Verh. Internat. Verein. Limnol.	28	1–4	Stuttgart, December 2002

The spatial coherence of alpine lakes

M. T. Dokulil and K. Teubner

Introduction

Many environmental problems and processes are regional, continental or global. Some of the most important natural factors are year-to-year variations in the weather, which follow a quasi-cycling pattern (GEORGE & HARRIS 1985). In Europe, changes are known to be largely associated with atmospheric circulation patterns across the North Atlantic (GEORGE et al. 1998, DOKULIL 2000). Analysing the impact of climatic change on European freshwater lakes poses the problem of how to scale up from single-site studies to regional coverage. Based on the expectation that neighbouring lakes within a lake district vary synchronously over time, coherence between locations within a region can be used.

Materials and methods

Long-term data from six alpine lakes in the Austrian 'Salzkammergut' district (near 47° 45' N, 13° 35' E) were analysed during an EC project on 'The Response of European Freshwater Lakes to Environmental and Climatic change' (REFLECT). All lakes were formed at the end of the last continental glaciation, about 10,000 years BP, and are embedded in the limestone of the Central Alps. The lakes lie within a circle of 35 km diameter, belong to two catchments (Rivers Ager and Traun) and have approximately the same ionic concentration, ca 300 µS cm^{-1}. They differ greatly, however, in their geomorphologic position in the landscape, their morphometry, (Table 1) and consequently in their exposure to climatic factors. The ratio of surface area to mean depth, a measure of exposure to climatic factors (MAGNUSON et al. 1990) ranges from 132 to 545 × 10^3 (Table 1). The lakes are exposed to the same climate, largely influenced by the North Atlantic Oscillation.

A set of variables common to all sites were selected, including physical, chemical, nutrient and biological parameters (Table 2). These data were consistently available for all of the lakes for the period from 1977 to the present. The sampling interval, however, varied from biweekly to bimonthly.

Pearson's product-moment correlation of non-transformed variables between lake pairs was used as a measure of coherence. Average coherence between lakes pairs was calculated as the arithmetic mean of all individual correlation coefficients. Similarly, average coherence for lakes within a watershed was calculated from all average coherence values of all possible lake pairs.

Table 1. Characteristics of the six long-term research lakes in the Salzkammergut region, Austria.

Lake	Altitude (m)	Area (km^2)	Volume ($10^6 m^3$)	Mean depth z (m)	Max. depth z_{max} (m)	Retention (y)	Catchment A' (km^2)	A/z	A/z_{max}
Irrsee	533	3.5	53.0	15.3	32.0	1.7	27.5	228,758	109,375
Mondsee	481	14.2	51.0	36.0	68.3	1.7	247.0	394,444	207,906
Attersee	469	45.9	3944.6	84.2	170.6	7.0	463.5	545,131	269,050
Hallstättersee	508	8.6	557.0	64.9	125.2	0.5	646.5	132,512	68,690
Wolfgangsee	538	12.8	667.1	52.0	113.1	3.9	124.8	246,154	113,174
Traunsee	422	25.6	2302.0	89.7	191.2	1.0	1417.0	285,396	134,031

0368-0770/02/0028-1 $ 1.00

Table 2. List of variables and units.

Type	Variable	Unit
Physical	Temperature	°C
	Secchi depth	m
Chemical	pH	
	Conductivity	µS cm^{-1}
	Oxygen	mg L^{-1}
Nutrients	Nitrogen	mg L^{-1}
	Phosphorus	mol L^{-1}
	N:P	mol L^{-1}
	Silicate	mol L^{-1}
Biological	Chlorophyll *a*	µg L^{-1}

Results and discussion

The grand mean correlation for the 150 correlation coefficients for the ten variables and all lake pairs was r = 0.47. Correlations for the combination of individual lake pairs and variables ranged from –0.73 to +0.99.

Positive correlation values, indicating trends in the same direction in all lake pairs, were observed for the physical variables temperature and Secchi depth, for ionic (conductivity), oxygen, nitrogen and silica concentrations (Fig. 1). Correlation coefficients for all other variables ranged from strongly positive to strongly negative, indicating a great deal of dissimilarity over time among several lake pairs. Variability was greatest for pH values, a reflection of individual lake processes. Coherence between all of the lake pairs was strongest for epilimnetic temperature, ranging from +0.95 to +0.99. Lake surface temperatures in the region are most directly related to air temperatures across Europe and the North Atlantic Oscillation (NAO), as demonstrated by LIVINGSTONE & DOKULIL (2001).

Average coherence between lake pairs decreased along the lake chain in both catchments (Table 3). The greatest synchrony in the

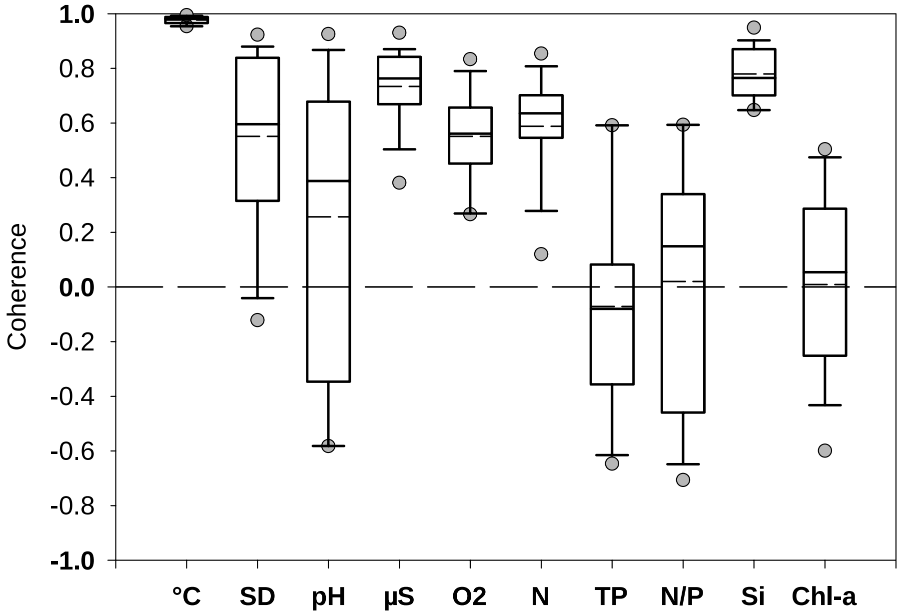

Fig. 1. Box-plot of coherence for individual variables indicated along the x-axis, and all lake pairs. Solid line for median and dotted line for mean.

Table 3. Statistics for all lake pairs and all variables for the two catchments.

Catchment	Lake pair		
	Lake 1	Lake 2	Average coherence
Ager	Irrsee	Mondsee	0.595
	Mondsee	Attersee	0.397
	Attersee	Irrsee	0.359
Average across catchment			0.450
Traun	Hallstättersee	Traunsee	0.658
	Hallstättersee	Wolfgangsee	0.451
	Wolfgangsee	Traunsee	0.364
Average across catchment			0.491

Ager watershed was found for the Irrsee–Mondsee lake pair, two lakes of similar exposure and landscape characteristics. The correlation coefficients for the other two lake pairs were lower, due to sheltering by mountains and greater distance. The highest average coherence in the region was observed for the Hallstättersee–Traunsee pair, two deep valley lakes connected by the dominating River Traun. Correlations of both lakes to Wolfgangsee, a lake in the same watershed, were weaker because of its position relative to Hallstättersee and Traunsee. Although lying in a different catchment, Wolfgangsee is more synchronised with Mondsee and Irrsee than with any lake of its own watershed, based on its position in the landscape and the surrounding landform. The average coherences were +0.55 and +0.65, respectively. The lowest coherence (+0.25) has been calculated for Irrsee–Hallstättersee, the two most distant lakes having the greatest morphometrical and landform difference. The total mean correlation for the two catchments, i.e. +0.45 and +0.49 (Table 3), was not significantly different.

Similarity in morphology, measured as the relative difference in mean depth or 'area/depth' ratios, did not significantly correlate with coherence, in contrast to findings elsewhere (Magnuson et al. 1990, George et al. 2000). Coherence decreased progressively with increasing size differences in the basins ($r = -0.66$, $P < 0.05$), similar to lakes in the English Lake District but less pronounced (George et al. 2000). The weaker connection between size and coherence in the alpine lakes may be partly explained by the more rigid regional geomorphology (e.g. higher mountain ridges, deeper valleys) and hence often localised weather effects. The levels of coherence between lake pairs was also weakly influenced by the relative difference in their retention times ($r = -0.56$, $P < 0.10$).

Conclusions

A high degree of spatial coherence was observed between alpine lakes in Austria, particularly for lake pairs of higher lake order. Area and retention time appeared to be the most influential variables, despite the variable and often pronounced geomorphology in the region. The highest coherence levels for individual variables ranked in the order of temperature > conductivity > silica. Coherence levels between groups of variables decreased sequentially from physical parameters > basic chemical > nutrients > biological.

Synchrony among lakes within a lake district will enable a broader interpretation of climatic impacts, e.g. by the North Atlantic Oscillation, on a regional scale.

Acknowledgements

This work has been funded by the EC-Project ENV4-CT97-0453 (REFLECT) and the Federal Ministry of Education, Science and Cultural affairs (BMBWK) of the Republic of Austria. Additional data support by the Federal Institute of Freshwater Ecology, Fisheries and Lake Research is gratefully acknowledged. We also thank all those individuals who have helped collecting and analysing samples over so many years.

References

Dokulil, M. T., 2000: Die Bedeutung hydroklimatischer Ereignisse für die Dynamik des Phytoplanktons in einem alpinen Klarwassersee (Mondsee, Österreich). – *Beiträge zur angewandten Gewässerökologie Norddeutschlands* 4: 87–93.

George, D. G. & Harris, G. P., 1985: The effect of climate on long-term changes in the crustacean zooplankton biomass of Lake Windermere, UK. – *Nature* **316**: 536–539.

George, D. G., Talling, J. F. & Rigg, E., 2000: Factors influencing the temporal coherence of five lakes in the English Lake District. – *Freshwater Biol.* **43**: 449–461.

George, D. G., Jones, J. G., Punčochář, P., Reynolds, C. S. & Sutcliffe, D. W. (eds.), 1998: *Management of Lakes and*

Reservoirs During Global Climate Change. – Kluwer Academic Publishers, Dordrecht, 336 pp.

LIVINGSTONE, D. M. & DOKULIL, M. T., 2001: Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperatures and the North Atlantic Oscillation. – *Limnol. Oceanogr.* **46:** 1220–1227.

MAGNUSON, J. J., BENSON, B. J. & KRATZ, T. K., 1990: Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. – *Freshwater Biol.* **23:** 145-159.

Authors' address:

M. T. DOKULIL, K. TEUBNER, Institute of Limnology, Austrian Academy of Sciences, A-5310 Mondsee, Austria.
E-mail: martin.dokulil@oeaw.ac.at
katrin.teubner@oeaw.ac.at