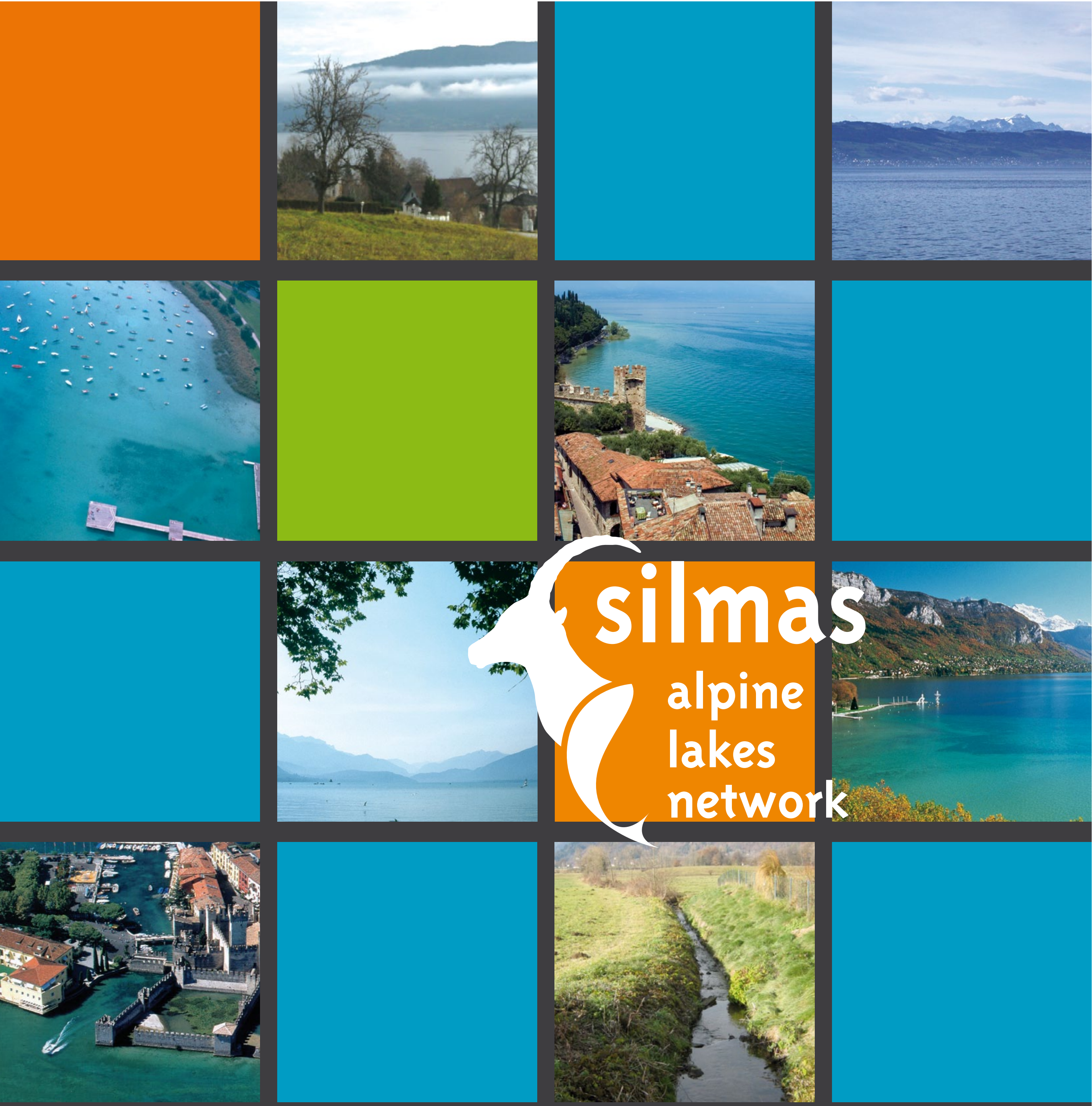

silmas
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network

Climate Change Impacts on Alpine Lakes

Alpine SPACE
EUROPEAN TERRITORIAL COOPERATION
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Summary

Introduction

Natural and artificial lakes are a main characteristic of the Alpine Space and belong, with their catchment areas, to the European heritage. They have much in common in their physical, ecological and even socio-economic features. Despite the administrative boundaries, they all convey the same identity. These lakes are important from the economical point of view, and they are used in different ways (touristic, industrial, agricultural, drinking water).

In 2004 was born the Alpine lake network through Alplakes Project, co-funded by European Regional Development Fund (ERDF) within the Alpine Space Programme Interreg IIIB, with the aim of sharing information and management tools between the lakes managers, for the strategic issues within the principle of sustainable development.

For a 3 year period (2004 - 2007) French, Italian, Austrian, Swiss and Slovenian institution worked on a range of issues, including ecotourism, sustainable development and the environment of the Alpine lakes, in order to preserve and improve the lake environment. The discussions and shared experience were recorded in a large body of documents, which are available on internet *(www.alpine-space.org)*.

Since the importance of this subject, the institutions involved in Alplakes decide to continue the activity started in 2004, starting up in 2009 with the 3-years project “Sustainable Instrument for lakes management tools in Alpine Space” (SILMAS), co-funded by European Regional Development Fund (ERDF) within the Alpine Space Programme co-funded by FESR, as completion of the Alplakes project.

In SILMAS worked 14 partners of 5 countries (Italy, France, Austria, Slovenia and Germany), leaded by Region Rhône-Alpes (France) *(Fig. 1)*.

SILMAS involved scientists, academics and technicians from the public authorities in charge of managing the lakes that pooled their knowledge, and identified methods and tools in order to preserve and protect the lakes environment.

SILMAS focused on three main areas: the effects on of climate change on alpine lakes *(Work package 4)*, Resolving conflicts between the different uses of the lakes *(Work package 5)* and Educating the public in sustainable development as it relates to the Alpine lakes *(Work package 6)*.

Within SILMAS project, Work Package 4 “Alpine Lakes running changes” worked on analysis of effects on climate change on lakes eco system: the partners involved, (the Institute for Lake Research State Institute for Environment for Germany, the National Institute of Biology per la Slovenia, Rhône-Alpes regional authority for French, the Regional Government of Carinthia and the Joanneum Research for Austria and the Regional Agency for the environment Protection in Piedmon, the Lombardy Region and the Agenzia per la Protezione Ambientale di Trento for Italy), shared methods and frames of references, and tested models in main types of lakes, to identify likely scenarios in which lakes could be involved. The network was designed as a virtual laboratory producing a dynamic vision of each situation, positioned into identified general trends and related to environmental requirements.

In order to reach the goals, WP4 has been subdivided in 4 actions:

- **Action 1:** Coordination and animation
- **Action 2:** Specifying lakes bodies and shores ecological functioning and trends by collecting and integration of ecosystem indices, related to climate variability
- **Action 3:** Characterizing hydrological impacts of climate change on lakes and catchments by applying hydro and thermodynamic models and isotopic analysis
- **Action 4:** Integrating biological hydrological and data into scenario in relation with main alpine lakes types

Action 1 is provided by Arpa Piemonte to plan meetings, fix methodologies and make transverse approach with other WPs possible, in order to define the timetable of activities

Since lakes are complex dynamic systems, interacting with local environment and connected to the water cycle, WP4 followed first two parallel ways to throw light on lakes evolution factors due to human activities and climatic variability: the biological approach and the physical/chemical approach

Action 2 concerns the biological approach: the collection of chemical, physical and biological historical data is used to analysed the trends and the significant ecological events. Action 4.3 concerns the determination of climate change on lakes and in the catchment areas (hydrological and thermodynamic aspects, mixing conditions, residence times). Applying models developed by LUBW PP and isotopic analysis will deliver data of past and scenarios of future hydrological and mixing conditions.

In a second stage this knowledge has been valorised by integrating findings of 4.2 and 4.3 investigations into helpful decision-making tool (action 4.4) They have been integrated in a temporal perspective, to describe likely scenarios to be expected from climate change, linked to the main types of lakes encountered in the alpine space. Adjustment strategies have been outlined for stakeholders, according to challenges every networking lake will have to meet, in terms of water resource management and ecosystems preservation or restoration.

1. Climate Change and Alpine Lakes

Global Climate Change

According to the IPCC (2007a) definition, atmospheric greenhouse gases (GHG) absorb more than other gases the thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. These GHG block the Earth back radiation to space causing a warmer atmosphere and a warmer earth surface.

This is a simplified sketch of the greenhouse effect showing one important process in the complicated radiation transfer processes in the atmosphere. Including all processes, the thermodynamic balance explains the long-term global surface temperature of about 15°C. Without greenhouse gases such as water vapor, carbon dioxide, nitrous oxide, methane and ozone, the mean earth's surface would be much colder -18°C.

Lakes exist by the presence of greenhouse gases because these gases store a part of the Sun's energy into the atmosphere and in diurnal cycles that create atmospheric motions so that finally move water rather than ice through the landscape, forming catchment areas as well as lakes. Lakes are the consequence of sensitive interactions among processes in the earth's atmosphere. As illustrated in Paragraph 2.1, there exists a strong connection between lakes and their local climate while their local climate is coupled to the global climate. In this general context, lakes are likely sensitive to changes in the global climate.

Life on Earth aspires as a perfect fitness by evolutionary optimization in all possible environments e.g. yielding a variety of living beings in, on, and around the lakes. This is especially true for human beings and their cultural and economic lake uses. Consequently, changes in global climate may bring life either in a more vulnerable position or adapt and redistribute into other species.

Definitions

Climate is defined as the worldwide (global) connection between numerous atmospheric, lithospheric, hydrologic, and anthropogenic processes. Climate is the mean condition within a period that is long enough for determining reliable statistics. The IPCC states: «*Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.*» (IPCC, 2007a).

Upon analyzing **changes** in the climate in terms of temporarily-averaged weather, long periods have to be considered. Notably, changes in climate conditions such as mean local air temperature cannot be detected over two or three years, but rather over decades. According to the IPCC the term climate change «*…refers to a **change** in the state of the climate that can be identified […] by **changes** in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate **change** may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.*» (IPCC, 2007a).

Climate change in the past

For understanding and discriminating the effect of **anthropogenic** greenhouse gas emissions on climate change from natural causes it is necessary to overview the history of the earth's climate.

In the Jurassic and cretaceous period dinosaurs breathed warm air with a CO_2 concentration up to a maximum of around 4000 ppm[1] (Berner and Kothavala, 2001) whereas the meanmeasured concentration at the Mauna Loa Observatory, Hawaii, was391.6 ppmin the year 2011 (Tans and Keeling, 2012). These low and precise values are estimated either byrecalculations of the past climate as by using proxy data like boron isotopes. Higher precision is achieved by ice core analysis dating several hundred thousand years back to present (e.g. Petit et al., 1999). From a geological perspective this period is very short although it covers the period of the evolution of Homo sapiens.

Figure 1.1 is quoted from the IPCC's 4th assessment report (IPCC, 2007a). One can see periods of high GHG concentrations but longer periods with low N_2O and CO_2 concentrations.

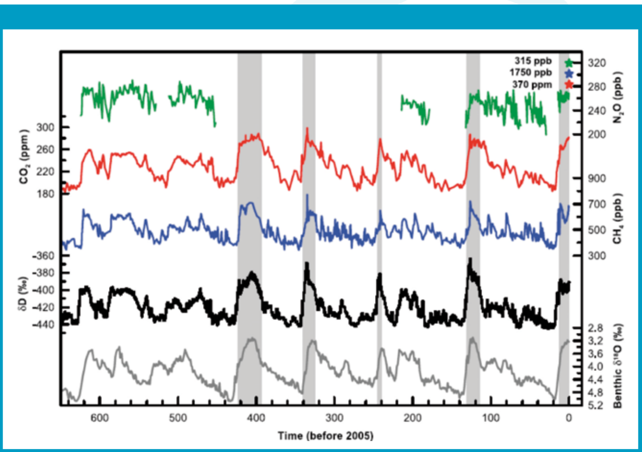

Figure 1.1 > Source: IPCC (2007), original figure description:'Variations of deuterium (dD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), methane (CH4), and nitrous oxide (N2O) in air trapped within the ice cores and from recent atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm periods'.

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[1] *«ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of greenhouse gas molecules to the total number of molecules ofdry air. For example, 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air.» (IPCC, 2007b)*

These changes correspond to the glacial-interglacial cycle. This 'Milankovitch Cycle' is caused by changes in the earth's orbit (Rahmstorf and Schellnhuber, 2006) and thus not by anthropogenic influences. Here, high GHG concentrations are caused by high temperatures with a GHG delay of centuries to a millennium. There are natural causes and anthropogenic causesfor climate change. In the last decades anthropogenic influences overlap dramatically these natural processes.

Within the ice core verified period climate changed several times very rapidly. There were changes within decades during glacial periods, e.g. the Dansgaard-Oeschger events with a warming in Greenland from 8°C to 16°C (Severinghaus and Brook, 1999; Masson-Delmotte et al.,2006). These changes are determined from local proxies and often they did not occur on the entire planet (Masson-Delmotte et al., 2005). Instead, the transitions from the glacial to the interglacial periods were slower but global. There were numerous cold and warm phases in the current interglacial that began around 10 thousand years ago. In this actual warm period there were several variations of GHG concentrations in the atmosphere and thus in the global mean temperatures, e.g. the 8.2ka[2] event (Alley et al., 1997). The 8.2 ka event was adecrease in global temperature approximately 8200 years ago.When focusing onto the last 2000 years volcanic aerosols and changing solar activity where the reasons for global climate changes (Böhm, 2008). Higher solar activity with the contribution of less active volcanos led to a 'Medieval Warm Epoch' around the 10th century. At that time parts of Greenland were settled by Norseman (Pettersson, 1914). The following cold conditions with minimum temperatures in the 16th century can be put down to the so called 'Maunder Minimum' that was characterized by less solar activity (e.g. Lean, 2000).

So we conclude that notable changes in the global climate occurred without anthropogenic influences. In other words, in principle not all changes in lakes can be attributed to (global) the anthropogenic influences presented in the next section.

Human caused climate change

From thousand years ago until the middle of the 1950s solar radiation and volcanoes caused climate changes. Since then, around 50 years ago, human activities appear to overwhelm the natural causes of climate change. In the time series of global mean temperature there is a significant upward trend before the 1950's *(see Figure 1.2)* but this trend is caused by increasing solar activity which reached a plateau in the middle of the 20th century. At that time humans caused their first noticeable climate signal. Firstly, from 1950s to 1970s a slight decrease in global temperature by extensive aerosol emissions (regarding sulfur see Stern, 2005). Subsequent efforts in reducing air pollution led to fewer aerosols in the air while GHG emissions continued to increase year by year.

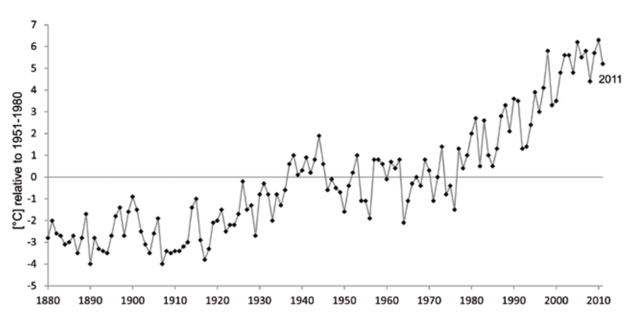

Figure 1.2 > Global Land-Ocean Temperature Index; base period: 1951-1980. Graph is based on data source: NASA Goddard Space Flight Center, Science and Exploration Directorate, Earth Science Division. http://data.giss.nasa.gov/gistemp

And that's why between the 1980s and today there is a change of global climate in a way that is unique in the younger climate history. The actual mean global CO2 concentration in the atmosphere of 391.6 ppm in the year 2011 (Tans and Keeling, 2012) is the highest since approximately half-million years (IPCC 2007). And this concentration rises with an exceptional speed but is still much less than the 4000 ppm analyzed for the Jurassic and cretaceous period.

Methane, being the major anthropogenic GHG beside nitrous oxide, reaches atmospheric concentrations exceeding those of the last 650ka (Spahni et al., 2005). The main source of methane are wetlands, rice agriculture, biomass burning, and ruminant animals (IPCC 2007). Since the end of the 1990s, the increase of methane concentration stopped (Simpson et al., 2002).

Water vapor is the dominant but not anthropogenic GHG. Water vapor is very uniformly distributed around the globe and indirectly influenced by other human GHG emission. Similar to the positive feedback of methane (higher concentration □ rising temperatures □ more methane production), feedback of water vapor content and air temperature is also positive. Warmer air cause more evaporation as well as evapotranspiration and consequently larger water vapor concentrations. Recent studies show that because of this feedback the positive temperature trend in Europe exceeds the global one (Philipona, 2005).

A constant global mean temperature implies an atmosphere in a global thermodynamic equilibrium. The earth's atmosphere, however, is far away from this equilibrium. Hence, climate change is better assigned as 'unbalancing' rather than warming. The patterns of the human caused climate change around the globe show this issue *(e.g. Figure 1.3).*

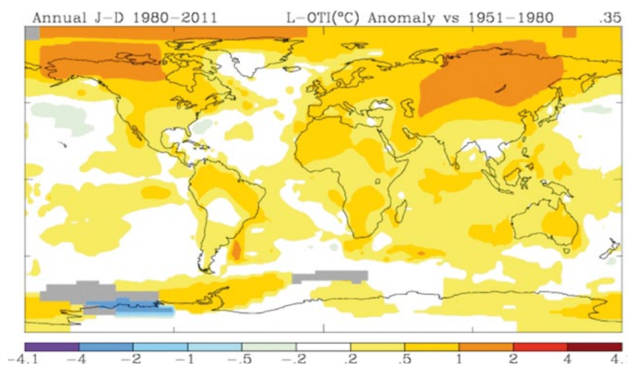

Figure 1.3 > Temperature Anomaly of annual mean temperature 1980-2011 vs 1951-1980. Data Data source: NASA Goddard Space Flight Center, Science and Exploration Directorate, Earth Science Division. http://data.giss.nasa.gov/gistemp/maps

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[2] *1 ka = 1000 years.*

Consequences of present climate change

There are numerous effects of present climate change around the globe: Thermal expansion and freshwater from melting inland ice enlarge the oceans volume (Folland et al. 2001). Consequently in the 20th century, the sea level rose 1.5 to 2 mm per year (Miller & Douglas, 2004).

Glaciers react sensitive to changes in atmospheric boundary conditions. Numerous studies yield decreasing glacier masses around the world (IPCC, 2007) since the 1970s.

Frozen grounds in the meaning of seasonal or continuous frozen grounds (permafrost) are defrosting due to changing heat balance at the surface (e.g.permafrost in the Alps: VonderMühll et al., 2004).

Further effects concerning ice are changes in snow cover, in river and lake ice, in sea ice, and in the stability of ice sheets and ice shelves.

Not only lakes are affected by climate changes *(see Chapter 1.3)* but also other hydrologic subsystems e.g. extreme events like floods and droughts are more often and there are shifts in annual precipitation (see Bates et al., 2008, for an overview regarding water sources and climate change). The list seems to be endless.

Future climate change

Predictions of the future global climate are highly uncertain because of the complexity and the chaotic character of the earth's atmosphere and atmosphere-surface interactions with its numerous positive and negative feedbacks. Furthermore, human beings and their future GHG emissions are unknown. There are infinite theoretical, possible developments of anthropogenic GHG emissions and all natural climate forcing. Nevertheless, a bundle of climate scenarios can cover a broad range of possibilities. Scenarios enable the assessment of the shape of a likely 21st century climate. For comparison of different model approaches, to assess future climate, the Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Emission Scenarios (SRES, Nakicenovic& Swart, 2000). Out of about 40 Scenarios three scenarios usually selected: A1B (moderate), A2 (pessimistic) and B1 (optimistic). In global analyses these scenarios enable together with Atmosphere-Ocean General Circulation Models (AOGCMs) a careful view into the 21st century. These calculations show a rising global average surface temperature in a range of 1.1 to 5.4°C between the periods 1980-1999 and 2090-2099 *(see Table 1).* Recent studies show, that actual GHG emissions are at the upper limit of the pessimistic IPCC-Scenarios (University of Copenhagen, 2009).

Scenario	Likely range of Temperature Change (°C at 2090-2099 relative to 1980-1999)	Sea Level Rise (m at 2090-2099 relative to 1980-1999)
B1	1.1 – 2.9	0.18 – 0.38
A1B	1.7 – 4.4	0.21 – 0.48
A2	2.0 – 5.4	0.23 – 0.51

Table 1 > Adapted and shortened from IPCC (2007), Table SPM.3. Projected global average surface warming and sea level rise at the end of the 21st century.

Climate change and lakes

Several long time series studies have shown close coupling between climate, lake thermal properties and individual organism physiology, population abundance, community structure and food-web structure (Weyhenmeyer et al., 1999; Straile 2000; Gerten and Adrian, 2000; Arhonditsis et al., 2004): understanding the functioning of this complex system of interactions is essential to assess the risk linked to the future management of alpine lake resources, and it is a main activity of SILMAS project.

Since 1970 freshwater biodiversity has decreased more drastically than marine or terrestrial biodiversity (Loh & Wackernagel, 2004). This is the result of a complex mix of stressors and impacts (Stanner & Bordeaux, 1995; Malmquist and Rundle, 2002). The major drivers can be summarized as multiple use (such as fisheries, navigation and water abstraction), nutrient enrichment, organic, acidification and habitat degradation. Climate change is adding further stresses (temperature increase, Hydrological changes) and interacts in complex ways with existing ones (Huber et al., 2008).

The main impacts of climate change on freshwater ecosystem result from changes in air temperature, precipitation and wind regimes. Freshwater system respond by changes in their physical characteristics including stratification and mixing regimes of lake water columns, catchment hydrology or changes in ice-cover which, in turn, may induce chemical changes in habitat (Kernan et al., 2010). Rising temperatures favour cyanobacteria in several ways. 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 (Paerl and Huisman, 2008).

Model studies predict that lake temperatures, especially in the epilimnion, will increase with increasing air temperature, so that temperature profiles, thermal stability and mixing patterns are expected to change as a result of climate change (Hondzo & Stefan 1993; Stefan et al., 1998).

In the vast majority of lakes, the vertical temperature distribution and the intensity of vertical mixing are determined predominantly by meteorological forcing at the lake surface. A change in climatic conditions affecting this local meteorological forcing will therefore alter both thermal structure and vertical transport by mixing, which in turn will affect the flux of nutrient and dissolved oxygen, as well as the productivity and composition of the plankton (Imboden 1990; Reynolds, 1997); Phenology is often strongly influenced by temperature and precipitation (Hughes, 2000).

In particular the climate change can cause, among others, the following effects in the lakes:

- Earlier water warming in spring (Gronskaya et al., 2001)
- Increase in water temperature both on the surface and at deeper levels in lakes (Endoh et al., 1999;).
- Lenghthening of period in summer when lake water temperature exceed 10°C (Jarvet, 2000);
- Shortening of periods with ice cover and decrease in its thickness (Todd and Mackay, 2003)

Analyses of long term data series demonstrate that such a change has already occurred in recent decades: American and Asian lakes in particular are analysed, and the results are an increase of water temperature of about 2°C in the last 10 years (Schindler et al., 1990; Hampton et al., 2008; Coats et al., 2006). In Lake Constance (warm monomictic Lake in Central Europe) the mean annual water temperature has increased by 0.17°C per decade since 1960 (Straile et al., 2003). This warming is strongly related to increasing winter air temperatures and affected the duration and extended of winter lake mixing, the heat content of the lake and the vertical distribution of oxygen and nutrients. Reduced winter cooling favours the persistence of small temperature gradients and may result in an incomplete mixing of the lake.

The increase of air temperature can bring to an increase of water temperature in the hypolimnio, as verified in Ambrosetti & Barbanti, 1999, in Lake Maggiore (Italy): the deep waters of Lake Maggiore contain a sort of climatic memory, represented by variations in the caloric content. This analysis, relating to the period 1963 – 1998, demonstrates that the caloric content in the hypolimnion at the end of limnological year (i.e. when deep waters are formed), depends strictly on winter meteorological parameters (wind run, air temperature and solar radiation), as well as on the quality of heat that can reach the deep layers before and after the onset of thermal stratification.

Ecologically, the enhances growth of cyanobacteria in warm, calm summer can be directly related to systematic variation in the local weather: such "blooms" were once considered to be an inevitable consequence of eutrophication but changes in the weather also play a major part in their seasonal development (Paerl and Huisman, 2008). In particular, even relatively small changes in the thermal characteristics of lakes can cause major shifts in phytoplankton, bacterioplankton and zooplankton populations as well as altering the rates of metabolic processes (e.g. Steinberg and Tille-Backhaus, 1990; Tulonen et al., 1994; Weyhenmeyer et al., 1999; Gerten and Adrian, 2000; Arvola et al., 2002; Jasser and Atvola, 2003). This is because organism are often adapted to certain narrow temperature ranges and because their life-cycle strategies can be highly sensitive to variations in ambient water temperature (Chen and Folt, 1996).

The importance of lakes to our understanding of potential effects of climate change has been demonstrated both from analyses of how biological components of lakes may respond (e.g. Meisner et al. 1987; Hill and Magnuson 1990; Shuter and Post 1990; Meisner 1990; Minns and Moore 1992), and from recent analyses showing that most lakes act as a source of CO2 because they are supersaturated relative to the atmosphere (Cole et al. 1994).

Impacts on physical, chemical and biological lake parameters

Alpine lake ecosystem are vital resource, on the hand for lake biodiversity, and on the other hand for human uses of the water bodies (navigation, bathing, irrigation, energy, tourism…). Any alteration could lead to implications from the ecological, cultural, social and economic point of view.

Climate warming has direct effects on the physical, chemical, and biological characteristics of lakes, and it also operates on lakes indirectly via modifications in the surroundings watershed, e.g. through shifts in hydrological flow pathways, landscape weathering, catchment erosion, soil properties, and vegetation.

The interaction between variables, the feedback effects that accelerate or dampen environmental change, and threshold effects by which lakes may abruptly shift from one environmental state to another are important topic to analyze in order to preserve the lake environment.

This chapter focuses some of main physical, chemical and biological responses of lakes to climate change that have been revealed by recent research.

Physical impacts

A lake is an open physical system with a direct coupling to the atmosphere in terms of energy, water mass and mixing. The distribution and transportation of thermal as well as kinetic energy within the water body strongly depends on the atmospheric input of momentum (wind and waves), radiation and heat, excluding lakes that are forced also by other (natural or man-made) sources of thermal energy.

In a clear lake the radiation penetrates deeper into the water. If there is an abundance of phytoplankton, a part of the solar radiation is converted to biomass by photosynthetic/chemical reactions rather than absorbed as heat. Even the absorption of solar radiation per unit surface area is the same, the surface temperature is higher than in clear lakes, when a fraction of the incoming radiation is also absorbed in deeper water layers, and when energy is distributed vertically on a larger water volume (Rinke et al., 2010).

Disregarding river outflow and withdrawal of heat by heat pumps, the heat loss is generally caused by wind-forced as well as free convective heat transport and evaporation at the free lake surface. Free convection occurs when air above the lake's surface is lighter than remote air. The rate of evaporation and related heat content depends on air and water temperature, wind speed and air humidity. The higher the wind speed and the deficit of the water vapor's partial air pressure, the more energy is lost by evaporation heat, and vice versa. The heat balance of a lake is also affected by the balance between thermal infrared radiation to the lake and the lake's back radiation to the atmosphere.

These heat-exchange processes, very briefly summarized above, may yield thermal water stratification. For the latter the surface lake water needs to exceed the temperature of maximum water density (typically 4 □C) and also requires mild turbulent mixing that limit downward heat transport into the deeper part of the lake.

In summer, colder water with higher density accumulates in the lake's depth (hypolimnion), while warmer water floats near the (mixing) surface, called epilimnion. The transition from the colder hypolimnion to the warmer epilimnion is characterized by the thermocline – the maximum temperature gradient indicating is a barrier for mixing. In a larger alpine or pre alpine lake (e.g. LakeConstance) in winter/spring there is an approximately uniform temperature, and consequently, if there are no salinity effects, uniform density distribution. In this case the input of momentum due to wind enables sufficient mixing of the entire water body, what is essential for O2, and nutrient contents in the deep water layers. And in winter the water temperature is closer to its maximum-density temperature so that temperature changes induce negligible density changes.

We conclude that the lake's physics strongly depends on the local climate and the local climate affected by the global climate. Consequently, changes in atmospheric conditions demand to study in detail the impact of these changes on the lake's mixing status and its ecological/biological evolution. If the climate conditions change, a lake is directly affected, hence, all live in, on, and around the water have to face changes in their ecological nice within the physical framework.

Therefore, lakes are sentinels, indicators and depending on their size also regulators of (local) climate change (Williamson et al., 2009). They are the deepest elements in a landscape and accumulate all the catchments information, e.g. in the sediments. Additionally changes in lakes physics often are reactions by a climate change. Furthermore, lakes are important accumulators and regulators in cycles of matter. For instance, each year all lakes and reservoirs store more carbons than all ocean sediments together (Dean & Gorham, 1998).

Numerous studies proved an often drastic relation between changes in a lake system of any kind and climate change. E.g. O'Reilly et al. (2003) found this sensitivity for Lake Tanganyika, Africa. LakeBaikal's environment dramatically changes within the last decades (Hampton et al., 2008).

Water temperature

Due to the heat fluxes at a lakes surface, water temperature can be highly correlated to the climate parameters, in particular to the air temperature. Thompson et al (2005) analyzed 45 small lakes in an altitude range of 1500m to 2000m in the eastern Alps (Niedere Tauern). They analyzed that the epilimnion's water temperature in summer is very sensitive to a change in air temperature. In an exceptional case a 6°C increase of air temperature is followed by an increase in the lake's surface water of about 12°C. In this case the distinct sensitivity is caused by the dependency of the duration and thickness of ice to the epilimnion temperature. With a smaller although significant sensitivity, all other lakes exhibit a change of epilimnic water temperature. Some examples: Between 1964 and 1998 the Lake Washington's epilimnic water temperatureincreased by 0.045°C per year (Arhonditsis et al., 2004). At Lake Zurich the epilimnic water temperature increased by 0.24°C per decade in the period between the 1950s and the 1990s (Livingstone, 2003). The earth's deepest lake, Lake Baikal, is warming up too: since 1946 the mean water temperature increased by 1.21°C (Hampton et al., 2008). Between 1962 and 2005 Lake Constance's surface water temperature increased by 0.03°C per year(Wahl, 2007). At Lake Geneva the surface water temperature increased by about 1°C since the 1970s (Perroud & Govette, 2010).

Climate change also affects the hypolimnion water temperature. This signal is not that intense as in the epilimnion, but it is as well significant (see the above mentioned studies).

Vertical mixing and thermal stratification

Stability of thermal stratification is a consequence of the density differences between the water layers. The warmer the epilimnion, compared to the hypolimnion, the more energy is required for mixing water against its buoyancy effects. Stability is here defined as the work that has to be spent to transfer stratification into a complete vertical mixing (Schmidt, 1928). The lakes stability changes increase if air temperature increases. For instance, at Lake Zurich the thermal stabilization increased by 20% in the period 1947-1998 (Livingstone, 2003).

Mixing is strongly reduced by increasing stability so that the present climate changes heat up the epilimnion more than the hypolimnion. Wahl (2005) proved for Lake Constance a shift of the maximum mixing from April to March, and ascribed this to warmer winter temperatures. Peeters et al. (2002) showed that increasing air temperatures lead to a suppression of deeply penetrative winter mixing events in Lake Zurich. De Stasio et al. (1996) calculated an earlier and longer onset of stratification in north-temperate lakes.

Despite the importance of vertical mixing to the trophic status in deep lakes (Salmaso et al. 2003) there are few publications which give a general perspective to physical issues in Alpine lakes.

Chemical impacts

Climate is a master variable for ecologically important chemical processes (Kernan et al., 2010). An increase in water temperature has an important impact on lakes chemical processes with increases in pH and greater in lake-alkalinity generation (Psenner and Schmidt, 1992).

The pH, ionic strength, ionic composition, and conductivity are very sensitive and easily measurable indicators of changes in weathering rate, as well as water balance. For many lakes, there can be challenges in disentangling the roles of internal and catchment changes with respect to water chemistry, which may be further complicated by confounding factors such as eutrophication, acidification, or atmospheric nitrogen deposition (Hessen et al. 2009).

In alpine environment, within small lakes catchment area, with a bedrock of granitic gneiss (by silica nature), the pH is influenced mainly by solubility of rocks, that increases with the temperature (Zobrist e Drever, 1990) and from reduction processes that could be able, for depletion of Oxygen, to determine an increase in pH (Koinig et al, 1998). In European rivers, Zwolsman and van Boìkhoven (2007) and Van Vliet and Zwolsam (2008) observed an average increase in water temperature of around 2°C respectively in Rhine and Meuse rivers after the severe drought of 2003, with a pH increase (reflecting a decrease in CO2 concentration) and a decrease in dissolved oxygen (DO) solubility reflecting a lower DO solubility under higher water temperatures. A DO decrease can also be associated to an increase in DO assimilation of biodegradable organic matter by microorganisms (linked to an increase in Dissolved Organic Carbon (DOC) (Prathumrataba et al, 2008).

DOC concentrations is an important constituent of many natural waters: it may be stored in soils for varying lengths of time before transport to surface waters. The humic substances generated by organic matter decomposition impart a characteristic brown color to the water due to the absorption of visible light by these compounds. DOC thus influences light penetration into surface waters, as well as their acidity, nutrients availability metal transports and toxicity (Kernan et al., 2010) as well as changes observed in the catchment related to increased run-off, permafrost melting, shifts in vegetation, and changes in wetlands (Evans et al. 2006; Benoy et al. 2007; Keller et al. 2008), and increased CO2 concentrations (Freeman et al. 2004). The rising of DOC documented (Freeman et al., 2001; Evans et al., 2005, 2006; Vuorenmaa et al., 2006; Monteith et al., 2007) is interpreted as evidence of climate change impacts on terrestrial carbon stores due to rising temperatures and the increasing frequency and severity of summer drought (Freeman et al., 2001; Hejzlar et al., 2003; Worral et al., 2004). Increasing precipitation could also lead to increasing DOC concentrations, first by increasing the proportion of DOC-rich water derived from the upper organic horizons of mineral soils and secondly by reducing water residence time, and hence DOC removal , in lakes (Hongve et al., 2004) Rising levels of atmospheric CO2 influencing plant growth and litter quality were also proposed to explain increased rates of DOC production (Freeman et al., 2004).

Concerning nutrients concentration, an increase of N mineralization in soil due to an increase in mean soil temperature is expected (Durchane et al., 2007). Water bodies quality is subjected to weather seasonality which has an important impact on their nutrient patterns (Zhu et al., 2005). A warmer climate will create indirect impacts on water bodies like an increase nutrients load in surface and groundwater (Van Vliet and Zwolsman, 2008) and counteract policies effects of external nutrient loading reduction..

Nutrient concentrations and ratios in lakes are likely to be altered as a consequence of changes in terrestrial export related to climatic influences on weathering rates, precipitation, run-off (Sommaruga-Wögrath et al. 1997; Rogora et al. 2003; Bergström and Jansson 2006), fire frequency (Kelly et al. 2006; Westerling et al. 2006), or terrestrial primary productivity (Boisvenue and Running 2006). Nutrient concentrations can also be affected by internal processes related to changes in thermal structure and/or primary productivity (Jeppesen et al. 2005; Wilhelm and Adrian 2008). Furthermore, the longer water renewal times predictable in a warmer and drier climate could lead to a decline of SO4 and NO_3 concentrations and an increase in base cations and alkalinity (Schindler et al., 1990; Webster and Brezonik, 1995).

As regards the solutes concentrations in high mountain lakes, Thies et al. (2007) observed, during the last two decades, a substantial increase in two remote high mountain lakes (Rassass see, Italy, and Schwarzsee ob Solden, Austria): the high concentrations can be explained by an increase in the mobilization and release of solutes from active rock glaciers in the lake catchment entering the lakes via melt water, related to the observed increase in average air temperature in the region over recent decades (Auer et al., 2007).

Oxygen concentrations in lakes can indicate climate shifts because oxygen levels are strongly influenced by temperature and thermal structure (Hanson et al. 2006). For example, the extremely warm European summer of 2003 resulted in a long period of thermal stratification and increased hypolimnetic oxygen depletion in some Swiss lakes (Jankowski et al. 2006). When applicable, hypolimnetic oxygen concentrations have added value as indicators of climate change because they have widespread consequences for internal nutrient loading (Pettersson et al. 2003), habitat size, and refuge availability (De Stasio et al. 1996; Jansen and Hesslein 2004).

Biological Impacts

Phytoplankton

The increase of CO_2 in atmosphere has a direct effect on global temperature and, consequently, on many biological lake processes. Lake plankton is susceptible to the variation of temperature, although the plankton populations are relatively well buffered against the frequent fluctuations in temperature. The response of plankton populations to the climate change is more evident considering a long-time series the direct ecological effects of the influence of increasing temperature and it is relatively easy to predict future scenarios. More difficult is to understand the complicate indirect effects and to elaborate a future model of plankton response.

The most plankton algae are able to maintain a normal biological behaviour relatively wide range of temperature. Nevertheless there are important studies that shown the positive relationship between photosynthetic capacity and temperature for selected species of phytoplankton. Some species show an exponential increase of common physiological processes until the maximum of 25°C water temperature, other show the maximum at 41°C (Talling, 1957; Jewison 1979; Straskraba & Gnauk 1985). But most part of phytoplankton populations are able to growth ranging from 5-25°C with peaks between 10-20°C, while the population growth drops at temperature above 25°C.

Phytoplankton growth is also correlated to the availability of nutrients into the lake. Nutrient turnover could increase in warmer climate and cause or worsen the eutrophic status, removing the phosphorus stored in the sediments (Hamilton et al, 2001).

Increasing water temperatures favours Diatoms, but the bacterial biomass in summer is evened with shifts in dominance from Diatoms to Cyanobacteria and the seasonal development of phytoplankton composition could be quite different (Weyhenmaeyer, 2002). This effect is evident at temperature > 20°C when the populations of Cyanobacteria and filamentous algae are favoured at higher temperature (Straile, 2000). Moderate increase of water temperature in winter and spring causes a faster shift in phytoplankton population in early summer, when the algal species have a growth ratio lower than winter and spring algae that appear fast-growing (Vincon-Leite et al, 2002). This event often produce significant algal blooms that troubles lake managers.

The presence of ice cover and amount of snow fell in winter control the algal population (Petterson, 1990; Adrian et al, 1995) and influence the nutrient availability responsable for spring algal blooms with consequent higher peak of planktonic biomass (Muller - Navarra, 1997).

The limnological classic view of seasonal phytoplanktonic presences and compositions implies an order of dominance of species or groups during the annual cycle. Normally the scheme of dominance succession is expressed in simple way:

Pioneer ▸ B ▸ C ▸ D = Climax

Where B, C, D represent the succession of dominances of diverse phytoplanctonic groups.

In lacustrine ecosystem, the above mentioned succession can undergo a deviation or interruption caused by the external perturbation producing a reversed succession:

Pioneer ▸ B ▸ C
▼
perturbation
▼
B ▸ C ▸ D = Climax

The lacustrine ecosystem can be subjected to human pressure and in this case different “climax” can be changed in short-time, as shown below.

perturbation *perturbation*
Climax A ⟶ **Climax A’** ⟶ **Climax A’’**
short time

Imagining a lake free of human pressure, the depletion of succession is due only to the climate whims years by years. If the perturbation is not due to the sudden events but determinate by the slow and continuous increase of water temperature, then the ”climax” will be different and different will be the composition of phytoplankton community.

Climax A ⟶ **Climax A’** ⟶ **Climax A’’**
slow water temperature increase in long-time

Zooplankton

The zooplanktonic populations, formed mainly of Rotifers and microcrustaceans (Cladocera and Copepods) account the secondary production in lakes (Morgan, 1980). Higher water temperatures support the zooplankton population shift and change community compositions.
The abundance of Rotifers, Cladocera and Copepods depends to the trophic web of each zooplanktonic group. Some of these have a vegetarian behaviour, other are predator, besides every group has different tolerance to the increase of water temperature, i.e. Rotifers have a very broad temperature tolerance and many common species can live easily ranging from 1 to 25°C (Berzins&Pejler, 1989). therefore, it is often difficult to separate the effects of increasing temperature from the availability of food.
Nevertheless, considering that the phytoplanktonic community depends on the increase of water temperature in conditions of stable nutrients availability , it is possible to assume that there is a direct relationship between increasing phytoplanktonic biomass and increasing presence of grazing zooplankton. In fact, higher water temperature in the spring produce an increase of phytoplankton with consequent increase of Cladocera, with precision Daphnia, that leads to phytoplankton suppression in primis and shift from a dominance of larger to smaller species.
Temperature normally controls the growth rates, while the availability of food controls the reproductive capacity of population and a relevant increase of water temperature in winter has less effect than a smaller increase in the summer (Edmondson & Winberg, 1971). Such behaviour is typical of a wide part of aquatic invertebrates in case of slow, but continuous, increase of water temperature.

Fish

Many species of fish depend on changes of water temperature (De Stasio et al 1996; Magnusson, 1997) for their survival and growth. Temperature-increased could lead to a change in structure and distribution of fish population, mainly producing a different growth rate of predatory influencing on food-web (Carpenter et al, 1985). Can be expected that a warmer spring induce a forward shift from planktivory to piscivory feeding caused to the increased by wider pressure of piscivora predation (Olson, 1996). In an other hand, the rate of predation by planktivorous fish can provoke a strong drop of the zooplankton presence, especially of Daphnia (Meher, 2000).
So, the water temperature could induces a direct effect on prey-predator interaction, modifying the structure, dominance and behaviour of fish population and conditioning also the ratio inter and intra feeding planktonic groups (Dodson & Wagner, 1996; Beisner et al, 1996).

Conclusions

There is strong evidence that climate change had and will have in the future an effect on the physical, chemical and biological characteristics of lake ecosystem, both directly though changes in climate driven both indirectly through interaction with other stressors. On the one hand, physical impacts as unregulated water levels, changes in water temperature in epi- and hypolimnion, in stability, and in vertical mixing are of high importance for the lakes ecology. On the other end, climate driven changes may lead to a strong variablitiy in chemical compounds in the lakes. The residence time of a lake influences the chemical composition of lake waters by controlling the time available for biogeochemical and photochemical processes to operate, the extent of accumulation and loss of dissolved and particulate materials, and the duration of biogeochemical interactions with the lake sediments and littoral zone. In lakes that experience anoxic bottom water conditions and nutrient release from the sediments, a prolonged residence time caused by reduced precipitation and inflows can result in increased phosphorus accumulation (internal phosphorus loading) and eutrophication. Conversely, in regions that experience increased precipitation and water flow, the increased flushing of nutrients and phytoplankton may result in reduced algal production (Vincent, 2009).

The weather conditions also influence the biological dynamics both the phytoplanktonic successions and the growth of zooplankton (Cushing, 1982). The verified increase of water temperature of the lakes in the last years has surely influenced little changes in the compositions of the phytoplankton community and has outcome the change of zooplankton community, but often for our lakes it is very difficult to separate the influence of warmer climate from the local impulse caused by human impact. Nevertheless for our lakes, that are substantially free of outcome nutrients, the analysis of long-term data sets could confirm a closed relationship between increasing water temperature and changes in community structure (Blenkner, 2005).

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