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The Impact of Climate Change on Lakes in Central Europe

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20.1 Introduction

In Europe, the effects of global warming are expected to be particularly acute in areas exposed to a more extreme continental climate. The climate change scenarios summarized in Chapter 2, this volume, suggest that the average summer temperatures in some areas of Central Europe could increase by as much as 6°C by 2071–2100. The associated projections for the rainfall give even more cause for concern with the reductions in some areas approaching 50% in summer. In this chapter we analyse impacts of changing weather conditions on lakes in Central Europe. Long-term data sets from a number of lakes are used to link measured variables to climate signals. Particular attention is paid to the lakes in the perialpine region which are known to be very sensitive to short-term changes in the weather (Psenner, 2003; Thompson et al., 2005). Here, the topography and the steep orography enhance the water cycle, and result in flooding, debris flows, avalanches, vertical plant migration etc. The Alps also form a barrier to the mass movement of air and are responsible for the sharp climatic divide between Atlantic, Continental and Mediterranean influences.

Central Europe is a variously and vaguely defined region. Rather than a physical entity, it is more a reflection of a shared history. The results summarized here are based on the analysis of long-term climatological and limnological data from the countries shown in Fig. 20.1. These include Germany (DE), Poland (PL), the Czech Republic (CZ), Slovakia (SK), Switzerland (CH), Lichtenstein (LI), Austria (AT) and Hungary (HU). The Central European countries are geographically diverse with landforms ranging from the North-German Lowlands, through the Alps to the Hungarian plain. The pannonian plain in the eastern part is also a major climatic 'crossing point' and is affected by the Eastern-European continental, the Western-European oceanic and the Mediterranean influence.

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Fig. 20.1 Map of Europe showing the location of the seven Central European countries defined in the text

20.2 The Region and the Lakes

Conceptually, lakes are commonly regarded as 'filters' which integrate and amplify the local climate (Blenckner, 2005; George, 2006). The lakes in Central Europe include a range of very different types, such as riverine lakes, deep stratifying holomictic lakes, meromictic and shallow lakes as well as artificial reservoirs. Lakes in the perialpine Region are mainly of the 'alpine lake' type. Although this term is widely used as a descriptor for a specific lake type, a precise definition is not possible. Depending on their origin and elevation, three main categories of alpine lakes can be distinguished with several sub-types in each category (Dokulil, 2004):

– high alpine lakes – high altitude, above the tree-line,
– alpine lakes – glacial valley or fjord-type lakes,
– pre- or subalpine lakes – at lower elevations in the perialpine lowlands.

The lakes in the northern lowlands range from shallow, polymictic, hypertrophic to deep, dimictic, oligotrophic. Müggelsee represents the shallow riverine lake type (Driescher et al., 1993). Heiligensee and Stechlinsee exemplify shallow and deep stratifying lakes respectively (Gerten and Adrian, 2001). High-altitude mountain lakes are found on both the Slovak and Polish sides of the Tatra Mountains (Gregor and Pacl, 2005). Reservoirs are widespread throughout the region but are especially numerous in the Czech Republic and in Germany (e.g. Bucka, 1998; Desertová and Punčochár, 1998; Horn, 2003).

According to Meybeck (1995), lakes in the Alps cover approximately 3,440 km^2 and small lakes of less than 0.1 km^2 in size are most abundant. The largest lakes in the region are Lac Leman (581 km^2) and Lake Constance (593 km^2). Most lakes are deep and therefore stratify during summer. Freezing during winter largely depends on lake size and elevation (Dokulil, 2004). The mixing regimes of the lakes are either dimictic when they freeze, or warm monomictic if they mix throughout the winter. Lakes at higher elevations are cold-monomictic and ice-covered for the greater part of the year (Eckel, 1955). The main difference between the alpine lakes and lakes in other deglaciated regions is the much greater depth of the lakes. The maximum to mean depth ratio of 0.46 is very similar to the world average and is also close to that commonly reported for deep lakes (Dokulil, 2004). Several lakes in the region are characterised by metalimnetic populations of the filamentous cyanobacterium *Planktothrix rubescens*. Examples include Mondsee, Wolfgangsee in Austria and Ammersee in Bavaria.

In the south, the region includes the largest shallow lake in Central Europe, Lake Balaton (mean depth 3.2 m) and the alkaline, turbid steppe lake Neusiedler See (mean depth 1.2 m), both located on the Austro-Hungarian plain (Padisák, 1998). This area has a marked continental climate with abundant sunshine and high summer temperatures. As a consequence, the lakes are of the polymictic lake type which stratify only occasionally at irregular intervals. Both these lakes were originally endorheic, but now have artificial, regulated outflows. The water budget strongly depends on evaporation. Water temperatures follow changes in air temperatures with a time lag of hours and are very high during summer and often below freezing in winter.

20.3 The Historical Variations in the Weather

The climatological variations that characterize the region are illustrated in Fig. 20.2. In some cases, there is very little differences between the annual averages but the amplitude of the seasonal variations are much greater at the more continental locations.

Near the northern edge of the Alps at Salzburg, Austria precipitation is twice as high as that recorded elsewhere, exceeding 100 mm during the summer months. The average air temperature here is slightly below that at the other two stations. At the high altitude site on the peak of Sonnblick in Austria climatic conditions are entirely different. The annual average air temperature is –5.8°C and exceeds zero degrees for only about two month per year. Precipitation, at over 100 mm in almost every month, accumulates to produce a mean total of 1,832 mm per year.

The average increase in the observed annual mean temperature across Europe for the last century was 0.8°C. During the same period, above surface air temperatures in Austria increased by 1.8°C. The temperatures recorded during the winter have, in general, increased more than those recorded during the summer. In 2003, many countries in central Europe experienced the warmest summer on record and the last 30 years was the warmest period in the last five centuries. The winter of 2006/2007 was also the mildest on record and was followed by an unusually warm spring. Annual precipitation over Northern Europe has increased by between 10 and 40% in the last century while the Mediterranean basin has experienced reductions of up to 20%. In future, summer heat waves and intense winter precipitation events are projected to become more frequent and the risk of drought is likely to increase throughout central and southern Europe.

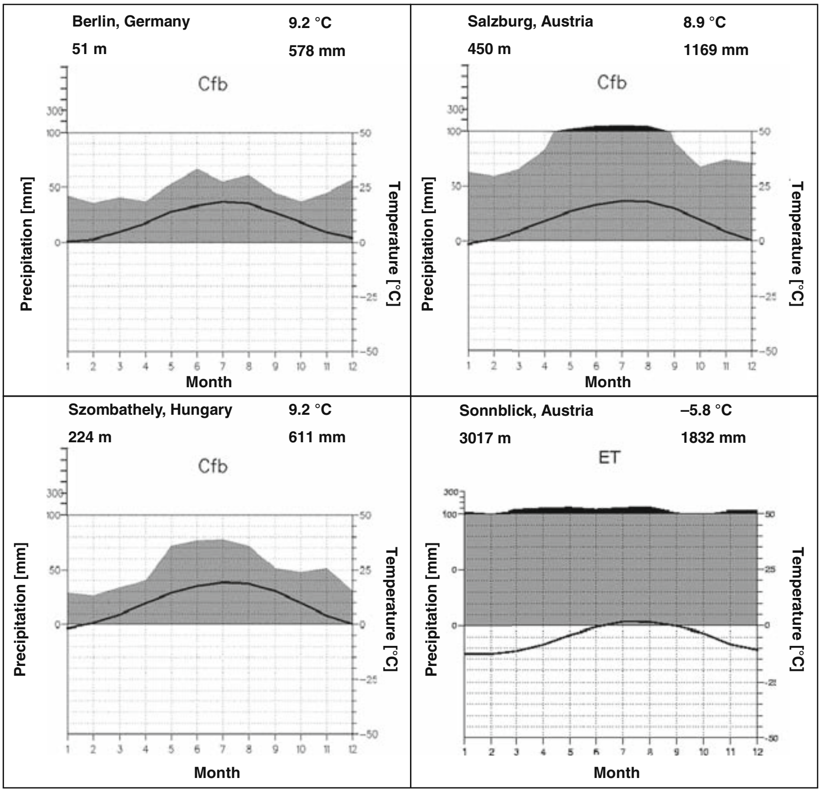

Fig. 20.2 Diagrams showing the climatological variations for three cities and a high elevation site in Central Europe (Berlin, Germany, Szombathely, Hungary, Salzburg and Sonnblick, Austria). Climate classification according to Köppen: Cdf = temperate, humid climate with warm summers; ET = Tundra climate. (Modified from Mühr, 2006)

The temperature increase in the Alpine region are synchronous with the global warming but have much greater amplitude (Fig. 20.3). The rate of warming is twice as great as the global average reaching anomalies close to 1°C and up to 2°C for individual sites (Beniston et al., 1997). Differences between west, east, north, south or sea level are also statistically significant (Auer, 2003; Auer et al., 2006). Long-term precipitation trends are highly variable between seasons, have large spatial differences or are even antagonistic in direction. Long-term trends in the NW and SE have even abruptly changed into their opposite in recent times (Auer, 2003, 2006; Böhm, 2006; Brunetti et al., 2006).

20.4 The Climate Change Projections

Several projections of future changes in climatic conditions are now available but many are based on different scenarios for the change in atmospheric CO_2 concentration. The regional climate model simulations documented by Räisänen

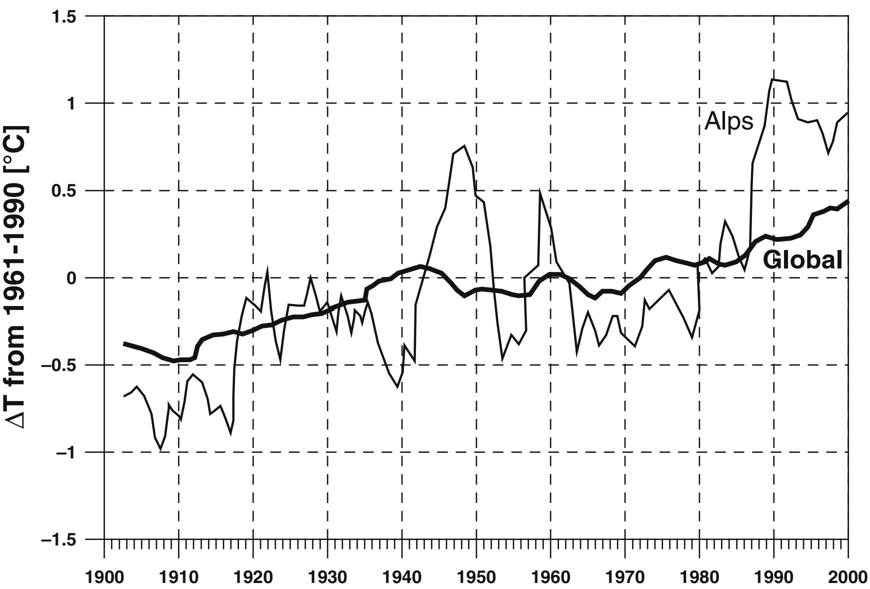

Fig. 20.3 Annual average temperature anomalies from high elevation sites in the Alps compared to global mean temperature anomalies. Expressed as deviations in °C from the IPCC base period 1961–1990 and smoothed with a five-year filter (Modified from Beniston et al., 1997)

et al. (2003) all indicate that warming in central Europe will be greatest in summer, locally reaching 10°C. This increase in temperature is associated with substantial decreases in precipitation, soil moisture and cloudiness. The projected temperature increase for the year 2035 is 2.0–3.5°C depending on the scenario and whether or not the damping by aerosols are considered (Kromp-Kolb and Formayer, 2001). In central Europe, the precipitation is projected to increase by at least 30% in winter and decrease by as much as 50% in summer (Chapter 2, this volume). The magnitude of these variations varies geographically and there is a general tendency for the number of precipitation days to decrease in central and southern Europe. The yearly extremes increase even in the areas of central Europe where there is a decrease in the mean annual precipitation. The simulated annual mean evaporation increases in most of central Europe under all the selected scenarios.

20.5 The Influenc of Global-Scale Changes in the Weather

Variations in the climate are usually characterized by 'anomalies' which are the deviations of the short-term situations from the long-term climatic average. Within these global circulation patterns there are some recurrent patterns of variability. For the Northern Hemisphere and Europe, the North Atlantic Oscillation (NAO) is of prime importance (Marshall et al., 2001; Ottersen et al., 2001). Based on this and other pressure gradients, a number of indices have been proposed as indicators for the teleconnections that regulate the climate in specific geographical regions.

The most commonly used proxy for Central Europe is the NAO-index (Hurrell, 1995). The NAO can be characterised by a family of related indices which all follow the same broad pattern of variation with no significant dominant periodicities (Stephenson, 2006). The most closely related index is the Arctic Oscillation (AO) which follows the same winter pattern (Shindell et al., 2001). In the positive phase, it is a better measure of the number and frequency of days with subzero temperatures or substantial snowfall in the mid-latitudes (University Washington, 2001). Another proxy used to explore the climatic responses of lakes situated close to the Atlantic coast is an index based on the position of the north-wall of the Atlantic Gulf stream, GSI (Taylor and Stephens, 1998; Taylor et al., 1998). This index is significantly correlated with the NAO at a lag of two years (George and Hewitt, 1998; Jennings and Allott, 2006) but adds very little to our understanding of weather patterns in Central Europe. Another index useful in more continental situations is the Mediterranean Oscillation index (MOI), defined by Palutikof et al. (1996) and Conte et al. (1989) as the normalized pressure difference between Algiers (36.4°N, 3.1°E) and Cairo (30.1°N, 31.4°E). On a regional scale, indices based on the classification of daily weather types have also proved useful and include those developed by Chen (2000), Lamb (1972) and Steinacker (2000) which are described in Chapter 16 of this volume. A reduced set of the circulation types proposed by Steinacker (2000) for the Alps has recently been used by Nickus and Thies (2004) to explore the effect of inter-annual variations in the weather on alpine lakes. The western, north-western and variable flow type was closely correlated to the winter NAO ($r^2 = 0.42$, $p < 0.001$). Analyses that relate the decadal trend in these regional indices to the NAO show a clear contrast between two recent decades. The years 1961–1970, dominated by negative NAO values, were characterized by the north-weather flow type while 1991–2000 had positive NAO values associated with increased frequencies of the west and variable flow types.

20.5.1 Impacts on Temperature, Stability and Timing of Events

One of the most important physical parameter in any lacustrine system is the temperature of the lake since it reflects meteorological forcing in a direct and sensitive way (Dokulil, 2000). In temperate regions, the highest surface water temperatures in winter are recorded in deep lakes that retain heat and the lowest in shallower lakes that loose more heat to the atmosphere. In ice-covered lakes the most sensitive climatic indicators are usually the timing and duration of ice cover (Chapter 4, this volume) but significant effects have also been observed in the open water (Chapter 6, this volume). At very cold locations, the year-to-year variations in the winter weather can also have important effects on the ecology of the lakes. These include the impact of the physical characteristics of the ice and the type and depth of snow on the underwater light regime and the convective currents that develop under the ice (Chapter 5, this volume). Changes in the freeze-thaw cycle of lakes at high latitudes and altitudes are often used as proxy indicators of regional changes in the weather (see Magnuson et al., 2000 and Chapter 4, this volume).

Long distance climatic forcing also affects the processes that regulate the summer dynamics of the lakes. These include the onset, timing and duration of thermal stratification, the depth and intensity of mixing and the heat content. Lake surface water temperatures (LSWT) are closely correlated with the air temperature at all elevations (Livingstone et al., 2005a). Both variables are strongly influenced by the North Atlantic Oscillation (NAO), especially during winter and spring (Livingstone and Dokulil, 2001). Some example correlations for several lakes, not analysed by Livingstone and Dokulil (2001), are shown in Fig. 20.4. These include Neusiedler See in the eastern part of Austria and two lakes from the Carinthian lake-district south of the Alps. Strong teleconnections are evident in all these examples, with the weakest recorded for lakes, like Altausserer See and Grundlsee in the inner alpine valleys, and those located to the south of the alpine ridge. At the more isolated locations, local climatic conditions are far more influential and other weather patterns are of greater importance at sites situated south of the alpine divide.

The situation of Neusiedler See in the pannonian plain suggests that 'Mediterranean' influences could be important there. We therefore compared the temperature records with the Mediterranean Oscillation Index (MOI), an index commonly used to analyse weather patterns in the Mediterranean region (Martin-Vide and Lopez-Bustins, 2006; Maheras and Kutiel, 1999). In fact, the MOI is a better predictor of

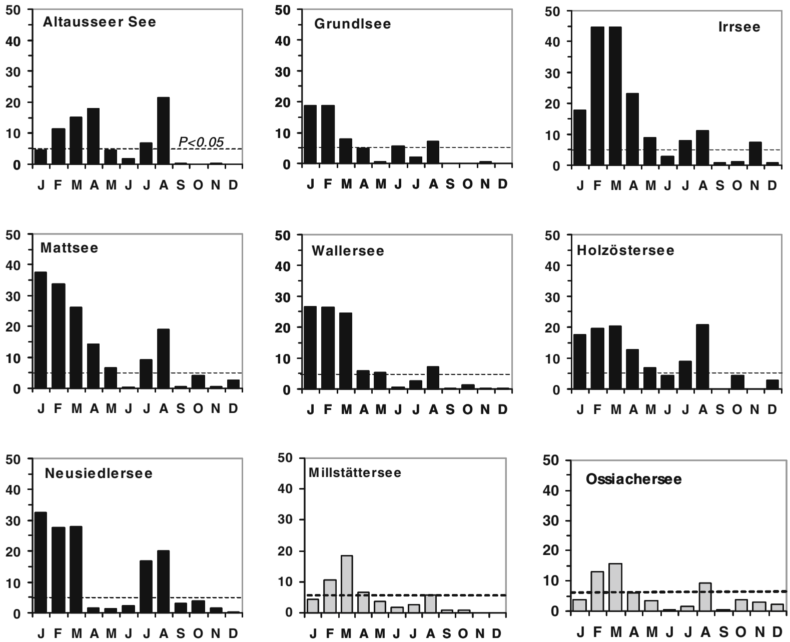

Fig. 20.4 Bar graphs showing the seasonal variation in the coefficients of determination (r^2) between winter NAO index and monthly mean lake surface temperature for nine lakes in the peri-alpine region of Austria

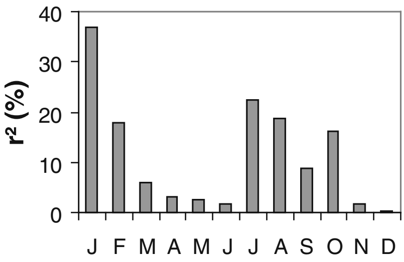

Fig. 20.5 Coefficient of determination (r^2) between winter MOI_{DJFM} index and monthly mean lake surface temperature in Neusiedler See, Austria

summer and early autumn water temperatures in Neusiedler See (Fig. 20.5) but the NAO still has a significant effect on the LSWT in winter.

Long-term trends in LSWT indicate considerable differences between seasons and regions. The average decadal increase between 1940 and 2000 in sixteen lakes north of the Alps was 0.17°C for the winter season and 0.25°C for both spring and summer (Table 20.1). The average rate of change in the autumn was 0.07°C per decade but there were large differences between the individual lakes (– 0.31 to + 0.21). The average increase in LSWT in three middle sized lakes south of the Alps was very similar to that north of the Alps but absolute values were smaller and less variable at all seasons (Table 20.1). The average increase per decade in shallow Neusiedler See was well above the average for the other lakes. Most noticeably, LWST in winter increased on average by 0.31°C per decade, which is the highest rate of change in the whole set of data. In all the lakes and in all seasons except winter, there was a logarithmic relationship between these rates of change and the maximum depth of the lakes. Temperature changes during the winter seem to depend more on orography and ice-cover than the depth of the lake.

The long-term increase in the summer lake water temperature is not simply a reflection of changes in air temperature. As shown by Wilhelm et al. (2006), the rate of increase of the daily night time minimum exceeds that of the daily maximum. This day-night asymmetry in epilimnetic temperatures is influenced by the flux of heat across the air-water interface which, in turn, depends on wind speed, relative humidity and cloud cover. Summer warming will cause increases in the frequency and the duration of stratification events in polymictic lakes such as Müggelsee. Summer stratification events in the extremely warm summers of 2003 and 2006 were the longest on record lasting for up to 8 weeks (Wilhelm and Adrian, 2007). In the long run, lakes currently dimictic or polymictic may well become monomictic in the future, if they are then free of ice during winter.

In the very deep Italian lakes south of the Alps Ambrosetti et al. (2003) found a reduction of winter mixing over the last 40 years and, consequently, the deeper layers have become less affected by seasonal variations which retain a 'climatic memory' in their hypolimnia. In such deep lakes, complete circulation becomes increasingly difficult affecting lake hydrodynamics, turnover, deep water chemistry and dissolved gases. Mixing events then require more energy, that is more wind,

Table 20.1 Long-term increase in lake surface water temperature (LSWT) for the four seasons

Lake	Geogr. position N/E	Elevation [m a.s.l.]	Surface area [km^2]	Max depth [m]	Season Winter	Spring	Summer	Autumn
Bodensee	47°38′/9°22′	395	536.00	254.0	0.3066	0.2395	0.2524	0.0927
Piburger See	47°11′/10°53′	913	0.13	25.0	0.2099	0.3478	0.2166	0.2273
Zeller See	47°19′/12°48′	750	4.55	68.0	**0.3989**	0.1641	–0.0655	0.1113
Holzöster See	48°03′/12°54′	460	1.82	4.7	0.0434	**0.7616**	**0.7854**	0.1299
Mattsee	47°59′/13°07′	503	3.60	42.0	0.3054	0.1690	0.3672	**0.2097**
Wallersee	47°54′/13°10′	506	6.10	23.0	0.1248	0.1036	–0.0426	–0.0004
Fuschlsee	47°48′/13°16′	636	2.65	66.3	0.0845	0.1605	0.3546	0.2076
Irrsee	47°54′/13°18′	533	3.47	32.0	0.0667	0.7222	0.2257	–0.3099
Mondsee	47°49′/13°22′	481	14.21	68.3	0.2212	0.3462	0.3278	0.1742
Attersee	47°54′/13°33′	469	45.90	170.6	0.1481	0.2038	0.2186	0.0764
Altausseer	47°38′/13°47′	712	2.10	52.8	0.2905	0.2744	0.4990	0.0837
Grundlsee	47°38′/13°51′	709	4.14	63.8	0.0715	0.0472	0.1131	–0.0316
Hallstätter See	47°34′/13°39′	508	8.58	125.2	0.0137	0.0903	0.1276	–0.1354
Wolfgang S.	47°45′/13°23′	538	12.84	113.1	0.0764	0.0861	0.2071	0.0727
Traunsee	47°52′/13°48′	422	25.60	191.0	0.1339	0.1640	0.1312	–0.0214
Lunzer See	47°51′/15°03′	608	0.68	33.7	0.1625	0.1658	0.2262	0.2120
Mean					**0.17**	**0.25**	**0.25**	**0.07**
Maximum					**0.40**	**0.76**	**0.79**	**0.23**
Minimum					**0.01**	**0.05**	**–0.07**	**–0.31**
Range					**0.39**	**0.71**	**0.85**	**0.54**
Millstätter	46°47′/13°34′	588	13.28	141.0	0.0699	0.1512	0.1497	–0.0228
Ossiacher	46°40′/13°57′	501	10.79	52.0	0.1513	0.0979	0.1980	0.1411
Wörther	46°37′/14°09′	439	19.38	85.2	0.1029	0.1916	0.0269	–0.0414
Mean					**0.11**	**0.15**	**0.12**	**0.03**
Maximum					**0.15**	**0.19**	**0.20**	**0.14**
Minimum					**0.07**	**0.10**	**0.03**	**–0.04**
Range					**0.08**	**0.09**	**0.17**	**0.18**
Neusiedler See	47°49′/16°44′	115	321.00	1.8	0.2444	0.5129	0.6622	**0.3059**

winter = DJF, spring = MAM, summer = JJA, autumn = SON. Data in °C per decade. Lakes are arranged according to geographical position or drainage basin marked by dashed lines. The elevation, surface area and maximum depth for each lake is given

to re-establish initial thermal conditions (Ambrosetti and Barbanti, 1999). The increased surface temperatures and enhanced thermal stability in the summer will affect nutrient flux and the growth of plankton organisms. The nature of these biological effects will largely depend on the physical characteristics and the maximum depth of the individual lake.

20.5.2 Regional Coherence

Despite the large distances separating sub-regions within Central Europe and the different character of the lakes, variations in surface water temperatures were highly synchronous (coherent) and related to fluctuations in air temperature. The surface temperatures in all the selected lakes, ranging from Müggelsee in the north to Lake Balaton in the south, were particularly coherent in summer and autumn. The proportion of variance shared pair wise between the residual time-series always exceeded 30%. For lakes located within tens of kilometres of each other, shared variances of 80–90% was not uncommon (Dokulil and Teubner, 2003; Livingstone et al., 2005b).

In general, coherence between lakes cascades down from physical parameters via chemical and nutrient variables to biological entities (Fig. 20.6 and Dokulil and Teubner, 2002). In other words, the effects of changes in climatic conditions on the biology of lakes are complex, difficult to disentangle from other influences, and not easy to generalise (see Livingstone et al., 2007 and Chapter 17, this volume).

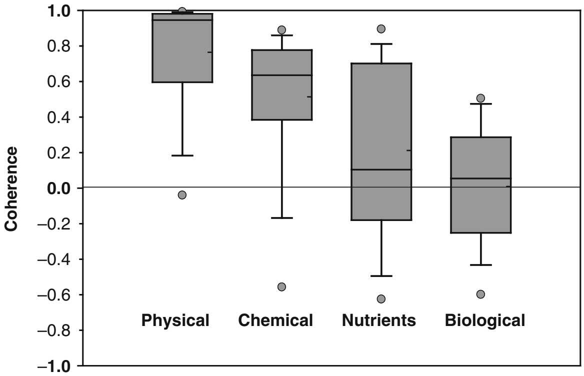

Fig. 20.6 Regional coherence (expressed as correlation coefficients) between pairs of six alpine lakes in the Austrian 'Salzkammergut' region shown as box-whisker plots. Box limits are the 25th and 75th percentile; whiskers indicate the 10th and 90th percentile. In these boxes, the *solid line* is the median, the *dashed line* the mean. Physical = surface temperature, light attenuation and Secchi-depth; chemical = pH, conductivity and oxygen concentration; nutrients = total phosphorus, total nitrogen and dissolved silica; biological = chlorophyll-a and phytoplankton biomass. (Modified from Dokulil and Teubner, 2002)

20.5.3 Chemical and Biological Effects

Small variations in climate are likely to have a particular dramatic effect on extreme habitats, such as high altitude lakes (Psenner, 2003) or shallow soda lakes (Kirschner et al., 2002). In these systems, many species live at the limit of their capabilities and will respond very quickly to any additional stresses such as a change in the duration of ice cover or summer drought. If these habitats dry out or become fragmented many species will disappear and be replaced by species with special adaptations. The effects of global warming on phytoplankton dynamics are not fundamentally different in different regions of the world (Gerten and Adrian, 2002b). In winter, effects are connected with light conditions, ice duration and variations in wind-induced mixing in ice-free lakes. Winter conditions are also largely responsible for the timing, magnitude and composition of the spring peak of phytoplankton, the clear water phase and the development of the zooplankton in both shallow and deep lakes (Gerten and Adrian, 2000; Straile, 2000). The propagation and cascading effect of the NAO on meteorological conditions, water temperature, zooplankton biomass and on the clear water phase has been discussed by (Straile 2000, Straile et al., 2003b) and is shown schematically in Fig. 20.7. These results demonstrate that the timing of the spring phytoplankton bloom, as measured by chlorophyll-a is strongly related to climate forcing during the winter.

In Mondsee (Fig. 20.8), the strongest correlation was that observed with an index derived by averaging the January and February NAO index of Jones et al. (1997). Here, the average timing of the spring chlorophyll maximum has advanced by about 48 days. In Northern Europe, the spring bloom of phytoplankton is more closely correlated with the NAO index for March (Weyhenmeyer et al., 1999). Simulation of phytoplankton growth during winter and spring in Upper Lake Constance, a deep monomictic lake, also indicates that changes in the meteorological conditions associated with warming alter the onset of phytoplankton growth and subsequent succession of species (Peeters et al., 2007). The phytoplankton growth rate increases when these lakes start to stratify but is soon regulated by zooplankton grazing, particularly from ciliates.

In summer, prolonged thermal stratification can influence hypolimnetic oxygen conditions, dissolved nutrient concentration and phytoplankton composition (Jankowski et al., 2006; Wilhelm and Adrian, 2008). Oxygen depletion and higher temperatures increase nutrient release processes at the sediment-water interface (Søndergaard et al., 2003) and increase the stress on aquatic organisms (Weider and Lampert, 1985; Saeger et al., 2000; Wilhelm and Adrian, 2007).

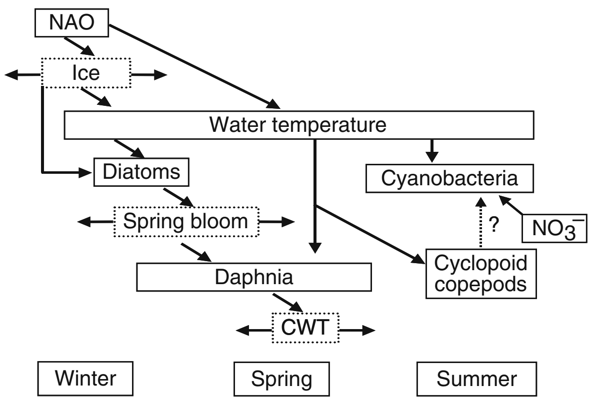

Fig. 20.7 Conceptual diagram of the effects of Winter NAO on lake ecosystems. Modified from Blenckner et al. (2007) after Straile (2000)

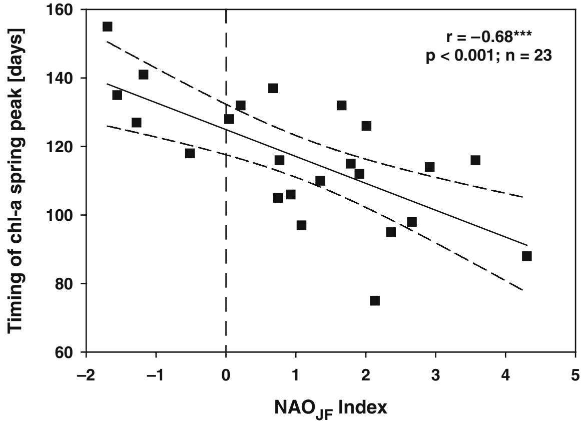

Fig. 20.8 The relationship between the timing of the chlorophyll-a spring peak in Mondsee (1982–2004) and the average January–February NAO Index (NAO_{JF})

An analysis of 81 shallow lakes from three climatic regions including lakes from Central Europe suggests that climate is an important predictor of zooplankton biomass, community composition and food-web dynamics (Gyllström et al., 2005; Straile, 2005). In Lake Washington, USA the trophic linkage between phytoplankton and zooplankton is disrupted by the systems differential sensitivity to vernal warming. In many lakes, the long-term decline in *Daphnia* populations is associated with the temporal mismatches that develop with the spring diatom bloom (e.g. Winder and Schindler, 2004). The response of freshwater copepods to the recent increase in the summer temperature appear to be species specific (Gerten and Adrian, 2002a).

In the shallow eutrophic Müggelsee, warming has increased both the number and size of newly developed larvae of *Dreissena polymorpha*, suggesting that conditions for overall reproductive success have improved. A sudden drop in the abundance of the larvae in 2003 is attributed by Wilhelm and Adrian (2008) to the low dissolved oxygen concentrations associated with an unusually long period of stratification.

The potential impacts of climate on fish are summarised by Ficke et al. (2005). A good example from Central Europe is that observed in Lake Constance (Straile et al., 2007). In this lake, the temperature variations associated with NAO affects the year-class strength of fish (*Coregonus lavaretus*, Blaufelchen) by regulating both the egg development time and larval growth rate. The duration of egg development is related to the NAO with a time lag of one year due to the mixing characteristics of this warm, monomictic lake. Larvae hatch earlier if the previous winter has been relatively warm.

20.5.4 Teleconnections

The long-term increase in temperature associated with mild winters influences the timing of ice formation, ice duration and ice-break up date. Both duration and ice-off are significantly correlated with winter NAO in lakes of Central Europe

Table 20.2 Correlation coefficients of ice conditions in Central European lakes versus winter NAO, AO and MOI. Lakes are arranged from North to South

Lake	Ice	NAO	AO	MOI
Müggelsee	Duration	–0.762***	–0.612***	n.s.
	Ice-off	–0.609***	–0.504*	n.s.
Irrsee	Duration	–0.494***	–0.410***	n.s.
	Ice-off	–0.671***	–0.330*	n.s.
Mondsee	Duration	–0.570**	–0.443*	n.s.
	Ice-off	–0.724**	–0.774**	n.s.
Neusiedler see	Duration	–0.451*	n.s.	–0.503*
	Ice-off	–0.511**	–0.461*	–0.650**
Balaton	Duration	–0.261*	n.s.	–0.381*
	Ice-off	–0.528***	–0.323**	–0.486**

*** = $p<0.001$, ** = $p<0.01$, * = $p<0.05$, n.s. = not significant

(Table 20.2). This teleconnection to climate signals is quite robust and does not depend on the version of the NAO index used (NAO_W Hurrell, 1995; NAO_W Jones et al., 1997). Ice conditions in all lakes are also significantly related to the AO also known as the Northern Annular Mode (NAM), a further indication of long distance climate effects. Lakes of continental position in Central Europe, e.g. Neusiedler See or Balaton (VITUKI, 1996) are also influenced by another, completely different, weather situation. Here, ice duration and ice-out is also related to the Mediterranean Oscillation (MOI) which is not the case in the other lakes listed in Table 20.2.

In common with other lakes in the Perialpine Region north and south of the Alps (Blanc et al., 1990; Livingstone, 1993, 1997; Ambrosetti and Brabanti, 1999), deep water warming was also evident in several lakes across Europe (Dokulil et al., 2006). Hypolimnetic temperatures increased consistently in all lakes by about 0.1–0.2°C per decade. The observed increase was related to large-scale climatic processes over the Atlantic. To be effective, the climatic signal from the North Atlantic Oscillation (NAO) must affect deep lakes in spring before the onset of thermal stratification. The most consistent predictor of hypolimnetic temperature is the mean NAO index for January–May ($NAO_{J–M}$), which explains 22–63% of the inter-annual variation in deepwater temperature in 10 of the 12 lakes (Fig. 20.9). A time lag of one year, as described by Straile et al. (2003a), was not evident but can result from reduced winter cooling and the persistence of small temperature gradients that resist complete mixing. Mixing in turn can determine the trophic status of lakes (Salmaso et al., 2003; Salmaso, 2005) which could have important implications for the assessment of ecological status over time relative to the Water Framework Directive (Eisenreich et al., 2005).

The most important physical process in the annual cycle of many lakes is thermal stratification. The enhanced physical stability of a thermally stratified lake has a profound effect on its chemical and biological characteristic in summer. The direct effects of the projected increases in the temperature may thus be more pronounced in shallow, isothermal lakes but the indirect effects associated with change in

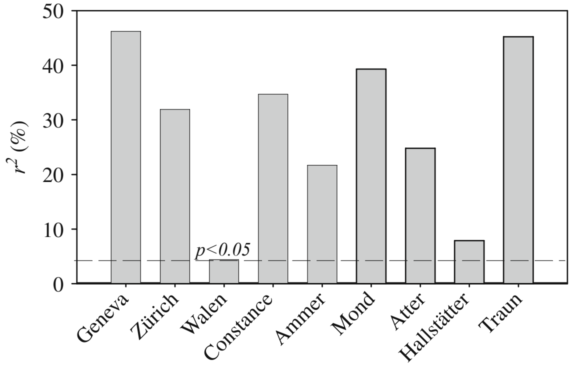

Fig. 20.9 Coefficients of determination (r^2) between the mean NAO index for January–May ($NAO_{J–M}$) and the deep-water temperatures of 9 Central European lakes. Modified from Dokulil et al. (2006)

stability is very important in moderately deep lakes. The responses of thermally stratified lakes to changes in the flux of heat and the intensity of wind mixing are complex and strongly influenced by the morphometry of their basins. The effects of winter NAO are, typically, of short duration in polymictic lakes but in deep lakes with stable summer stratification these signals can even be preserved until the following winter (Gerten and Adrian, 2001). This in turn may even affect the timing and duration of thermal stability in moderately deep alpine lakes. For example, in Lake Mondsee, Austria, (Fig. 20.10) the timing of the onset and maximum thermal stability critically depends on the status of the NAO between January and March. Positive NAO values during the spring period shift the onset earlier while maximum stability is reached later in the year. In contrast, negative values prolong mixing, resulting in later onset and earlier maximum stability.

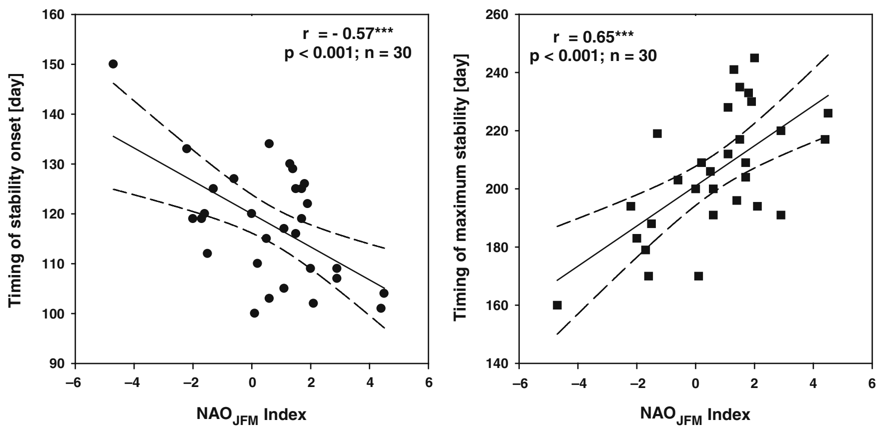

Fig. 20.10 The timing of thermal stratification (*left panel*) and the period of maximum stability (*right panel*) in Mondsee, Austria related to the average January to March NAO of Jones, 1997 (NAO_{JFM})

20.5.5 Impacts from the Catchment

In mild winters, more precipitation falls as rain rather than snow, the time of snow melt is earlier and there is an increase in the peak winter runoff which also occurs earlier in the year. In alpine areas, the accumulation and depletion of snow-pack is particularly important. Changes in the runoff characteristics are expected to be more pronounced in the southern catchments, whilst north facing catchments should be influenced to a lesser extent (Kunstmann et al., 2004).

Changes in nutrient loading to lakes will largely depend on water supply and water chemistry. Phosphorus loading is likely to increase due to enhanced wash-out from soil as a consequence of the increase in net precipitation and the increased frequency of extreme rainfall events (Kromp-Kolb and Schwarzl, 2003). These events are also likely to increase soil erosion ultimately leading to enhanced lake productivity and increased sediment accumulation rate. This will be especially pronounced and important in artificial reservoirs. Nitrogen loading to downstream lakes will be lowered because increased temperatures will result in higher denitrification rates, the main process responsible for N-losses within catchments. The response of in-lake nutrient concentration to climate variability depends on the size of the lake since smaller lakes are more sensitive than large lakes (Jankowski et al., 2005; Straile et al., 2003).

Catchments with a large number of lakes such as e.g. the Elbe river basin (>500 lakes larger than 50 ha) have a major impact on the rivers. If the nutrient loads to these rivers decrease as a consequence of climate change the mixing characteristics and the ecology of these lakes would also change, e.g. there could be a switch from a polimictic to a dimictic state causing drastic changes in the nutrient cycles and the dynamics of the entire ecosystem (Bergfeld et al., 2005).

20.5.6 Extreme Events

As the world becomes warmer the frequency of extreme climatic conditions such as exceptionally mild winters, extremely warm summers, heavy precipitation and flooding or storm events is also expected to increase with major consequences for lakes (Easterling et al., 2000).

In Vienna, the frequency of very warm summers has increased significantly over the last 50 years and there has been a corresponding reduction in the number of very cold winters (Brunetti et al., 2006). Heatwaves in summer are increasingly characterized by large departures from their average values, for example ΔT_{max} was +6.0°C in Basel in August 2003 and reached a maximum of +11.2°C on August 4, 2003 (Beniston and Diaz, 2004). The probability of extreme precipitation events has also increased by 12%, a feature associated with enhanced storm-track activity and 'wetter' conditions over much of central Europe (Palmer and Räisänen, 2002). In Austria, these heavy precipitation events have recently been linked to seven different synoptic patterns (Seibert et al., 2007). Large parts of Central Europe experienced extremely heavy rainfalls during the early days of August 2002 which, in some cases, exceeded the average August totals (DWD, 2002). Extremes of precipitation will also lead to a reduction in the duration of the snow cover period in the Austrian Alps ranging from about 4 weeks in winter to 6 weeks in spring (Hantel et al., 2000). Results for extreme storm events over Central Europe are rather inconsistent. In general, wind speeds tend to increase in winter and decrease in summer (Jonas et al., 2005).

Effects on lake water temperature, stratification and stability differ considerably between extremely cold and warm winters. During cold winters, the effects depend on whether the lake freezes. Frozen lakes have relatively stable water columns but mixing can be intense in open water. Similarly, frozen ground will result in reduced drainage and lower than normal winter nutrient loadings. During warm winters, water temperatures are higher than average and may remain high until spring. Higher than usual spring temperatures can, in turn, lead to higher hypolimnetic temperatures in summer. In Austria, the autumn of 2006 was the warmest on record and was followed by the mildest winter since measurements began. Lakes which usually freeze, such as the shallow Neusiedler See, were not frozen and several deep lakes also remained open throughout the winter.

In summer, very high epilimnetic temperatures are recorded in very warm years. During the 2003 heat-wave the surface temperature of Mondsee exceeded 25°C. The resulting increase in thermal stability can lead to increased rates of oxygen consumption in the hypolimnion which can become anoxic in its deeper parts. This has recently been observed in lake Mondsee, Austria and in a number of Swiss lakes (Jankowski et al., 2006). This increased and extended thermal stability also restricts the vertical transport of nutrients and reduces nutrient concentrations in the epilimnion which, in turn, effects both the composition and the seasonal dynamics of the phytoplankton. Between 2000 and 2003, a series of very dry years at Lake Balaton in Hungary had a major effect on the water budget and the biomass of phytoplankton (Padisák et al., 2006). Less than normal precipitation and increased evaporation drastically decreased lake level. As a consequence, there was an increased incidence of nuisance algal blooms.

Extreme precipitation events increase the loading of nutrients and suspended particles, as was the case with the flood experienced in the Salzkammergut region in 2002. In Mondsee, this increase in turbidity was associated with increased nutrient concentrations, particularly reactive silica (Dokulil and Teubner, 2005). Similarly, Lake Constance experienced dramatic lake level fluctuation during the 1999 centennial flood (Jöhnk et al., 2004).

Short but severe storm events can even have an effect on the water quality of large, shallow lakes. Data from Müggelsee demonstrate that the impact of storms is critically dependent on the antecedent conditions i.e. whether they occur suddenly or build up gradually (Wilhelm et al., 2006).

20.6 Summary and Conclusions

The climate of Central Europe is essentially dependent on weather conditions experienced over the Atlantic. Long-term changes in the circulation of the atmosphere are primarily responsible for the observed changes in the weather. These changes can be expressed by a number of climatic indices. Here we have shown that a clear teleconnection exists between climate signals, weather conditions and the response of the lakes over very large distances.

The rate of warming in Central Europe is now likely to exceed the 0.2°C for the next two decades projected for a range of emission scenarios by the IPCC summary report (2007). Regional differences in Europe are also expected to increase with flash floods and erosion becoming more common. Reduced snow cover and glacier retreat will affect tourism and reduce the quantity of water available to consumers. Central European projections for the summer period suggest drastically increased air temperature and decreasing precipitation. In contrast, winter run-off will significantly increase due to reduced snow cover. The number of extreme events affecting the catchment of lakes is also likely to increase.

Ice cover of lakes is expected to shorten in duration. Lake surface temperature during summer will rise by about 4°C. Deep water temperatures are projected to increase by about 0.1–0.2°C per decade and will have a significant effect on oxygen levels and the internal re-cycling of nutrients. The duration and strength of thermal stratification will expand. Associated with these changes are shifts in algae, plankton and fish abundance.

Increased erosion due to high winter run-off combined with higher water temperatures and more prolonged stratification in summer will, almost certainly, lead to widespread, climate-related eutrophication.

Alterations in catchment processes will affect the external loading of nutrients and change the residence time of most lakes. Together with in-lake changes, particularly in nutrient cycles which are biologically mediated and thus temperature dependent, climate change will adversely affect the objectives of good water quality as defined in the Water Framework Directive (WFD). The anticipated changes depend strongly on lake type and local conditions. Biological changes induced by climatic changes are inherently unpredictable because of complex interactions which influence shifts in community structure and increase the risk of harmful algal blooms, the severity of deep water anoxia and the subsequent mortality of commercial fish species. In addition to these anthropogenic changes, there is also natural variability. To enable distinction, the WFD introduced a detailed typology of water bodies as the basis for water quality assessment. As the world becomes warmer, these typologies will need to be revised and new reference conditions established to take account of the changing climatic conditions (see Chapter 24, this volume).

Monitoring fresh-water ecosystems in a changing world requires not only permanent meteorological and hydrological observations, but also a network of automatic water quality stations to record the short-term responses of lakes and rivers. Such stations should, ideally, be installed at sites where long-term environmental data is already available. For large water-bodies, such observations can readily be augmented by remote sensing. Only then we will be able to answer the questions how much natural variation can be accommodated within types and how to differentiate between natural variation and impact. To cope with the more pronounced, irreversible impacts, the classification scheme of the WFD will need to be updated at regular intervals with due regard to the non-static reference conditions that characterize a warmer world.

Finally, socio-economic development and changes in socio-economic structures in combination with climate change must be considered which could seriously alter natural conditions by e.g. habitat destruction and loss of biodiversity. Socio-economic impacts of climate trends will clearly not be the same in all the European regions. Some areas might benefit while others are adversely affected. Overall, climate change will certainly affect many aspects and facets of Central Europe and poses a constant challenge for future development.

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