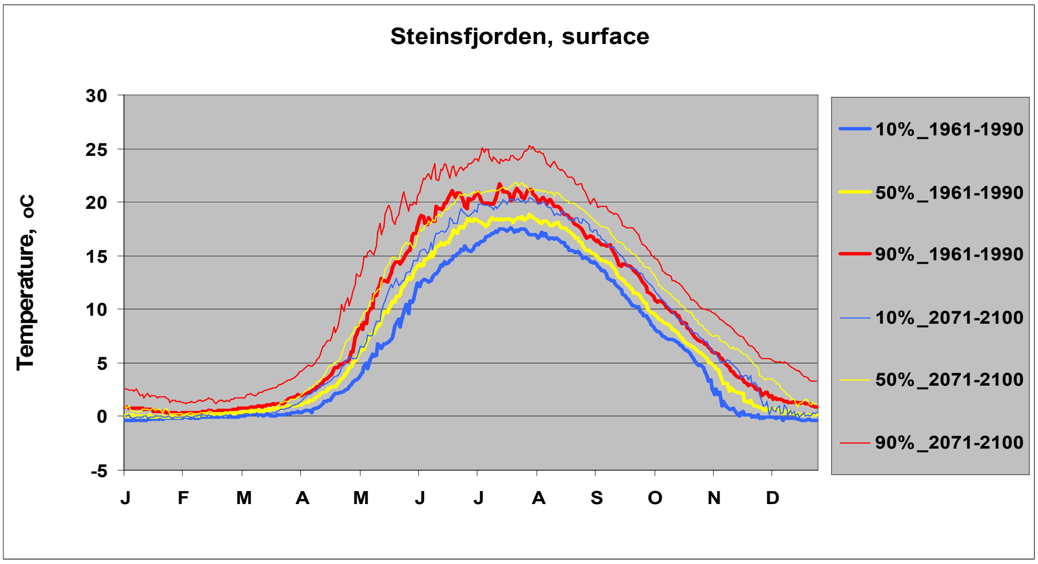


Figure 16. Lake Steinsfjorden. Percentils of surface temperature.

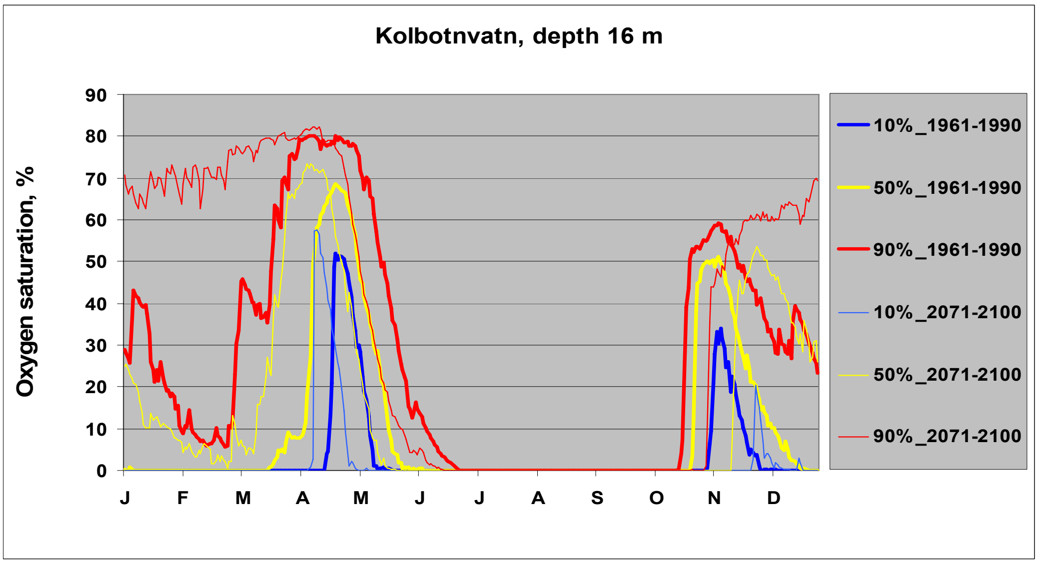


Figure 17. Lake Kolbotnvatn. Percentiles of oxygen near bottom

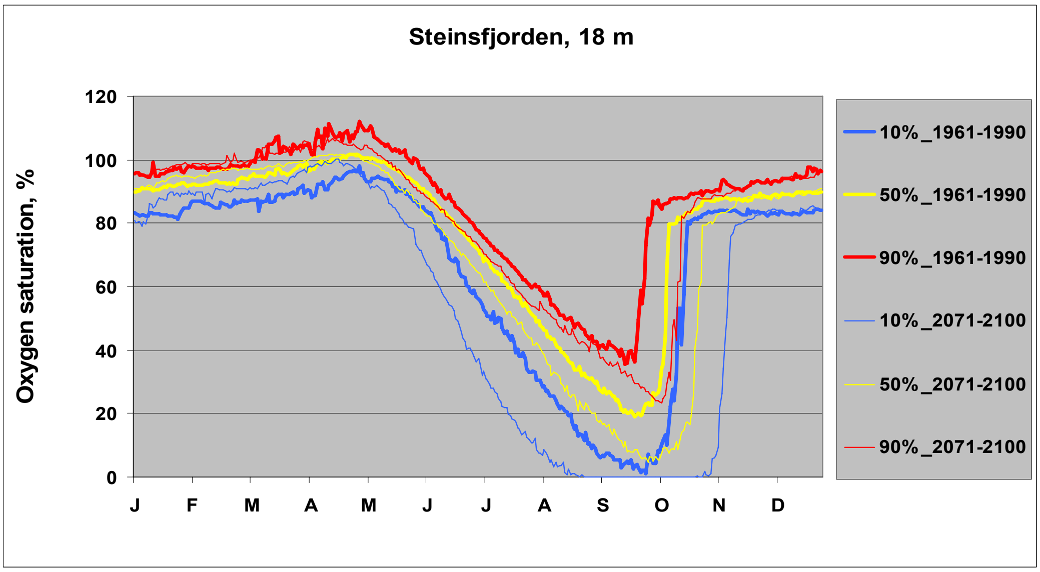


Figure 18. Lake Steinsfjorden. Percentiles of oxygen near bottom

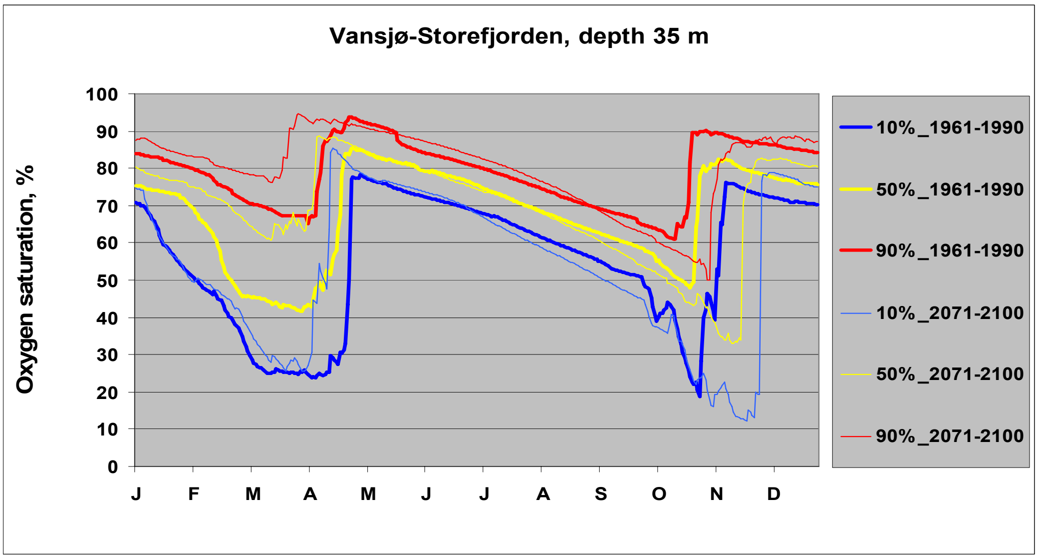


Figure 19. Lake Vansjø-Storefjorden. Percentiles of oxygen saturation near bottom.

3.1.4 Algae

The mean differences during the year of the nutrients were small, **Table 4** and **Table 5**. The loadings to the lakes were equal in both the today and future scenarios. The differences represented changes in lake processes that concern algal growth and to some extent also leaquage from sediments in periods with oxygen deficit. For Lake Steinsfjorden and Lake Tyrifjorden nitrogen were kept out of the result table. This was because of unrealistic high values. The phosphorus were limiting nutrient for algal growth. Therefore this error did not affect the result of the algal concentration in a noticeable way.

The effect of climate change on the total amount of phytoplankton, its composition and the mean concentration of chlorophyll-a, another measure of phytoplankton density, is shown in **Table 6 and Figures 19-28.** The predicted changes in water circulation patterns, water temperature, and oxygen saturation will not affect the total amount of phytoplankton biomass to be expected in the future Steinsfjorden, Tyrifjorden and Kolbotnvatn. Obviously, these lakes are nutrient limited and the available nutrient resources are efficiently used to produce biomass already under present conditions. Climate change effects on lake internal processes have therefore limited consequences for the phytoplankton community as a whole as long as nutrient loading remains constant. The results for Lake Vansjø emphasise this conclusion by predicting an increase in phosphate concentration and consequently total algal biomass.

The simulations demonstrate a change in start and length of growth season for the phytoplankton. Phytoplankton growth in spring will start 1-2 weeks earlier as compared with present conditions. The maximum density will also be reached earlier. In addition, the growth season may be prolonged. These effects can be explained with the consequences of climate change for water temperature and mixing patterns.

According to model predictions, cyanobacteria will benefit from climate change. This may be due to a combination of factors. An earlier onset of growth in spring and a prolonged growth phase in autumn favours cyanobacteria such as *Planktothrix* spp. that are adapted to low light conditions. A longer summer stagnation with higher water temperatures at the surface favours cyanobacteria that are adapted to such conditions including *Microcystis* and *Anabaena* species occurring in Lake Vansjø. A climate change induced shift in phytoplankton composition towards potentially toxic cyanobacteria may have serious consequences for recreation and drinking water production. Already today, Lake

Kolbotnvatn and Lake Vansjø are affected by the occurrence of toxic cyanobacterial blooms. This problem is likely to increase in the future. To day efforts are done to prevent algal bloom. Climate change may antagonize mitigation measures.

Table 5. Mean values depths of nutrients

Lake	Depth	PO4		NO3		totN		totP	
	m	1961-1990 µg/l	2071-2100 µg/l	1961-1990 µg/l	2071-2100 µg/l	1961-1990 µg/l	2071-2100 µg/l	1961-1990 µg/l	2071-2100 µg/l
Steinsfjorden	0	2	3					5	5
	12	3	3					6	7
	18	5	7					8	10
Tyrifjorden	0	2	2					4	4
	100	4	4					5	5
	250	4	4					5	5
Kolbotnvatn	0	23	23	160	143	452	417	35	35
	6	29	27	263	213	573	510	42	40
	16	46	50	282	251	586	553	58	62
Vansjø_Storefjorden	0	10	13	803	560	1247	1045	33	36
	15	23	29	1089	1060	1532	1526	45	52
	35	26	31	1140	1099	1609	1566	51	55
Vansjø_Vanemfjorden	0	16	23	463	277	934	758	39	46
	15	42	51	999	996	1446	1480	62	71

Table 6. Mean values depths of algae

Lake	Depth	Cyanobacteria		Other algae		Sum algae		Chlorophyll a	
	m	1961-1990 µg dw/l	2071-2100 µg dw/l	1961-1990 µg dw/l	2071-2100 µg dw/l	1961-1990 µg dw/l	2071-2100 µg dw/l	1961-1990 µg/l	2071-2100 µg/l
Steinsfjorden	0	78	121	52	11	129	132	2.6	2.6
	12	145	211	45	9	190	220	3.8	4.4
	18	118	169	32	6	150	175	3.0	3.5
Tyrifjorden	0	5	10	40	32	45	43	0.9	0.9
	100	1	2	1	1	3	2	0.1	0.0
	250	1	1	1	0	2	1	0.0	0.0
Kolbotnvatn	0	71	154	183	75	254	228	5.1	4.6
	6	246	423	195	84	440	507	8.8	10.1
	16	152	256	95	39	247	295	4.9	5.9
Vansjø_Storefjorden	0	2	750	507	71	508	821	6.8	10.9
	15	2	439	282	28	283	467	3.8	6.2
	35	1	198	125	9	125	207	1.7	2.8
Vansjø_Vanemfjorden	0	6	969	858	85	864	1055	11.5	14.1
	15	3	625	466	42	469	667	6.3	8.9

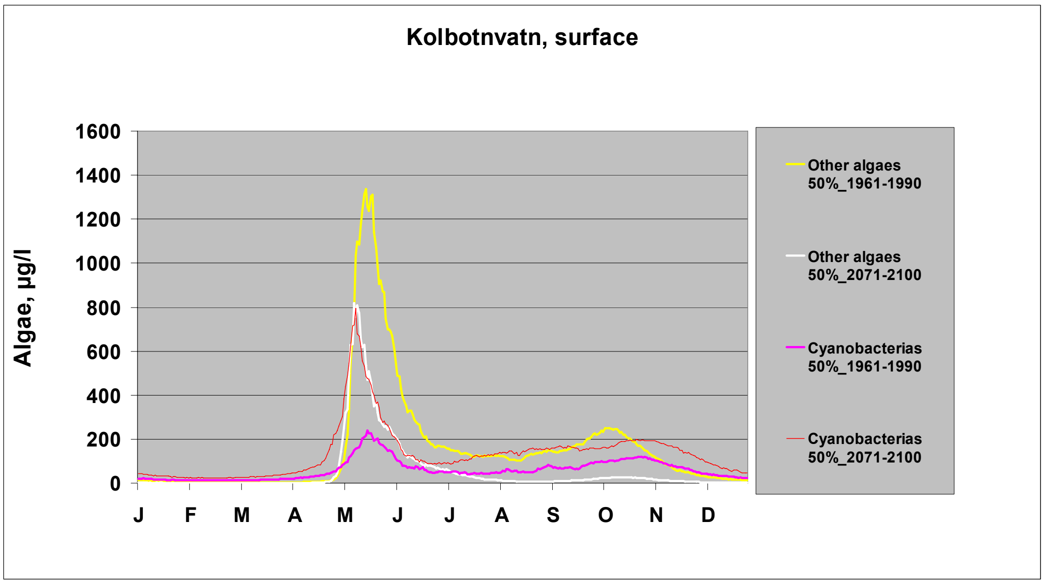


Figure 20. Lake Kolbotnvatn. Median algae concentration in the surface layer.

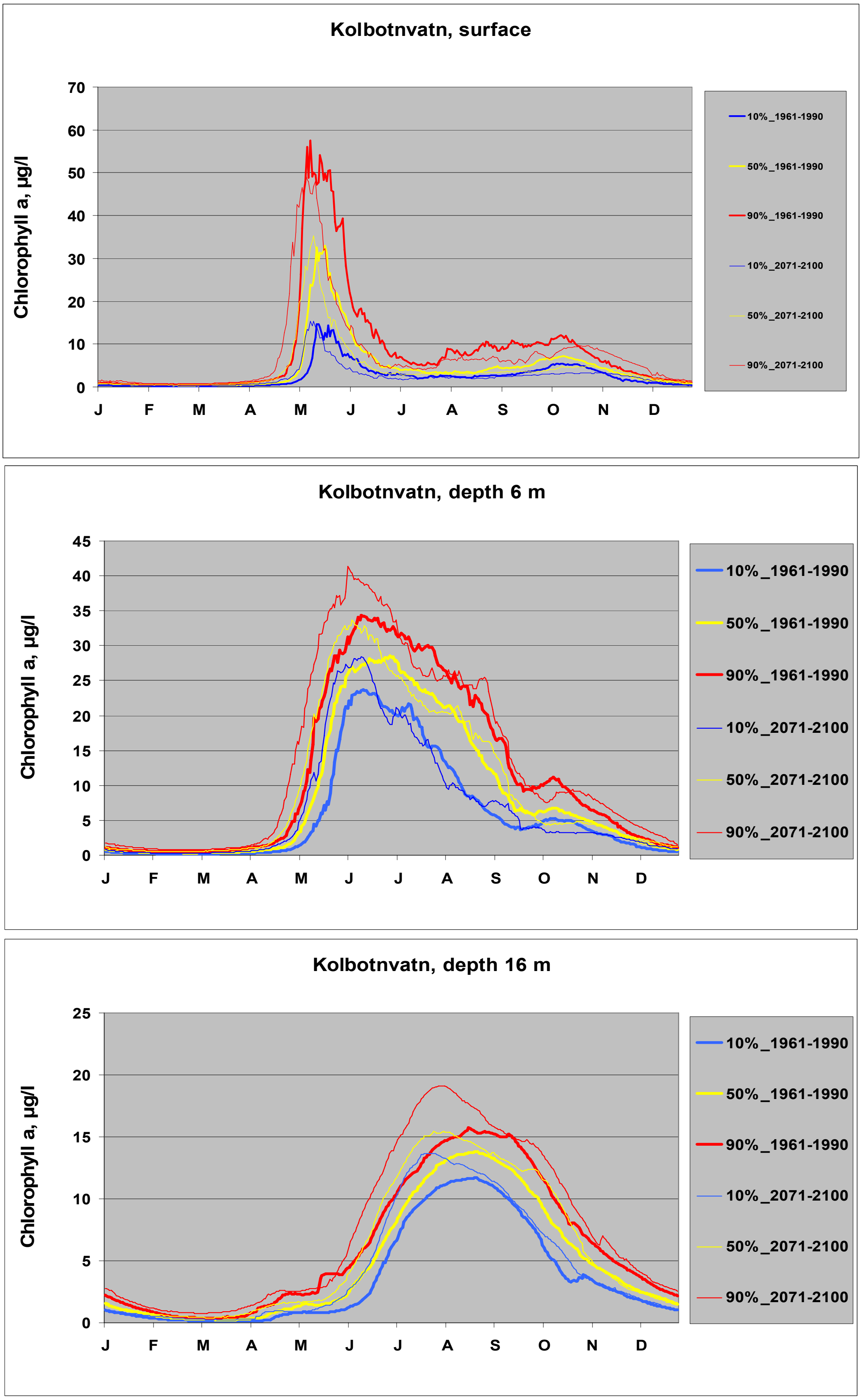
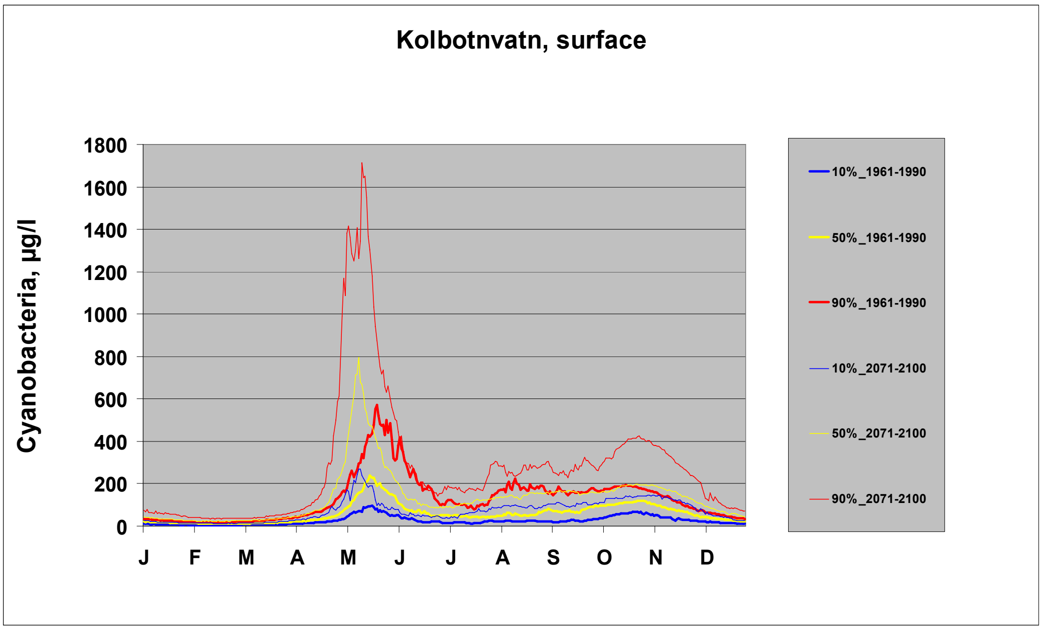


Figure 21. Lake Kolbotnvatn. Percentiles of algae measured as chlorophyll at 0, 6 and 16 m below surface.



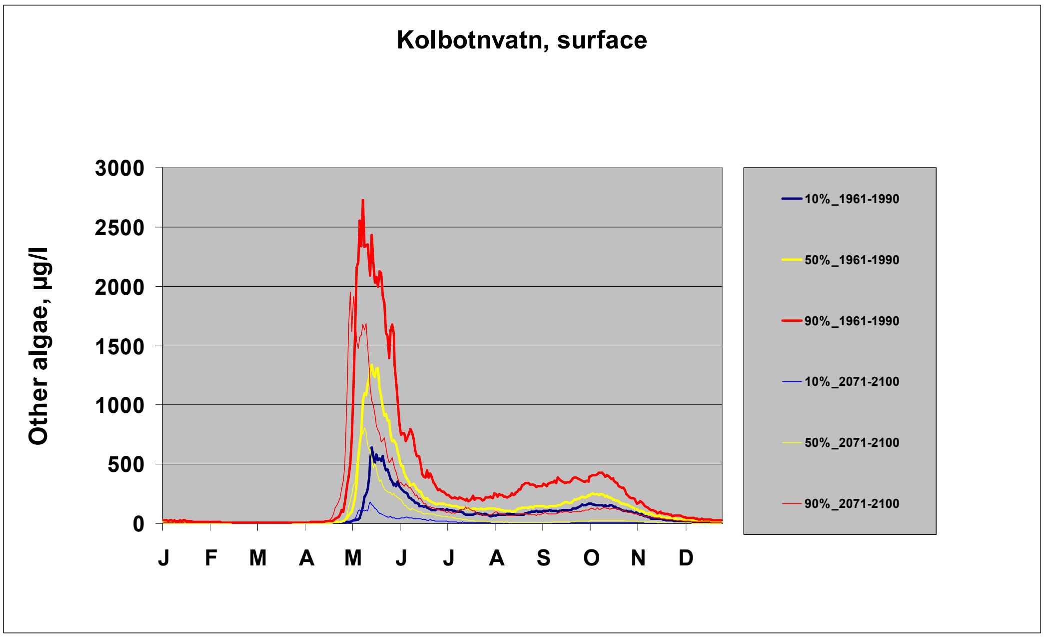
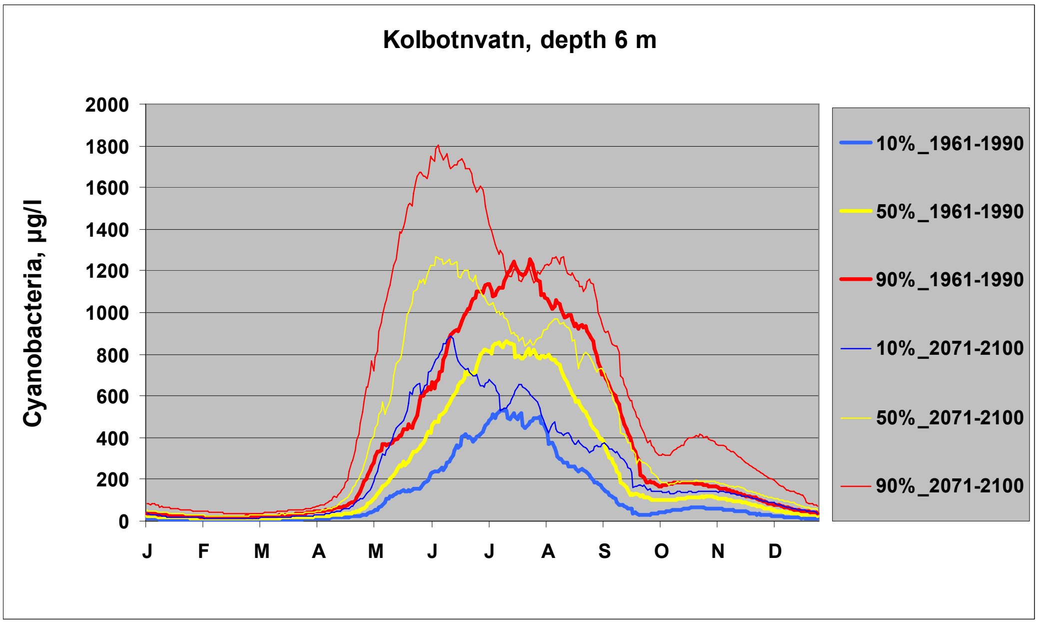


Figure 22. Lake Kolbotnvatn. Percentiles of algae in the surface layer



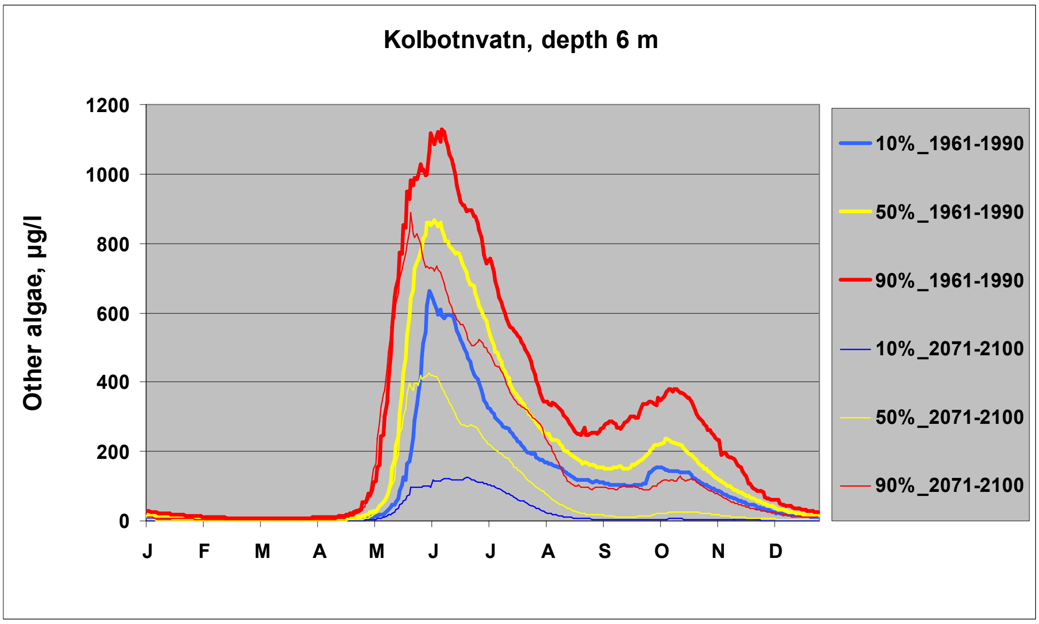


Figure 23. Lake Kolbotnvatn. Percentiles of algae 6 meter below surface.

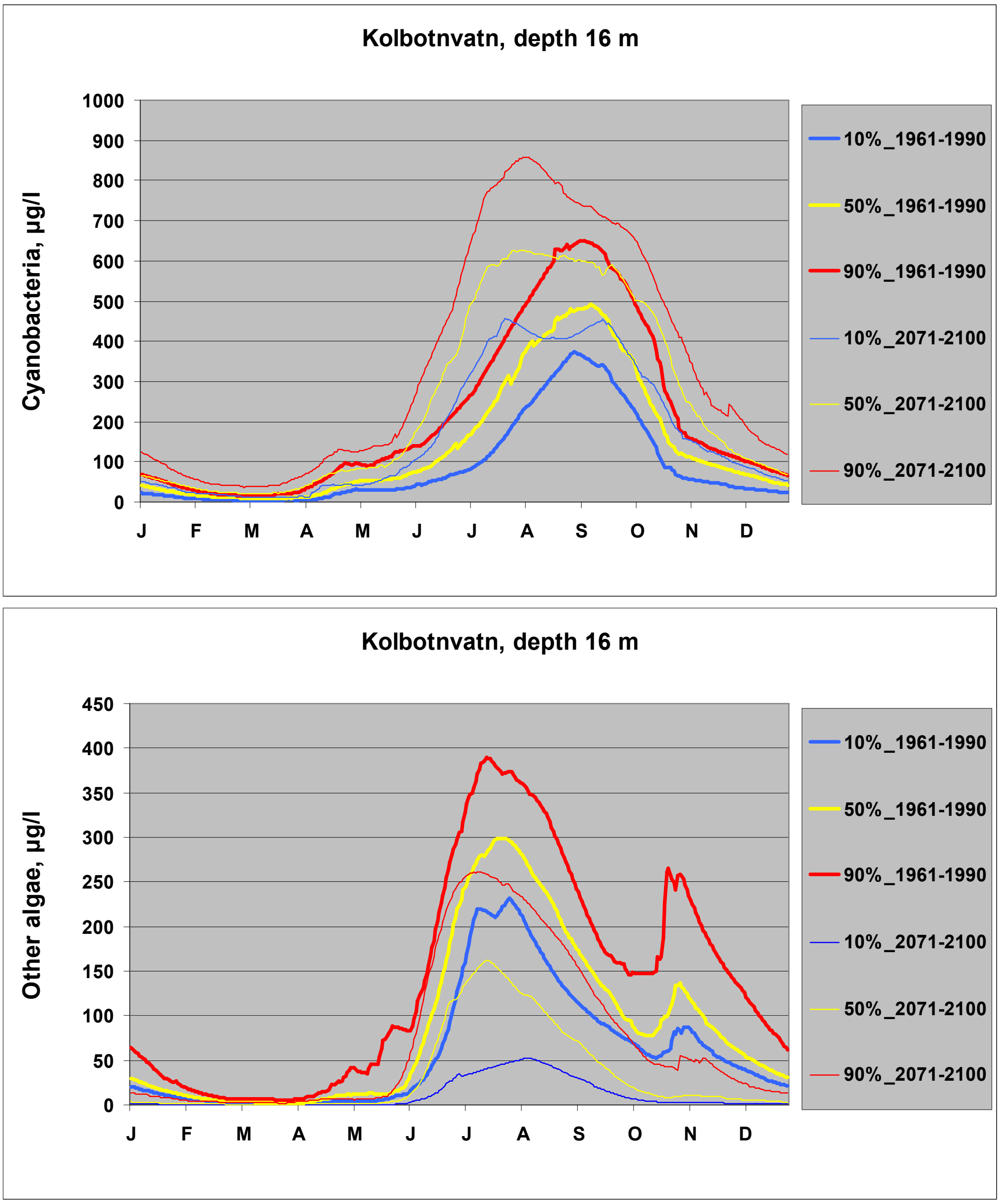


Figure 24. Lake Kolbotnvatn. Percentiles of algae 16 meter below surface.

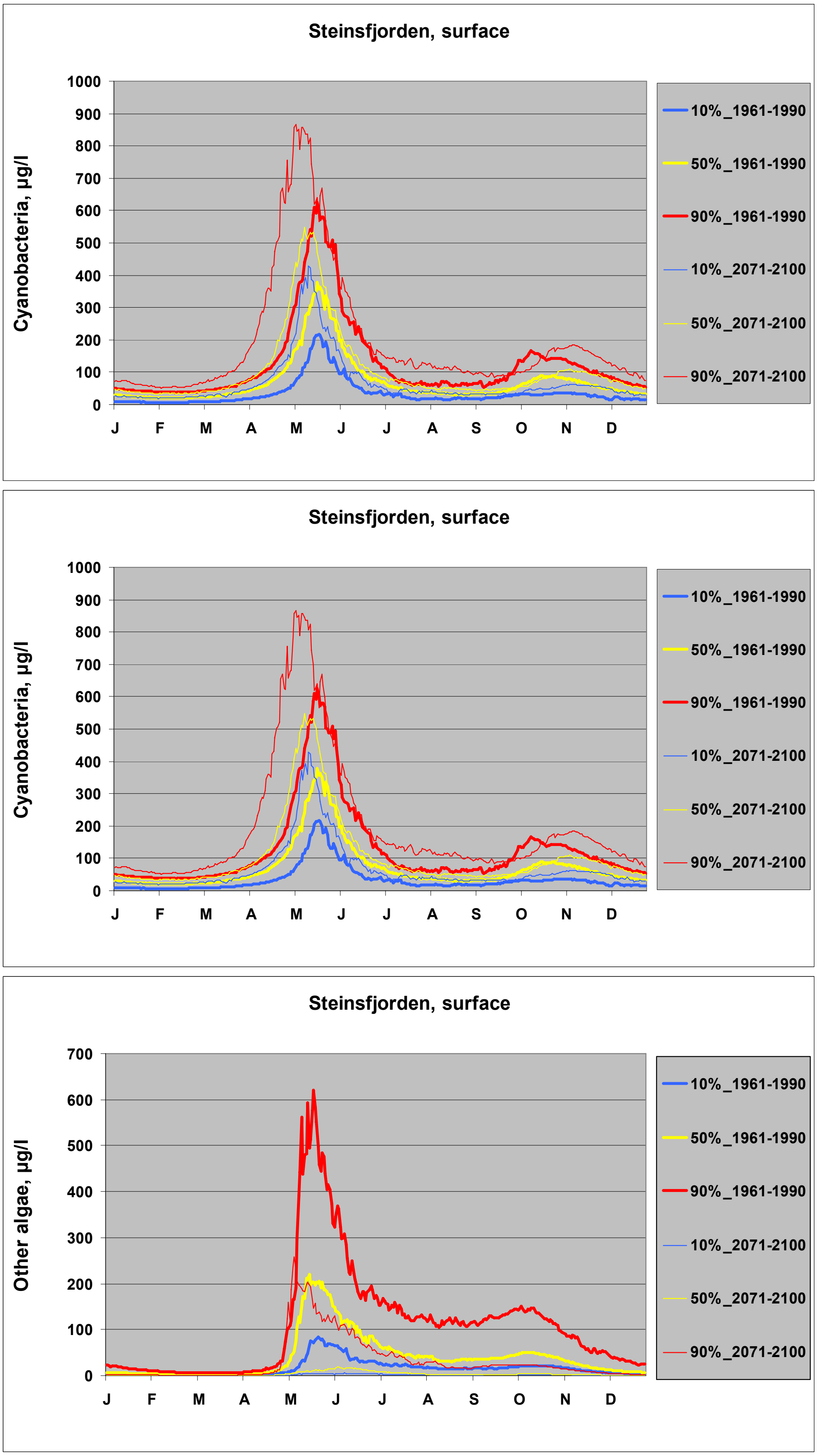


Figure 25. Lake Steinsfjorden. Percentiles of algae in surface layer.

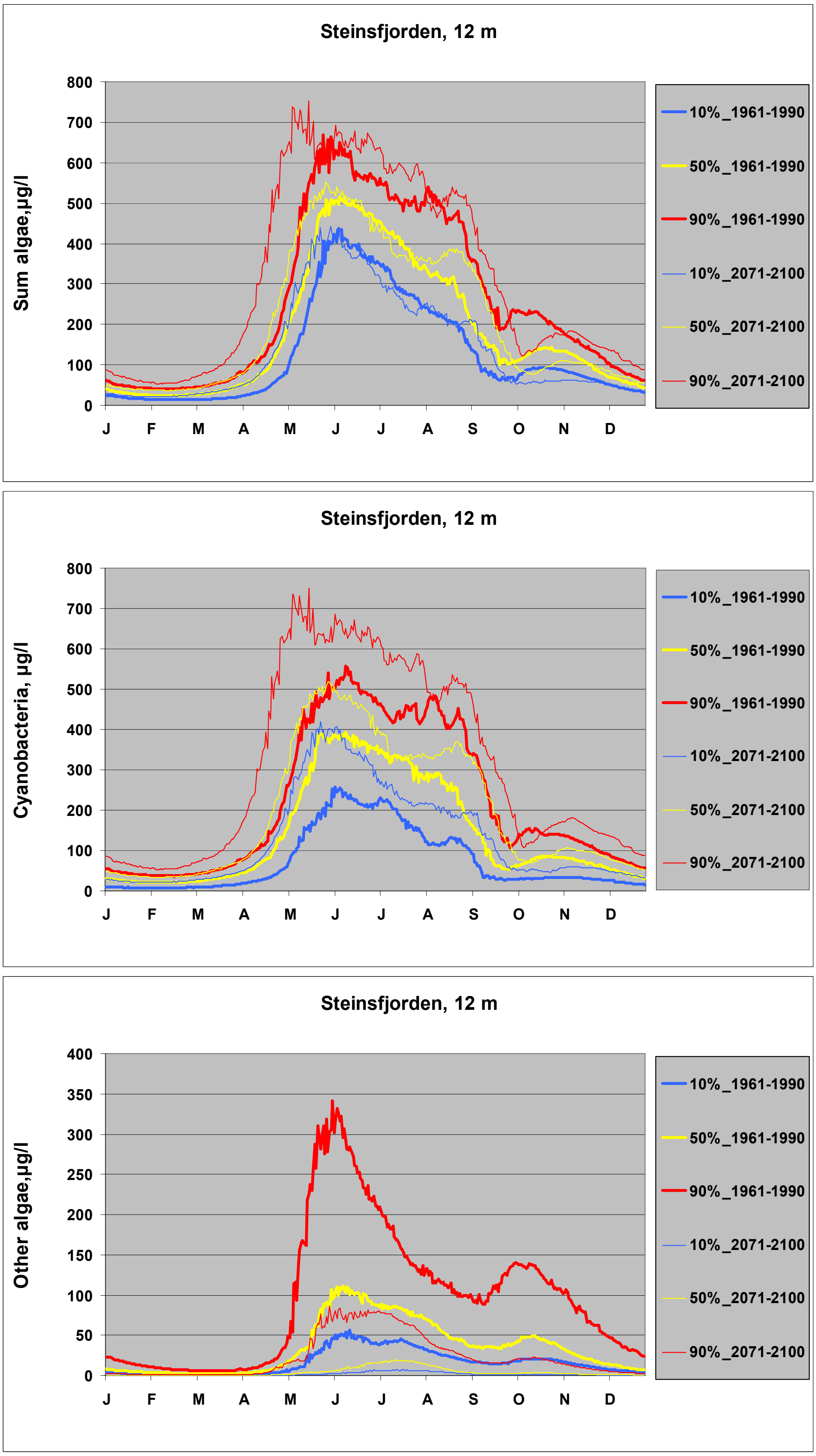


Figure 26. Lake Steinsfjorden. Percentiles of algae 12 m below surface.

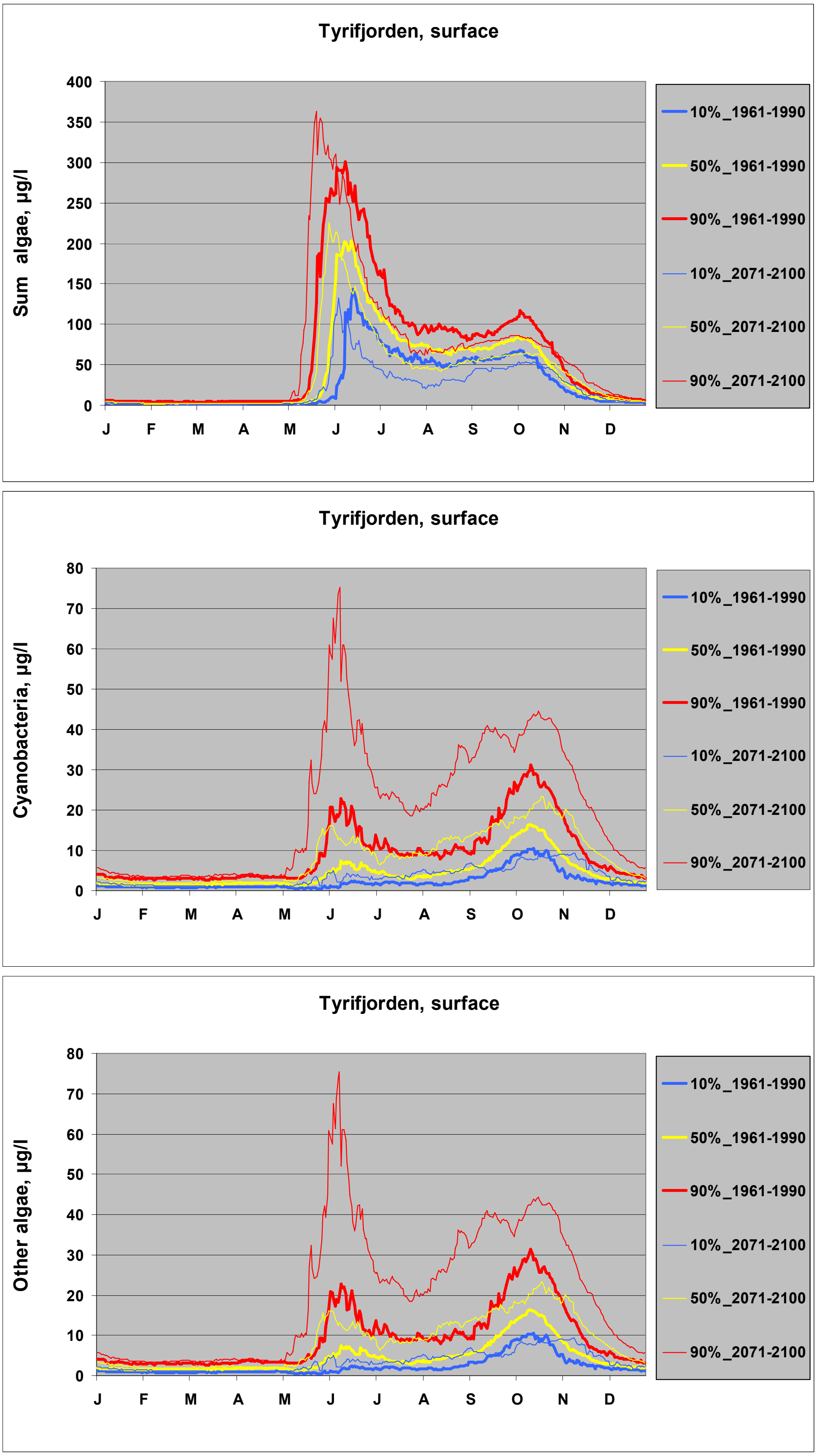


Figure 27. Lake Tyrifjorden. Percentiles of algae in surface layer.

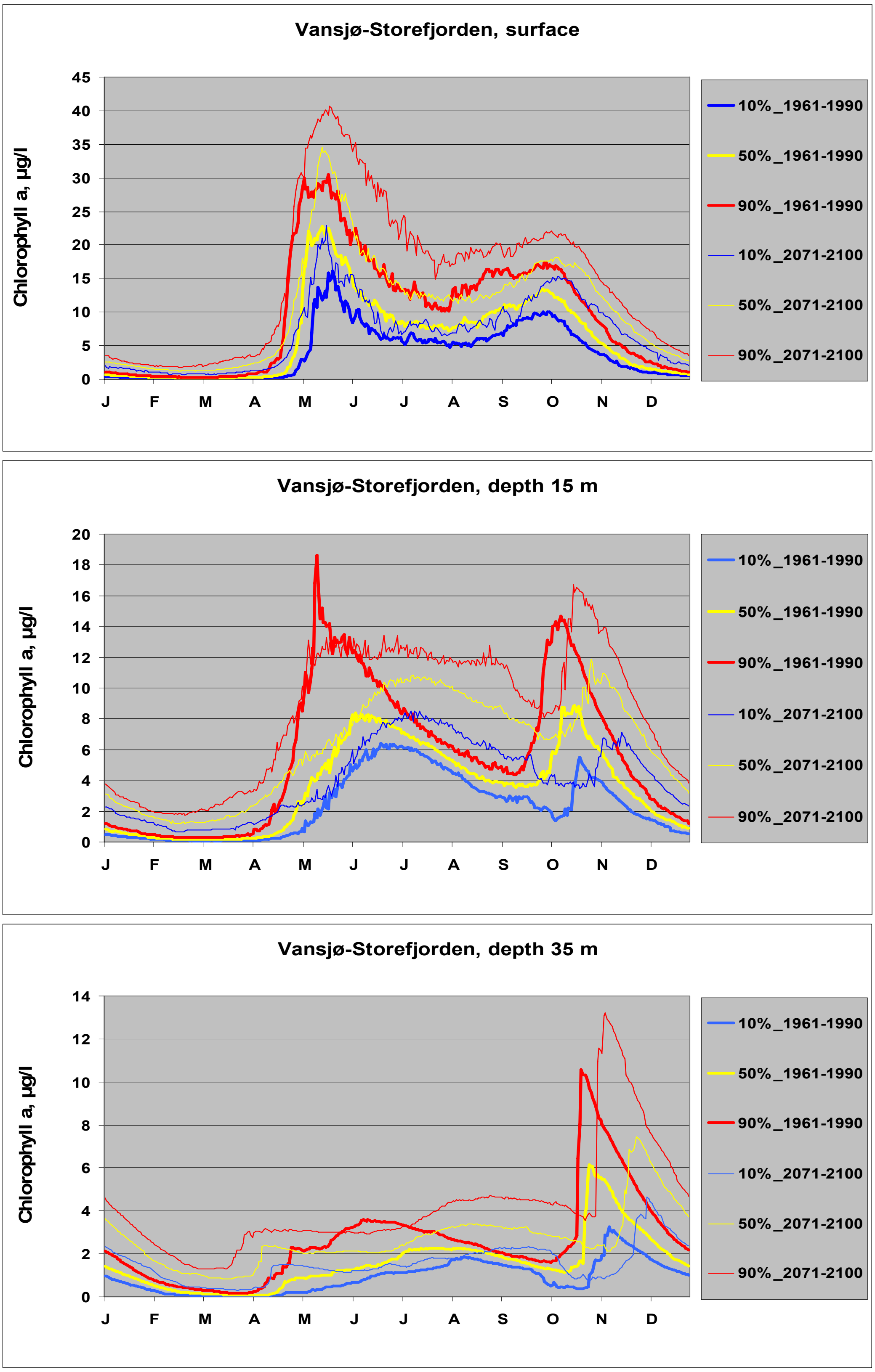


Figure 28. Lake Vansjø-Storefjorden. Percentiles of algae measured as chlorophyll a at 0, 15 and 35 meter below surface.

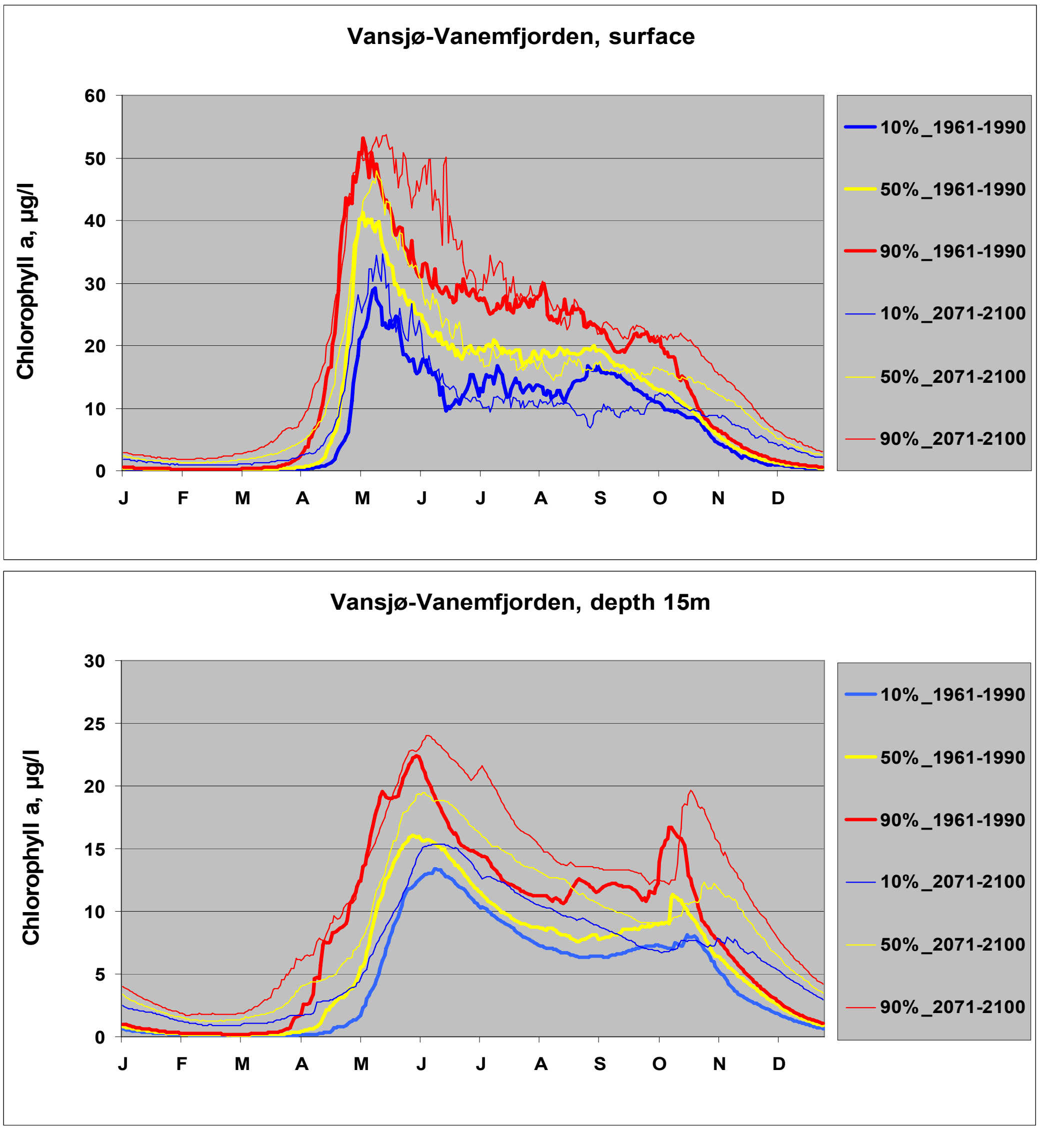


Figure 29. Lake Vansjø-Vanemfjorden. Percentiles of chorophyll a at 0, 15 meter below surface

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