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## Vulnerability of two European lakes in response to future climatic changes

Pierre-Alain Danis,<sup>1,2,3</sup> Ulrich von Grafenstein,<sup>1</sup> Valérie Masson-Delmotte,<sup>1</sup> S. Planton,<sup>4</sup> D. Gerdeaux,<sup>5</sup> and J.-M. Moisselin<sup>4</sup>

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[1] Temperate deep freshwater lakes are important resources of drinking water and fishing, and regional key recreation areas. Their deep water often hosts highly specialised fauna surviving since glacial times. Theoretical and observational studies suggest a vulnerability of these hydro-ecosystems to reduced mixing and ventilation within the ongoing climatic change. Here we use a numerical thermal lake model, verified over the 20th century, to quantify the transient thermal behaviour of two European lakes in response to the observed 20th-century and predicted 21st-century climate changes. In contrast to Lac d'Annecy (France) which, after adaptation, maintains its modern mixing behaviour, Ammersee (Germany) is expected to undergo a dramatic and persistent lack of mixing starting from ~2020, when European air temperatures should be ~1°C warmer. The resulting lack of oxygenation will irreversibly destroy the deepwater fauna prevailing since 15 kyrs. **INDEX TERMS:** 1630 Global Change: Impact phenomena; 1655 Global Change: Water cycles (1836); 1833 Hydrology: Hydroclimatology; 1803 Hydrology: Anthropogenic effects. **Citation:** Danis, P.-A., U. von Grafenstein, V. Masson-Delmotte, S. Planton, D. Gerdeaux, and J.-M. Moisselin (2004), Vulnerability of two European lakes in response to future climatic changes, *Geophys. Res. Lett.*, 31, L21507, doi:10.1029/2004GL020833.

[2] The impacts of future climate change on freshwater systems have been investigated using three approaches: (i) synoptic-scale vulnerability assessments based on modern climate/biodiversity relationships [Magnuson et al., 1997; Moore et al., 1997; Gerdeaux, 1998; Stenseth et al., 2002]; (ii) lake-specific observations showing recent changes in ice-cover duration [Magnuson et al., 2000], instrumental lake vertical temperature profiles, mixing behaviour, and eventually ecological consequences [Gerdeaux, 1998; Verburg et al., 2003; Quayle et al., 2002; Carvalho and Kirika, 2003; Dabrowski et al., 2004; King et al., 1999; Livingstone, 2003]; (iii) lake-specific steady-state numerical

modelling for idealized climatic changes [Blenckner et al., 2002; Peeters et al., 2002]. However, in order to face future potential impact as expected from these studies, regional administrations require quantitative and temporal forecasting for each lake, which can only be provided by dynamical lake-specific modelling [George et al., 1998].

[3] Here we explore the transient thermal behaviour of two European lakes to recent and future climatic changes. Lac d'Annecy (France), and Ammersee (Germany) are both deep pre-alpine lakes, well documented by instrumental meteorological and lake observations. The benthic faunal assemblage preserved in the deep lake sediments indicates that the bottom waters have been regularly ventilated throughout at least the last 15 000 years [von Grafenstein et al., 1999]. These specific lakes were chosen originally because they are representative of the two main types of mid-latitude deep lakes. In deep and fresh lakes, the spring-summer surface heating induces the formation of a warm and light water layer (epilimnion), which "floats" over the colder and denser hypolimnion. The winter turn-over occurs when the density of the epilimnion is close enough to the density of the hypolimnion to allow wind-driven full mixing and oxygenation of the bottom water [Famer and Carmack, 1982]. Due to the large seasonal cycle of local temperatures and the high water-discharge rates, we consider only the thermodynamic control of temperature on density, with a maximum density at 4°C. In cold enough climatic conditions, two mixing periods can occur each year, interrupted by an inverse winter thermal stratification; this dimictic behaviour is represented here by Ammersee. Lac d'Annecy represents the monomictic lake type, with a mean winter water temperature systematically above 4°C and consequently only one winter turnover period. By comparing Lac d'Annecy and Ammersee, we can test the sensitivity of modern monomictic and dimictic lakes to climatic changes and evaluate their risk to develop year-long thermal stratification (meromixis) [Garibaldi et al., 1999].

[4] We have specifically adapted a 1D thermal lake model in order to represent the intra- to inter-annual changes in lake temperature vertical profiles with a focus on bottom temperatures. The one-dimensional eddy diffusion model [Henderson-Sellers, 1986] and lake-ice model [Patterson and Hamblin, 1988] was improved by a water transparency model to take into account the seasonal cycle of the algal activity. The adjustment of the thermal lake model for each site requires a good knowledge of the lake bathymetry, a local meteorological monitoring, and at least a decadal monitoring of the lake vertical temperature profile [Danis et al., 2003]. The comparison between simulations and lake observations for the last decade confirms the ability of our 1D model to capture the physical mechanisms responsible

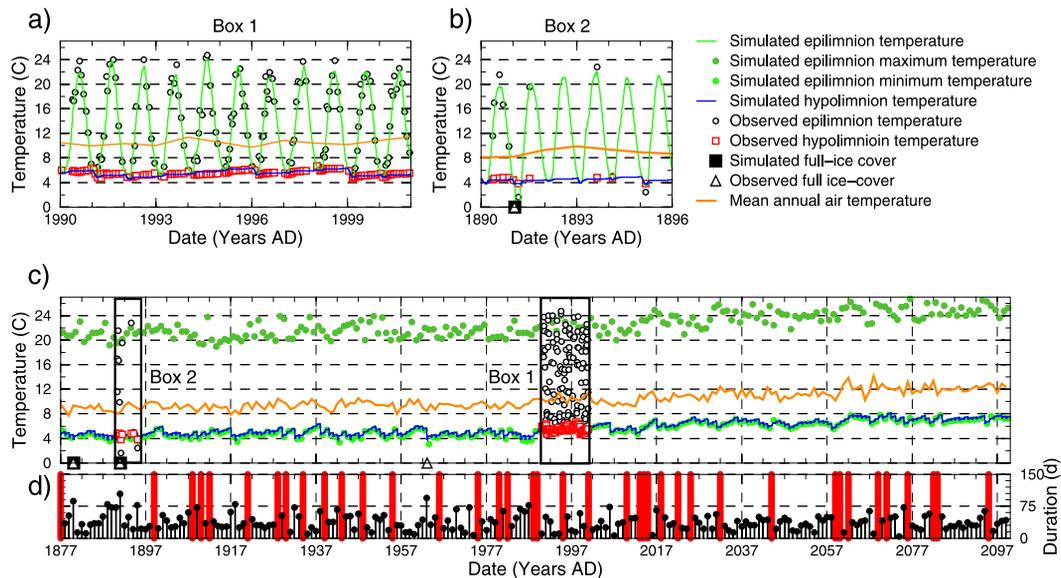
<sup>1</sup>Laboratoire des Sciences du Climat et de l'Environnement, L'Institut Pierre-Simon Laplace, Gif-sur-Yvette, France.

<sup>2</sup>Also at Agence Nationale pour la Gestion des Déchets Radioactifs, Châtenay-Malabry, France.

<sup>3</sup>Also at Laboratoire de Géodynamique des Chaînes Alpines, Le Bourget du Lac, France.

<sup>4</sup>Centre National de Recherches Météorologiques, Météo-France, Toulouse, France.

<sup>5</sup>Institut National de la Recherche Agronomique, Station d'Hydrobiologie Lacustre, Thonon, France.

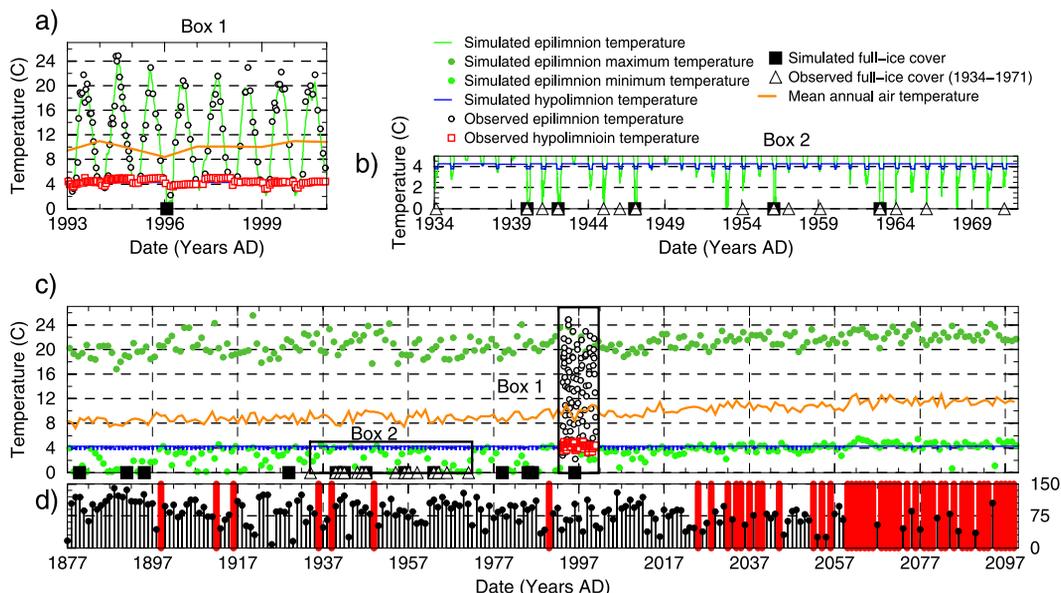


**Figure 1.** Observations and simulations of the mixing behaviour of Lac d'Anney ( $06^{\circ}07'E$ ,  $45^{\circ}54'N$ ; surface area  $27.5 \text{ km}^2$ ; maximum depth 65 m) from 1877 to 2099. (a, c, d) Observations (symbols) and simulations (lines) of the epilimnion (opaque circle and green line) and hypolimnion (open squares and blue line) water temperature. Observations (open black triangles) and simulations (filled black squares) of the full ice-cover events. Observed before 2000 and predicted after 2000 yearly air temperature (orange line). (b) Duration (number of days) of the winter homogenisation and/or inverse thermal stratification (black circles). This duration is null when no mixing occurs (vertical red lines), is empirically below 75 days for a monomictic behaviour and above 75 days for a dimictic situation.

for the intra-seasonal to inter-annual lake surface and bottom temperature variability, including the winter turnover (Figures 1 and 2).

[5] For each lake, the model was forced with monthly homogenised meteorological data for the 20th century and with the predictions of the Météo-France climate model [Douville *et al.*, 2002; Gibelin and Déqué, 2003] run under IPCC SRES-B2 scenario for the 21th century [Houghton, 2001]. The lake model calibration was achieved by scaling the meteorological parameters in a range of observable

micrometeorological variations [Danis *et al.*, 2003]. The scaling was performed with respect to lake thermal observations available from 1993 to 2000 for Lac d'Anney and Ammersee (Figures 1 and 2). The thermal lake model is then run at daily time steps from 1993 to 2000, for each site, and forced by a linear interpolation of monthly averaged meteorological parameters controlling the lake surface energy budget: air temperature ( $T_a$ ), wind-speed ( $W$ ), cloud cover ( $CC$ ), relative humidity ( $RH$ ), surface pressure ( $Pr$ ), precipitation ( $Pp$ ). Sensitivity studies showed that the inter-



**Figure 2.** Same as Figure 2 but for Ammersee ( $11^{\circ}10'E$ ,  $48^{\circ}00'N$ ;  $46.5 \text{ km}^2$ ; 81 m).

and intra-annual variations of the bottom water temperature can be reproduced by considering the intra- and inter-annual variations of the air temperature and only the mean seasonal cycle of the other parameters. At Lac d'Annecy, monthly homogenised  $T_a$  data are available at the closest meteorological station of Meythet, located 3 km northwards of Lac d'Annecy and 11 m above the lake level [Moisselin *et al.*, 2002] and homogenised  $P_r$  and  $C_C$  are also available from another nearby weather station over the last century. At Ammersee, daily meteorological data ( $T_a$ ,  $P_p$  and  $W$ ) are available from the meteorological station of Hohenpeissenberg (24 km southwards of Ammersee and 443 m above the lake level) since 1876; local  $C_C$  observations started only in 1937. When the observations for a specific parameter were not available, the model was forced by the mean seasonal cycle of this parameter. For continuity, the local Météo-France climate model outputs were scaled towards the 1990–2000 observations;  $W$  and  $P_p$  seasonal cycles were corrected using a polynomial function to fit with the local observations. Since 1960, meteorological observations and climate model results have progressively been combined.

[6] The ice-cover model [Patterson and Hamblin, 1988] considers here the formation of a full ice-cover. When the surface water temperature decreases below  $0.1^\circ\text{C}$ , the energy available to freeze water is stored until it is sufficient to freeze all the lake surface with 0.1 m of ice thickness. Generally, the observed duration of the full ice-cover period is less than one month in Ammersee and Lac d'Annecy, whereas the model is forced by monthly meteorological values. The years in which the ice-cover has been historically observed and simulated are noted in Figures 1 and 2. For Lac d'Annecy, the full ice-cover period of the winter of 1880 and 1891 are simulated. Even if the ice-cover period of the year 1963, which lasted 3 days, is not simulated, the model simulates the very cold winter surface water temperature. In Ammersee, the model simulates ice formation corresponding to one third of the observed full ice-cover events from 1935 to 1971; during the other two third of the observed ice episodes, an inverse lake stratification is correctly simulated. Even with a monthly forcing, the model successfully simulates some of the observed full-ice cover periods for Lac d'Annecy and Ammersee, which is an independent validation of both the forcing methodology (including the homogenisation and the scaling of meteorological data) and the model results.

[7] Our simulations show that, before 1987, incomplete mixing for more than one year was only exceptional (Figures 1c and 2c). The regular annual mixing is consistent with the continuity of the benthic fauna observed in sediment cores from the deepest parts of Ammersee [von Grafenstein *et al.*, 1999] and Lac d'Annecy (unpublished data). In agreement with observations, our simulations show a constant monomictic behaviour of Lac d'Annecy (Figure 1c) whereas Ammersee is essentially dimictic during the 20th century (Figure 2c).

[8] The climate change scenario for the 21th century was performed with a variable resolution global atmospheric general circulation model reaching a resolution of about 50 km over the lakes region [Gibelin and Déqué, 2003]. In this calculation, the atmospheric model was constrained with sea surface temperatures and sea-ice extents inferred from a coupled ocean-atmosphere low resolution climate

change scenario [Douville *et al.*, 2002]. Under the radiative forcing resulting from SRES-B2 greenhouse gases and sulfate aerosol concentrations [Houghton, 2001], the model simulates a global annual warming at screen level of 2.3 K between 1960–1989 and 2070–2099. This warming lies within the lower range of temperature change calculated by present climate models [Houghton, 2001], partly due to a lower than average climate sensitivity of the Météo-France climate model, and partly due to a rather moderate increase of greenhouse gases for the chosen scenario compared to the ensemble of IPCC emission scenarios. Our lake model simulates drastic reactions in both lakes in response to future climatic change. We see a common increase in epilimnion temperatures. However, the reaction of the hypolimnion shows surprisingly distinct behaviours for Lac d'Annecy and Ammersee. Lac d'Annecy undergoes an increase in the annual mean hypolimnion temperature from  $5.3^\circ\text{C}$  in the 1990s to  $7.5^\circ\text{C}$  in the 2090s (Figure 1c), with an amplitude similar to the annual mean air temperature increase. It however maintains its monomictic behaviour, apart from two episodic periods of 4 successive years with almost no overturning following rapid rises in annual mean air temperature after 2013 and 2059, respectively. In contrast, Ammersee bottom water temperature remains almost unaffected, but the lake cannot maintain its dimictic behaviour. Starting from 2025 onwards, the frequency of meromixis increases dramatically until a persistent decadal-long stagnation in the 2060s.

[9] The differential reactions of the two lakes is due to complex interplays between local climatic conditions and two main lake characteristics: (i) the individual lake morphology, because the lake volume controls its thermal inertia; (ii) the lake transparency, which controls the warming of deep water masses due to solar radiation absorption. In the case of Lac d'Annecy, the deep water temperature increase is favoured by both its smaller lake volume and a higher transparency. A  $1^\circ\text{C}$  deep water temperature increase is already observed between late 19th century and late 20th century measurements (Figure 1). Thus, the bottom water of Lac d'Annecy can follow more easily the increasing surface temperatures, which enables the regular onset of full mixing at warmer mean water temperatures. For Ammersee, the large thermal inertia inhibits such a regulation mechanism, and persistent stratifications will systematically occur in the second half of the 21th century, even if the transparency is increased by 30%.

[10] Even though Lac d'Annecy preserves most of the time a regular overturning, the increased bottom water temperatures will deeply affect the cold-water fauna [Gerdeaux, 1998]. The fish arctic char, *Salvelinus alpinus*, will disappear from the middle of the century because its ovogenesis is impossible above the threshold of  $7^\circ\text{C}$  [Gillet, 1991]. However, the persistence of the monomixis in our model is strongly dependent on transparency. Sensitivity studies have shown that a 15% decrease in lake transparency may double the occurrence and duration of periods of several successive years without overturning. In Ammersee and Lac d'Annecy, the increased duration of meromixis would affect the lake ecosystems differently depending on the fraction of the deep lake water affected by a lack of ventilation and oxygenation, and could also have significant impacts on nutrient recycling [Alefs and Müller, 1999] and

heavy metal mobilisation. In Ammersee, persistent anoxic conditions below 40 meters are very likely to be installed by the mid-21st century, irreversibly destroying the highly specialised deep lake fauna which has thrived there since the deglaciation and which constitutes the food resource for fishes such as arctic char therefore endangered. Consequently, for both lakes, the commercial and recreational fishery, presently very opulent, will lose a big part of its interest without salmonids species.

[11] This work is the first step towards an integrated transient lake modelling including chemical and biological interactions with physical processes. For example, our model does not take into account chemical consequences following persistent anoxic conditions, which further increase the bottom water density and could lock the lakes in a persistent stratified mode. Integrated models tailored for individual lakes are now required to provide realistic evolution predictions for regional administrations. These models could also be used to test the efficiency and full consequences of practical lake management policies such as a control of lake transparency by reducing suspended matter and nutrient inflow. More generally, the IPCC statement that “hydrological changes have the potential to be more significant for freshwater organisms than a temperature increase” [Intergovernmental Panel on Climate Change, 2001] strongly underestimates the vulnerability of deep lake circulation to mid-latitude winter temperature changes, the most robust signal in IPCC projections.

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P.-A. Danis, V. Masson-Delmotte, and U. von Grafenstein, IPSL/Laboratoire des Sciences du Climat et de l’Environnement, 91191 Gif-sur-Yvette Cedex, France. (masson@lscce.saclay.cea.fr)

D. Gerdeaux, INRA, Station d’hydrobiologie lacustre, BP 511, 74203 Thonon cedex, France.

J.-M. Moisselin and S. Planton, CNRM, Météo-France, Toulouse, France.