an example and Lake Okeechobee. Lake Chad is in a dry environment. It is formed in a low interior region of Africa due to subsidence. Lake Okeechobee was formed from the uplift of the ocean floor.

Fluvial lakes

Fluvial lakes are very shallow. Although they constitute almost 10% of all lake surface area, they hold only about 0.3% of the volume. Sediments transported by rivers may accumulate, for example, in river bends, and create a form of dam, or running water may excavate depressions. Meandering rivers may take a new course through a river bend and then a lake, oxbow lake, may be created. A river system with an oxbow lake often includes many such small lakes. Fluvial lakes may also be created near the coast, when longshore coastal currents deposit sediments that block river outflows. The fluvial lakes can be created due to processes acting over a longtime, or as a consequence of very extreme events.

Lakes formed by other processes

Some lakes have origin different from the three major ones. Lakes may be formed by volcanic activity, by solution in karst terrains, meteorites, and landslides or formed by the wind.

Volcanic lakes formed from volcanic activity can be found in Iceland, Italy, and New Zealand. In karst terrain there is solution of subsurface rocks by groundwater leading to formation of hollows which can be filled with water forming usually small *karst lakes*. This kind of lakes is common on the Balkan Peninsula.

Landslides may dam water in mountainous terrain. Lakes created in this catastrophic way may be temporary and can be drained again almost in a catastrophic way. Damming of rivers may also be due to *accumulation of plant material*. Mammals, especially the beaver may build dams so that a lake is formed upstream.

Lakes (*wind formed lakes*) can be formed by wind action. Sediments transported or eroded by the wind may form irregularities in the terrain. Windblown sand may block rivers. These lakes are shallow.

In large regions of the Northern Hemisphere the land is still rising. The sill between some shallow bays or fjords and the sea is slowly coming above the sea level cutting of the bays from the sea, and the bays and fjords turn into fresh water lakes sometimes called cutoff lakes. There are numerous such examples along the Baltic in the north of Sweden and Finland.

Of course, the very large dams are built by man. *Man-made lakes* or *reservoirs* are a very special form of lakes. They are found almost all over the world. They are described in several entries in the encyclopedia.

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Cross-references

Lakes on Earth, Different Types
Origin of Lakes and Their Physical Characteristics
Paleolimnology

CLIMATE CHANGE EFFECTS ON LAKES

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Introduction

The global environmental changes that are apparent today are mainly anthropogenic due to the growing human population and its high activity of resource consumption. The most obvious trends concerning ecosystem impacts are the anthropogenic changes in biological diversity and alterations in the structure and functioning of the food web. Climate change is one of the most important factors within the global change issues, and therefore, the impact of climate on ecosystems has been widely tested using historical data, experiments, and model simulations.

In temperate aquatic ecosystems, most of the ecologically important characteristics are influenced by climate change such as changes in temperature, evapotranspiration, frequency and magnitude of precipitation, wind, storm, and fire events, length of the ice-free season, and the depth of the mixed layer. In general, many water quality problems may worsen by climatic change, particularly those relating to eutrophication, such as bottom-oxygen depletion. However, an extreme uncertainty exists at any case-specific level, which is related often to specific characteristics of lakes (e.g., depth, retention time) and/or catchments, such as land use patterns.

In the following, four physical responses will be discussed followed by presenting an overview of ecosystem-wide changes and the potential effects of no direct-related drivers.

Ice cover

The timing of ice freeze and breakup, one of the longest and widespread limnological variables, has been used often as an indicator for regional climate change. Duration of ice cover is driven by several meteorological variables, of which air temperature has been shown to be the most important one.

A long-term trend toward shorter periods of ice cover due to a later freezing and an earlier ice breakup has been reported for lakes around the northern hemisphere. The trend of an earlier ice-out increases the ice-free period and raises lake temperatures in spring in many reported studies from global distributed lakes. In Northern Europe, the duration of the ice cover period and the timing of freeze and breakup greatly affect lake systems, in particular, the succession events in plankton and partly underwater plant dynamics.

Water temperature

Surface water temperatures often show a strong coherent increase following the warming of air temperature across European lakes. A faster temperature rise in the spring (due to earlier ice-out dates) preceded the beginning of spring stratification, which may influence nutrient cycling and phytoplankton dynamics. Consequently, effects of higher water temperatures on the lake mixing regime could lead to dimictic lakes (fully mixed twice a year) turning into warm monomictic lakes.

Overall, temperature affects all physiological processes, thereby influencing the growth of organisms. The magnitude in which physiological rates change with respect to temperature is generally in good agreement with an Arrhenius formulation. For example, zooplankton found in lakes can tolerate fairly high summer temperatures, but small increases in the winter temperature, in some lakes significantly related to the timing of ice breakup, can strongly affect the overwintering and seasonal dynamics of zooplankton species such as *Daphnia* and *Eudiaptomus* through a strong temperature-dependent growth rate.

The survival and growth of fish species, for example, depends often on temperature. Thermal limits of some fish species, altered by global warming, can induce changes in spatial distribution. Temperature-induced changes in the growth rate of predatory fish may result in cascading effects through the entire food web.

Stratification

Most temperate deep lakes are stratified during summer, with a warm surface water (epilimnion) and cold deep water (hypolimnion). The most crucial triggering factors for the timing of phytoplankton blooms are light and turbulence, which are both influenced by stratification and therefore directly affected by climatic variation and change. Consequently, strong relationships between the timing and the winter climate were found in European lakes. Differences in the individual lake response depend often on the morphometry of the lake. For example, in Lake Constance (Germany) – a large and deep lake which generally is not covered by ice in winter – the spring bloom only occurs under stratified conditions, because reduced mixing increases light availability for phytoplankton. Generally, an enlarged mixing depth increases the proportion of incoming light, which is attenuated abiotically within the mixed layer. This leads to a decrease in phytoplankton production averaged over the mixed layer with increasing mixing depth. By contrast, in shallow lakes with a lower mixing depth, the phytoplankton spring bloom is often associated with ice cover disappearance (determined by winter climate), influencing the light availability as observed for example in Lake Müggelsee, Germany, and Lake Erken, Sweden. Later in the year, conditions in the lake appear to be more complex and stratification becomes the predominant triggering factor. For example, longer periods of stratification can promote a dominance of potentially toxic cyanobacteria as higher water temperatures prolong the stratification period and create favorable conditions for cyanobacteria. Additionally, large cyanobacteria colonies (besides other phytoplankton groups) are resistant to grazing by zooplankton, especially in eutrophic lakes. These two mechanisms partly promote the dominance of cyanobacteria in stratified lakes at a warmer temperature regime. Longer periods of summer stratification and higher hypolimnetic temperature are also projected to cause increased hypolimnetic anoxia, or at least lower oxygen concentrations. This condition often leads to an enhanced phosphorus release from the sediment, in particular, important as phosphorus is the main limiting factor in lakes.

Hydrology

The inflowing water from streams and rivers and their loading depends very strongly on precipitation and land use, e.g., the intensity of agriculture. The amount of the inflowing water further affects the hydrological water residence time in the lake which further influences how long for example phosphorus molecules are recycled within a lake. Stratified lakes with a water residence time longer than 1 year have a higher potential to suffer from an amplified climate-related eutrophication as the warmer climate may intensify the stratification and thereby cause a P released from P-rich sediments. In contrast, in lakes with short residence time (months), the phosphorus released from the sediment is flushed out relatively quickly and therefore cannot contribute to next-year phytoplankton development. Decreases in water residence time, for example, through an increase in precipitation with an associated higher runoff, can decrease concentrations of nutrients, as water residence time scales the rate of the ecosystem response to chemical inputs and to climate change and variability. The water level of closed lakes where the hydraulic load is counterbalanced by evaporation and rather stable seepage serves as one of the best indicators of long-term climatic variation.

Ecosystem changes

Climatic changes relevant at a species level are likely to vary at the ecosystem scale among lakes. Weak links in food web interactions, in particular, dampen oscillations between consumers and resources. This implies that not all responses at a specific trophic level are propagated to lower trophic levels or have significant impacts on ecosystem processes. Additionally, a prolongation of the climate signal due to food web interactions is possible as the signal of, for example, winter climate can be detected in the clear water phase in early summer (induced by high zooplankton grazing) or in summer phytoplankton composition and biomass. A system approach is necessary to examine the cascading effects in response to climatic change and variability. The magnitude of a climate-driven response of an autotrophic organism does not necessarily have to be mediated or cascaded to the heterotroph species, or vice versa. Another example indicates that a consecutive period of five mild winters led to a complete change of the spring phytoplankton bloom, from a dominance of diatoms and cryptophytes to a dominance of cyanobacteria in a German lake. This illustrates, furthermore, that the response of phytoplankton, and probably also other lake biota, to climatic variation might be totally different from the response of a warming trend, as many ecosystem processes are nonlinear. Furthermore, the nonlinearity in the response to environmental variables of animals and plant may cause progressive changes to be interrupted by drastic switches to a contrasting ecosystem state. One such example is the shift between the clear water (macrophyte dominated) and the turbid (plankton dominated) state of shallow lakes. A recent study in a Swedish lake showed that climate variability alone cannot explain such a shift, but is likely to amplify this to a multi-causal stress and, therefore, reduces the resilience of the clear-water state in shallow lakes.

Impacts of other anthropogenic drivers

In the past 40–50 years, many lakes, particularly in Europe and the USA, have been subjected to an anthropogenically caused increase in the supply of nutrients and other substances, e.g., organic pollutants. This supply decreased partly in the late 1980s or early 1990s. While improvements in wastewater treatment over the last decades have reduced inputs of nutrients from point sources, the increase in nutrients from diffuse sources is still a major problem and, for many lakes, remains the predominant concern. Additionally, catchment alteration, acidification, dam regulation, agriculture, and the waterborne sanitation solution can complicate a separation of the various influences on ecosystems. Therefore, to clearly disentangle the effects of climate on important lake processes from anthropogenic nutrient effects are very difficult. The effects of multi-stressors on ecosystems is very complex in particular, as the stochastic interplay of these effects and the nonlinear or time-lagged response of the food web are very difficult to foresee.

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Cross-references

Climate Change: Factors Causing Variation or Change in the Climate
Hydrodynamics of Very Shallow Lakes
Ice Covered Lakes
Lake Ice
Thermal Regime of Lakes

CLIMATE CHANGE: FACTORS CAUSING VARIATION OR CHANGE IN THE CLIMATE

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Introduction

Climate changes are variations that happen in the climate on a certain location or globally and on different time perspectives. On a geological time perspective, the climate of the Earth has changed drastically in the past. It has experienced long periods (thousands of years) of very high or very low temperature if compared to the temperature experienced today (Figure 1). After the latest ice age (about 13,000 years ago), the variations in climate have been milder if compared to the previous ones. Changes in the past climate in a geological perspective, also known as paleoclimate, can be inferred through traces left on glaciers or on ice sheets, three rings, lake beds, caves, among others.

Causes and consequences

The causes for changes in climate can be many, and the consequences of each of them can last for longer or shorter time periods. On a *geological* perspective, the drift of the continents have caused changes on the global climate that follows a geological time scale, that is, hundreds of thousands of years. On the other hand, *volcano* outbreaks that are also related to the continents' drift can change the climate on a shorter time scale by throwing ashes into the atmosphere. The ashes shade the solar radiation by increasing the albedo of the upper atmosphere and cool down the atmosphere below. Climate changes caused by volcano outbreaks can last from a few days to a few years depending on the intensity of the outbreak, the amount of ashes liberated, and the altitude reached by the ashes. An example of the consequences of volcano outbreak is the year 1816, known as the "year without a summer." From late spring to early fall that year, temperatures were abnormally low mostly in the Northern

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