Leibniz-Institute of Freshwater Ecology and Inland Fisheries

# Lakes under climate change

Diagnosis and prognosis from long-term research

IGB Dossier

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## Diagnosis and prognosis from long-term research



## 1. Introduction: lakes under climate change

Lakes are important both ecologically and culturally. They provide "ecosystem services" such as storing drinking water for humans and livestock, providing agricultural irrigation, and contributing towards flood control. They are the grounds for professional and sport fishing, the natural infrastructure for inland waterway transport, and a hub for recreation and tourism. In addition to these practical benefits, lakes can have a decisive influence on the microclimate in their respective catchment area; they are also biodiversity hotspots. Consequently, lakes are key natural and cultural assets, and are appreciated as landscape features for their beauty. In a nutshell: lakes and humans are closely entwined. Lake researchers at the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB) explore the long-term developments and underlying natural processes in and around lakes, as well as the human impact on these waters.

One particular factor that lake scientists view with concern is the impact of climate change on lake ecosystems. Climatologists predict a rise in global air temperatures and an increase in the frequency of extreme weather events such as heat waves, heavy rainfall and summer storms (IPCC 2013). At the United Nations Climate Change Conference in Paris in 2015 (UNFCC, COP 21), the international community agreed to cap the increase in global average air temperature at 2 °C above pre-industrial levels. In fact, efforts are to be made to limit the temperature increase even further to 1.5 °C in a bid to minimise the risks of global warming. No such limit has been agreed as yet for surface waters. **However, long-term data show that the summer surface temperature of lakes worldwide rose by an average of 0.34 °C every ten years between 1985 and 2009 (O'Reilly et al. 2015), i.e. by more than half of the tolerable increase of 1.5 °C in this short period of 24 years alone.**

Exactly how waters and their communities respond to this "climate stress", and whether their ecosystem health and stability are endangered, are key issues addressed in climate impact research on waters. However, relationships and interactions in lake ecosystems are highly complex, making it virtually impossible to make blanket statements, which are not supported by scientific findings. Lakes respond very differently to global warming, depending on the type of lake and its catchment area. The aim of this *IGB Dossier* is to describe what basic developments are expected, and to explain the likelihood of certain scenarios occurring.

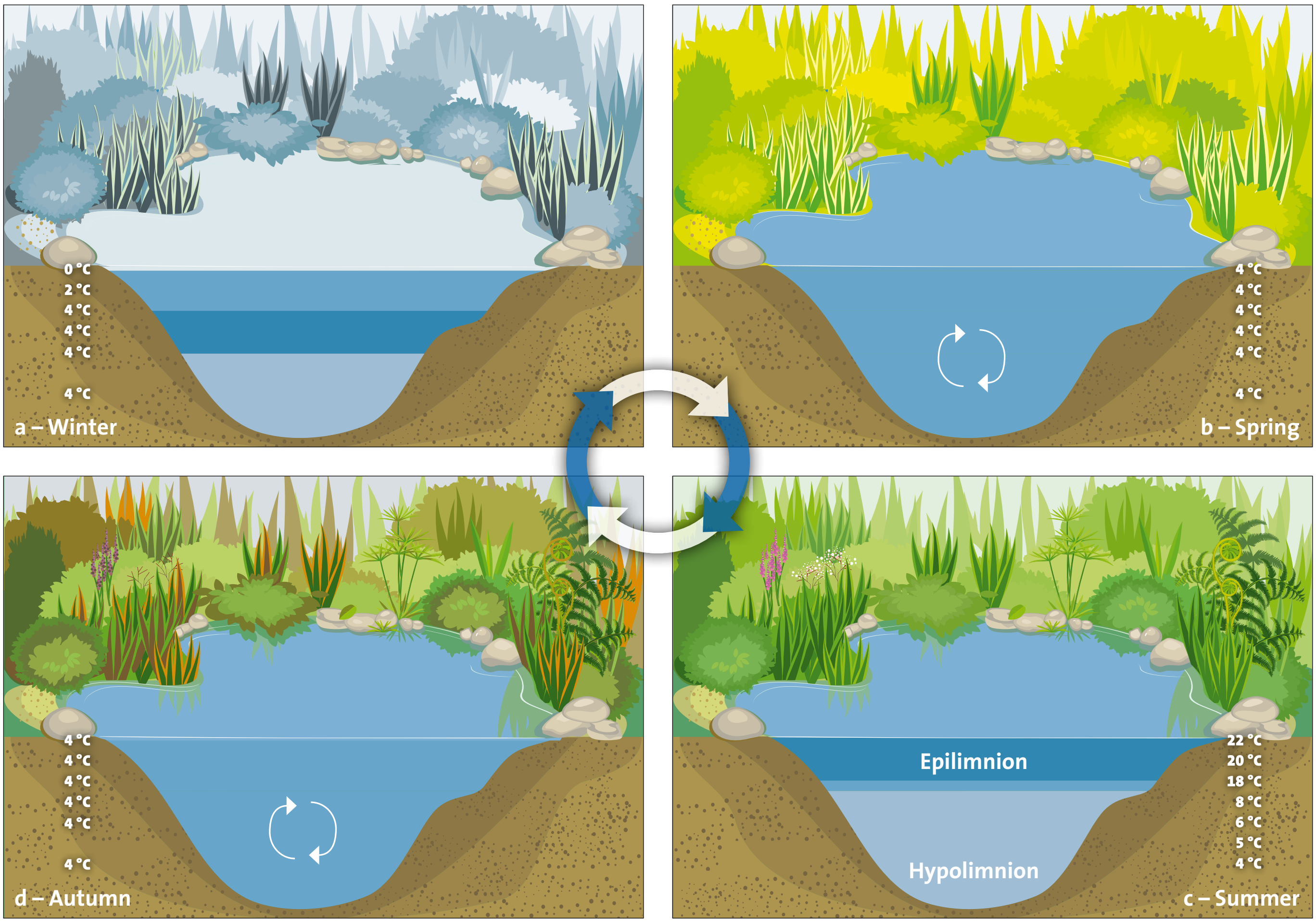
First of all, some of the basic principles governing the physical, chemical and biological processes of lakes in temperate latitudes (the climate zone in which Germany is also located) are described in the next section. This is followed by a presentation of the latest results of climate impact research in lakes.

# 2. Foundations: physical, chemical and biological processes in lakes

## 2.1 Physical processes in lakes: the annual thermal cycle

Lakes in temperate zones are subject to pronounced seasonal cycles that are fundamentally regulated by the water's physical properties. These seasonal cycles in turn influence most chemical and ecological processes, and are particularly sensitive to global warming. In the annual cycle of the mixing of lakes, we differentiate between monomictic lakes, which thoroughly mix once a year, dimictic lakes, which mix twice a year, and polymictic lakes, which mix several times a year.

In a typical **dimictic lake,** surface temperatures fall below 4 °C in winter and the lake is usually covered by ice, which prevents the surface water from mixing with deeper water (Figure 1a). Since the maximum density of water occurs at 4 °C (density anomaly), colder water stratifies above the 4 °C warm water in winter – which is why lakes do not usually freeze to the bottom. Once the ice has melted in spring, water temperature becomes uniform from top to bottom, and the water column mixes completely. This process is called circulation, or turnover (Figure 1b). Towards the end of spring, intense sunlight heats up the surface water more quickly than the deeper water. As a result, a warm layer of water is created at the surface, known as the **epilimnion.** This layer "floats" above the denser, colder water layer,






high oxygen concentration    medium oxygen concentration    low oxygen concentration

*Figure 1: The cycle of a typical dimictic lake: the water column mixes twice a year (spring and autumn circulation), which has a major impact on its oxygen concentration and its communities. Temperature differences between surface water and deep water that develop under ice, as well as in summer, prevent mixing.*

which is called the **hypolimnion** (Figure 1c). The term for this formation of different layers, which remain throughout the summer, is stratification. In autumn, thermal stratification breaks down. The surface water continuously cools down, and turnover occurs a second time (Figure 1d).

Polymictic and monomictic lakes undergo a similar seasonal process to that as dimictic lakes, but with a number of key differences (Kirillin & Shatwell 2016). In contrast to the process described above for dimictic lakes, **polymictic lakes** are too shallow (depth of less than ten metres) to develop a stable hypolimnion. The water is therefore regularly mixed throughout summer, and stratification only occurs briefly. **Monomictic lakes,** on the other hand, differ to dimictic lakes in that they do not freeze over in winter. There may be two reasons for this: either the lake is located in a warmer climate where the surface water does not fall below 4 °C in winter (this is not the case in the temperate climate zone) or the lake is too deep (depth of more than 100 metres) and the high heat storage capacity of the water prevents the lake from freezing over, as is the case with Lake Constance and Lake Zurich, for example. Consequently, monomictic lakes also mix during winter and only develop stratification from spring to autumn.

## 2.2. Chemical and biological processes in lakes

**Oxygen concentration** is a key indicator of the health of a lake. Not only is oxygen essential for aquatic animals, it is also crucial in maintaining the chemical balance of a lake. Oxygen is produced in water in the upper sunlit water layers during the photosynthesis of phytoplankton (algae, plant plankton). Oxygen from the surrounding air also enters the water at the surface of the lake. Consequently, the surface water is rich in oxygen, while the deep water may become oxygen-depleted (anoxic) during long stratification periods or below an ice cover.

Oxygen is consumed when bacteria degrade organic substances and when aquatic organisms respire (breathe). Depleted oxygen is replenished during circulation once the oxygen-rich surface water has been distributed throughout the lake. Dimictic and monomictic lakes therefore have the highest oxygen concentration in spring, following circulation, and the lowest concentration at the end of the summer stratification (Figure 1). In polymictic lakes, oxygen becomes depleted in deep water as a result of prolonged ice coverage or, in summer, due to prolonged stratification events.

**Plankton** (microscopic aquatic organisms) also undergoes a seasonal cycle. In most lakes, **phytoplankton** (algae) exhibits a characteristic bloom in spring. Blooms occur when light intensity and temperature increase rapidly after winter and there is an abundance of dissolved nutrients. **Zooplankton** (animal plankton), which feeds on phytoplankton, decimates the spring algal bloom and produces what is known as the clear water phase. This phase is marked by high water clarity for a period of around two weeks. This is followed by the development of a summer community of phytoplankton and zooplankton, including Cyanophyceae (commonly known as “blue-green algae”), which also collapses in autumn due to the lower water temperature and weaker light intensity. During summer stratification, organic matter continuously sinks to the bottom of the lake. In this way, **nutrients** accumulate in deep water and in the bottom sediment of stratified lakes. When the next autumn and spring circulations occur, the nutrients are distributed throughout the water column, making them available for growth once again. In polymictic lakes, the water and the nutrients it contains are periodically mixed and continuously used.

# 3. Changes: specific impacts of climate change on lakes

### 3.1 Methods used to investigate the impact of climate change on lakes

Identifying the impact that climate change already has on our lakes and how this process will develop in the future is a highly complex task. Lake scientists investigate the impact of climate change on waters by collecting and analysing **long-term data** on lakes. Long-term trends cannot be described using experimental approaches conducted over short periods of time. In order to understand the underlying mechanisms, it makes sense to combine experimental research and modelling with long-term research. For the latter, scientists use comprehensive data series collected over several decades (more than 40 years). These data series include abiotic factors (climate, weather, nutrient inputs from the catchment area, thermal stratification or oxygen conditions) as well as the interactions of organisms in food webs. Using statistical and deterministic modelling of long-term climate-induced changes, scientists are able to identify and quantify trends and the possible exceedance of critical limits. They are also able to identify the effects of extreme events as opposed to long-term natural variability.

The wide range of methodological approaches available to research (modelling, experimentation and long-term research) differ in their degree of controllability, the understanding gained of the mechanisms at work, and the system complexity achieved: although **models** can be used to effectively monitor the mechanisms under investigation, they are unable to represent the complexity of ecosystems. In contrast, long-term data show the development of ecosystems taking into account the entire complexity of abiotic and biotic interactions, as well as the "memory" of a lake (e.g. resistant stages deposited in the sediment). And yet they have limited capabilities of identifying interrelations. **Large-scale experiments,** located somewhere between theory and long-term observations, enhance the understanding of the underlying mechanisms. At the same time, however, they are only able to reproduce the overall complexity and the seasonality of ecosystems to a limited extent.

The results and forecasts produced using the different research approaches are summarised in the next sections.

### 3.2 Increase in air and water temperatures: direct and indirect effects

Global warming over the past 50 years has led to general and system-specific changes in lake ecosystems. Besides direct effects, a multitude of indirect effects have primarily contributed to changes in lakes.

**Direct effects:** The increased air temperature has caused a rise in surface water temperature and a decline in ice development in winter. Higher water temperatures have also resulted in a change in the thermal structure of lakes (see Section 3.3; Figures 1 and 2).

The altered thermal structure and reduced ice development lead to **indirect effects** such as different light, oxygen and nutrient dynamics. This is compounded by an increase in external inflows from the catchment area (see Section 3.5 and Figure 2). These indirect effects have a major impact on the development of phytoplankton and on the structure of food webs. Such effects are often more drastic than the changes caused directly by an increase in temperature.

### 3.3 Changes in thermal stratification

One of the most apparent effects of global warming on lakes is an increase in thermal stratification. In polymictic lakes such as Berlin's Müggelsee, stratification events are becoming more prolonged and more frequent, owing to the increased occurrence of hot weather periods in summer. Several temperate polymictic lakes will become dimictic in the future if these stratification events persist throughout summer (Kirillin 2010). In seasonally stratifying lakes (dimictic and monomictic lakes), milder winters cause stratification to begin earlier in spring, and may also end later in autumn. This development results in a prolonged growth period.

Warming in winter also affects mixing in lakes (Arvola et al. 2009). Milder winters mean less ice coverage, which stimulates mixing in polymictic and dimictic lakes. If the ice layer disappears completely, dimictic lakes become monomictic lakes, because the lack of ice coverage means that mixing takes place continuously throughout winter (Figure 1). The situation is different in very deep monomictic lakes such as Lake Constance (see Section 2.1), which only develop a complete ice cover in very cold and prolonged winters. Milder winters can prevent lakes from dropping below 4 °C, leaving some residual stratification. These lakes become oligomictic, i.e. they no longer turn over annually. On the whole, it can therefore be assumed that climate change may alter lake stratification types: polymictic lakes may become dimictic more frequently; dimictic lakes may have a greater tendency to become monomictic; and monomictic lakes may tend to become oligomictic.

## 3.4 Changes in oxygen concentration

Global warming is expected to reduce **oxygen concentrations in lakes.** This phenomenon can best be observed in deep water layers of seasonally stratified lakes in late summer. The higher water temperatures result in higher oxygen consumption. Due to more prolonged stratification, more oxygen is consumed before it can be replenished by turnover, exacerbating the problem (North et al. 2014). This can cause the development of oxygen-free (anaerobic) zones in the hypolimnion, which may lead to the internal fertilisation of lakes (see Section 3.5; Figure 2) and hence to a deterioration in water quality (Carpenter 2003).

The situation is no less complex in winter: prolonged ice coverage can cause oxygen depletion and "winter fish kill" in relatively shallow lakes. If winters become milder in the future, the supply of oxygen will improve and there will be less fish mortality (Fang & Stefan 2009). On the other hand, such mild winters may cause less intensive mixing in very deep monomictic lakes, preventing the supply of oxygen to deep water (Rempfer et al. 2010). Such an oxygen deficit in deep water will then be carried over from winter to summer, causing the oxygen-deficient areas to spread even further. Therefore the effect of warming on oxygen in lakes can be quite variable, depending mainly on lake depth and nutrient levels.

## 3.5 Internal fertilisation and Cyanophyceae blooms

Prolonged thermal stratification leads to a decrease in the oxygen concentration of deep water. As a result, chemical processes trigger the release of nutrients previously bound in sediment, such as phosphorus (Wilhelm & Adrian 2008). This climate-induced intensification of the **internal fertilisation of lakes** counteracts the major efforts taken in recent decades to reduce external nutrient inputs and the associated eutrophication of lakes. Under future warmer climate scenarios, this means that external nutrient loads would have to be decreased to

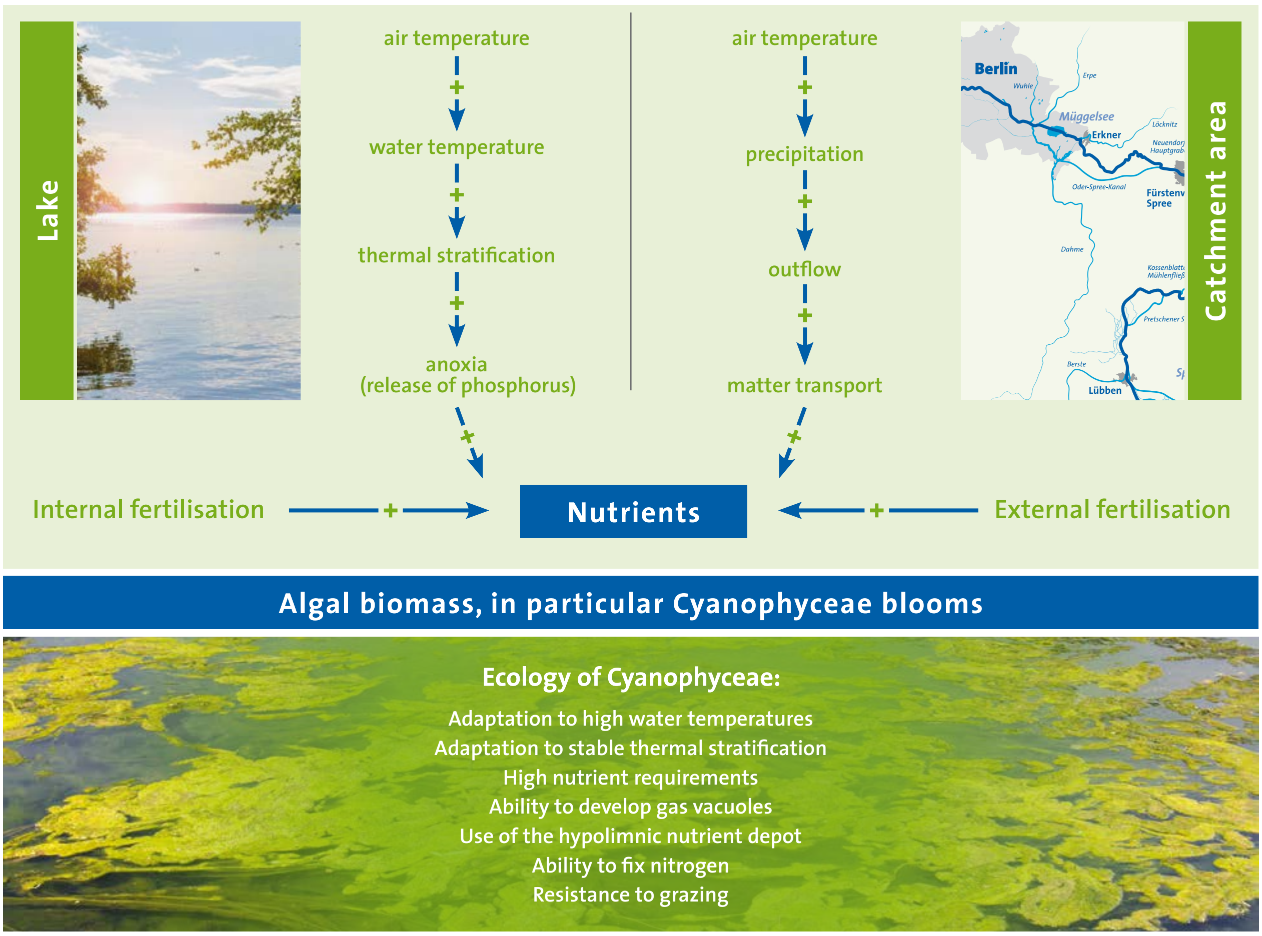





*Figure 2: Comparison of the internally and externally caused fertilisation of lakes in the context of global warming: nutrient accumulation in water encourages the growth of algae, particularly the development of Cyanophyceae, which, owing to their ecology, are among the beneficiaries of climate change.*

an even greater extent than before to compensate for the effect of internal fertilisation – just to maintain the current nutrient status of a lake. In northern regions, however, global warming results in increased precipitation in the form of rain or snow, which leads to a further increase in external inputs to lakes, and hence higher nutrient loads from the catchment area (Figure 2).

High water temperatures, prolonged stratification and high nutrient concentrations encourage the growth of algae, particularly the **development of Cyanophyceae,** which are optimally adapted to such conditions (Wagner & Adrian 2009). In addition, some Cyanophyceae species are able to form gas vacuoles within their cells that help them to float or sink to regulate their vertical position in the water column. This enables them to reach the deep water nutrient depot that accumulates during periods of stable thermal stratification and also the light at the surface that they need to grow. In this way, they avoid temporary nutrient deficiency in the epilimnion, making them more competitive than non-mobile species. Another advantage that some Cyanophyceae have is their ability to use atmospheric nitrogen ($N_2$) as a nutrient when other nitrogen compounds present in the water have been depleted. They often have a filament-like structure and a tendency to form colonies, enabling them to largely avoid grazing from zooplankton. In this way, Cyanophyceae may form dense carpets, especially at the water surface, also severely limiting the recreational value of a lake for swimming (Figure 2).

## 3.6 Phenology: time shift of seasonal events

The most widespread climate-induced changes in ecosystems are changes in **phenology,** the timing of seasonal events in the course of the year. Lakes freeze over later in the year, while ice breaks up earlier. The earlier melting of ice leads to enhanced light conditions in the water, resulting in the earlier onset of the spring algal bloom. Increased water temperatures encourage the earlier development of zooplankton, and consequently the clear water phase also occurs earlier. A further forward shift of events into spring is limited by day length, which remains constant and determines light availability.

## 3.7 Communities: changes in the size of individuals and in the species spectrum

Climate-induced changes in biological communities are much more lake-specific than changes in the physical characterstics. Not all lakes within a climate zone respond biologically the same. In addition, changes are strongly influenced by the lake's trophic status (nutrient level). In addition to phenology changes, another of the few changes that appears to be generalisable is the **reduction in body size of organisms** as temperatures rise. This effect has been demonstrated in phytoplankton, zooplankton and fish populations (Adrian et al. 2016). Higher temperatures usually lead to higher growth rates, and a subsequent decline in body size. This phenomenon is described by the temperature-size rule (Kingsolver & Huey 2008). Essentially, this rule states that fast growth occurs at the cost of body size, since sexual maturity is attained earlier.

An indirect effect has a major impact on phytoplankton: higher temperatures encourage the **growth of algae,** until the available nutrients have been consumed. Due to their higher surface-to-volume ratio, small algal cells can absorb nutrients more efficiently and are capable of crowding out larger species of algae.

In addition, communities change due to **south to north migration.** Species originating in the Mediterranean are increasingly spreading northwards, for instance. Coldwater fish such as Arctic char, *Coregonus* species and smelts, which have only a narrow tolerance to temperature change (stenothermal species), lose their habitats in previously cooler regions. In contrast, species that tolerate greater variations in temperature (eurythermal species), such as pike-perch and common bream (freshwater bream, bronze bream), are on the increase. It can generally be assumed that thermophilic (heat-loving) species will continue to spread, displacing cryophilic (cold-loving) species (for a detailed summary, see Jeppesen et al. 2012, Adrian et al. 2016).

The warming-induced eutrophication (accumulation of nutrients) of lakes restricts light availability. This has a negative effect on larger **underwater plants** (submersed macrophytes). These underwater plants normally ensure that the lake water is kept clear; they prevent the excessive growth of Cyanophyceae; and act as a nursery ground, refuge and pantry for fish, waterfowl and insects. Due to the lack of light, macrophyte growth becomes limited by light. The lake is then dominated by phytoplankton, creating a rather murky appearance (Jeppesen et al. 2003, van Donk et al. 2003, Mooij et al. 2009). Mild winters with little ice coverage or none at all, can also lead to a change in the species composition of underwater plants. At higher water temperatures, evergreen free-floating species that overwinter may have an advantage over species that recede completely in winter (Netten et al. 2011). Non-native species such as the free-floating *Salvinia natans* (floating fern) and straight vallisneria (*Vallisneria spiralis*) are capable of displacing native species in mild winters (Hussner et al. 2014). Based on the empirical studies available, it is difficult to draw further conclusions on dynamics due to climate change and on the composition of the macrophyte community (Adrian et al. 2016).

## 3.8 Interactions with the catchment area of lakes

Lakes collect and store water from their catchment areas. As a consequence, they react very sensitively to changes in their surrounding areas. In this respect, the responses of lakes are often highly individual. The largest impact is probably attributed to regional differences in rainfall fluctuations, which are strongly superimposed by extreme weather phenomena such as drought and flooding (see Section 3.5). These result in changes to the water retention time in the water body and in external nutrient and sediment input (Figure 2). Therefore global warming not only increases internal fertilisation, but also **external fertilisation.** Especially noteworthy is the increased input of dissolved organic carbon (DOC) from the catchment area, particularly as a consequence of milder, wetter winters.

If these inputs are rich in humic substances (substances released from the bottom sediments), the water **turns brown,** referred to as browning or brownification. In this case, less light is available, restricting the development of algae and macrophytes. In this way, the increase in nutrient inputs on the one hand and the deterioration of light conditions due to browning on the other can cushion each other's effect on the development of algae. Browning not only influences light under water, and hence primary production, it also increases the stratification period and decreases the temperature of deep water in seasonally stratified lakes (Snucins & Gunn 2000, Shatwell et al. 2016).

## 3.9 The significance of extreme weather events and critical limit exceedance

Climate researchers assume that extreme weather events will become more frequent. Very mild winters, summer heat waves, and extreme storm or rainfall events are of relevance to lakes. Under future climate scenarios, ice-free winters will be more frequent (Adrian et al. 2016). **Ice-free winters** result in higher oxygen concentrations, since the continuous mixing of the water body counteracts oxygen consumption in deep water. Light and mixing conditions in winter change, and a phytoplankton community develops that is adapted to these conditions. The size spectrum may shift to slightly larger cells and non-mobile species (Özkundakzi et al. 2016), which are kept afloat by the turbulence of the water body in the event of a lack of ice coverage. If nutrients are not limited, larger algal cells have no competitive disadvantage over smaller species in winters.

**Summer heat waves** may encourage Cyanophyceae blooms, as a result of higher water temperatures and more intensive thermal stratification (see Section 3.5 and Figure 2). However, this depends to a great extent on the temporal course of warming and critical limit exceedance in the length of thermal stratification. Persistent thermal stratification and high surface temperatures can lead to summer fish kill as a consequence of temperature stress in the upper water layers and a lack of oxygen in the deeper water layers (Kangur et al. 2013).

**Storm events** can cause the thermocline (the transition layer between the warm surface water and cold deep water) to shift deeper. This shift can redistribute nutrients stored in deep water or plankton communities that were previously concentrated within the thermocline (known as a deep chlorophyll layer) into the epilimnion. As a consequence, an increased growth of algae has been observed (Kasprzak et al. 2017, Giling et al. 2017).

**Intense rainfall events** lead to an increased input of nutrients and organic carbon into lakes from their catchment area. These inputs can encourage algal development and bacterial activity (see Section 3.8 and Figure 2).

# 4. Conclusion and prognosis for the future

Throughout the world, lakes are becoming warmer as a result of global warming. The international community seeks to keep global warming to less than 2 °C. And yet many lakes have already experienced a rise in surface water temperatures in summer that has reached or even exceeded the 2 °C limit in recent decades. The consequences of this warming could have a serious impact on the protection and use of lakes in the future.

**Direct climate-induced changes** in the physical characteristics of lakes can be predicted with a high degree of certainty (see Sections 2.1 and 3.2). Predictions at the chemical level and especially the biological level, however, are much more difficult to make. It is certain that there will be rising water temperatures, an altered stratification, and lower oxygen concentrations in summer. This means that the internal fertilisation of lakes with nutrient-rich sediments will also increase. Changes in phenology, the temporal patterns of seasonal events, are very well to predict (see Section 3.6). There is considerable uncertainty in future projections of matter inputs that are linked to the hydrology and characteristics of the catchment area of lakes. So far, effects on communities, biodiversity and food webs have only been predicted with very limited reliability. Generally, however, there is a tendency for organisms to become smaller and for heat-tolerant species to spread towards the poles, displacing cold-adapted species. Generally speaking, not only global warming, but also the **occurrence of additional stressors** such as eutrophication (with regard to water quality) or greater water consumption and scarcity (water quantity) make it difficult to classify the direct effects of climate change.

This means that **water managers** are confronted with new uncertainties and challenges in the context of climate change adaptation. Climate impact research and long-term monitoring programmes can contribute to the development of robust adaptation strategies. Scenario development and the use of ecological models play a key role in this respect. It has become more urgent to adopt holistic, flexible and long-term water management that considers the dynamics of entire catchment areas (see Section 3.8) beyond state borders. However, this also means that the complexity of policy decisions and the need for coordination will increase.

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**Cover picture**
The Lake Müggelsee, located in the southeast of Berlin, is a polymictic, eutrophic shallow lake that has been the subject of research at IGB for many years.
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