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DOI: 10.1029/2011WR011222

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Interfacing a one-dimensional lake model with a single-column atmospheric model: 2. Thermal response of the deep Lake Geneva, Switzerland under a $2 \times \text{CO}_2$ global climate change

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Received 30 July 2011; revised 24 April 2012; accepted 27 April 2012; published 19 June 2012.

[1] In the companion to the present paper, the one-dimensional $k$-$\varepsilon$ lake model SIMSTRAT is coupled to a single-column atmospheric model, nicknamed FIZC, and an application of the coupled model to the deep Lake Geneva, Switzerland, is described. In this paper, the response of Lake Geneva to global warming caused by an increase in atmospheric carbon dioxide concentration (i.e., $2 \times \text{CO}_2$) is investigated. Coupling the models allowed for feedbacks between the lake surface and the atmosphere and produced changes in atmospheric moisture and cloud cover that further modified the downward radiation fluxes. The time evolution of atmospheric variables as well as those of the lake’s thermal profile could be reproduced realistically by devising a set of adjustable parameters. In a “control” $1 \times \text{CO}_2$ climate experiment, the coupled FIZC-SIMSTRAT model demonstrated genuine skills in reproducing epilimnetic and hypolimnetic temperatures, with annual mean errors and standard deviations of 0.25°C ± 0.25°C and 0.3°C ± 0.15°C, respectively. Doubling the CO$_2$ concentration induced an atmospheric warming that impacted the lake’s thermal structure, increasing the stability of the water column and extending the stratified period by 3 weeks. Epilimnetic temperatures were seen to increase by 2.6°C to 4.2°C, while hypolimnion temperatures increased by 2.2°C. Climate change modified components of the surface energy budget through changes mainly in air temperature, moisture, and cloud cover. During summer, reduced cloud cover resulted in an increase in the annual net solar radiation budget. A larger water vapor deficit at the air-water interface induced a cooling effect in the lake.


1. Introduction

[2] European climate experienced a surface air temperature warming of 0.9°C during the 20th century [Jones and Moberg, 2003], resulting in a wide range of impacts that followed the first signs of change [Alcamo et al., 2007]. According to projections made for future climate, southern and central Europe would experience the largest changes in mean air temperature during summer while the northern regions would be more strongly affected during winter. The warming would also have a number of impacts on the distribution of precipitation throughout Europe [Christensen et al., 2007]. Annual precipitation is predicted to increase in the north, decrease in the south and increase during winter but decrease during summer in central Europe, resulting in more frequent summer droughts. In Switzerland, the recent trends of these variables are consistent with projections for central Europe [Schmidli et al., 2002; Organe consultatif sur les changements climatiques, 2008]. In the Alps, changes in winter precipitation have reduced the length of the snow season and the amount of snow [Beniston, 1997] and with higher summer temperatures, have caused glacial mass wasting [Paul et al., 2004]. In the lowlands, the severe heat wave of the summer 2003 has caused crop losses and water shortages, like in the regions of the Swiss Jura and Swiss Plateau [Luterbacher et al., 2004; Della-Marta et al., 2007].

[3] In many western European lakes changing climate has resulted in increased water column stability, longer stratified periods, and warmer temperatures in the epilimnion [Peeters et al., 2002; Livingstone, 2003]. These findings are in agreement with the observations for other middle- and high-latitude lakes [Robertson and Ragotzkie 1990; Schindler et al., 1996; King et al., 1997; McCormick and Fahnenstiel, 1999]. While the impacts of changes in climate in the Alps have been reported by many authors [Theurillat and Gissian, 2001; Abegg et al., 2007; Uhlmann et al., 2009; Beniston et al., 2011], very few studies have attempted to relate future climate projections to their potential
impacts on perialpine lakes [Peeters et al., 2002, 2007; Perroud and Goyette, 2010]. This enhances the need to lead investigations on a variety of lakes, grabbing the opportunity to develop new methods. 

This study examines the thermal evolution of the waters of Lake Geneva, which is located at an altitude of 372 m above sea level between Switzerland and France. Long-term monitoring (since the 1950s) of Lake Geneva at its deepest point (309 m), has shown that the lake has changed in response to recent warmer conditions [Lazzarotto et al., 2004; Dokulil et al., 2006]. Despite large interannual variability, trend analyses have shown that bottom temperatures have risen over the last 50 years from 4.5°C to ~6°C in 2002. The annual mean surface temperatures have increased by more than 1°C since the early 1970s [Lazzarotto et al., 2004].

The objective of this study is to investigate the lake response with a coupled lake-atmosphere model. This approach, as described by Goyette and Perroud [2012], might also ultimately contribute to understanding the impacts of Lake Geneva on local warming. In such numerical experiments, results, as it is likely to be at the time of a doubling of CO₂, are compared to those achieved in a control “1 x CO₂” climate. This method, used in former studies, assume initial concentrations of GHG in the atmosphere close to the one recorded in the second half of the 20th Century (i.e., 1 x CO₂) and then the final concentrations (i.e., 2 x CO₂) similar to these projected by the IPCC-SRES A2 scenario in the middle of 21st Century, [Nakicenovic et al., 2000].

Using coupled models to numerically investigate long-term lake-atmosphere interactions is innovative. Currently lake sensitivity analyses use meteorological forcing computed by atmospheric models rather than observations to run lake models for both current and future climate scenarios [Hostetler and Giorgi, 1995; Blenckner et al., 2002; Malmaeus et al., 2005]. However, interactions between the lake and the overlying atmosphere have not been taken into consideration in most investigations. In the two-way coupling experiments that have been found in the literature for climate simulations, lake models are still rather simple and simulations are run over short periods of time [Hostetler et al., 1994; Hostetler and Small, 1999; Small et al., 1999; Song et al., 2004]. Thus, studies that focus on the effects of climate on lakes are generally confined to stand-alone experiments, i.e., that lake models are forced with a prescribed atmosphere. The inclusion of a lake model, rather than prescribed surface conditions, may also better reproduce processes involved in the energy and radiation budgets, impacting air mass stability and cloud formation. The lack of literature dealing with such coupled models was recently highlighted by MacKay et al. [2009], and pointed to the need to better understand the role of lakes and reservoirs in the climate system.

Here we describe a procedure to calibrate the lake model parameters using a 6 year test period. The optimal parameters were determined by minimizing the error to observed thermal profiles and were then used to run the coupled model under the influence of 1 x CO₂ and 2 x CO₂ climates. Lake warming caused by a doubling of the CO₂ concentration in the atmosphere was quantified by comparing the water column thermal profiles for both climate conditions. A description of changes at the air-water interface is made in terms of surface fluxes and other atmospheric variables. Epilimnetic and hypolimnetic water temperature obtained using this coupled model are compared to water temperatures from an uncoupled, one-way driven lake model.

2. The Coupled Model

The FIZC-SIMSTRAT coupled model used in this study is a two-way computational method where feedbacks between the lake and the atmosphere are allowed in the vertical dimension. The readers are referred to the companion paper [Goyette and Perroud, 2012] for a broader description of this coupled model. The climate change application described in this paper may be considered as a follow-up study of the work undertaken earlier by Perroud and Goyette [2010]. In the former case, the one-way modeling methodology assumed that the lake model SIMSTRAT [Goudsmid et al., 2002] is driven initially by observations that were subsequently perturbed to emulate a climatic change in the atmosphere. The lake then responded to atmospheric perturbations that were considered as differences diagnosed on the basis of outputs from a Regional Climate Model (RCM) in the context of the EU 5th Framework project “PRUDENCE” over the period 2071–2100 [Christensen et al., 2002].

The column model of the atmosphere, nicknamed FIZC, has been designed to compute the temporal evolution of the prognostic variables \( \Psi = \{ u, v, T, q \} \) in the column, where \( u \) and \( v \) represent the horizontal components of the wind velocity, \( T \) the air temperature and \( q \) the specific humidity. Because models evolve continuously, very minor changes have been made to the column model compared to the version presented in the companion paper [Goyette and Perroud, 2012]. A description of the updates and the validation of this version of the model with the native “on land” surface scheme are described in the auxiliary material. While improvements were observed in the simulated annual mean surface variables and fluxes, the conclusions of the previous study are not affected.

The lake model is the numerical one-dimensional SIMSTRAT model, a buoyancy-extended \( k-e \) model [Rodì, 1984; Burchard et al., 1998] that has been updated to include the effects of internal seiches on the production of turbulent kinetic energy. In a models comparison study, this model turned out to be the most accurate to reproduce the water temperature profiles of Lake Geneva [Perroud et al., 2009]. To study thermal evolution of this lake with sufficient vertical resolution, 390 layers have been used.

The coupling between the two models is achieved through the energy and momentum budget components at the air-water interface [Goyette and Perroud, 2012]. Downward solar and longwave radiation fluxes at the surface, \( R_{S,sfc}^{\downarrow} \) and \( R_{L,sfc}^{\downarrow} \), respectively, and the anemometer-level wind speed components \( [u, v] \), diagnosed at 10 m above the lake surface are passed to the lake model. These can be further scaled as \([s_u, u, s_v, v]\), with parameters \( s_u \) and \( s_v \) to remove wind speed bias if needed. The reflected solar and emitted longwave fluxes, \( R_{S,sfc}^{\uparrow} \) and \( R_{L,sfc}^{\uparrow} \), respectively, are then computed as a function of the varying lake albedo.

1Auxiliary materials are available in the HTML. doi:10.1029/2011WR011222.
and surface water temperature. The atmospheric model computes the sensible and latent heat fluxes, \( Q_H \) and \( Q_L \), that can supply or extract energy to or from the lake, depending on the conditions at the air-water interface. In these runs, the surface drag coefficient has been kept at a constant value of \( C_D = 1.3 \times 10^{-3} \) [Goyette et al., 2000].

3. Application of the Coupled FIZC-SIMSTRAT to the Deep Lake Geneva

3.1. Calibration

[12] In the companion paper, a sensitivity of the water temperatures in Lake Geneva to calibration parameters was assessed [Goyette and Perroud, 2012]. The water thermal profiles were reproduced with a root-mean-square error (RMSE) averaged over winter (DJF), spring (MAM), summer (JJA) and autumn (SON), of 0.75°C from the surface down to a depth of 10 m (group of depths 1 or GD1), 0.4°C from 10 to 50 m (GD2), 0.25°C from 50 m to 200 m (GD3) and 0.15°C from 200 m to 309 m (GD4). Because of the sensitivity of the water temperatures to the computed atmosphere, the calibration parameters of this coupled version of FIZC-SIMSTRAT needed further optimization.

[13] A reference simulation, referred to as Sim\(_{ref}\), was run for a 6 year period and served to assess the ability of the model to reproduce observed seasonal thermal profiles in Lake Geneva from 1978 to 1983 (Database INRA of Thonon-Les-Bains, Data CIPEL). Sim\(_{ref}\) used the mean observed profiles recorded between December 1980 and January 1981 as initial conditions. The simulated anemometer wind speed was scaled \([u, s, v]\) to fit observed meteorological data \([u, v]_{obs}\) over the lake, as recalculated statistically from data taken at the inland station Changins, part of the Automatic Network (ANETZ) of the Federal Office of Meteorology and Climatology, MeteoSwiss [Bantle, 1989]. During these simulations, the atmospheric profiles of \( \Psi \) were not strongly nudged toward the GCM\(_{Mii} \) archived profiles \((N_{s} = [0.1, 0.1, 0.1]; \) i.e., FIZC prognostic variables \( \Psi \) were not strongly relaxed toward those of the GCM\(_{Mii} \) archives; the description is given by Goyette and Perroud (2012)) and a weak scaling of the contributions to the dynamics tendencies \((S_{q} = [1, 1, 1]; \) reformulated in the auxiliary material), induced intraday variability on the order of \( D_{q} \), fluctuations had a zero mean value. Subsequent simulations were then performed to reduce possible biases in the observed water profiles by varying the parameters as follows: \( q_{s} = [1, 2, 3], \) \( N_{q} = [0.1, 0.2, 0.5, 1], \) and \( s_{q} = [0.9, 0.95, 0.98], \) \( s_{q} \) being an option to scale the driving specific humidity profiles (see the auxiliary material). The anemometer-level wind speed, the screen-level air temperature and specific humidity were also evaluated with respect to GCM\(_{Mii} \) values, \( \Psi_{s,GCM_{Mii}} = \{q_{s,GCM_{Mii}}, T_{s,GCM_{Mii}}, [u, v]_{s,GCM_{Mii}}\} \) and for consistency with Changins observed meteorological data \( \Psi_{s,obs} = \{q_{s,obs}, T_{s,obs}, [u, v]_{s,obs}\}; \) an assessment was done with observed incoming surface solar and longwave radiative fluxes.

[14] In order to compare the observed and simulated seasonal mean profiles, lake soundings recorded 1 to 2 times a month at discrete depths (to a maximum of 20 depths) were interpolated and seasonally averaged. Values over the period lie within 5.2°C (spring) and 5.3°C (autumn) at the bottom and within 6.55°C (winter) and 19.4°C (summer) at the surface.

[15] Sim\(_{ref}\) showed that seasonal water temperature profiles increased continuously over the 6 years at all depths and a positive bias to the observed profiles appeared. At the depths of smallest intra-annual variability (depths below 100 m), the mean seasonal warming went from 0.5°C to 0.9°C. A bias was noticed in the uppermost layers and particularly at the surface where the maximal bias reached 1.85°C in winter, 1.5°C in spring and 0.05°C in autumn. However, in summer, temperatures were underestimated from the surface down to 25 m (−1.7°C). Looking at the annual evolution of bottom water temperatures during the winter season, the warming changed at a mean rate of 0.057°C yr\(^{-1}\). At the end of the 6 year calibration period, the lake had not reached equilibrium and at the end of 14 years, the overall lake warming rate was still 0.049°C yr\(^{-1}\).

[16] Water temperature profiles resulting from the multiple calibration runs were then compared to Sim\(_{ref}\), with the hope that an optimal calibration would prevent the continuous warming of the simulated lake water temperature profiles. Changing values of \( S_{q} \) produced seasonal variations throughout the profiles of less than 0.15°C. Also, changes due to variations in \( s_{q} \) were small, particularly at depths below 150 m where they did not exceed 0.1°C. Above 150 m, a low value of \( S_{q} \) decreased the water temperature, reducing the bias in observations in winter and spring but increasing the bias in summer and autumn. The lake response was the opposite with higher \( S_{q} \). Sensitivity of the lake to changes in \( N_{q} \) was significant. Compared to Sim\(_{ref}\), cooler water temperature profiles were simulated, reducing the seasonal error, throughout the profile in winter and spring and below 100 m during summer and autumn. However, changes remained lower than 0.05°C from 200 m to the bottom, except when both \( N_{q} \) and \( N_{T} = 1 \), in which case variations of 0.15°C to 0.3°C (below 200 m) indicate a significantly different behavior of the profiles. Increasing the value of \( N_{u,v} \) caused a reduction in wind speed, decreasing the penetration of heat to deeper portions of the lake and reduced the error in the simulated profiles below 100 m. However, higher values of \( N_{u,v} \) were not optimal as at the same time that deeper waters cooled, surface waters warmed causing significant errors in the upper layers (e.g., an error increase of 0.5°C in spring for \( N_{u,v} = 1 \)).

[17] Cross calibration of parameters indicated similar trends, with water temperature profiles only being significantly affected by the value given for the nudging parameters. Simulations obtained by varying \( s_{q} \) and \( S_{q} \), with \( N_{u} \) and \( N_{T} = 1 \), caused small changes throughout the profiles but did not result in significant improvement. For example, while \( s_{q} = 0.9 \) lowered the bias in the observed deep-layer temperatures, it increases the bias in the upper layers (Table 1).

[18] Compared to Sim\(_{ref}\), which produced a positive bias with respect to the observed volume-weighted temperatures in the epilimnion, \( T_{epi} \), from January to July and in the hypolimnion, \( T_{hyp} \), at any time, the simulations with \( N_{T} \) and \( N_{q} = 1 \) substantially reduced those errors (Figure 1). Under these conditions, the lake reached a steady state (i.e., no significant trend in the mean values) more rapidly and bottom water temperatures no longer varied. The annual rate of change in the bottom water temperatures in winter
was between −0.05°C and 0.05°C for the 6 year simulation, and the range was only slightly wider for a 20 years simulation (between 0.2°C and 0.05°C). Simulation with \( N_q = 1 \) and \( N_t = 1 \) produced mean winter surface water temperature that varied by less than 0.2°C over the 6 year simulation, far smaller than the 1.1°C increase found for Simref.

[19] Annual mean \( q_s \), \( T_s \), and \( [u, v]_s \) obtained using the set of calibration parameters, were systematically overestimated (Table 2) with respect to both the observations and the GCMii values. Annual mean \( [u, v]_s \), was stronger than \( [u, v]_s, \) and \( [u, v]_s, \) but this was a consequence of using a lower value for the roughness height \( z_o \) of the water surface. Indeed, the lower frictional drag imposed on the flow at the lake boundary (here 3.5 time lower) gave rise to a smoother decrease in the horizontal wind speed. The scaling applied to the simulated anemometer-level wind speed ensured the right transfer of momentum to the lake. The overestimation of \( q_s \) and \( T_s \) was mainly related to surface water temperature and specific humidity over the lake surface. However, \( q_s \) and \( T_s \) simulated with \( N_q = 1 \) and \( N_t = 1 \) compared better with the observed values and thus diverged significantly from those resulting from the other calibrations, revealing again the need to apply the highest nudging to \( q_s \) and \( T_s \). This simulation produced lower \( q_s \), and colder \( T_s \) than Simref in winter (bias of 0.8 g kg\(^{-1}\) and 2.2°C, respectively) and autumn (0.75 g kg\(^{-1}\) and 1.35°C, respectively), higher \( q_s \) and \( T_s \) in summer (1.05°C and 1.1 g kg\(^{-1}\), respectively) and similar values in spring.

The effect of this strong nudging was noticed on the simulated screen-level temperature and specific humidity from the beginning of the simulation (as shown during the first 10 days of the simulation in Figure 2). A strong nudging value resulted in systematic cooling of \( T_s \) in winter and an effective variation of \( q_s \) at archived time intervals. Compared to Simref, the benefit of such a simulation with strong nudging was to cool the uppermost layers of the epilimnion (Figure 2), and to prevent unexpected warming of the water profiles.

[20] If the substitution of a low nudging value for a complete nudging of \( T \) and \( q \) induced seasonal changes in
radiative forcing that were less than 10% during the first year, the sensible and latent heat flux diverged significantly. A cooler and drier atmosphere (i.e., when \( N_q = [1, 1, 0.1] \)) caused a loss of energy in the lake by latent heat on average 3 times higher in winter, by sensible heat 3 times larger in autumn and a loss instead of a supply of heat by sensible heat in winter. This resulted in a negative energy budget for the lake, \( Q_{\text{sfc}} \), with \( Q_{\text{sfc}} = R_{\text{sfc}}^1 + R_{\text{sfc}}^L - \varepsilon \sigma (T_{\text{sfc}}^4 + 273.15)^4 - Q_H - Q_E \) in \( \text{W m}^{-2} \), with \( \sigma \) being the Stefan-Boltzmann constant and \( \varepsilon \) the emissivity of the lake water), in winter and autumn less significant for \( N_q = [0.1, 0.1, 0.1] \) than for \( N_q = [1, 1, 0.1] \), so that the former winter and autumn daily total of \( Q_{\text{sfc}} \) were of \(-1.27 \text{ MJ d}^{-1} \text{ m}^{-2} \) and \(-4.44 \text{ MJ d}^{-1} \text{ m}^{-2} \), respectively, instead of \(-3.23 \text{ MJ d}^{-1} \text{ m}^{-2} \) and \(-7.3 \text{ MJ d}^{-1} \text{ m}^{-2} \), respectively. Nudging the prognostic variables \( T \) and \( q \) is thus required to prevent an excess of heat from diffusing downward with time. Consequently, the net heat storage in the lake averaged over the 6 year simulation period differed widely according to the nudging values. While \( N_q = [1, 1, 0.1] \) produced a fairly low annual net heat storage, daily total of \( Q_{\text{sfc}} \) were of \(0.04 \pm 0.12 \text{ MJ d}^{-1} \text{ m}^{-2} \) for \( q_s = 0.9 \), of \(0.07 \pm 0.16 \text{ MJ d}^{-1} \text{ m}^{-2} \) for \( q_s = 0.95 \), and of \(0.071 \pm 0.18 \text{ MJ d}^{-1} \text{ m}^{-2} \) for \( q_s = 0.98 \), this storage was, however, highly positive in Simref because of the amount of heat accumulated in deep layers (0.41 ± 0.34 MJ d^{-1} m^{-2}). Since a decrease in the nudging value caused a warmer and wetter atmosphere, that then resulted in the positive growth of the annual net heat storage, \( N_q \) other than 1 is currently not acceptable in these coupled lake-atmosphere experiments.

[21] Comparison of the observed incoming solar radiation flux, \( R_{\text{sfc}}^1 \), and the incoming longwave diagnosed on the basis of the observed cloudiness at the Changins station, \( R_{\text{sfc}}^L \), was done with respect to radiation fluxes simulated by FIZC using \( N_q = [1, 1, 0.1] \), with \( q_s \) varying over the range of 0.9 to 0.98. Even though different values of \( q_s \) did not improve the simulated water temperature profiles, they may yet change the moisture content of the atmosphere.

The annual mean fluxes of \( R_{\text{sfc}}^1 \) and \( R_{\text{sfc}}^L \) were overestimated when \( q_s = 0.95 \) (Table 3), but compared well to the GCMii values. Cloudiness (+20%) following an increase in \( q_s \) to 0.98 had a positive effect on the bias of \( R_{\text{sfc}}^1 \), but a negative effect on the bias of \( R_{\text{sfc}}^L \). Conversely, the reduction of the cloudiness (−35%) when \( q_s = 0.9 \) produced a higher \( R_{\text{sfc}}^1 \) but a smaller \( R_{\text{sfc}}^L \) bias. On a monthly basis, simulated \( R_{\text{sfc}}^1 \) and \( R_{\text{sfc}}^L \) were also systematically higher, but the bias was low, a little bit higher (up to 50 W m^{-2}) in spring for \( R_{\text{sfc}}^1 \) and in winter for \( R_{\text{sfc}}^L \) (Table 3).

[22] Sensible and latent heat flux, \( Q_H \) and \( Q_E \) have not been measured at the lake interface and thus it was not possible to undertake any comparisons. However, a seasonal analysis of surface prognostic variables suggests some bias in the convective fluxes. Even though mean air temperature was correctly reproduced with respect to the observations, variability was lower than the observations. For instance, the observed air temperature was 18.5°C ± 4.5°C while the simulated value was 18.4°C ± 1.9°C when \( q_s = 0.95 \) in summer.

### 3.2. Simulated Lake Water Thermal Profiles Under a 1 × CO₂ Climate

[23] A simulation with the FIZC-SIMSTRAT coupled model under the 1 × CO₂ climate condition, termed Sim1 × CO₂, was investigated to assess the model’s performance in reproducing Lake Geneva water temperatures over the period 1961-1990. The model was run with calibration parameters that minimized the error in the simulated water temperature profiles with observed water soundings and reproduced the observed fluxes more accurately (i.e., \( N_q = 1 \), \( N_{\alpha} = 1 \), \( N_{\alpha} = 0.1 \), \( q_s = 0.95 \), \( S_q = 1 \)). The simulation started using the mean water thermal profile from January for each year from 1960 to 1990. A spin-up period was required to allow the lake to reach its equilibrium state. Fields generated by the GCMii allowed this coupled model to run over a 20 year period.

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<th>Observations</th>
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<td>( R_{\text{sfc}}^L ) (MJ d^{-1} m^{-2})</td>
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Two runs over 20 years only were necessary to spin up the water temperature profiles. The differences in the daily profiles between the first and the last 20 year run decreased rapidly with time. Less than 1% of the daily records over the profile showed differences higher than 0.1°C after the fourth year of simulation. This was significant since these differences were up to 0.3°C at the surface, 0.5°C at 100 m, and 0.2°C at the bottom during the first year.

The onset of stratification may be diagnosed when a 1°C difference appears between the 100 m and the 2 m layer [Jacquet et al., 2005], and the stability of the water column $N^2$ may be calculated from the Brunt-Väisälä frequency $N$ at the depth with the highest vertical temperature gradient.

The simulated daily water temperature profiles in Sim$_1$ and CO$_2$ were averaged over the last 20 years and compared to the observed values (Figure 3). The simulated profiles agreed well with the observations on a seasonal basis. The seasonal biases in the observation lay within the range of 0.4°C to 0.7°C from 150 m downward. Above 150 m, the seasonal biases were generally on the same order, i.e., lower than 0.2°C in winter and lower than 0.7°C otherwise. However, a positive bias of 0.7°C to 1°C close to the surface was noticed in spring. Conversely, lower simulated water temperatures may occur, but mainly at depths of 10 m to 50 m in summer and from the surface to 50 m in autumn, with maxima of 1.9°C and 1.8°C at 20 m, respectively. These biases resulted from the slightly too strong stability simulated in the metalimnion in spring, which prevented heat from penetrating deeper. The position of the thermocline was correctly simulated during the stratified months. The volume-weighted temperature in the epilimnion, $T_{epi}$, and in the hypolimnion, $T_{hyp}$, were also well simulated. The mean error was 0.25°C ± 0.25°C in $T_{epi}$ and 0.3°C ± 0.15°C in $T_{hyp}$. The largest differences were found from April to mid-June and corroborate the lower location of the simulated thermocline. These model biases were not detrimental to model performance since they were related to small shifts in the thermocline locations, which affected only a small slab of water within the profile.

Figure 4 shows the monthly energy budget components of the lake averaged over the last 20 years of the simulation. The net radiation was positive from February to October, reached a maximum in June, and was the source of heat for the lake. In contrast, the sensible and latent heat fluxes were negative on a monthly average and served as energy sinks. The evolution of the net heat storage in the lake was strongly correlated with the net radiation, storing heat from March to August, with a maximum in June. Periods of lowest correlation were initiated by variations in the latent heat flux and only to a minor extent by the sensible heat flux as the latter remained nearly constant. The increase in the net heat storage from April to May and its decrease from September to October were proportionally lower than for the net radiation. The cooling by latent heat flux was lowest from December to April (−36 to −51 W m$^{-2}$) and was roughly twice those amounts in July, August, and September. The latent heat flux was always at least 3 times higher, in absolute values, than the sensible heat flux.

### 3.3. Simulated Lake Thermal Profiles Under a 2 × CO$_2$ Climate Warming Scenario

Changes in the Lake Geneva water temperature profiles in response to global warming after a doubling of the atmospheric CO$_2$ concentration were simulated and then compared to the control 1 × CO$_2$ simulation outputs. In this simulation, the time it took to stabilize the warming throughout the whole column was longer than in Sim$_1$ because of a “cold start” procedure (i.e., initial water
temperature set to a 1 × CO₂ profile). Three 20 year spin-ups were required to produce temperature variations lesser than 0.1°C at the bottom (the temperatures reached equilibrium after 37 years). The profiles generated during the third 20 year series thus served to assess the expected changes in temperature, as well as in the stability, duration, and evolution of the thermocline in the lake water.

[29] The daily water temperature profiles produced by Sim₁ × CO₂ and Sim₂ × CO₂ were both averaged over a 20 year period. The differences between the daily means of both periods, shown in Figure 5, were used to assess the expected monthly mean changes in the lake temperature profiles. The interannual variability of the lake thermal profiles between both simulations was not considered in this study. An annual mean temperature increase of 2.1°C to 3.3°C was expected from the bottom up to the surface. Although the water warms more in the upper layers, a zone of lower increase was noticed in the lower metalimnion, with a minimum of 2.1°C at 20 m. The main daily increase in temperature was in the epilimnion and upper metalimnion. Temperatures may warm up to 4°C down to 7 m from mid-June to mid-August. At the surface, the increase exceeded 4.5°C during 2 weeks in late July and early August, with a maximum of 4.8°C. In Sim₂ × CO₂, the stability of the metalimnion was expected to strengthen, hampering the penetration of summer heat into deeper layers in the future. As a result, the lower metalimnion warms less during stratified periods. These layers of lower increase moved

Figure 4. Monthly averaged energy amounts are given for net radiation, sensible and latent heat fluxes, and the energy budget under a 1 × CO₂ (solid lines) and 2 × CO₂ climate (dashed lines).

Figure 5. Contour plots of mean daily temperature differences in the first 100 m below the surface between simulated profiles under a 2 × CO₂ and 1 × CO₂ climate.
with the dynamic deepening of the thermocline. Warming of less than 2°C was simulated between 13 and 18 m in mid-June, between 14 and 28 m in mid-August, and between 16 and 32 m in mid-October. The increases in hypolimnion temperature were between 2°C and 2.5°C after the onset of the stratification, whereas the warming of the entire water column was between 2°C and 3°C during the weakly stratified period.

[30] Changes in monthly mean water temperature were investigated using $T_{\text{epi}}$ and $T_{\text{hyp}}$ (Figure 6a). The increases in $T_{\text{epi}}$ varied between 2.6°C (January–February) and 4.2°C (July). $T_{\text{hyp}}$ rose between 2.2°C (January) and 2.3°C (March). While $T_{\text{epi}}$ was equal or slightly higher than $T_{\text{hyp}}$ (<0.3°C) in Sim1 CO2 from January to March, such values were simulated only in February for Sim2 CO2.

[31] Warmer conditions also impacted the lake metalimnetic characteristics. The lake stability was 2 times stronger in Sim2 CO2 than in Sim1 CO2 during spring, summer, and autumn (Figure 6b). Moreover, the differences between $T_{\text{epi}}$ and $T_{\text{hyp}}$ increased by 12% to 20% during the stratified months and by more than 30% during the coldest months, confirming the stronger stability of the water column. The stronger stability of the lake water and the systematically higher $T_{\text{epi}}$ than $T_{\text{hyp}}$ (Figure 6) may indicate a severe reduction in the frequency of complete overturns (which currently occur less than once per decade). The changes in wind speed (currently 3.1 ± 1.2 m s−1 and expected to be 3.1 ± 1.1 m s−1) were insignificant and thus did not moderate a decrease in the convective mixing depth. In summer, the depth of the thermocline was similar for both simulations, but slight changes were expected in autumn. Because of more stable conditions, the thermocline should resist colder conditions longer, and the decay of the stratification should be delayed. The thermocline remained closer to the surface during a longer period, and its mean depth was 2–3 m shallower in autumn. As a result, the duration of the stratification period lasted 2 weeks more. Since the lake was also expected to stratify earlier in Sim2 CO2, the stratification period lengthens by more than 3 weeks.

[32] The change in radiative forcing was initially due to increased concentrations of CO2 in the atmosphere. The temperature and specific humidity profiles were then modified accordingly, having an impact on the energy budget, namely, on the downward solar radiation, $R_{\text{down}}$, due to the change in cloudiness, the sensible heat due to changes in air temperatures, and the latent heat due to changes in both the air temperature and the saturation state of the atmosphere.

[33] Differences in the daily totals, due to warmer air temperature, modified cloudiness, and lake surface temperature, were diagnosed in the downward (+1.39 MJ d−1 m−2) and emitted (+1.40 MJ d−1 m−2) longwave radiation fluxes at the surface, $R_{\text{LW,down}}$ and $R_{\text{LW,up}}$, respectively (Figure 7). If the net longwave budget was more positive early in the 2 × CO2 climate simulation, it balanced out at equilibrium once the surface temperatures stabilized.

[34] As shown in Figure 7, an increase in the incident shortwave radiation at the surface, $R_{\text{S,down}}$, was simulated in spring (+0.68 MJ d−1 m−2) and summer (+1.89 MJ d−1 m−2), resulting from a reduction in cloud cover during both seasons. In fact, although an increase in the specific humidity at the screen level was simulated on average (+1.2 g kg−1 in winter and +3.8 g kg−1 in summer), a higher increase in air temperatures at the screen level was simulated in summer than in winter (+2.8°C in winter and +4.2°C in summer), which amplified the dew point depression during warm months. This produced drier atmospheric profiles in summer and a reduction in cloudiness. The larger increase in the surface air temperature compared to the lake water temperature in winter and autumn reduced the thermal gradient, and less heat was extracted from the lake by sensible heat flux (Figure 7); the reductions were 0.48 and 0.56 MJ d−1 m−2, respectively. A decrease in the latent heat flux was particularly important in summer (Figure 7), while a slight shift was observed in spring and autumn. In fact, although both the air and lake surface water vapor pressure increased in the future, the water vapor deficit became larger. A summer increase in this deficit caused an additional loss of heat through evaporation of 1.95 MJ d−1 m−2. The seasonal changes in the energy budget components simulated in the $2 \times CO_2$ experiment implied monthly variations in the lake heat storage (Figure 4). As the climate warmed, the January to March period exhibited a stronger gain in heat because of the warming effects of sensible heat. Conversely, an earlier onset of evaporative cooling processes implied a stronger loss of heat during April. While the simulations indicated that there would be larger net radiation from May to August in the future, the cooling by latent heat had a compensatory effect. The net heat storage thus remained similar to the current values during that period and may even decrease in August. Despite the cumulative changes in the fluxes, the effective annual energy budget of the lake reached equilibrium in both simulations. Only 6 years out of 60 years of simulation were needed to reach equilibrium. This agreed with the time required to stabilize surface temperatures. Note that, as mentioned earlier, the warming of the deepest water layers is a long process; the lake thus takes more than 8 times longer to reach a steady state.

[35] The variations in the hourly mean latent and sensible heat fluxes in winter and autumn were particularly
pronounced. These were due to the high nudging values applied to the atmospheric profiles (Figure 7). Since fluxes were computed on the basis of the air temperature and specific humidity differences between the surface and the lower atmosphere, the effect of the nudging on the energy budget components was expected.

4. Discussion

The coupled FIZC-SIMSTRAT lake-atmosphere model used in this study was applied to the Swiss Lake Geneva under current and future climate conditions and directly follows the earlier work of Perroud and Goyette [2010] and Goyette and Perroud [2012].

This study showed that the values given to the calibration parameters have a more decisive impact on the surface energy budget when it concerns a water rather than a land surface. Indeed, the annual mean surface energy budget took several years to reach equilibrium in this lake experiment, depending on the calibration parameter values. This contrasts with the land simulation (see the auxiliary material), where a “close-to-zero” net energy budget was rapidly attained. This can be explained by the large thermal capacity of the lake compared to the land surface, to the large amount of heat that can be stored in the deep Lake Geneva, and to the time lag for heat to reach the lake bottom. However, our experiments have shown that steady state conditions can still be reached if the specific humidity and air temperature were more strongly nudged toward the GCMii profiles (i.e., $N_q$ and $N_T$ close to 1). This results in increased energy loss by sensible and latent heat at the surface during winters and autumns and thus reduces the amount of heat to be mixed to greater depths by convective overturning and wind mixing, preventing unrealistic warming of the deep hypolimnion over the year and helping to close the annual energy budget in less than a decade.

The lake thermal profiles were less sensitive to variations in the other calibration parameters (i.e., $S_q$, $s_q$, etc.) than to variations in the nudging parameters. However, the option to scale the humidity was of particular interest for this lake experiment where the interactions and feedback between the lake and the atmosphere were strong. Variations in $s_q$ helped to reproduce all the individual fluxes of solar, atmospheric longwave, in addition to the sensible and latent heat fluxes and improved simulated water profiles, helping to close the annual lake surface energy balance. Lower values of $s_q$ caused an increase in $R_{L,sfc}$ and a decrease in $R_{U,sfc}$. For $s_q$ ranging from 0.9 to 0.98, the simulated total cloud cover was nearly doubled over the lake surface. The optimal value of $s_q$ for reproducing the water

![Figure 7](image-url)
While the net radiation was the main source of heat for
flux used in the [2] summer (more than a month after the maxima of net radia-
tion started increasing in spring, reached a maximum in late
summer, and could thus not reach similar values in early November.

Unlike in the work of Lenters, Work, et al. [2005], who studied vari-
tions in lake evaporation rates, the cooling by latent heat
began increasing in spring, reached a maximum in late
summer (more than a month after the maxima of net radia-
tion), and decreased in autumn. However, the sensible heat
flux used in the $1 \times \text{CO}_2$ experiment may differ in details
from that of other studies. In autumn, the sensible heat had a
lower cooling effect than in summer. Unlike in the work of Lenters et al. [2005], the sensible and latent heat fluxes
could thus not reach similar values in early November.

Analysis of the sensible and latent heat fluxes simu-
lated by FIZC with respect to observations was not possible
as such observations were not available over the lake.
Thus, a comparison was done with the seasonal trends
reported in the literature. Vercauteren et al. [2008] carried
out an experiment over Lake Geneva during the summer
that indicated negative values for latent heat flux but hourly
averaged sensible heat flux values, either negative (loss of heat) or positive (gain of heat), in the range of -40 to
15 W m$^{-2}$. If the negative seasonal latent heat flux agrees
with our study in summer, the simulated sensible heat flux
produces a permanent loss of heat at the lake surface. Pre-
sumably, the lack of variability over the warm season was
due to the lack of variability in the simulated atmospheric components, particularly over diurnal cycles. Over Lake Geneva, the simulated air temperatures rarely exceeded the water temperature in summer and lead to an underestima-
tion of positive values of sensible heat flux. The sensible heat fluxes may also be affected during other periods. In
winter, for instance, it is likely that the loss of heat by sen-
sible heat flux (due to low air temperature compared to the
water surface temperature) may be underestimated. This
could be an issue in simulating complete mixing events in
the water column. Despite these biases, the coupled FIZC-
SIMSTRAT model reproduced the annual mean value of the
lake energy budget. Although slight differences with the
observed fluxes were noticed, an accurate value of the
overall energy budget appeared to be of larger importance
than the values of the individual fluxes.

Once calibrated, the third step involved a simulation with the concentration of atmospheric carbon dioxide
doubled ($2 \times \text{CO}_2$) and a comparison with the control
experiment ($1 \times \text{CO}_2$). Water was warmed throughout the
column, with significant monthly variations in the epilim-
non only. The monthly $T_{\text{hyp}}$ variations were lower than
0.1°C, for a maximum increase in water temperature of
2.25°C at the time of lowest stratification. The changes in
$T_{\text{epi}}$ were between 2.55°C and 4.2°C, with minima and
maxima synchronized with lower and higher screen-level
air temperature increases (January–February and July, respectively).

The sensitivity of the lake to increases in green-
house gas concentrations leads to conclusions that agree
good with other studies. Not only was the warming of the
epilimnion closely linked to increases in air temperature
[Hondzo and Stefan, 1993; Stefan et al., 1993; De Stasio
et al., 1996; Peeters et al., 2002, 2007], the epilimnitic
warming was also only slightly lower than the projected
increase in air temperature [Robertson and Ragotzkie, 1990;
De Stasio et al., 1996]. Studies by Peeters et al. [2002, 2007]
investigated changes in several perialpine lakes of
analogous geographic elevation and latitude due to a fixed
4°C atmospheric warming and found similar increases in
upper layer water temperatures. In our study, the monthly
maximum increase in epilimnetic temperatures occurred
during summers (July). This was not entirely consistent with
other studies [Huttula et al., 1998; Peeters et al., 2007;
Saloranta et al., 2009]. The lower evaporation simulated in
this scenario likely did not dampen, as discussed in the
conclusions of Perroud and Goyette [2010], the warming pro-
duced by air temperature increases in summer. It may also
be argued that the more intense stratification in the simula-
tion under current conditions than was observed may have
dampened the increase in water temperatures in spring.
Indeed, the “control” $1 \times \text{CO}_2$ simulation produced a warm
bias in April and May.

Unlike with surface water temperature, the changes
in the monthly hypolimnetic temperature are not signifi-
cantly related to atmospheric forcing [Robertson and
Ragotzkie, 1990; Fang and Stefan, 2009], thus, a warming of
deeper layers may or may not be detected in lake simula-
tions [Hondzo and Stefan, 1993; Stefan et al., 1998;
Lehman, 2002; Komatsu et al., 2007; Fang and Stefan,
2009]. In many stratified lakes, the increase in bottom tem-
peratures is related to the sensitivity of lakes to the condi-
tions prevailing before the onset of summer stratification and
after its breakdown [Robertson and Ragotzkie, 1990; De
Stasio et al., 1996]. Indeed, when complete mixing occurs,
the water column is homogenized and hypolimnetic temper-
atures increase in accordance with the trend observed in
the epilimnion during the coldest period [Fang et al., 1997;
Peeters et al., 2002; Perroud and Goyette, 2010]. In Lake
Geneva, overturns should still occur in the future (as the epi-
limnetic and hypolimnetic temperatures are similar during
February and March). While their frequency is not well
known, this suggests that bottom layers might not be isolated,
at least systematically, from surface layers; the increase in
bottom water temperatures might still be related to winter
surface water conditions.

Since a stronger warming of the upper layers com-
pared with the lower layers of the water column has been
noticed in most investigations of the effects of climate
change on lakes [Hondzo and Stefan, 1991, 1993; Gaedke
et al., 1998; Fang and Stefan, 2009], a strengthening of
the stratification was expected for Lake Geneva. However, the
changes in the duration of the stratification remained
unknown. In this numerical investigation of Lake Geneva’s
response to climate change, the response tended toward an
earlier onset of stratification and a delay in its decay at the
end of summer, leading to a mean increase in the period of
stratification of 3 weeks. Other studies that examined the
increase in the number of days during which a lake was stratified reached similar conclusions, although the predicted increase in the current study was near the lower end of the range predicted by other studies with a similar climatic scenario [Boyce et al., 1993; Stefan et al., 1993; Lehmann, 2002].

[45] Matzinger et al. [2007] studied the effects of various rates of atmospheric warming on vertical mixing and stratification in a deep lake and showed that the increases in the bottom temperature and the stability of the stratification were not linear. Assessing the impact of climate change on Lake Geneva with a $2 \times CO_2$ climate rather than a transient climate could thus amplify the stratification, rapidly decoupling deep water from the upper layers, suggesting that the bottom temperatures are underestimated. The FIZC-SIMSTRAT coupled model does not currently allow us to verify this hypothesis as the GCMii provides archives under current and doubled CO$_2$ concentrations only. However, Perroud and Goyette [2010] give us confidence in the conclusions of this work. They showed that the water temperature profiles as well as energy budgets produced from two 120 year simulations compared well during the last decade when either an absolute temperature change or an increase in atmospheric warming rate was applied to the atmospheric data driving the lake model. The only condition, fulfilled here, was that the absolute temperature change method be run over a period sufficiently long to allow the lake to reach a steady state (more than four decades).

[46] Compared to the one-way driven experiment [Perroud and Goyette, 2010], the main challenge of this method was related to controlling the feedback between the lake surface and the atmosphere that has shown sensitivity to the moisture variations in the atmospheric column and to cloud formation, which influences both the downward solar and longwave radiative fluxes. However, the optimal parameter values for this “lake” experiment to reproduce the observed lake thermal behavior suggest that a strong nudging of $T$ and $q$ should be applied. This can thus be interpreted as a model limitation, where the vertical transfer of heat and moisture should be done in close association with the horizontal transfer of these quantities, i.e., that the parameterization of the contributions to the dynamic tendencies of $T$ and $q$ should be carefully designed.

[47] Compared to the one-way method described by Perroud and Goyette [2010], the simulated changes in cloud amounts in summer modulate radiation fluxes. The reduction in the water vapor diffusion in the atmospheric column decreased the development of clouds, increased downward solar radiation, and decreased longwave radiation at the surface. Changes in the annual mean screen-level air temperatures simulated in the coupled compared to the uncoupled experiments (3.3°C and 3.9°C, respectively) also caused a lower annual mean change in $L_{sc}$. Increases in air temperature in turn modified the partition of the sensible and latent heat fluxes in both experiments, resulting in a higher energy budget at the surface and in more heat being diffused throughout the atmosphere. However, in the uncoupled experiment, the larger monthly mean screen-level air temperature, coupled with lower dew point temperatures, caused a decrease in relative humidity during summer. The atmosphere became drier, and more heat was lost by the lake in the uncoupled than in the coupled experiment. Although the coupled FIZC-SIMSTRAT model predicted a smaller increase in air temperature, the total energetic gains were higher, 3.71 MJ d$^{-1}$ m$^{-2}$ compared to 3 MJ d$^{-1}$ m$^{-2}$, for the coupled and the uncoupled experiment, respectively. This comparison highlights the importance of the humidity component in the lake response. For instance, while a 6.9°C increase in the mean screen-level air temperature is predicted by the HIRHAM RCM (PREDUENCE [Christensen et al., 1998]) in August, against a 3.35°C increase by the FIZC-SIMSTRAT coupled model, the simulated $T_{epi}$ is higher in the coupled experiment. In addition, because of the change in atmospheric humidity, the increase in air and water temperatures were not similarly correlated using both methods; the increase in $T_{epi}$ represented 55 to 98% versus 90 to 99% of the monthly mean increase in air temperature in the uncoupled and the coupled method, respectively. Despite the differences in the monthly values of the energy budget components, the monthly differences in the change in $T_{epi}$ (less than 0.2°C, except in March and July) and $T_{hyp}$ (less than 0.1°C) were small, and the increase of 3 weeks in the duration of the stratification was consistent. Finally, the minimum and maximum $T_{epi}$ corresponded to lower and higher increases in air temperature in both studies, with the maximum occurring one month earlier in the coupled experiment.

5. Conclusion

[48] This study was the first attempt at using a coupled lake-atmosphere model to investigate the thermal evolution of Lake Geneva, Switzerland, under warmer global climatic conditions caused by a doubling of carbon dioxide concentrations in the atmosphere. The FIZC-SIMSTRAT model was first used to reproduce the mean daily water temperature profiles of Lake Geneva over the years 1960 to 1990 using a control experiment, called $1 \times CO_2$ climate. During that experiment, the optimal parameter values for running the coupled model were determined. These values were then used in the $2 \times CO_2$ experiment to evaluate the impacts of climate change on the lake thermal structure.

[49] In this lake experiment, the fluxes computed by the SCM for a $1 \times CO_2$ global warming scenario were consistent with those archived by the GCMii model. Feedback from the lake to the atmosphere was hindered by the strong nudging toward the GCMii that had been applied to allow the lake to reach a realistic equilibrium. With the help of calibration, the coupled FIZC-SIMSTRAT model demonstrated genuine skills in reproducing the observed water temperature profiles recorded prior to the intense warming over a 20 year period (RMSE < 0.7°C).

[50] The entire water column of Lake Geneva responded to the $2 \times CO_2$ global warming scenario, with the lowest temperature increase in the hypolimnion, and in the epilimnion as well, during the weakly stratified period. In the epilimnion, the seasonal variability was strong, with the largest increases in temperature occurring during summers. Water column stratification is expected to be stronger as climate warms, causing the decay of the thermocline to be delayed in autumn. These projections agreed with changes that have been observed in the water temperature monitoring records for Lake Geneva over the past 5 decades [Lazzarotto et al., 2004; Dokulil et al., 2006]. Few studies have correlated
the observed changes in lacustrine ecosystems to the effects of warmer air temperatures [Anneville et al., 2005; Jacquet et al., 2005; Molinero et al., 2007]. These studies provide insight into how changes in biochemical mechanisms and other biological activities (such as those related to population and phenology) may be altered if the global temperature continues to rise. Gillet and Quétin [2006] demonstrated the effects of changes in temperature on the reproduction cycle of the roach. A recent study by Tadonléke [2010] showed long-term seasonal variations in the sensitivity of phytoplankton productivity to the observed warming trends in water temperature.

Although this coupled model showed realistic results in reproducing current climate conditions (i.e., 1 × CO₂), some improvements to the numerical formulation are needed for future studies. The first concerns the lack of variability simulated in the meteorological variables, especially at the lake surface. It is likely that the diurnal cycle of the sensible and latent heat fluxes, as well as the convection in the lake, may be better reproduced if the daily variability of atmospheric components were higher. In section 3.1, it was shown that the underestimation of maximum air temperatures in summer prevented intraday episodes of lake warming by sensible heat flux.

If this was not detrimental to the annual surface energy budget, the overestimation in minimum air temperatures had consequences on the performance of the coupled model by using a low nudging value, especially in winter. The option to strongly nudge atmospheric profiles prevented an unrealistic accumulation of heat in the lake. However, should a number of feedbacks between the lake and the atmosphere take place, some freedom needs to be allowed for the FIZC to generate its own internal variability rather than precisely reproducing GCMi profiles by using high nudging values.

This single-column coupled model, locatable over any surface on the globe, requires inputs inferred from global model archives as well as few lake-specific morphometric variables. However, the locatable option requires that parameter values must somehow be adjusted for any location.

As shown in this study, low archival frequency and coarse spatial resolution inputs, may have impact on intraday variability or hinder topographic influences, and thus be limiting factors. However, if the same approach is used with RCM outputs (instead of GCM’s) having a high archival frequency and a high horizontal and vertical resolution, these limits would not be the same. In this case, it is presumed that the model parameter values would somewhat be different and even likely that we should get rid of the scaling parameters used to prescribe the contributions to the dynamics in the atmospheric column.

There are many indications that this coupled model will reproduce realistic thermal profiles in other lakes of various depths and sizes. However, while the lake model SIMSTRAT performed well in numerous studies, some constraints might appear in the case of subgrid lakes especially when their physical characteristics are unknown. Sensitivity analysis is currently under way to determine variability of heat exchanges with respect to the depth given to the lake in the simulation. Also, because of the intrinsic inability of one-dimensional models to physically reproduce all processes in lakes, large uncertainties exist in how the coupled model will perform at other grid points. Larger biases, for instance, are expected closer to the shore as the horizontal gradients of temperature and salinity, such as those resulting from the varying depths or turbulence generated by rivers flowing into water layers, are significantly larger than those at the central location of the lake.

In principle, this model works using default parameter values but may not reproduce accurately either corresponding atmospheric Global Model or observed flow fields, or vertical water thermal profiles. It has been shown in these papers that this version of the coupled FIZC-SIMSTRAT has been tuned (not as heavily as one might think) to reproduce as closely as possible the atmospheric flow fields of the corresponding GCMi column. Then, it has been tuned separately to reproduce observed vertical atmospheric and lake profiles. Consequently, one may change the model user-defined parameter values and tune it over another location. Consequently, one may argue that we have gone beyond the “proof of concepts” with this study.

In the future, it would be useful to assess the sensitivity of the water temperature of Lake Geneva to climate change by testing other warming scenarios. Multimodel ensemble experiments would better test the robustness of the simulated thermal profiles, and reduce and quantify the uncertainty in the representation of the lake warming in the future.

The coupled model used in this study provides an economical framework for assessing the sensitivity of water temperature profiles to current and perturbed climatic conditions. This study demonstrated some of the difficulties related to processes occurring at an air-water interface compared to an air-land interface and provides explanations to understand some of these drifts. The results may be useful for modelers developing full three-dimensional lake-atmosphere coupling in RCMs since because of the fine computational grid, the preprocessing and computational load of such experiments is often too large to reach the conclusions drawn in this paper.

Acknowledgments. The authors would like to thank Martin Beniston for providing helpful comments and Aaron Adamack for proof-reading the manuscript. We are thankful to the Canadian Centre for Climate modeling and analysis (CCCma) for providing access to the GCMi outputs.

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