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Impacts of Climate Change on Physical Characteristics of Lakes in Europe

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CONTENTS

A DECISION SUPPORT SYSTEM TO ASSESS THE IMPACTS OF CLIMATE CHANGE ON PHYSICAL CHARACTERISTICS OF LAKES IN EUROPE. FINAL TECHNICAL REPORT, 17 PP.

CLIME MAPS – DECISION SUPPORT SYSTEM. MANUAL. 15 PP.

1 PREFACE

The European Ecological Water Quality and Intercalibration action (EEWAI - 22002) of the Rural Water and Ecosystem Resources Unit of the JRC-IES, carries out research to help the implementation of the Water Framework Directive (WFD) through developing and harmonising the assessment methods for water quality of surface water bodies and provides scientific and technical support for the Commission Services, other European institutions (such European Environment Agency, EEA), and EU Member States on development and implementation of EU water policies. The environmental objectives of the WFD should be reached by 2015. In some exceptional cases, the Directive allows the possibility for a delay until 2030. This sets a time frame for restoration of the water bodies during which a considerable change in climate can be expected.

The anticipated effects of the climate change will affect most of the physical parameters of lakes used in lake typology, such as the duration of ice cover and underwater light climate, water temperature, thermal stratification and mixing type, water balance and water residence time. These changes will directly affect nutrient recycling, oxygen conditions, bioproductivity, and biodiversity of lake ecosystems, i.e. the chemical and biological parameters used for ecological water quality assessment. It is often hard to disentangle the climate change effects on surface waters from the local human impact.

One of the tasks of the EEWAI action is the assessment of the impacts of climate change on ecological water quality in order to support the implementation of the Water Framework Directive, and the long term reporting needs of the EEA. This task requires development of comprehensive knowledge base, models, and databases to provide tools for the evaluation of the adaptation needs of the EU water resources management with respect of the anticipated changes in water quality due to climate change. This goal is pursued by carrying out institutional research, collaborating with national research institutes, participating in competitive projects, and where possible, identifying already existing tools and databases as a basis for further developments. Recently, the work has included evaluation of the existing scientific knowledge on the Climate Change impacts on lakes (Eisenreich, 2005) and participation in the preparation of the joint EEA-JRC-WHO climate change report (EEA, 2008). In this context, the need for development of models, to produce projections of the possible evolution of the physical characteristics of lakes in Europe based on the agreed IPCC scenarios has been identified. Such information would be crucial for further work to develop climate change impact indicators on ecological water quality of lakes.

Within the recently completed EU RTD FP5 research project CLIME (EVK1-CT-2002-00121), the group led by Prof. Ari Jolma at Helsinki University of Technology developed the CLIME Decision Support System (accessible at: http://geoinformatics.tkk.fi/bin/view/Main/CLIMEDSS) to summarize and make available results conducted in the CLIME project. This DSS was a computerized, web-based tool to summarize and illustrate the main results of the CLIME project in an easily accessible and comprehensible form to interest groups both within and outside of the research community. The DSS used as its basis the long-term limnological databases owned by the CLIME consortium and the results of climate scenario modelling carried out by the Swedish Meteorological and Hydrological Institute (SMHI). The CLIME-DSS presented information about projected changes in the climate of Europe, and in lake characteristics driven by the changing climate. It enabled calculating of actual and projected probability distributions of a number of lake parameters for any location in Europe based on regional climate models (RCM) and empirical relationships between local climate and lake parameters. However, there was no possibility to create maps, to reveal regional differences, or find out climate change hot spots, i.e. areas with increased sensitivity to climate change. EEWAI found that a model based decision support system, which would allow testing the effect of various climate change scenarios on lake physical parameters and visualising the regional differences of these effects on a map of Europe, would be of great help for water managers in setting achievable targets for lake restoration.

In 2008, EEWAI initiated a procurement procedure for a service contract between Joint Research Centre and Helsinki University of Technology in order to develop further the CLIME Decision Support System (DSS) into a product named CLIME Maps. The aim was (1) to extend the central lake database beyond the specific CLIME sites including data from external sources, especially from the Global Lake and River Ice Phenology database (http://nsidc.org/data/lake_river_ice/), (2) to update the computational basis of lake physical parameters by applying the newest achievements in this field of science, e.g. the air temperature probability function (Livingstone & Adrian, in press) to calculate the duration of the ice cover, and the altitude – temperature relationship for Alpine region (Šporka et al. 2006), and (3) enable creating map views of the projected changes of physical parameters of basic lake types virtually placed into each of the 50x50 km grid cells of the RCM.

In March 2009, as the result of the service contract nº 384208 between JRC and Helsinki University of Technology, Prof. Ari Jolma and MSc. Joni Kaitaranta delivered the Final Technical Report and the User's Manual of CLIME Maps (see Annex 1 and 2). CLIME Maps has a focus on the physical characteristics of the lakes. It produces simple and understandable maps depicting the impacts of climate change on lake surface water temperatures, ice break-up times and the duration of ice cover on lakes in Europe. The predictions are targeted for the years 2071-2100 and are based on daily averages of air temperature obtained from high resolution climate change scenarios produced by the PRUDENCE project. The CLIME Maps can be freely accessed at http://clime.tkk.fi/jrc and is aimed to help a broad scale of limnologists and water managers visualizing the effect of climate change on the main physical driving factors for lake ecosystems.

The aim of the present report is to introduce the main results of CLIME Maps and to interpret the implications the physical changes could have to ecological water quality of lakes.

2 INTRODUCTION

According to the IPCC Fourth Assessment Report (IPCC, 2007) global mean surface air temperatures have risen by 0.74 °C ± 0.18 °C when estimated by a linear trend over the last 100 years (1906–2005). The rate of warming over the last 50 years is almost double of that over the last 100 years (0.13 °C ± 0.03 °C vs. 0.07 °C ± 0.02 °C per decade). For the global average, warming in the last century has occurred in two phases, from the 1910s to the 1940s (0.35 °C), and, more strongly, from the 1970s to the present (0.55 °C). Since 1979, warming has been strongest over western North America, northern Europe and China in winter, Europe and northern and eastern Asia in spring, Europe and North Africa in summer and northern North America, Greenland and eastern Asia in autumn (Trenberth et al., 2007).

Freshwater is one of Earth's resources most jeopardized by changing climate. Although lakes and reservoirs make up a small percentage of Earth's surface, they act as sentinels that reflect the influence of climate change in their much broader catchments. Global climate change is transforming aquatic ecosystems and the sediments of inland waters integrate the signals of these changes over time. The deposition of terrestrially derived carbon and outgassing of greenhouse gases make inland waters hot spots of carbon cycling and regulating climate change. Thus, as lakes and streams are integrators, sentinels, and, to some extent, regulators of environmental change, the understanding of their resistance, resilience, and responses to environmental change is crucial to their effective management (Williamson et al., 2008, 2009).

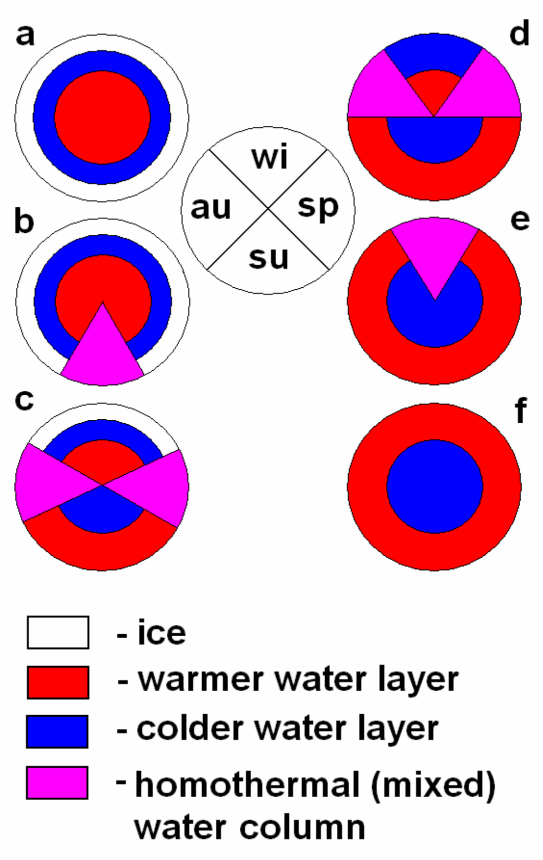

Figure 1. Generalized pattern of the basic mixing types and ice regimes of lakes in their seasonal and latitudinal (altitudinal) sequence. a – cold amictic glacial lakes under continuous ice cover; b – cold monomictic arctic or alpine lakes with one mixing period in summer; c – typical dimictic lakes in temperate climate with winter ice cover; d – dimictic lakes without winter ice cover; e – warm monomictic lakes with one full mixing in winter; f – tropical warm amictic lakes.

Climate change is complex, but one of its most fundamental metrics is temperature. Temperature controls many ecological processes, including ecosystem metabolism. Water temperature and ice cover are most directly affected by climate forcing, the existence of consistent trends has been demonstrated in river water temperatures (Hari et al., 2006), lake water temperatures (e.g., Livingstone, 2003; Straile et al., 2003; Arhonditsis et al., 2004; Coates et al., 2006; Dokulil et al., 2006) and ice phenology. One of the best integrators of regional temperature is the timing of ice cover on lakes and rivers, because long-term records are available for this metric. A 1.2°C warming of air temperatures in northern temperate regions has led to freeze dates that average 5.7 ± 2.4 days later (± 95% confidence interval) and ice-breakup dates that average 6.3 ± 1.6 days earlier per 100 years (Magnuson et al. 2000). These changes alter lake phenology in ways that may upset aquatic food webs by causing a mismatch between the seasonal timing of populations of primary consumers and their food resources (Winder and Schindler, 2004). Reductions in ice cover also create a positive feedback mechanism that accelerates warming, due to the greater absorbance of solar radiation by open water in comparison to snow and ice (Williamson et al., 2008).

All the physical lake processes analysed in this report are more or less depending on changes in air temperature and through that strongly interrelated. Figure 1 shows the generalized pattern of the basic mixing types and ice regimes in their seasonal and latitudinal (altitudinal) sequence.

As a result of different morphometric features of lakes and depending on their geographic location, regionally some physical features may gain higher importance and affect lake ecology in a specific way. For instance, changes in winter air temperature affect northern lakes first of all through modified ice regime while in deep perialpine lakes the same factor affects the completeness of winter mixing. Both processes have far reaching ecological implications.

Compared to the response of physical lake parameters to climate forcing, the chemical and biological responses are much more complex and site specific. Even in ecosystems containing only simplified food webs, the interactions of environmental parameters such as temperature within the system are still complex and may be propagated in ways that are not readily predictable, i.e. in a form of nonlinear or stepwise threshold responses in community dynamics and stability (Nyman et al., 2005).

Evidence accumulated during recent years, especially within specific EU projects like CLIME and EURO-LIMPACS, allow still defining some trends and drawing some general conclusions on the ecological responses. In this report we give an overview of the main ecological consequences that can be expected as a response to the changes of lake physical parameters resulting from climate change.

3 METHODS

In the present report we introduce a decision support system (DSS) CLIME Maps (Annexes 1 & 2), which is designed to implement models that predict climate change driven transitions in the physical characteristics of European lakes. CLIME Maps was developed at Helsinki University of Technology and is an improved version of the CLIME DSS developed in 2007 (located in http://geoinformatics.tkk.fi/bin/view/Main/CLIMEDSS). Compared to its earlier release, CLIME Maps is focused only on the physical characteristics of lakes producing simple and understandable maps depicting the impacts of climate change. The CLIME Maps can be accessed with any standard Internet web browser on the web page http://clime.tkk.fi/jrc.

Clime Maps predicts the impacts of climate change on physical characteristics of lakes. These predictions are targeted for the years 2071-2100 and are based on daily averages of air temperature according to IPCC Scenarios A2 (describes the future where the rate of greenhouse gas emissions continue to increase until year 2050) and B2 (describes the future where the rate of greenhouse gas emissions does not increase until year 2050). Control scenario represents the present situation, which is calculated from years 1960-1990.

The DSS is able to map the following impacts of climate change on physical characteristics of lakes:

- Regions whose lakes may start experiencing ice-free winters
- Shortening of the duration of ice cover
- Becoming earlier of the timing of ice-off
- Increase in lake surface water temperature in summer

Lakes are divided into four groups for the analysis of the impacts. Lakes of size much less than 100 square km are considered small, large lakes may have the size of several hundred or even thousands of square km. Lakes with mean depth up to 6 meters were considered shallow, deep lakes have typically mean depth well over 10 meters.

4 RESULTS AND DISCUSSION

4.1 The importance of lake physical processes for lake ecology

Climate variables (particularly temperature and insolation, but also precipitation and wind) are clearly important drivers of freshwater ecosystem processes, both via direct biological effects (e.g. photosynthesis, rate of metabolism) and indirectly via effects on lake hydrology, stratification, nutrient cycling and so on. Impacts described in a number of studies from the Baltic Sea region (Smidt et al., 2008) include:

- A longer annual ice-free period and earlier breakup of ice cover leading to community structure changes such as dominance shifts among phytoplankton taxa, changed successions, reduced species diversity, and transformations from a clear-water (macrophyte-dominated) to turbid (phytoplankton-dominated) state.

- Increased water temperatures leading to increased primary production, higher phytoplankton biomass and the incidence of blooms in some northern European lakes.

- Changes in fish communities associated with the effect of earlier and warmer summers on zooplankton biomass.

- Increased nutrient loads and/or increased contributions of nutrients from diffuse sources under a warmer and wetter climate, with dominance shifts in phytoplankton assemblages as a possible result.

Statements of the potential impacts of future climate changes on freshwater ecosystems vary in robustness depending on the available data, process understanding and system complexity. Potential impacts of projected climate scenarios for the Baltic Sea Basin (Smidt et al., 2008) include the following:

- Warmer water temperatures combined with longer stratified and ice-free periods in lakes could accelerate eutrophication. Shallow lakes and littoral zones may be particularly vulnerable.

- Cold-water fish species may be extirpated from much of their current range while cool- and warm-water species expand northwards.

- Altered lake nutrient status: increased remineralisation and higher diffusion rates of nutrients in warmer water would be expected to increase nutrient availability, especially in lakes with longer water residence times. Reduced N:P status combined with higher temperatures could result in phytoplankton community structure shifts favouring N-fixing and warm-temperature species, including cyanobacteria.

- Increased influxes of humic substances to ecosystems downstream of boreal and arctic peatlands would steepen light attenuation with negative impacts on lake periphyton and benthic communities, while potentially increasing the contribution of northern lakes to regional CO_2 emissions and climate forcing.

Plausible direct and indirect impacts of climate change on lake and ecosystem properties in Northern hemisphere are summarised in Fig 2 (modified from Smidt et al., 2008). The associated uncertainties are characterised on a three-step scale:

<u>High confidence</u> – impact has been described based on observations or measurements of several species, ecosystems or lakes and the mechanism of climate response is well understood; and there are no known or suspected antagonistic mechanisms or feedbacks that could mitigate or reverse the impact.

<u>Medium confidence</u> – impact has been projected or modelled using several approaches and the mechanism of response to climate change is well understood.

<u>Low confidence</u> – impact is hypothesised or has been projected or modelled in a single study; or antagonistic mechanisms or feedbacks exist which could mitigate or reverse the projected impact.

In general, changes in physical lake properties (higher water temperature, earlier ice-off) and ecosystem functioning (enhanced primary production, earlier spring bloom) may be expected with some confidence, while net effects on lake chemistry, food webs and community structure remain far less certain. It should be also noted that responses of lake ecosystems to climate forcing may be highly sensitive to lake and catchment characteristics, and this can result in highly individualistic responses in different lakes (Blenckner, 2005).

Further we review the most characteristic changes in lake water surface temperature and ice phenology that are projected to take place in European lakes until 2100, and describe their most relevant specific impacts on different lake ecosystem components.

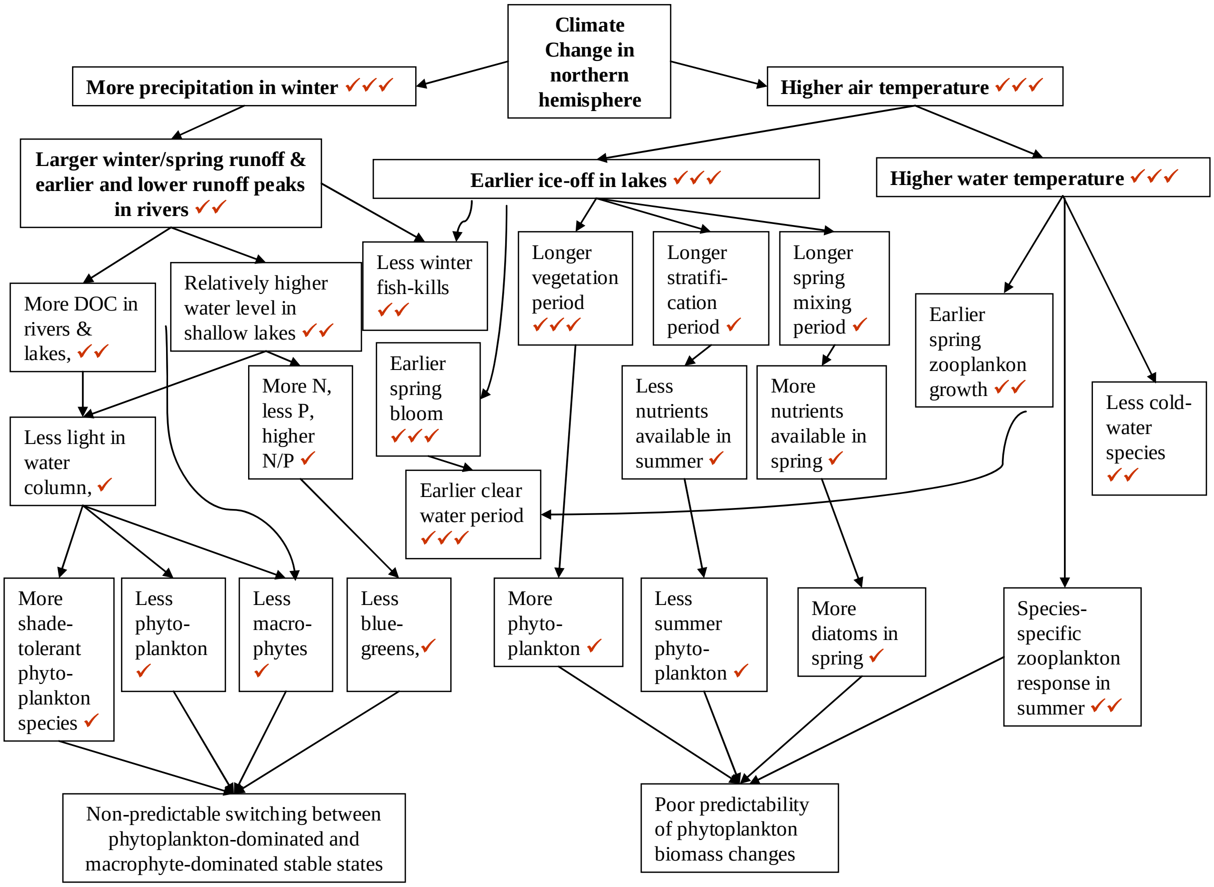

Figure 2. Climate change impacts on freshwater ecosystems of the Baltic Sea Basin (modified from Smidt et al., 2008). ✓✓✓= high confidence; ✓✓= medium confidence; ✓= low confidence

4.1.1 Lake surface water temperature

Surface and epilimnetic (upper mixed layer) water temperatures, which can be highly correlated with regional-scale air temperatures, exhibit a rapid and direct response to climatic forcing, making epilimnetic temperature a useful indicator of climate change. Long-term changes in thermal structure might in the future be responsible for mixing regimes shifting from amictic to monomictic, polymictic to dimictic, dimictic to monomictic, or monomictic to oligomictic.

In many lakes, the epilimnion has undergone recent warming (Adrian et al., 2009). According to IPCC Scenario A2, CLIME Maps projects a 2-7^{o}C increase of lake surface water temperatures in Europe by year 2100 with the range not strongly dependent on lake morphometry (Fig. 3). The application of the milder emission scenario B2 reduces the projected increase by about 1^{o}C (Fig. 4).

<u>In cold regions</u> at higher temperatures cold monomictic lakes may start stratifying during summer becoming dimictic.

<u>In temperate ecoregions</u> many dimictic lakes will become warm monomictic with a long stratification period in summer and a single circulation period in winter, which is not interrupted by ice cover, thus becoming similar to Mediterranean lakes (Blenckner et al., 2002; Pettersson & Grust, 2002).

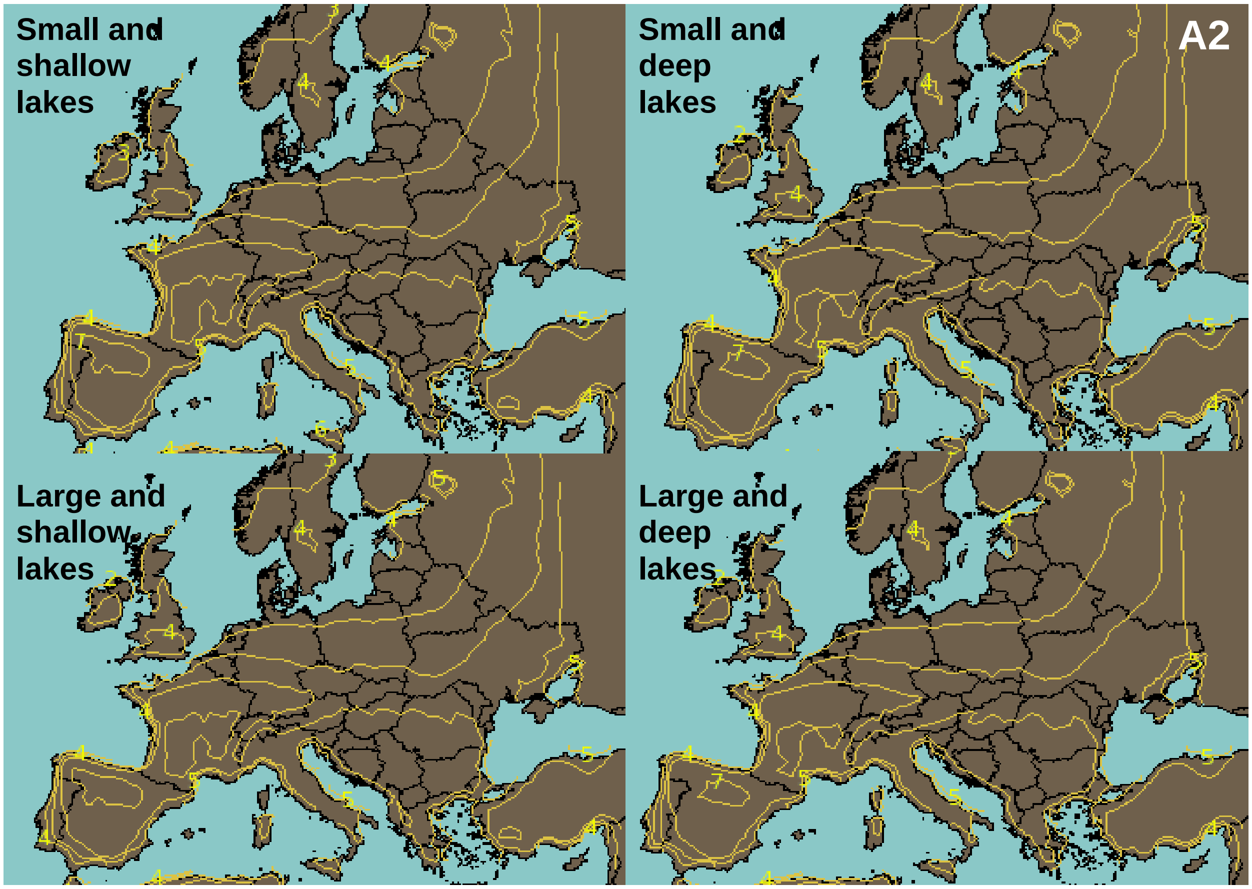

Figure 3. Projected increase of summer surface water temperature in lakes at IPCC scenario A2 until 2100.

Ecologically, even relatively small changes in thermal characteristics of lakes can cause major shifts in phytoplankton, bacterioplankton and zooplankton populations as well as altering the rates of metabolic processes. This is because organisms are often adapted to certain narrow temperature ranges and because their life-cycle strategies can be highly sensitive to variations in ambient water temperature (Arvola et al., 2009).

In the deep perialpine lakes of Central Europe, the internal recycling of nutrients and the subsequent development of the phytoplankton are strongly influenced by the duration and intensity of vertical mixing in winter and early spring (Salmaso, 2002, 2005; Straile et al., 2003). The occurrence of several consecutive mild winters leads to incomplete mixing in such lakes, which further results in a gradual increase in deep-water temperature and a simultaneous decrease in deep-water oxygen concentrations. These gradual changes can be terminated by the occurrence of an unusually cold winter - or even an average winter, if the deep-water temperature has risen to a sufficiently high level. This then results in deep penetrative mixing, an abrupt fall in deep-water temperature and an abrupt rise in deep-water oxygen concentrations (Livingstone, 1997). Late winter and early spring may therefore be considered the most critical period in the annual cycle of deep lakes (Salmaso, 2005). During cold winters with a complete overturn in Lake Garda, total phosphorus concentrations in the euphotic layer exceeded those of milder winters by a factor of three and favoured the development of *Mougeotia* sp. and Oscillatoriales (Salmaso, 2002).

In shallow Mediterranean lakes and all lakes in warm ecoregions, climate change will further reduce the water volume thus making lakes more susceptible to eutrophication and all forms of pollution. Increased demand for freshwater and higher evaporation will increase these problems (Catalan et al., 2002).

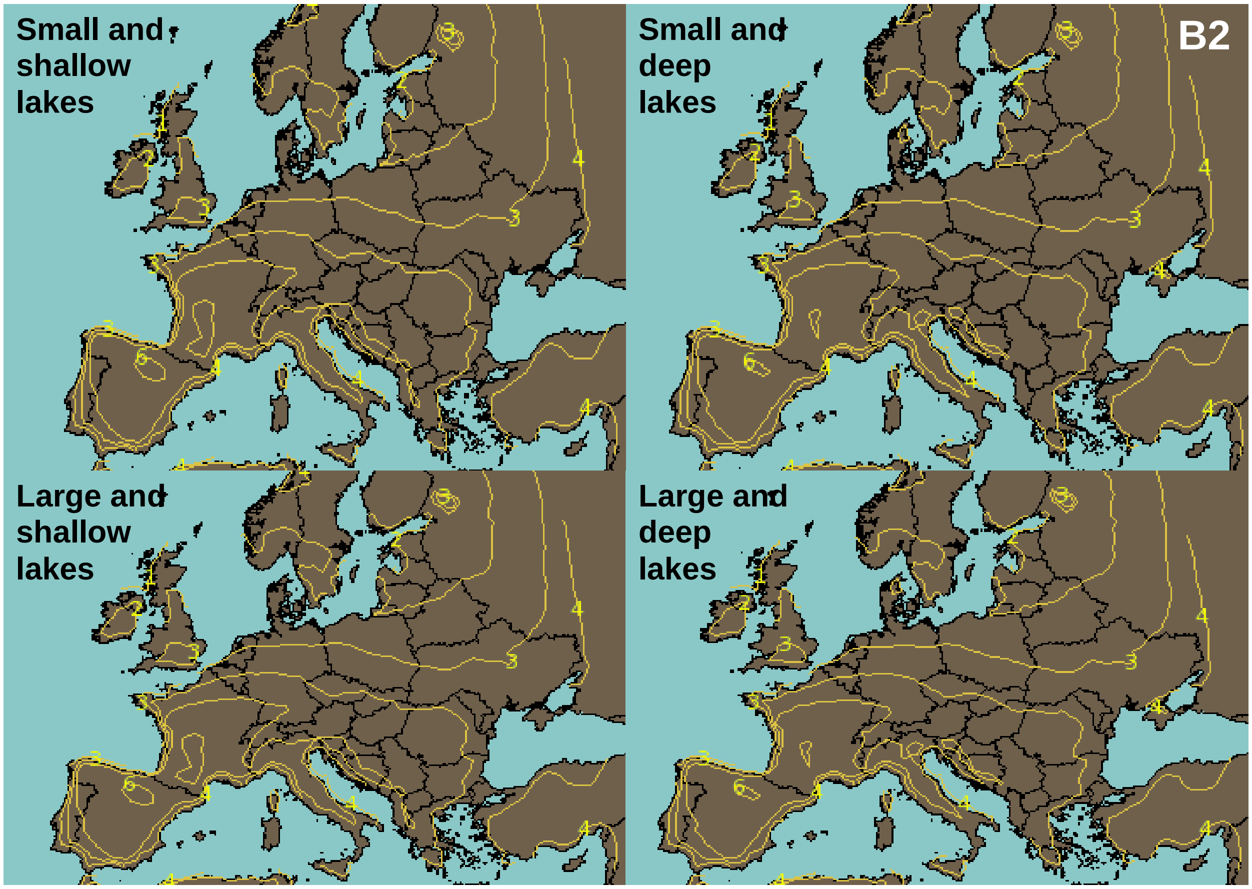

Figure 4. Projected increase of summer surface water temperature in lakes at IPCC scenario B2 until 2100.

Growth rates, abundance, and species composition of biological groups can each be considered an indicator of climate change. Given sufficient resource availability, increasing temperatures generally accelerate growth and development rates of individual organisms, although changes in absolute abundances tend to be species-specific. Changes in species composition have been used as a climate indicator on longer geological timescales as well as in contemporary studies. Shifts in phytoplankton species composition, especially among those taxonomic groups that are sensitive to temperature and mixing, such as cyanobacteria, diatoms, and flagellates, can be considered indicators of climate-induced enhancements in thermally stratified conditions. Changes in fish species distribution, abundance, and community structure are also indicative of climate effects, particularly if they reflect changes in available habitat for cold-water species. Other climate-related responses of lake biota (changes in primary productivity, zooplankton body size, increased bacterial cell densities, and benthic net photosynthesis and dark respiration rates) may be effective indicators for particular systems. Climate may also affect species diversity and composition through the invasion of non-native species that expand their geographical range as water temperatures warm (Adrian et al., 2009).

Increasing water temperatures lead to higher probability of cyanobacteria blooms with subsequent oxygen depletion in the hypolimnion and effects on zooplankton and benthic fauna. The effect might be strongest in shallow and/or eutrophic lakes in cold regions with anoxic hypolimnia. Rising temperatures favor cyanobacteria in several ways (Pearl & Huisman, 2008):

- Cyanobacteria generally grow better at higher temperatures (often above 25°C) than do other phytoplankton species such as diatoms and green algae. This gives cyanobacteria a competitive advantage at elevated temperatures.

- Warming of surface waters also strengthens the vertical stratification of lakes, reducing vertical mixing. Furthermore, global warming causes lakes to stratify earlier in spring and destratify later in autumn, which lengthens optimal growth periods. Many cyanobacteria exploit these stratified conditions by forming intracellular gas vesicles, which make the cells buoyant. Buoyant cyanobacteria float upward when mixing is weak and accumulate in dense surface blooms.

- These surface blooms shade underlying nonbuoyant phytoplankton, thus suppressing their opponents through competition for light.

- Cyanobacterial blooms may even locally increase water temperatures through the intense absorption of light. This positive feedback provides additional competitive dominance of buoyant cyanobacteria over nonbuoyant phytoplankton.

- Global warming also affects patterns of precipitation and drought. These changes in the hydrological cycle could further enhance cyanobacterial dominance.

Increased water temperature generates principal shifts in food webs. As cyprinid planktivorous fish species are favoured by warming, large zooplankton species are suppressed and grazing intensity is reduced. Following reduced grazing intensity, phytoplankton density increases, thus leading to effects similar to eutrophication, most pronounced in shallow lakes (Petchey et al., 1999). Changes in mixing processes lead to decreased nutrients entrainment. Less intense mixing and increased thermal stability result in oxygen depletion in deeper regions with subsequently phosphate and ammonium (i.e. nutrients in general) release from the sediment. Anoxia in the hypolimnion leads to extinctions of benthic species, especially sensitive chironomids. Nutrient (N, P) availability leads to eutrophication with several effects such as increased algae growth, oxygen depletion during night times, extinction of sensitive species such as brown trout (*Salmo trutta*).

Earlier growing seasons, as predicted by climate change models, would result in greater biomass and distribution of submerged macrophyte communities, thereby modifying the structure and functioning of north temperate lakes. The effect will be a function of lake morphometry and most pronounced in shallow systems (Rooney & Kalff, 2000). However, as a functional component of north temperate shallow lake and pond ecosystems, elodeid macrophyte communities may be broadly resilient to the small increases in temperature associated with climate warming, even when these temperature increases occur in combination with increased nutrient loading and the presence of fish (Mckee et al., 2002).

Higher water temperature leads to shifts in zooplankton community composition. Higher, earlier population growth rates of *Daphnia* and earlier summer decline occurs due to higher spring temperatures. As a result, higher *Daphnia* biomass leads to earlier phytoplankton suppression and a shift from a dominance of large-bodied to smaller species. Shifts in zooplankton composition and suppressed phytoplankton growth leads to earlier clear water phase. Furthermore, changed phytoplankton dynamics have effects on food-web interactions (Straile, 2002).

Temperature may influence chironomid life cycles either directly via hatching of the eggs, diapause, growth, feeding, emergence (Ward & Stanford, 1982) or indirectly via changes for example in food quality and quantity, oxygen conditions, inputs of allochthonous materials and ice cover duration (Sweeney & Vannote, 1978). Laboratory experiments have further demonstrated that in Chironomidae, as in other insects, temperature significantly affects developmental rate and size of emerging adults (Frouz et al., 2002; Lobinske *et al.*, 2002).

In cold ecoregions, higher water temperatures (especially in the epilimnion) lead to the progressively reduction of the habitats for cold water fish species (e.g. *Salvelinus namaycush*), which disappear from littoral areas in spring and summer. Furthermore, higher water temperatures will reduce reproduction success of cold water species and increase parasitic and predator pressure on the egg and young life stages. As secondary effects, warm water species might invade lakes in cold regions with subsequent changes in food webs (McDonald et al. 1996; Nyberg et al., 2001). Increasing water temperature in spring in Estonian inland waters has affected differently the spawning of roach and bream. Within forty years (1951--90), the spawning of bream shifted, on average, to a ten days earlier period but the range of spawning temperature remained unchanged, while there was no shift in the spawning time for roach, which started to spawn at about three degrees higher water temperature than earlier (Nõges & Järvet, 2005).

4.1.2 Ice phenology

At present, in most parts of Europe winter temperatures are low enough to create winter ice cover on lakes. Only in Western Europe where the Atlantic influence creates a maritime climate, and in Mediterranean coastal regions lakes never freeze. In areas experiencing winter ice cover on lakes, its duration varies from some days in northern Spain, northern Italy and Scotland to more than 200 days in Scandinavian mountainous areas and high alpine regions (Fig. 5).

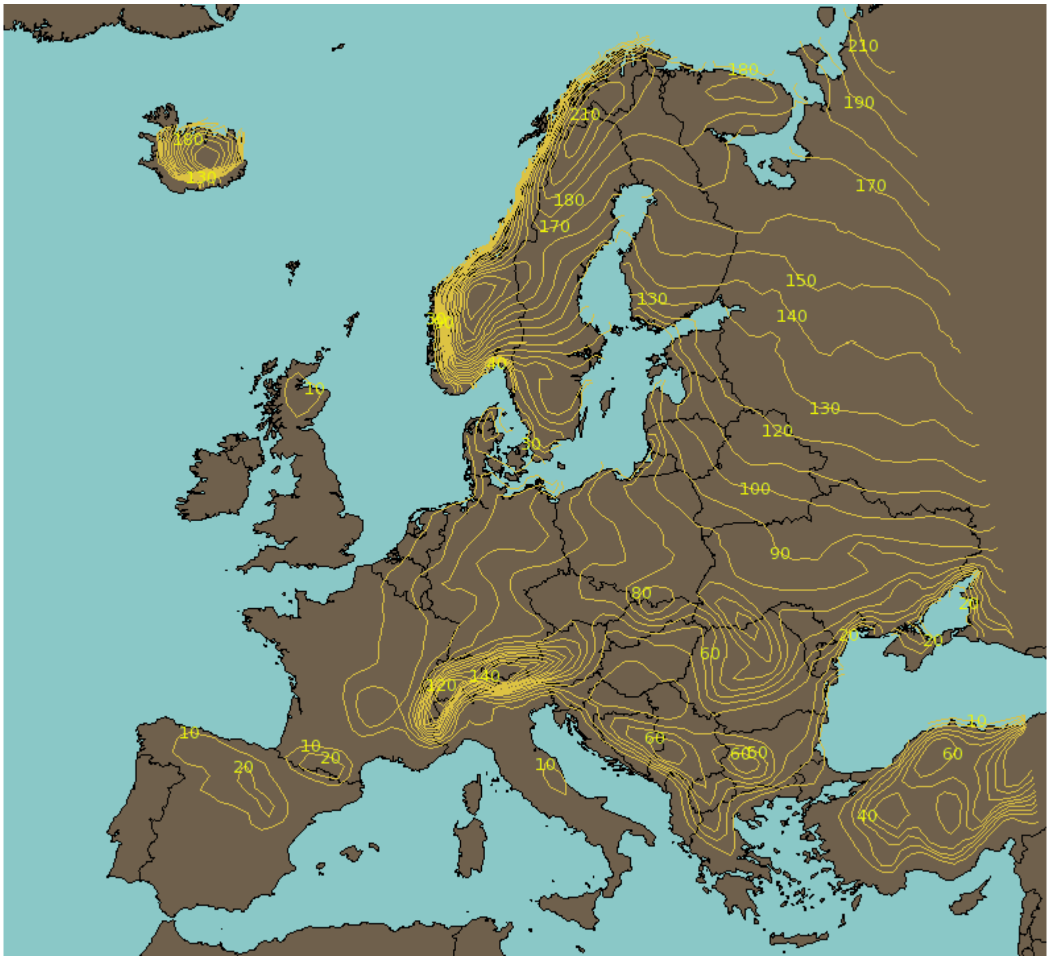

Figure 5. Duration of lake ice-cover (days). Model results for shallow lakes based on air temperature record for the control period 1960-1990. Deep lakes that store more heat may represent exceptions.

In Northern Europe and the Alpine regions of Central Europe, the lakes are usually covered with ice throughout the winter. The formation and duration of ice-cover depend not only on air temperature but also on basin morphometry, lake volume, inflow to lake, and dynamics and physiochemical properties of water, including mineralization in particular (Marzelewski & Skowron, 2006).

Most recent climate change scenarios suggest that there will be a marked increase in European winter temperatures accompanied by a pronounced extension of the ice-free period. Biggest ecological changes can be expected in lakes, which presently have ice-cover in most winters and will be mostly ice-free in the future. According to our projection, the regions in Europe, which will experience the biggest changes in ice-cover duration ("hot spots") will extend from Central to Eastern Europe and will not overlap for shallow, small and deep, and large and deep lakes (Fig. 6), where lakes in green areas may shift from being typically always ice-covered in winters to being ice-free in some winters; the lakes in blue areas may shift from being ice-free in some winters to being typically never ice-covered in winters; the lakes in red areas may shift from being typically always ice-covered in winters to being never ice-covered in winters).

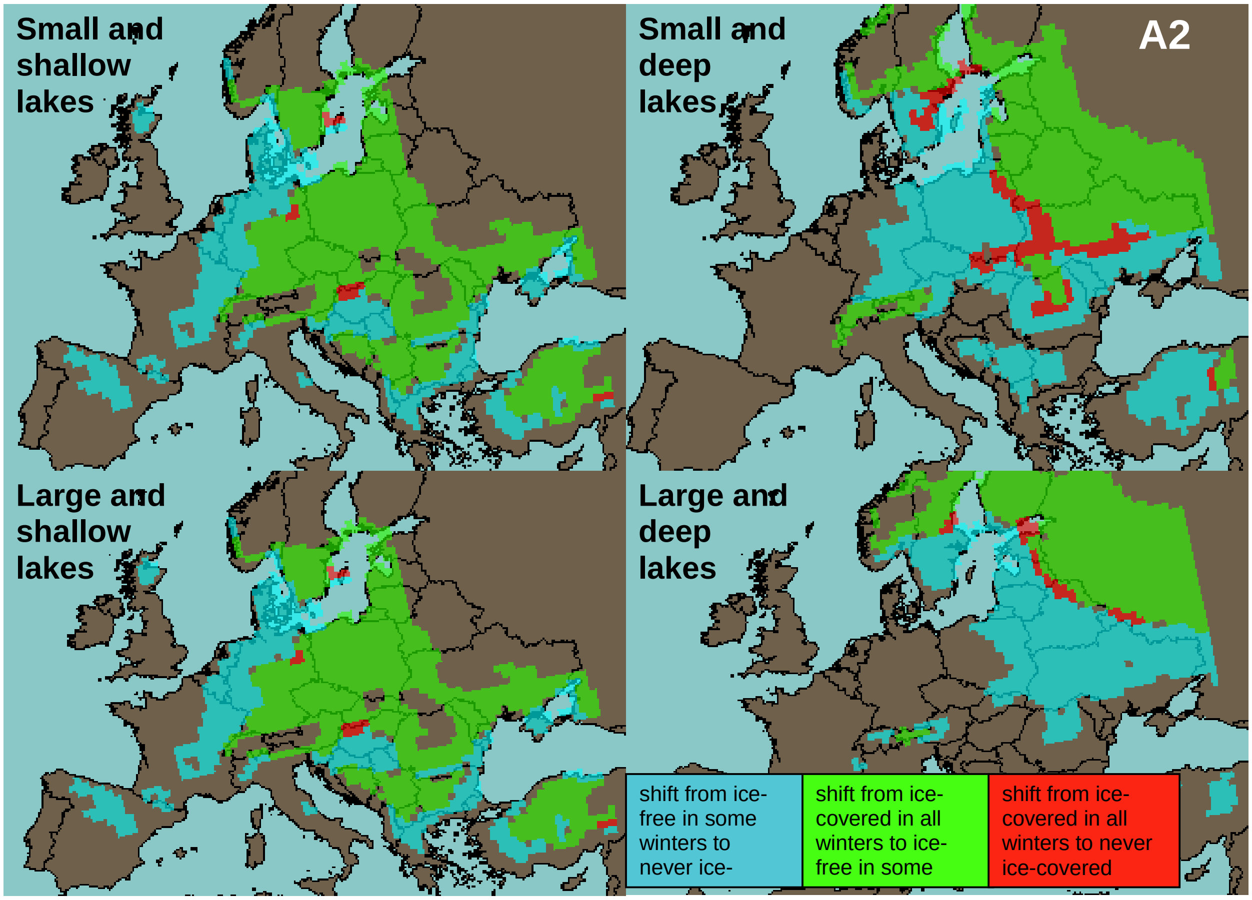

Figure 6. Projected ice regime changes in lakes at IPCC scenario A2 until 2100.

4.1.2.1 Effect on lake chemical processes

Ice cover isolates the water mass from the atmosphere and creates a disbalance characterized by increasing CO_2 and decreasing dissolved oxygen (DO) concentrations in the water as a consequence of biological oxidation of organic matter. As the result of the changed gas regime, the pH and the redox pontential drop and the carbon equilibrium is shifted towards the dissolution of carbonates and often formation of aggressive CO_2 corrosive to metals and able to damage concrete constructions (Lea & Hewlett, 2004). Photosynthesis of algae and aquatic plants that in the open-water period enriches water with DO, becomes light-limited and decomposition processes prevail. During long ice-cover periods, aerobic processes consume all DO available and create anoxia, especially in eutrophic waters where large amounts of organic matter are produced during the growing season. The anoxic zone forms first at the lake bottom, i.e. at the site of most intensive decomposition, and extends further towards surface. In shallow lakes with a small DO pool, winter anoxia may reach the surface layers. As the formation of anoxia is a function of ice-cover duration, a decrease of the frequency of this phenomenon is expected in warmer winters (Eisenreich, 2005).

As there is very little nutrient uptake by light-limited phytoplankton and plants in winter, any nutrients discharged by rivers or released from decomposition in the water column or the bottom sediments accumulate under the ice in inorganic forms (nitrates, ammonia, phosphates). The release from the sediments of dissolved phosphorus, the main element causing eutrophication in lakes, is strongly dependent on the redox potential. An oxidized microlayer at the sediment–water interface partially inhibits sediment P release, especially that of the iron-bound P. At the onset of bottom anoxia high P release rates are observed (Penn et al., 2000; Kleeberg, 2002). In this way, milder winters with shorter ice-cover and less anoxia formation may decrease P-release in winter, however, there is an opposite effect for summer. Shortening of the ice cover period prolongs the duration of summer stratification. This may lead to oxygen depletion in deep zones during summer that enhance P-release and eutrophication. In shallow lakes where sediment resuspension during ice-free periods contributes significantly to internal P-loading, the latter will increase by one third in some nordic shallow lakes if the 2 x CO_2 climate scenario comes true (Niemistö & Horppila, 2007).

4.1.2.2 Effect on phytoplankton

Changes in the timing of ice break-up represent indirect temperature effects and have the most obvious impact on phytoplankton. Increase in temperature leads to an earlier ice break-up which, in turn, has a large impact on light conditions, turbulence, and thereby nutrient availability. Temperature increase speeds up organic matter mineralization of and hence changes nutrient dynamics and availability. The complex interactions of direct and indirect temperature effects should affect different phytoplankton groups differently (Weyhenmeyer, 2001).

Ice-cover on lakes, both thickness and duration, strongly affects phytoplankton development due to reduced light conditions and reduced turbulence (Nebaeus, 1984). High nutrient concentrations accumulated in winter allow a rapid growth of phytoplankton after ice break-up when light conditions improve. A spring phytoplankton (e.g. diatom) peak usually appears around ice break-up when light conditions in the water no more limit algal growth. The only exception is a spring phytoplankton bloom dominated by species which can develop under ice, at low light intensities (e.g. small dinoflagellates), if the ice is clear (Weyhenmeyer et al., 1999).

During the ice-cover period, especially when there is thick snow on the ice, photosynthesis becomes severely light-limited and most species of phytoplankton sink in the water column despite some convective mixing. The sinking speed of spherical phytoplankton cells is proportional to the square of the radius and is negligible for small picoplankton cells. Also thin filamentous algae and those having spines sediment slowly and will take about two months of continuous ice-cover even in a shallow lake for most of the algae to settle. Because of their heavy silica shells, diatoms settle most rapidly while species with gas vacuoles have a positive buoyancy and they may concentrate at the ice-water surface. Different settling rate is one of the factors causing the succession in the under-ice phytoplankton communities. Exceptionally, some motile algae like dinophytes (Arvola and Kankaala, 1989; Weyhenmeyer et al., 1999), cryptophytes (Arvola and Kankaala, 1989; Phillips and Fawley, 2002), chrysophytes (Watson et al., 2001) or flagellated chlorophytes (Arvola and Kankaala, 1989) can concentrate near the surface and give rise to late winter blooms particularly if the ice is clear of snow (Jones, 1991). Winter diatom blooms, like those dominated by the very small *Stephanocostis chantaicus* in Lake Stechlin, Germany (Scheffler and Padisák, 2000) or by *Aulacoseira baicalensis* in Lake Baikal (Kozhov, 1963; Kozhova and Ismest'eva, 1998), are most probably supported by convectional currents (Kelley, 1997; Granin et al., 1999). Thinner ice and snow cover in milder winters favour phytoplankton growth in winter below ice resulting in increasing chlorophyll levels. An intermediate ice break-up in winter that ends the light limitation may increase phytoplankton biomass by a factor of tens or even hundreds compared to normal winter levels.

Large ecological changes have been observed in lakes which have totally lost their winter ice-cover and lakes which were previously covered with ice but have now become temporarily ice-free (Psenner, 2003). Ohlendorf et al. (2000) concluded from their observations on a remote high alpine Lake Hagelseewli (2339 m asl, Swiss Alps) that the mere occurrence of an ice-free period, creating a short productivity pulse, was more important than its duration for preserving a climatic signal in the sedimentary record. Diatom analyses in the water column, sediment traps, surficial sediments as well as in a short sediment core give information about the present-day seasonal cycle of diatom blooms. The lake is characterised by a very short period (2-3 months) of open water during which planktonic diatoms bloom, whereas mainly periphytic *Fragilaria* species entered the traps during the ice-covered period (Lotter & Bigler, 2000). These results suggest that plankton development is strongly inhibited by the ice-cover, with longer periods of ice-cover favouring *Fragilaria* species in Hagelseewli. The diatom analysis of a short sediment core that includes the last five centuries revealed several changes in the proportion of planktonic diatoms to *Fragilaria* species.

As shown above, in lakes covered with ice, the disappearance of snow from the ice and the timing of break-up are crucial events for the development of the spring phytoplankton. In contrast, the duration of the spring bloom and the length of the post-bloom period are primarily controlled by nutrient availability (Blenckner, 2001). Since the size of the available nutrient pool differs from lake to lake, the decline of spring phytoplankton is not directly linked to the timing of ice break. Early ice-break combined with an early spring bloom may, however, result in an accelerated rate of nutrient depletion and an earlier decline in the early spring phytoplankton (Weyhenmeyer, 2001; Järvinen et al., 2006).

Owing to their smaller volumes, reduced heat storage, and shorter residence times, shallow lakes respond in a more direct way to inter-annual variations in the weather. In small, non-stratified, lakes, the climatic ‘signal’ captured during the spring turnover persists for only a short period of time (Gerten and Adrian, 2000). In contrast, some large but shallow lakes, like Lake Võrtsjärv, have an extended ‘climate memory’ and here the meteorological conditions experienced in winter and early spring determine to a large extent both the water level and the dynamics of the phytoplankton throughout the ice-free period (Nõges, 2004; Nõges et al., 2003).

4.1.2.3 Effect on fish

The anticipated changes in physical conditions forced by climate change are expected to cascade through northern dimictic lake ecosystems and increase thermal habitat for cold, cool, and warm water fish. This habitat enlargement is caused both by water temperature increase and by increased duration of periods with suitable temperatures. However, in southern lakes that will freeze less often and reach higher maximum temperatures, and where the anoxic region enlarges, cold water fish habitats may also decrease (DeStasio et al., 1996).

Projected shorter ice-cover duration will also decrease the risk of winter fish-kills in northern shallow lakes (Nõges et al., 2007). Ice cover affects lake productivity by controlling light availability and dissolved oxygen concentrations. Dissolved oxygen levels decline progressively through the ice-cover period, and can drop to levels that are lethal for fish. A decrease in duration of ice cover could therefore reduce overwinter fish mortality (Fang & Stefan, 2000).

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Relevant webpages http://www.climate-and-freshwater.info/

ANNEX 1:

A decision support system to assess the impacts of climate change on physical characteristics of lakes in Europe. Final Technical Report

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A DECISION SUPPORT SYSTEM TO ASSESS THE IMPACTS OF CLIMATE CHANGE ON PHYSICAL CHARACTERISTICS OF LAKES IN EUROPE

FINAL TECHNICAL REPORT
March 12 2009

Contract n° 384208
Contractor: Helsinki University of Technology

Ari Jolma
Joni Kaitaranta

Executive summary

A new version of the CLIME DSS was developed for mapping the impacts of climate change on physical characteristics of lakes in Europe. CLIME was a framework programme 5 research project, which developed a web-based DSS that was released in December 2005. The new DSS comprises an extended relational database, tools for preparing, computing, and adding content to the new DSS, and new interactive web pages that exploit the latest Internet mapping technology. The development work exploited results from the CLIME research project, literature, and new datasets.

The scientific basis of the DSS

Mapping the impacts of climate change relies on availability of geospatio-temporal data about the climate change. The data that was used in this project is from the PRUDENCE project, which was another framework programme research project. The regional climate simulations provide comparable descriptions of current and future climate. The simulation results have been used only through a statistical interpretation, i.e., it was not assumed that they provide actual descriptions of weather. The climate projections for the future were produced in PRUDENCE assuming certain driving scenarios. The scenarios that were used in this project are the IPCC A2 and B2.

Lakes are in general individuals, whose behavior is driven by the weather, but which are characterized by the morphometry of their catchment and of themselves. Limnological research has developed many characterizations of lakes, such as ice phenology and mixis and trophic level, the last one being an ecological one. These kinds of characterizations are normally based on limnological field studies. Studies, which link lake morphometry, climate and lake characteristics, and which would enable predictions of lake characteristics are rather few. Even fewer studies consider the climatic variability in this context. The main modern tool for studying the behavior of lakes under varying weather is a lake simulation model. Such models are difficult to set up and often require a lot of detailed data.

Mapping the impacts of a global phenomenon over large areas using locally developed models requires regionalization. The method of regionalization employed in this project was either developed for this purpose or the regionalization was done naively. In the project we developed a regionalization model for a model of intermittent ice cover. The model relates climatic variables with lake characteristics and it was developed and used with the help of GLRIP data. The GLRIP data is free lake and river ice phenology data that is available from the U.S. National Snow and Ice Data Center.

The DSS and delivery of content

The DSS contains separate components, which interoperate through industry standard data formats and communication protocols. The web browser based component communicates with the server using Web Map Service (WMS) calls. WMS is an Internet mapping standard developed by the Open Geospatial Consortium. The use of WMS and OpenLayers Javascript library for the client, makes it relatively easy to extend the DSS with other data services or to use the DSS to serve data in other services.

All the tools and intermediate data products are delivered with this report. It is expected that in the near future new regional climate datasets become available. The new datasets will, however, be basically in similar format and the DSS tools are delivered, thus this issue does not constitute a dead-end.

1. The JRC CLIME DSS map generator

The JRC CLIME DSS map generator (referred to as DSS later in this document) is a new version of the CLIME DSS that was developed within the research project CLIME (EVK1-CT-2002-00121).

The purpose of the DSS is to produce georeferenced information, which depicts the potential impact of climate change on physical characteristics of lakes in Europe.

The DSS consists of three components:

1. The Database, from which maps are generated
2. Tools for preparing, computing, and adding content to the DSS
3. The interactive web pages for visualizing, i.e., mapping, the Database content

The technical details of these three components are described below in chapters 2, 4 and 5. The description is mostly technical. This technical report is accompanied with a user manual for the interactive web pages, which describes the web pages from the user's point of view.

The literature and algorithms, on which the computational tools and advanced interactivity of the web pages are based, are described in chapter 3.

The annexes to this report contain program code listings of some of the tools. All software used in the project and for the web pages is free and open source (FOSS). The main software platform that has been used consists of Perl, which is a widely used general purpose programming language, and of several Perl modules, especially from the Geo namespace. The Geo and other Perl modules are often interfaces to commonly used libraries such as PROJ.4, NetCDF, and GDAL. The progamming platform is available as an integrated package at http://map.hut.fi/files/Geoinformatica/win32/. More information is available from the web page of the Geoinformatica package http://trac.osgeo.org/geoinformatica/. The home pages of the tools packaged into Geoinformatica are easily found on the web using search tools or starting from the Geoinformatica pages.

This report is accompanied with a delivery of tools and data in digital format.

2. The Database of the DSS

The database of the DSS is a relational database (RDB) extended with a geospatial extension that adds geometry as a data type. The database is implemented in the PostgreSQL FOSS RDB management system (RDBMS) equipped with the standard-conforming PostGIS geospatial extension. The core tables in the database are shown in figure 1.

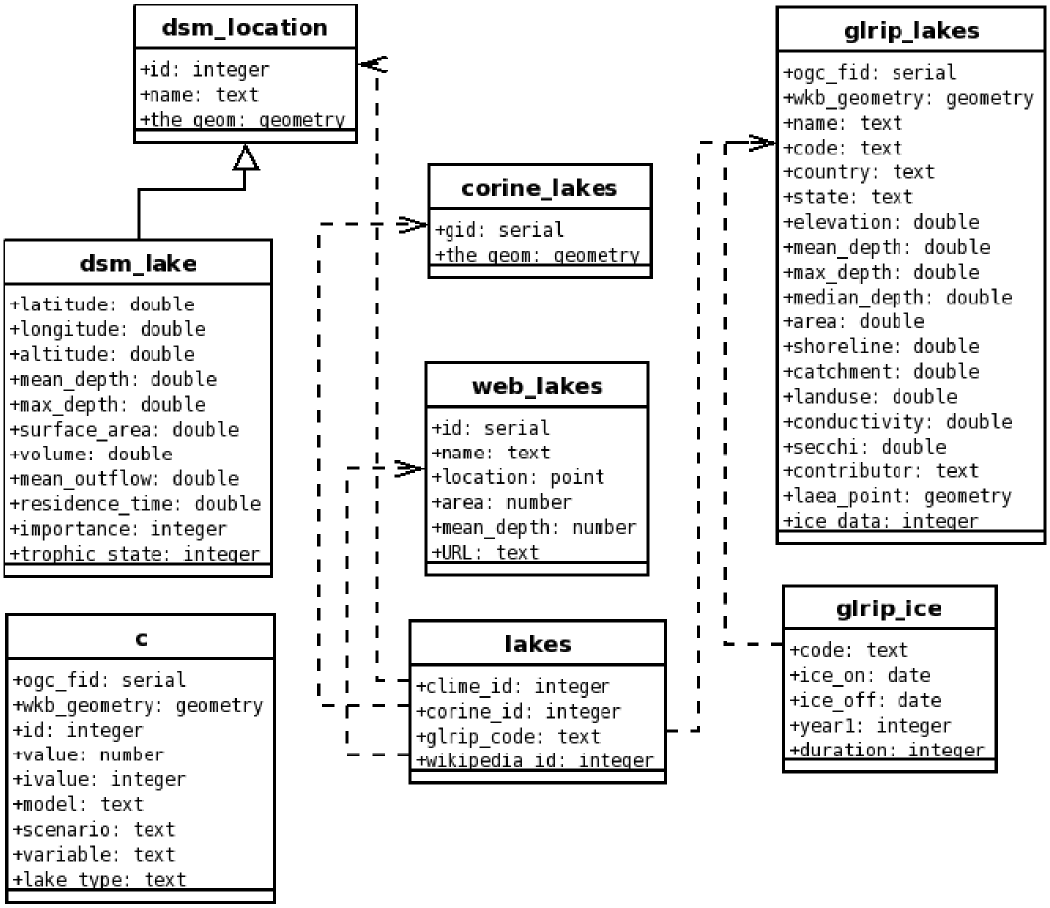

Figure 1. The core tables in the Database of the DSS.

The CLIME DSS Database has been extended with data from the Global Lake and River Ice Phenology database[1] (GLRIP), whose data is available without restrictions. The lakes in the GLRIP are described with a point location and several numerical characteristics. The characteristic data is, however, often incomplete. There are 141 lakes in the GLRIP database that are within countries having territory in Europe. Most of the lakes are in Finland (87) and Russia (45) and only a few are from other countries (Switzerland, Germany, Estonia, Hungary). The GLRIP lakes are stored in the glrip_lakes table. Associated with the GLRIP lakes (link through the lake code) are dates of (first) ice-on and (last) ice-off and duration of the ice cover (which is less or equal to ice-off minus ice-on). The ice phenology data is stored in the glrip_ice table.

The database contains two other lake tables that are new. The corine_lakes contains a dataset that is obtained from the 100 m x 100 m Corine Land Cover raster acquired from the European Environment Agency[2]. To produce the lake dataset the continuous (in Moore sense) areas of inland water body cells were converted into polygons, discarding polygons with size less than 1 km^2, and saved into the table. The corine_lakes table contains 10547 lakes. The web_lakes contains a lake dataset that is obtained from the English language Wikipedia. The web_lakes contains lakes from Finland, Sweden, Estonia, Poland, and Germany. The location of the lake is stored in web_lakes as a point.

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[1] http://nsidc.org/data/g01377.html

[2] Version 8/2005 was used.

The computed intermediate variables and variables depicting the ice phenology of the lakes are stored in the table c. The geometry column in c contains either contour lines or RCM grid cells as polygons, depending on the variable. The original data, from which the contour lines are computed are delivered as data and are not in the database.

The database contains also the RCM grids and the map of Europe. The grid tables consist of grid cells as polygons and an associated value, which tells the raster coordinates of the cell (rotated latitude and longitude). The map of Europe contains country borders.

The geospatial data that is stored in the database is in Lambert Azimuthal Equal Area map projection (EPSG 3035).

There are two important datasets that are outside the database. The climate data, i.e., the regional climate model (RCM) simulation outputs that were used in this work are from the PRUDENCE project[3]. The details of the data are given in table 1. This data is not included in the digital delivery attached to this report. The PRUDENCE data is available from the PRUDENCE website as multidimensional NetCDF datafiles.

Table 1. The details of the RCM data that was used in the work. The "x" in the filenames is replaced by the variable name. Variable name for air temperature at 2 meter height is "t2m".

Name	SMHI HC	SMHI MPI	HadRM
Organization	SMHI	SMHI	Hadley Centre
GCM	HadAM3h	ECHAM4/OPYC3	HadAM3p
RCM	RCAO	RCAO	HadRM3p
Grid table in database	smhi_grid	smhi_grid	hadrm_grid
Filename for the Control run	x.SMHI.HCCTL.nc	x.SMHI.MPICTL.nc	x.HC.adeha. 1960-1990.nc
Filename for the Scenario A2	x.SMHI.HCA2.nc	x.SMHI.MPIA2.nc	x.HC.adhfa. 2070-2100.nc
Filename for the Scenario B2	x.SMHI.HCB2.nc	x.SMHI.MPIB2.nc	x.HC.adhfd. 2070-2100.nc
Code in data files	HC	MPI	ad

The intermediate datasets that were computed from the RCM outputs are described below.

3. The methods

The DSS is able to map the following impacts of climate change on physical characteristics of lakes:

1. Regions whose lakes may start experiencing ice-free winters
2. Shortening of the duration of ice cover
3. Becoming earlier of the timing of ice-off
4. Increase in summer temperature of lake surface water

---

[3] http://prudence.dmi.dk/

Lakes were divided into four groups for the analysis of the impacts. Lakes of size much less than 100 square km were considered small when assessing the results of the models. Large lakes may have the size of several hundred or even thousands of square km. Lakes with mean depth up to 6 meters were considered shallow when assessing the results of the models. Deep lakes have typically mean depth well over 10 meters.

The duration of ice-cover

The impacts (1) and (2) are based on a method that is based on a model developed by Livingstone and Adrian (in press) (L&A). The L&A model uses linear dependence between an estimate of the duration of negative air temperature (D^{-}_{prob}) and the total duration of, possibly intermittent, ice cover D_{ice}. The estimate of D^{-}_{prob} is based on a cosine function, fitted to the daily temperature data. D^{-}_{prob} can be computed from the cosine function as an integral

L&A present a linear dependence between D^{-}_{prob} and D_{ice} for Müggelsee. To apply this for whole Northern Europe requires a solution to the problem of regionalization.

Regionalization of all the impacts is based on the RCM simulations, which are assumed to characterize the current and future climate in Europe. The variation between models characterizes the uncertainties that there are of the climate and its change. For the regionalization it is assumed that the control and scenario runs of the simulations produce samples from the probability distribution of the meteorological variables. Thus, the various meteorological that can be computed from the RCM simulations must be treated in regionalization as random variables.

Regionalization of the impacts (1) and (2) is based on a relationship between the cumulative probability of D^{-}_{prob} and that of D_{ice}. Figure 2 has an example of this relationship. For regionalization D^{-}_{prob} is modelled as a line $\mu+m(p\text{-}0.5)$ and D_{ice} as $m_h(p\text{-}p_f)$, where p is the cumulative probability and μ, m, m_h, and p_f are parameters. The ratio $c = m_h / m$ and the value $d_f = \mu + m(p_f\text{-}0.5)$ were considered to be lake characteristics.

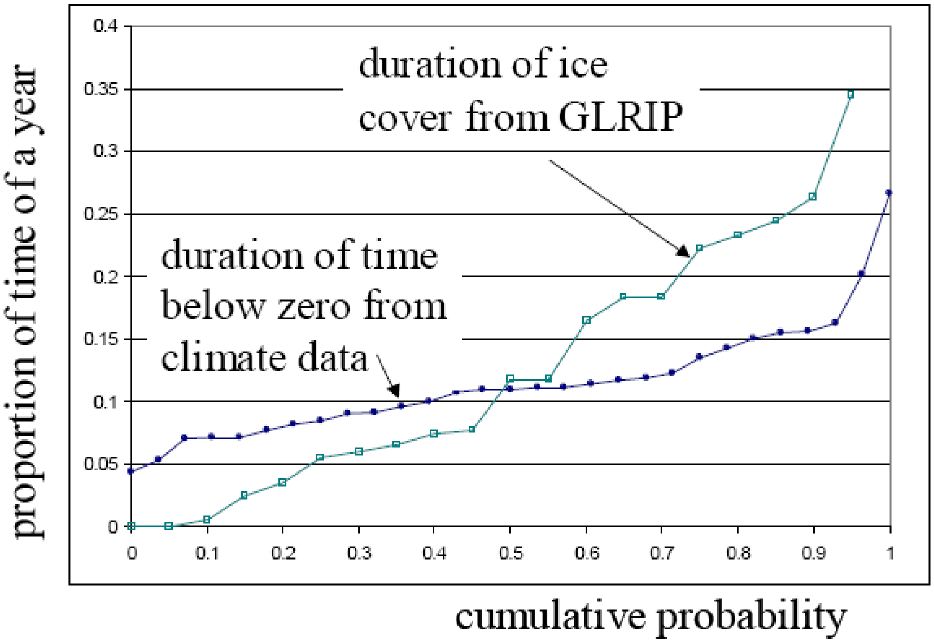

Figure 2. Cumulative probabilities of D^{-}_{prob} and D_{ice}. D^{-}_{prob} is computed from SMHI HC and the lake in question is Müggelsee. The cumulative probability is estimated as i/N.

Computations and results

The cosine model was fitted to all RCM grid cells that intersect with land. The data files `grids/smhi-land` and `grids/hc-land` were computed using a geospatial procedure, which converted the RCM grids and the map of Europe in the database into rasters. Those rasteres were then overlaid to see which grid cells intersect with land.

The fitting of the cosine model was done using an Octave program that was run for all cells. The Octave program is in Appendix 1. The results were saved into text files `cosine/*.out`. The coding is as in table 1. The results are stored in the files as:

y=<year>
lat=<rotated latitude>, lon=< rotated longitude>
$<\theta_m> <\alpha_m> <\tau_m> <\sigma>$
$< D^{-}_{prob} >$
…

The *.out files were then processed further to produce a set of model and scenario specific hdr/bil raster files (stored into the directory `var/`). The hdr/bil files are in the native grid rotated latitude and longitude coordinate systems.

These results were then compared against D_{ice} values from GLRIP to determine the values of c and d_f for different types of lakes. For regionalization it was determined that for the parameter d_f the value of 0.05 best represents shallow lakes, the value of 0.15 small deep lakes, and the value of 0.25 large deep lakes; and the value of 2 for the parameter c best represents all lakes. However, there are many lakes that deviate from this general pattern regarding the value of these parameters and the results should be interpreted with caution.

Becoming earlier of the timing of ice-off

Computation of this impact was based on a model for lake ice ice-off developed by Weyhenmeyer et al (2004). The equation they obtained for the Julian day of ice ice-off of Swedish lakes is

$$t_b = \left(\frac{365\mathrm{d}}{2\pi}\right)\arccos\left(\frac{2T_m}{24^\circ\mathrm{C} - T_m}\right) + 55\mathrm{d}$$

Where T_m is the annual mean temperature at the site.

The equation for becoming earlier of the timing of ice-off is thus

$$\Delta t_b = \left(\frac{365\mathrm{d}}{2\pi}\right)\left[\arccos\left(\frac{2T_{mc}}{24^\circ\mathrm{C} - T_{mc}}\right) - \arccos\left(\frac{2T_{mf}}{24^\circ\mathrm{C} - T_{mf}}\right)\right]$$

Where T_{mc} is the current annual mean temperature at the site and T_{mf} is the future annual mean temperature at the site.

Computations and results

The annual mean temperature was computed from the RCM simulations and stored in model and scenario specific hdr/bil raster files. The maps for becoming earlier of the timing were then computed using raster algebra.

Increase in summer temperature of lake surface water

Computation of this impact was based on a model for the summer lake surface water temperature developed by George et al (2007). The equation they obtained for the summer lake surface water temperature is

$$T_s = (-0.004*Z_t + 1.10)*T_a + (-0.146*Z_t + 2.33)$$

Where Z_t is the depth of thermocline, and T_a is the mean summer air temperature. It should be noted that the depth of thermocline is also in general a function of the mean summer air temperature.

The equation for the increase in summer temperature of lake surface water is thus, assuming no change in thermocline depth:

$$\Delta T_s = (-0.004*Z_t + 1.10)*(T_{af} - T_{ac})$$

Computations and results

The summer mean temperature was computed from the RCM simulations and stored in model and scenario specific hdr/bil raster files. The maps for the increase in summer temperature were then computed using raster algebra. The depth of thermocline was set to 3 m in the case of shallow lakes and to 8 m for large lakes.

The equation for the change in summer temperature of lake surface water includes thermocline depth. There are very few models that relate thermocline depth with climatic variables. It is common to predict the thermocline depth using morphometric characteristics (Hanna 1990). Pompilio et al (1996) present a synthesis of predictive models for thermocline as a function of fetch.

The physical simulations of Lake Erken in CLIME give a small decrease (0.8 m ... 0.9 m) in max thermocline depth during the months June - August depending on model and scenario (Table 2).

Table 2. Average values from the PROBE simulations done on Lake Erken.

Scenario	T surface (ºC)	T lake (ºC)	Z thermocline (m)	T air (ºC)	Wind (m/s)	Cloud cover (%)
Control	16.4	15.1	13.6	14.5	5.4	82
B2	20.0	18.3	12.8	18.3	4.7	79
A2	20.7	18.9	12.7	19.0	4.5	76

4 The data preparation workflow

The workflow for preparing data for the interactive web pages is shown in figure 3.
The RCM data is referred to in table 1. They are NetCDF files obtained from the PRUDENCE website. The main tool for reading data from the RCM files is the NetCDF library, which is used through the PDL::NetCDF Perl module. Table 3. describes the tools and data files that are related to the grid metadata[4]. Table 4. describes the tools and data files that are related to computing rasters from the RCM data. Table 5 describes the tools for computing the impact mapping data. Table 6 describes the tools and data files that are related to computing the mapping data.

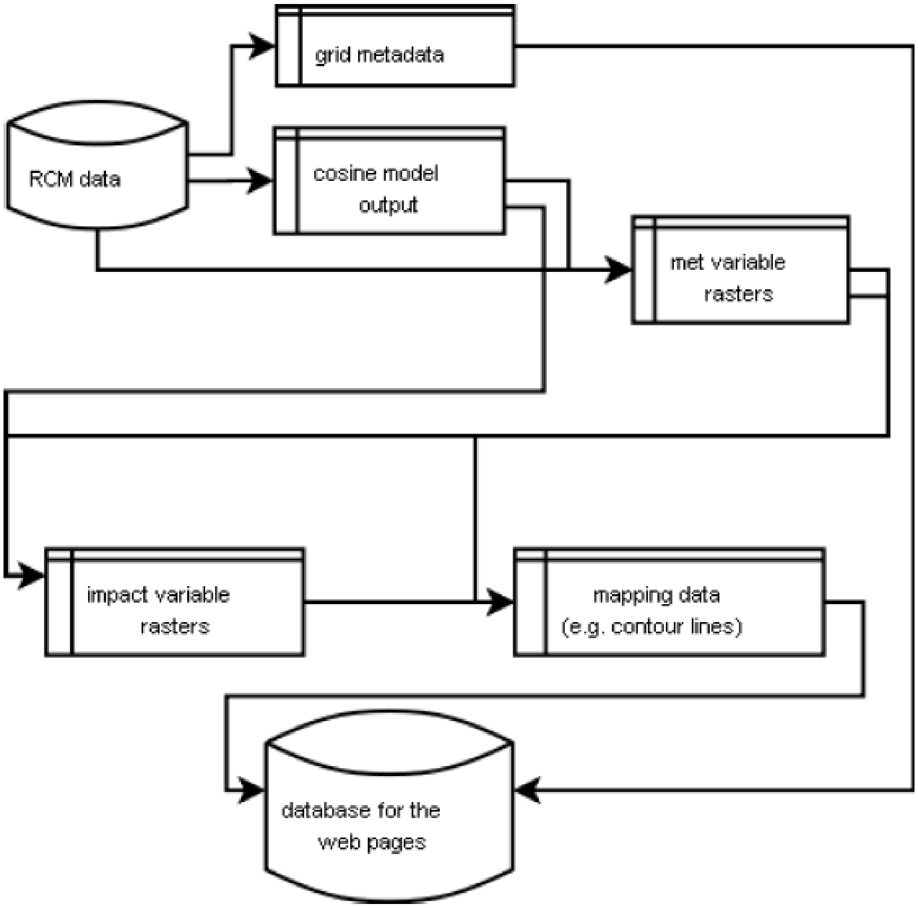

Figure 3. The data preparation workflow for producing mapping data from the RCM data.

Table 3. The grid metadata and related tools.

Datafile / tool	**Description**
grids/*-land	Grid cells that contain land. Column 1 is rlat*100+rlon, column 2 is not used (it was the amount of land cells – in view resolution at the time of preparation – within the grid cell)
grids/grids.pl	A simple tool to pull the rotated coordinates of grid cells from a NetCDF file.
grids/*.rlon and grids/*.rlat	The rotated coordinates of the grid cells. Grid cells are referred to with integers and these integers can be converted to rotated coordinates using these values. The axes of the grids are perpendicular to the axes of the rotated coordinates.
grids/rotate2.xls	An excel workbook for converting coordinates between rotated coordinat and latitude and longitude. The mathematics of this is explained below in section *rotation of latitude and longitude.*
Subroutine my_rotate in rotate.pl	The same coordinate conversion math as in rotate2.xls. Used together wit *.rlon and *.rlat files and a map projection converter Geo::Proj4 for converting data in grid coordinates to map coordinates (subroutine transform in rotate.pl).

Table 4. Tools for computing meteorological rasters

Datafile / tool	Description
cosine/octave.m	An Octave program for fitting the cosine model and estimating the tota duration of the periods of negative mean air temperature.
cosine/dprob.pl	A Perl program, which retrieves data from the NetCDF files and runs octave.m (the program is rewritten into the Perl program) for all land cells and for all years there is data from in the NetCDF file.
cosine/dprobs.sh	A shell script for running the dprob.pl for all model and scenario combinations.
cosine/*.out	Output from dprob.pl. The format is described above in *duration of the ice cover*.
T_summer.pl	A tool for computing the average summer (from June 1. to August 31.) air temperature rasters.
out2var.pl	A tool to prepare data for the regionalization of the duration of ice cov model. Reads the cosine model output data from the *.out files, performs a linear regression for the cumulative probability function, an saves the results into rasters theta, alpha, tau, sigma, mean, m, r, D. Th first four and the last are averages of the cosine model, and mean is μ, and m is *m* of the regionalization model. r is the correlation coefficient of the regression.
var/*.bil and var/*.hdr	Meteorological and impact variables stored as rasters. The rasters are i the grid coordinates.

Table 5. Tools for computing impact mapping data

Datafile / tool	Description
var/*.bil and var/*.hdr	Meteorological and impact variables stored as rasters. The rasters are i the grid coordinates.
ice-intermittent.pl	A tool for computing the mapping data for the impact analysis 1 (Regions whose lakes may start experiencing ice-free winters). This to creates vector mapping data directly using the Polygonize method.
ice-duration.pl	A tool for computing the mapping data for the impact analysis 2 (Shortening of the duration of ice cover).
ice-earlier.pl	A tool for computing the mapping data for the impact analysis 3 (Becoming earlier of the timing of ice-off).
summer_surface_temp.pl	A tool for computing the mapping data for the impact analysis 4 (Increase in summer temperature of lake surface water).
thermocline.pl	A tool for computing the mapping data for the impact analysis 5 (Change in thermocline depth).

Table 6. Tools for analysing the met and impact rasters and for computing the mapping data and importing it into the database of the web pages.

Datafile / tool	**Description**
mhpf.pl	A tool to fit the cosine model for all GLRIP lakes and retrieve respective RCM control run regionalization parameters from the rasters computed with out2var.pl.
mhpf2.xls	This is an excel workbook, which contains output from mhpf.pl. This tool was used to determine the values for the regionalization parameters c and d_f for the web pages.
contours.pl	A tool for generating contour lines from rasters. The contour line intervals are hard-coded into the code. The tool is merely a wrapper to run the utility program gdal_contour, which is used to create contours from the met and impact rasters. No coordinate conversion is done.
contours/*.shp, contours/ *.dbf, and contours/*.shx	The mapping shapefiles. These data are still in the grid coordinate system. The format is shapefile. These are mostly contour lines but may also be polygonized rasters.
rotate.pl	A tool to convert mapping data (which is shapefiles) into the EPSG 3035 map coordinates and import them into the RDBMS. The tool prints to the stdout SQL code, which can be used to move the data from separate tables into table c which is used to store all variable data.

Rotation of latitude and longitude

The DSS displays maps of Europe where data computed from the rasters is overlaid on top of a base map. The visualization data is firstly created from the raster data using polygonization or the gdal_contour program from the GDAL suite of utility programs; and secondly it is transformed to the ETRS LAEA 5210 (EPSG:3035) map projection using a program developed for the DSS (appendix 2). The program uses the Geoinformatica framework.

In the tool the transformation to the map projection is done using the PROJ.4 library through the Geo::Proj4 Perl module, but the rotation of the latitude and longitude from a RCM grid is programmed here. The rotation is based on a rotation matrix:

$$p' = \mathbf{A}p$$

$$\mathbf{A} = \begin{pmatrix} \cos\beta\ \cos\gamma & -\cos\beta\ \sin\gamma & -\sin\beta \\ \sin\gamma & \cos\gamma & 0 \\ \sin\beta\ \cos\gamma & -\sin\beta\ \sin\gamma & \cos\beta \end{pmatrix}$$

$$\beta = -(90^\circ - \varphi)\pi / 180^\circ$$

$$\gamma = -\lambda\pi / 180^\circ$$

where

p contains the coordinates of a point in non-rotated coordinate system,

$\mathbf{A}$ is the rotation matrix,

p' contains the coordinates of a point with respect to the rotated pole coordinate system,

φ is the latitude of the rotated pole in degrees

λ is the longitude of the rotated pole in degrees

The φ and λ for the grid that SMHI has used are 32 and 25 respectively, and for that used by Hadley Centre are 38 and 10 respectively (Corripio, not dated).

5 The interactive web pages

The CLIME DSS JRC website consists of several components; its architecture is depicted in figure 4. The website components are in the subdirectory web of the digital delivery.

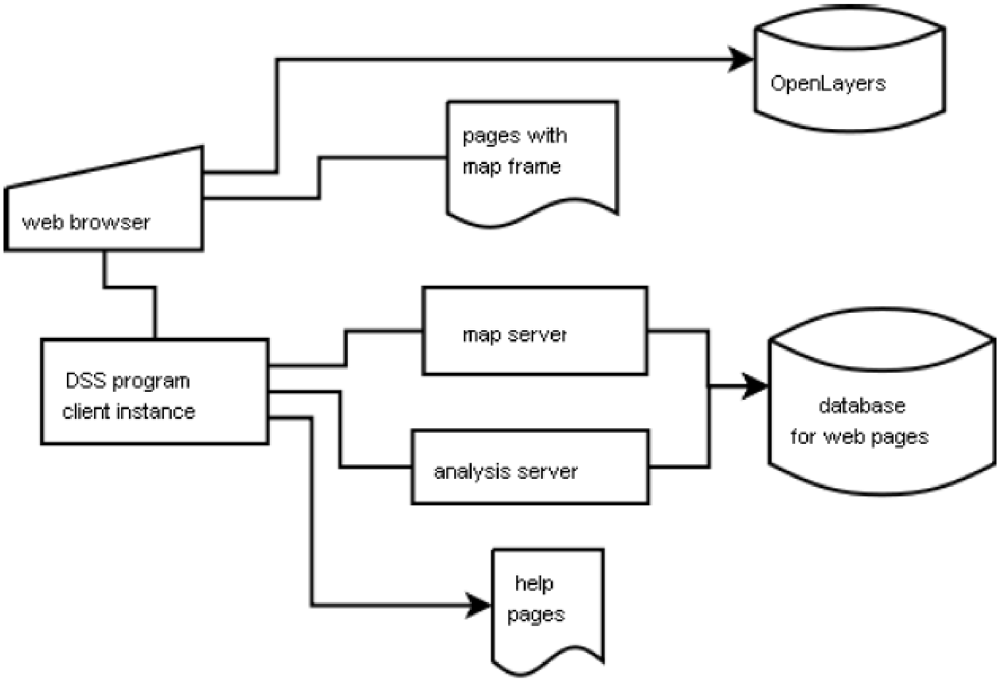

Figure 4. The architecture of the DSS.

The mapping functionality of the DSS is based on the OpenLayers, which is a FOSS Javascript library for mapping. When a user starts working with the DSS, she opens the page of the DSS[5] and her web browser gets with the main page also the OpenLayers Javascript library. The main page consists of a map frame, a set of controls, and a javascript program. The program works in the background, at the browser, and responds to the actions the user does with the controls.

OpenLayers implements several industry-standard methods for accessing geospatial data. The DSS exploits only one of them, namely view-based (non-tiled) WMS[6]. In view-based WMS, a map layer is generated every time anew, when the view changes. The DSS is based on layers, there is a base map, possibly a lake layer, and an impact layer. The impact layer is replaced with a met variable layer in the climate variable map page. All layers are generated on-demand by the map server.

The map server is, as most of the other tools, based on the Geoinformatica software platform. The map server itself is a Perl program, whose web-functionality comes mostly from the CGI Perl module. In the program there are two main subroutines (GetCapabilities_1_1_1 and GetMap_1_1_1), which implement some functionality according to the WMS 1.1.1 standard. The

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[5] http://clime.tkk.fi/jrc

[6] WMS is Web Map Service, a standard developed by OGC: http://www.opengeospatial.org/standards/wms

jrc-wms.pl program is able to generate map layers in EPSG 3035 projection from the country dataset, lake datasets, and the variable datasets.

The DSS programs in the map frame pages are simple and configured to use only the jrc-wms.pl map server at the CLIME website http://clime.tkk.fi but it is very easy to configure it to use other servers in addition or instead of the CLIME server.

The DSS consists of three web pages. The main page is the impacts page. From the impacts mapping page there is a link to the climate variable mapping page. From the climate variable mapping page one gets to the analysis page. The analysis page is an advanced feature of the DSS. It is meant for interactive study of the duration of ice-cover model regionalization. It uses the GLRIP data in the Database and performs the linear regression analysis for the selected site and the nearest GLRIP lake. The regionalization parameters can then be changed by the user. More information about how to use the tool is in the user manual.

The help pages are small text pages, which are opened in a new browser window, when help links are clicked on the pages.

References

Corripio, J.G. (not dated) RotateGrid software manual http://www.arolla.ethz.ch/IDL/RotateGridInfo.pdf (accessed 15.11.2008)

George, G., Hurley, M. and Hewitt, D. (2007). The impact of climate change on the physical characteristics of the larger lakes in the English Lake District. Freshwater Biology, 52 (9), 1647-1666.

Hanna, M. (1990) Evaluation of Models Predicting Mixing Depth. Can. J. Fish. Aquat. Sci. 47(5): 940–947

Livingstone, D.M., and Adrian, R. (in press). Modeling the duration of intermittent ice cover on a lake for climate change studies.

Pompilio, L., W. Ambrosetti And L. Barbanti. (1996) Morphometry and thermal stratification in Italian lakes. 1. Predictive models. Memorie dell'Istituto Italiano di Idrobiologia. Vol 54.

Weyhenmeyer,G.A., Meili, M., and Livingstone, D.M. (2004). Nonlinear temperature response of lake ice breakup. Geophysical Research Letters Vol. 31, L07203, doi:10.1029/2004GL019530, 2004.

Appendix 1. The octave model for fitting the cosine model and estimating the total duration of the periods of negative mean air temperature

```
y = 1;
x = […data…]';
t = (1:360)';
theta = mean(x);
air = inline(“theta - p(1)*cos(2*pi*p(2)*(x.-p(3)))”, “x”, “p”);
[f1, p1, kvg1, iter1, corp1, covp1, covr1, stdresid1, Z1, r21] = leasqr(t,x,[-9,0.002,12],air);
sigma = std(x-f1);
f = inline(“erf((theta-p1(1)*cos(2*pi*x))/(sigma*sqrt(2)))”, “x”);
[dprob,ierror,nfneval] = quad(f,0,1);
```

Appendix 2. A Perl program for converting a vector data layer in rotated grid coordinates to projection (specified as EPSG:3035 in the program code).

```
use PDL;
use PDL::NetCDF;
use Geo::GDAL;
use Geo::Proj4;
use Geo::Vector;

$grid = shift @ARGV;

my @rlon = read($grid.'.rlon');
my @rlat = read($grid.'.rlat');

$in = shift @ARGV;
$out = shift @ARGV;

$v1 = Geo::Vector->new(datasource=>'.', layer=>$in);
$v2 = Geo::Vector->new(datasource=>'.', update=>1, layer=>$out, schema=>$v1->schema);

$pi = 3.14159265;

my @Ainv;

if ($grid eq 'smhi') {
    @Ainv = ([0.480269956,    -0.422618262,  -0.768592593],
             [0.223953558,    0.906307787,   -0.358400612],
             [0.848048096,    0,      0.529919264]);
} else {
    @Ainv = ([0.606308194,    -0.173648178,  -0.7760391],
             [0.106908493,    0.984807753,   -0.136836631],
             [0.788010754,    1.07697E-17,   0.615661475]);
}

my $proj = Geo::Proj4->new(init => "epsg:3035") or die Geo::Proj4->error;

$i = 0;
$n = $v1->feature_count;
$v1->init_iterate;
while ($f = $v1->next_feature) {
    $i++;
    my $g = $f->GetGeometryRef->Points;
    transform($g);
    my $l = _length($g);
    next if $l < 300000;
    $f->GetGeometryRef->Points($g);
    $v2->add_feature($f);
    print "$i/$n\n";
}

sub _length {
    my $l = 0;
    if (ref $_[0][0]) {
        for (@_) {
            $l += _length(@$_);
        }
    }
    else {
        for my $i (0 .. $#$_-1) {
            $l += sqrt(($_->[$i+1][0]-$_->[$i][0])**2+($_->[$i+1][1]-$_->[$i][1])**2);
        }
    }
    return $l;
}

sub transform {
    if (ref $_[0][0]) {
        for (@_) {
            transform(@$_);
        }
    }
    else {
        for (@_) {
            @l = rotate(@{$_});
            @{$_} = $proj->forward($l[1], $l[0]);
```

```
            }
        }
}

sub rotate (;@) {
    my($x, $y) = @_;

    my $i = int($x);
    $i = $#rlon if $i > $#rlon;
    my $f = $x - $i;
    my $i2 = $i+1;
    $i2 = $#rlon if $i2 > $#rlon;
    my $rlon = $rlon[$i] + $f * ($rlon[$i2] - $rlon[$i]);

    $i = int($y);
    $i = $#rlat if $i > $#rlat;
    $f = $y - $i;
    $i2 = $i+1;
    $i2 = $#rlat if $i2 > $#rlat;
    my $rlat = $rlat[$i] + $f * ($rlat[$i2] - $rlat[$i]);

    my $theta = $rlon/180*$pi;
    my $phi = (90-$rlat)/180*$pi;

    my $cos = cos($phi);
    my $tan = tan($theta);
    my $xp = sqrt(( 1 - $cos**2 ) / ( 1 + $tan**2 ));
    my $yp = $xp * $tan;
    my $zp = $cos;

    my $x = $Ainv[0][0]*$xp + $Ainv[0][1]*$yp + $Ainv[0][2]*$zp;
    my $y = $Ainv[1][0]*$xp + $Ainv[1][1]*$yp + $Ainv[1][2]*$zp;
    my $z = $Ainv[2][0]*$xp + $Ainv[2][1]*$yp + $Ainv[2][2]*$zp;

    $theta = atan2($y, $x);
    $phi = acos($z);

    $lon = $theta/$pi*180;
    $lat = 90-$phi/$pi*180;
    return ($lon, $lat);
}

sub read {
    my $fn = shift;
    my @data;
    open FN, "$fn" or die "$fn $!";
    while (<FN>) {
        chomp;
        s/\r//;
        push @data, $_;
    }
    close FN;
    return @data;
}
```

ANNEX 2:

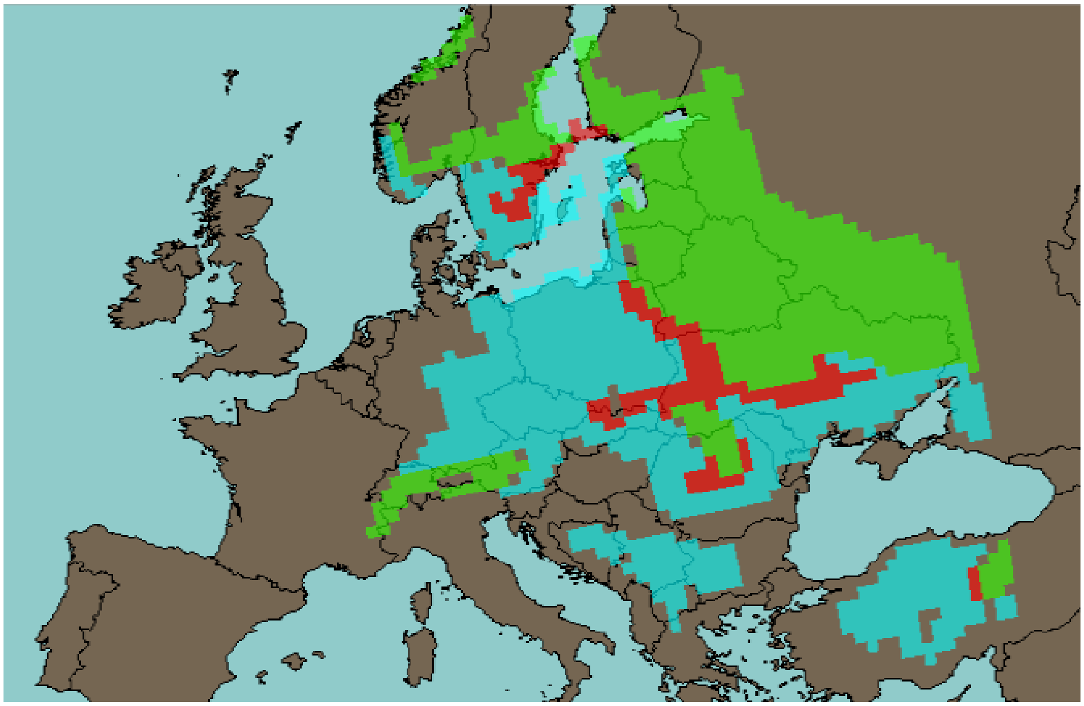
CLIME Maps – Decision support system. Manual

Helsinki University of Technology - TKK
Otakaari 1, FI-02150 Espoo, Finland

CLIME Maps – Decision support system

Manual

March 2009



1 Table of contents

2 General

2.1 About CLIME Maps

CLIME Maps is a decision support system designed to implement models that predict climate change driven transitions in the physical characteristics of European lakes. CLIME Maps was developed in the Helsinki University of technology. CLIME Maps is an improved version of the CLIME DSS developed in 2007 (located in http://geoinformatics.tkk.fi/bin/view/Main/CLIMEDSS). Compared to its earlier release, CLIME Maps is focused only on the physical characteristics of the lakes and producing simple and understandable maps depicting the impacts of climate change. Also the structure of the application has been changed in order to make it easily accessible for users. The lake database is extended from the earlier release.

Clime Maps predicts the impacts of climate change on physical characteristics of lakes. These predictions are targeted for the years 2071-2100 and are based on daily averages of air temperature obtained from high resolution climate change scenarios produced by the PRUDENCE project.

The CLIME Maps can be accessed with any standard Internet web browser. The application is available at CLIME web page http://clime.tkk.fi/jrc. This address opens the front page of the CLIME Maps web application.

The CLIME Maps application is divided into two main map windows:

1) Impacts map page i.e. front page

2) Climate variable map page

In both these pages the user can select the scenario and study the impacts of climate change on the selected variable. The impact is presented as different colors or contour graphs on the map or in an analyze window depending on the chosen variable. Climate variable map page contains information in more detail and untreated way and is directed for advanced users. Climate variable map page can be accessed by clicking a link on the front page or by accessing it directly at http://clime.tkk.fi/jrc/variables.html. Functionality and graphical user interface of both pages is described in this manual.

2.2 About this manual

This manual explains the operations built in the CLIME Maps web application. The most importan objective of this manual is to explain how the graphical user interface works. This manual contains all information needed to view the predrawn maps integrated into the CLIME Maps. Also a brief explanation of the models behind the map presentations is described.

2.3 Frequently used terms

There are certain terms and concepts that are used consistently throughout this manual. For a clear understanding these terms are collected here and explained:

Button: A button is a virtual operation element which can be activated by single click.

IPCC Scenario A2: IPCC Scenario A2, later refered simply as A2, is a climate change scenario which is one possible outcome of future. The A2 scenario describes the future where the rate of greenhouse gas emissions continue to increase until year 2050.

IPCC Scenario B2: IPCC Scenario B2, later refered simply as B2, is a climate change scenario which is one possible outcome of future. The B2 scenario describes the future where the rate of greenhouse gas emissions does not increase until year 2050. The climate change impacts of B2 scenario are therefore less drastic than A2.

3 Impacts map page

Impacts map page is the front page of the CLIME Maps (Figure 1). Impacts map page includes these following parts (from top to bottom):

1) Map window

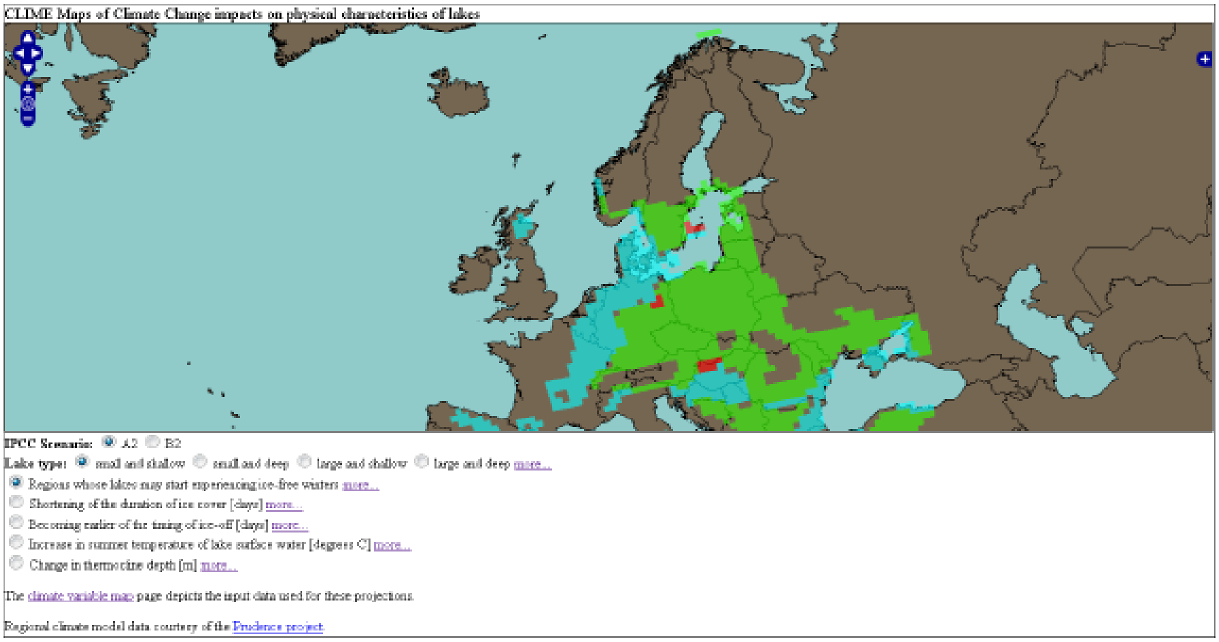
2) IPCC Scenario selection buttons

3) Lake type selection buttons

4) Presented map variable buttons

5) A link to the climate variable map page

6) A link to the Prudence project



CLIME Maps of Climate Change impacts on physical characteristics of lakes

IPCC Scenario: ● A2 ○ B2

Lake type: ● small and shallow ○ small and deep ○ large and shallow ○ large and deep more...

● Regions whose lakes may start experiencing ice-free winters more...

○ Shortening of the duration of ice cover [days] more...

○ Becoming earlier of the timing of ice-off [days] more...

○ Increase in summer temperature of lake surface water [degrees C] more...

○ Change in thermocline depth [m] more...

The climate variable map page depicts the input data used for these projections.

Regional climate model data courtesy of the Prudence project.

Figure 1. Front page of the CLIME Maps-application.

3.1 Map window

The map window at the front page (Figure 1) presents a map of Europe with chosen layers. The user can zoom in or out by using the zoom tool located in the upper left corner of the map window (Figure 2). The map can be panned to desired direction by clicking the arrows located in the upper left corner of the map window. In the impacts map page the user can also move the map by simply clicking and holding mouse button pressed and moving mouse.

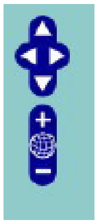


Figure 2. Navigation arrows (above) and zoom tool (below) located in the upper left corner of the map window.

The user can change the map layers by clicking the "+" icon on the top right of the map window. This opens the layer selection window, which contains two layer alternatives and five overlays (Figure 3). The default layer presented in the map window is Basemap-layer which is a vector layer containing shoreline and nation borders. Alternative to the base layer is Corine land cover raster layer. The user can select from five overlays to be viewed on top of the chosen layer:

CLIME lakes: Lakes from the CLIME project database

CORINE lakes: Lakes larger than 1 km^2 (10 547 lakes) from the Corine land cover dataset

GLRIP lakes: Lakes that are in the GLRIP (Global lake river ice phenology) database.

A2: IPCC Scenario A2

B2: IPCC Scenario B2

Base Layer
● Basemap
○ CORINE
Overlays
☐ CLIME lakes
☐ CORINE lakes
☐ GLRIP lakes
☑ A2
☐ B2

Figure 3. Layer selection window.

3.2 Scenario selection

IPCC Scenario selection is found in the first row below the map window. There user can choose between two scenarios A2 and B2 (Figure 3). Only one scenario can be visible on the map at a time

3.3 Lake type selection

Lake type can be selected similarly as the scenario by simply clicking the option button of the certain lake type user prefers (Figure 4). Lake type classification is based on area and depth of lake (Table 1). By clicking "more"-link a window containing brief characterization of lake type effect is opened. Only one lake type can be selected at a time.

IPCC Scenario: ● A2 ○ B2
Lake type: ● small and shallow ○ small and deep ○ large and shallow ○ large and deep more...

Figure 4. IPCC Scenario selection and lake type selection buttons.

Table 1. Lake classification used in the CLIME maps.

Lake Type	Area (km^2)	Depth (m)	Thermocline depth (m)
Small and shallow	< 100	< 6	3
Small and deep	< 100	> 6	8
Large and shallow	> 100	< 6	3
Large and deep	> 100	> 6	8

3.4 Ice-free winters map

By clicking the button "Regions whose lakes may start experiencing ice-free winters" a map visualization predicting the change in lake ice conditions is shown in the map window. Prediction is presented for the IPCC scenario and lake type that are chosen by the user. By clicking "more"-link a window containing brief characterization of ice-free winters analyze is opened.

The map illustrates predicted changes as different colors, where:

Green: The lakes on green areas may shift from being typically always ice-covered in winters to being ice-free in some winters.

Blue: The lakes on blue areas may shift from being ice-free in some winters to being typically never ice-covered in winters.

Red: The most drastic change is described with red color. Lakes on red areas may shift from being typically always ice-covered in winters to being never ice-covered in winters.

No colour: No predicted change to present conditions.

The Ice free winter map was calculated with cosine model presented by Livingstone & Adrian (in press). The model is based on linear dependence between number of days below zero calculated from the regional climate data model and the total duration of ice cover. This approach is applicable for intermittent ice cover since it describes total duration of ice cover.

3.5 Duration of ice cover map

By clicking the button "Shortening of the duration of ice cover", a map visualization predicting the change in lake ice conditions is shown. The prediction is presented for the scenario and lake type that are chosen by the user. By clicking "more"-link a window containing brief characterization of shortening of ice-cover analyze is opened.

The map illustrates the predicted change in days as contour lines. Each contour line demonstrates a shift of ten days. The shortening of the duration is calculated based on the same model as the ice-free winters map, though results are demonstrated in a different way.

3.6 Timing of ice-off

By clicking the button "Becoming earlier of the timing of ice-off", a map visualization predicting the change in lake ice-off is shown. The prediction is same for all lake types due to the characteristic of the used model. By clicking "more"-link a window containing brief characterization of becoming earlier of ice-off analyze is opened.

The map illustrates an average of how many days earlier lake ice-off is predicted to happen. Number of days is presented as contour lines, where each line demonstrates a shift of ten days. The timing of ice-off is based on model developed by Weyhenmeyer *et al.* (2004). The model is developed for Swedish lakes and it is applied in the Clime Maps to present the possible changes that temperature increase would have on the ice-off date, not the actual ice off date. Due to model structure, this map is applicable for areas with regular ice cover. Thus it is not suited for areas with intermittent ice cover (in the map areas with no change).

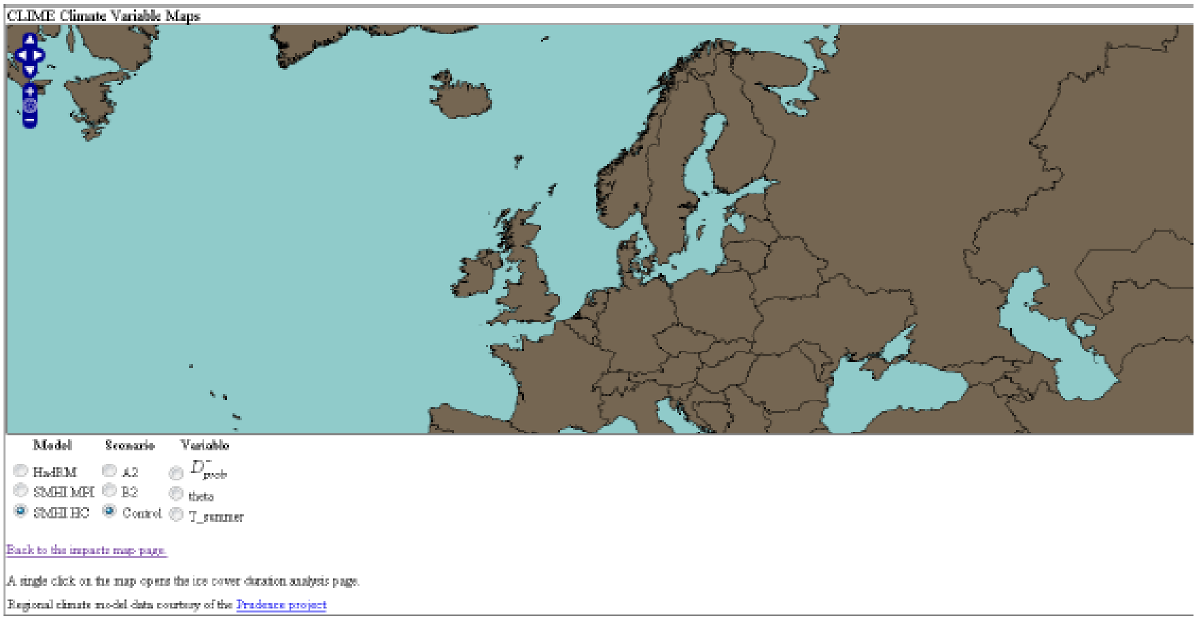
3.7 Increase in summer temperature of lake surface water

By clicking the button "Increase in summer temperature of lake surface water", a map visualization predicting the change in lake surface temperature is shown. The prediction is presented for the scenario and lake type that are chosen by the user. By clicking "more"-link a window containing brief characterization of shortening of ice-cover analyze is opened.

The map illustrates an average of summer temperature of lake surface water in °C. Temperature is presented as contour lines, where each line demonstrates a shift of one °C. The model used to calculate lake water summer surface temperature is presented by George *et al*. (2007) and the model is designed for English lake district. The model predicts summer surface temperature from air temperature and depth of thermocline. The calculations were done using temperature data from regional climate models and the depth of thermocline set to 3 m in shallow lakes and 8 m for deep lakes. In this calculation it was assumed that depth of thermocline would be constant.

4 Climate variable map page

Climate variable map page (Figure 5) is a feature for advanced users. With climate variable map page analysis window user can study interactively the duration ice-cover model regionalization by changing the regionalization parameters. The Climate variable map page uses the GLRIP data to perform linear regression analysis for the selected site and nearest GLRIP lake.



CLIME Climate Variable Maps

Model	Scenario	Variable
○ HadRM	○ A2	○ D^{-}_{prob}
○ SMHI MPI	○ B2	○ theta
● SMHI HC	● Control	○ T_summer

Back to the impacts map page.

A single click on the map opens the ice cover duration analysis page.

Regional climate model data courtesy of the Prudence project

Figure 5. Climate variable map page.

4.1 Model

The user can choose one from three regional climate models, which is the basis of calculation of chosen variable map. The models are:

1) HadRM: Hadley Centre Regional Climate Model.

2) SMHI MPI: SMHI (Sweden's Meteorological and Hydrological Institute) regional model with ECHAM4 global model.

3) SMHI HC: SMHI regional model with HadRM global model.

4.2 Scenario

The user can choose one from three scenarios, which is the basis of calculation of chosen variable map. The scenarios are:

1) A2: Results are predicted for years 2071-2100.

2) B2: Results are predicted for years 2071-2100.

3) Control: Control scenario represents the present situation, which is calculated from years 1960-1990.

4.3 Variable

The user can choose between three variables which are presented as contour graphs in the map window from results precalculated for the chosen scenario/model-combination. The variables are:

1) D^{-}_{prob} = Estimated number of days below zero.

2) theta = Estimated yearly average temperature

3) T_summer = Computed summer (June-August) average temperature.

4.4 Analysis page

4.4.1 Content

In the climate variables map page the user can click a single location in the map window which opens a new analysis page (Figure 6).

The analysis page includes following information (from top to bottom)

1) Coordinates of the clicked point

2) The chosen model used to produce analysis graph

3) The closest lake in CLIME database

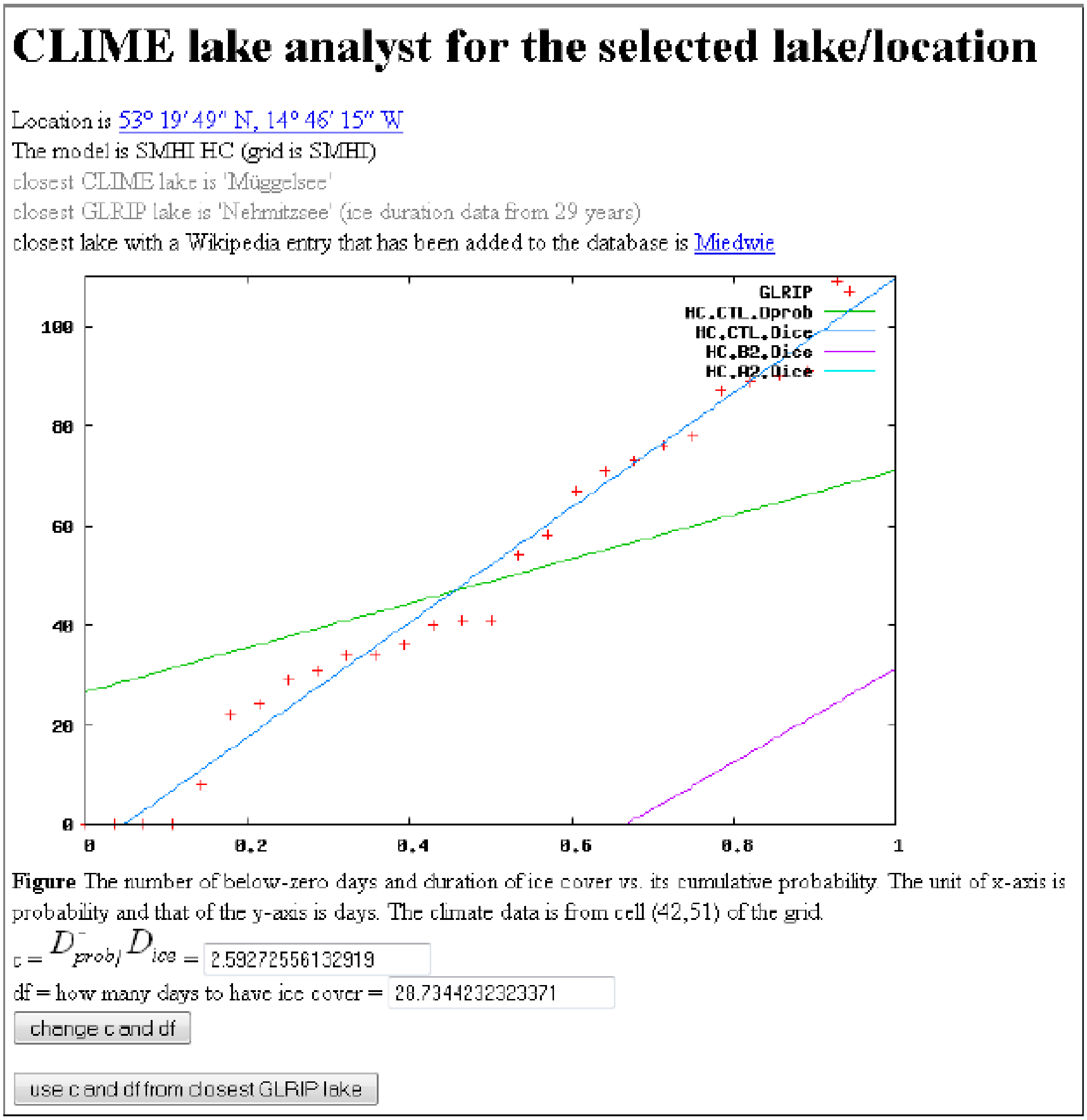
4) The closest lake in GLRIP database and length of the ice duration data of the lake in question.

5) The closest lake with an English Wikipedia entry and a link to this entry.

6) Analysis graph

7) c-value

8) df



CLIME lake analyst for the selected lake/location

Location is 53° 19′ 49″ N, 14° 46′ 15″ W

The model is SMHI HC (grid is SMHI)

closest CLIME lake is 'Müggelsee'

closest GLRIP lake is 'Nehmitzsee' (ice duration data from 29 years)

closest lake with a Wikipedia entry that has been added to the database is Miedwie

Figure The number of below-zero days and duration of ice cover vs. its cumulative probability. The unit of x-axis is probability and that of the y-axis is days. The climate data is from cell (42,51) of the grid.

$c = D^{-}_{prob} / D_{ice} =$ 2.59272556132919

df = how many days to have ice cover = 28.7344232323371

Figure 6. Analysis page for the selected location.

4.4.2 Analysis graph

The analysis graph, which is presented in Figure 6, is a graph showing cumulative probabilities of ice cover duration for different scenarios.

Red dots represent the ice duration data for different years from the closest GLRIP lake.

Green line is variable D^{-}_{prob}, number of days below zero, in control conditions, which is calculated from the NetCDF climate data for the chosen model/scenario-combination for the grid cell of the selected location.

Blue line is D_{ice}, number of days with ice cover, in control conditions fitted from ice data from GLRIP database.

Purple line is D_{ice} in B2 conditions

Cyan line is D_{ice} in A2 conditions.

The value c is D^{-}_{prob} divided by D_{ice}. This calculated value represents the relationship between number of days below zero to the duration of ice cover in the selected location. This value is used for regionalization of

The df value is the number of below zero days required for the lake in the selected location to freeze. In other words, it is a value describing lakes tendency to freeze: the lower the df value, the faster the lake freezes.

The regionalization parameters c and df are related to lake features. The df values for used lake types were obtained from the GLRIP database and applied for the ice duration analysis (Table 2).

Table 2. Values c and df for different lake types.

Lake Type	c	df
Small and shallow	2	0,05
Small and deep	2	0,15
Large and shallow	2	0,05
Large and deep	2	0,25

The user can study interactively the duration ice-cover model regionalization by changing the regionalization parameters c and df. At default, the regression analysis is done for the nearest GLRIP lake. By changing c and df it is possible to test lake ice duration of different lake types at the selected point.

5 Example: Climate change impacts on Lake Müggelsee

Here is demonstrated a step-by-step example how the user can make good use of CLIME Maps to produce information about the selected lake of interest. In our example the lake is Müggelsee located in Central Germany near Berlin.

1. First thing to do is to access the impacts map page at http://clime.tkk.fi/jrc. At the map page the view can be centered and zoomed in at the location of interest with zoom and arrow tools.

2. Select the scenario. In the example interest is on the worst case scenario impacts so the chosen scenario is A2.

3. Select the proper lake type describing the study lake. Lake Müggelsee is best fitted to the class "small and shallow lake" in the classification used in the CLIME Maps

4. Choose the first analysis variable, which is "Regions whose lakes may start experiencing ice free winters". Lake Müggelsee is located in the red area of the appered analysis map. This means that based on scenario A2, Müggelsee will experience totally ice-free winters in the predicted future.

5. Select second analysis variable, which is "Shortening of the duration of ice cover". A new analysis map appears with contour lines presenting the change in days. Lake Müggelsee is located between contour lines 70 and 80. This means that based on scenario A2, Müggelsee will experience shortening of 70-80 days in total ice cover duration in the predicted future.

6. Select the third analysis variable, which is "Becoming earlier of the timing of ice-off". A new analysis map appears with contour lines representing the change in days. However, Lake Müggelsee is located in an area with typically intermittent ice cover which is why it is located outside the circle of 0 days in the analysis. The analysis of the change of ice-off is suitable for lakes/areas with uniform ice cover.

7. Select the fourth analysis variable, which is "Increase in summer temperature of lake surface water". An analysis map appears with contour lines presenting the change in days. Lake Müggelsee is located between contour lines 4 and 5. This means that based on scenario A2, Müggelsee water surface temperature during summer time will increase 4-5 °C in the predicted future.

8. A more detailed analysis can be obtained from the Climate variable map page. The chosen model is HadRm. The view is centered and zoomed in at the location of interest.

9. Selection of variable "D^-_{prob}" opens a contour map of number of days below zero. By selecting scenario "Control" it can be seen that number of below zero days in tha area of Lake Müggelsee is 40-50 under present conditions. Changing the scenario to "A2" opens new map with D^-_{prob}, which is 10-20 in the area of Lake Müggelsee predicted for the future.

10. Selection of variable “theta” opens a contour map of number of yearly average temperatures. By selecting scenario “Control” it can be seen that yearly average temperatures in tha area of Lake Müggelsee is 9-10 °C under present conditions. Changing the scenario to “A2” opens new map of theta, which is 14 °C in the area of Lake Müggelsee predicted for the future.

11. Selection of variable “T_summer” opens a contour map of average summer (June-August) temperatures. By selecting scenario “Control” it can be seen that average summer temperature in the area of Lake Müggelsee is 18-20 °C under present conditions. Changing the scenario to “A2” opens new map with T_summer, which is 24°C in the area of Lake Müggelsee predicted for the future.

12. Clicking the location of Lake Müggelsee opens an analysis window is opened for more detailed view. From the analysis page regression analysis it can be concluded that a) Lake Müggelsee has a ice duration record of 15 years with variation in range between 0 and 95 days b) For scenario B2 the probability for winter being is free of ice is 0.70 c) For scenario A2 the probability of winter being free of ice is 0.92 d) Lake Müggelsee requires average of 24 below zero days in order to freeze.

Summary of the results obtained from CLIME Maps for Lake Müggelsee with A2 climate change scenario:

- Lake Müggelsee will experience very likely totally ice free winters in the future with changing climate

- Total annual ice cover duration of Lake Müggelsee will decrease 70-80 days from the present state

- Summer surface temperature of Lake Müggelsee will increase 4-5 °C.

- The yearly average air temperature in the area of Lake Müggelsee will increase from 9-10 °C to 14 °C

- The summer (June-August) average air temperature at Lake Müggelsee location will increase from 18-20 °C to 24 °C.

- Average of 24 below zero days will form ice cover to Lake Müggelsee.

6 References

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Livingstone D.M & Adrian R. (in press) Modeling the duration of intermittent ice cover on a lake for climate-change studies. Limnology and Oceanography.

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Abstract

One of the tasks of the EEWAI action is the assessment of the impacts of climate change on ecological water quality in order to support the implementation of the Water Framework Directive. This task requires development of comprehensive knowledge base, models, and databases to provide tools for the evaluation of the adaptation needs of the EU water resources management with respect of the anticipated changes in water quality due to climate change. In 2008, EEWAI initiated a service contract between Joint Research Centre and Helsinki University of Technology in order to develop further a Decision Support System elaborated within the EU project CLIME into a new tool called CLIME Maps. The aim was to extend the central lake database, to update the computational basis of lake physical parameters by applying the newest achievements in this field of science, and enable creating map views of the projected changes of physical parameters of basic lake types. Based on the model results, this report gives an overview of the impacts that climate change may have on physical properties of lakes and demonstrates further implications that these changes have on lake ecosystems. The technical report on CLIME Maps and the users' manual are included in annexes of the report.

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