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The impact of lakes on the European climate as simulated by a regional climate model

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The impact of lakes on the European climate is considered by analysing two 30-year regional climate model (RCM) simulations. The RCM applied is the Rossby Centre regional climate model RCA3.5. A simulation where all lakes in the model domain are replaced by land surface is compared with a simulation where the effect of lakes is accounted for through the use of the lake model FLake coupled to RCA. The difference in 2m open-land air temperature between the two simulations shows that lakes induce a warming on the European climate for all seasons. The greatest impact is seen during autumn and winter over southern Finland and western Russia where the warming exceeds 1 °C. Locally, e.g. over southern Finland and over Lake Ladoga, the convective precipitation is enhanced by 20%–40% during late summer and early autumn while it is reduced by more than 70% over Lake Ladoga during early summer.

Introduction

One of the most important issues in climate modelling and numerical weather prediction (NWP) is the interaction of the atmosphere with the underlying surface. For decades, the interaction with land and sea surfaces has received much attention, whereas lakes have been either disregarded or treated in a very simplistic way. The reason for this is of course that land and sea dominate the earth's surface while lakes are only regionally important.

In regions where lakes represent a non-negligible fraction of the surface their large thermal inertia, as compared to the land surface, may cause them to have a significant impact on the regional climate. This is particularly the case in the northern parts of Europe, Asia and North America where the lake concentration is high. Our intention in this paper is to quantify the impact of lakes on the European climate by applying a regional climate model (RCM). Similar studies have been performed by Bonan (1995) and Krinner (2003). These authors investigated the impact of lakes and wetlands on a global scale using lake and wetland parameterisations in general circulation model (GCM) simulations. Bonan did not distinguish between lakes and wetlands while in the study by Krinner lakes and wetlands were treated both separately and in combination. An important assumption made in these studies is that all lakes have a fixed depth of 50 m. As we shall see in what follows, this is an overestimation for the vast majority of lakes, at least in Europe, which has important consequences for the results as to the lake impact on regional climate.

In this study, as in Bonan (1995) and Krinner (2003), a tiled surface scheme is used. That is, any water in a grid square is treated independently of other sub-grid surfaces. The energy fluxes from each individual tile are area weighted to form grid-averaged fluxes. The advantage with a tiled scheme is that contributions from surfaces not dominating a landscape but still representing important physical processes can be accounted for. Another model where a tiled surface scheme, including a 1-D lake model for the lake tile, is introduced is the RCM CRCM5 (Zadra *et al.* 2008). In a non-tiled scheme a grid square can only be represented by a single surface type. Thus, as inland water bodies seldom dominate the area of a grid square for the horizontal resolution used in today's GCMs and RCMs, except for a few very large lakes, the water fraction is often totally disregarded in such cases. For example, this is the situation in ECHAM5 (Roeckner *et al.* 2003) and in RACMO (van Meijgaard *et al.* 2008). In ECHAM5 the lake temperature is solved from the heat budget equation, including growth equations for ice and snow, assuming a constant-depth mixed layer of 10 m. In RACMO a deep soil temperature is used for the lake surface temperature assuming that the lag of the deep soil temperature with respect to the soil surface temperature is representative also for a lake surface.

In RCMs and in NWP models, thermal fluxes (i.e. fluxes of sensible and latent heat and radiation fluxes) and momentum flux at the underlying surface must be calculated over all surface types, including lakes. To this end, the lake surface temperature (temperature of the water surface or of the ice surface if the lake in question is frozen) is required. It is this variable that communicates information between lakes and the atmosphere. Then, the lake model can be made simple as long as the lake surface temperature is well simulated. For climate simulations, computationally efficient models (parameterisation schemes) are of high priority. There are both 1-D and 3-D lake models available (*see* Mironov 2008, and references therein) but 3-D models are seldom considered for climate and NWP applications due to their high computational cost (Leon *et al.* 2005). The 1-D lake models applied in GCMs and RCMs range from one-layer bulk models to multi-layer turbulence closure models. For example, the RCMs RCA3 and RegCM3 use multi-layer models proposed by Ljungemyr *et al.* (1996) and Hostetler *et al.* (1993), respectively. The one-layer bulk models yield good results only for shallow lakes since they assume complete mixing down to the lake bottom thus neglecting thermal stratification. The multi-layer models are more appealing from the physical standpoint but they are still considered computationally expensive in many climate and NWP applications. A two-layer bulk model with a parameterised temperature structure of lake thermocline (Mironov 2008) is a computationally efficient lake model that incorporates much of the essential physics. That model, termed FLake (http://lakemodel.net), is capable of realistically simulating the vertical temperature structure of shallow to medium-depth lakes (up to 40 or maybe 50 m in depth). FLake is especially well suited for being coupled to NWP and climate models. In this study, FLake is coupled to the RCM as used by Rossby Centre at SMHI.

Description of the models

The models applied are the Rossby Centre regional climate model RCA and the lake model FLake. In what follows, an overview of these models is given and the coupling of the two models is outlined.

The regional climate model RCA

In this study, we use an updated version of the Rossby Centre regional climate model RCA3 (Kjellström *et al.* 2005, Samuelsson *et al.* 2006). RCA3 is developed at Rossby Centre, SMHI, and has been extensively used in a number of climate scenario studies. RCA3 is one of the RCMs participating in the European projects PRUDENCE (Jacob *et al.* 2007) and ENSEMBLES (Sanchez-Gomez *et al.* 2008). Climate scenarios based on RCA3 have been used as the basis for recommended adjustments due to climate change by the governmental Commission on Climate and Vulnerability in Sweden (Persson *et al*. 2007).

RCA3 includes parameterisations of radiation (Savijärvi 1990, Sass *et al*. 1994), turbulence (Cuxart *et al*. 2000), large-scale clouds and microphysics (Rasch and Kristjánsson 1998), convection (Kain and Fritsch 1993, Jones and Sanchez 2002), near-surface fluxes of momentum and scalar quantities (Louis *et al*. 1982), and land surface processes (Samuelsson *et al*. 2006). In the updated version RCA3.5 (from hereon referred to as simply RCA), the lake model PROBE (Ljungemyr *et al*. 1996) is replaced by FLake and the land-surface physiographic information dataset is replaced by ECOCLIMAP (Masson *et al*. 2003). The convection parameterisation is based on the scheme of Bechtold *et al*. (2001; *see* also Kain and Fritsch 1993) which distinguishes between shallow and deep convection.

The lake model FLake

FLake is a two-layer bulk model based on a self-similar representation (assumed shape) of the temperature profile in the mixed layer and in the thermocline (Mironov 2008, Mironov *et al*. 2010). The model incorporates (i) a flexible parameterisation of the evolving temperature profile, (ii) an advanced formulation to compute the mixed-layer depth, including the equation of convective entrainment and a relaxation-type equation for the depth of a wind-mixed layer, (iii) a module to describe the vertical temperature structure of the thermally active layer of bottom sediments and the interaction of the water column with bottom sediments, and (iv) a snow-ice module. FLake carries a number of ordinary differential equations for the quantities that specify the evolving temperature profile in lakes. These are the temperature and the thickness of the upper mixed layer, the temperature at the water-bottom sediment interface, the mean temperature of the water column, the shape factor with respect to the temperature profile in the thermocline, the temperature of the upper surface of the ice, and the ice thickness. Optionally, the bottom sediment module can be activated to determine the heat flux at the water-bottom sediment interface. In that case two additional quantities are computed, namely, the depth of the upper layer of bottom sediments penetrated by the thermal wave and the temperature at that depth. If the bottom sediment module is switched off, the heat flux at the water-bottom sediment interface is set to zero. If the snow module is switched on, prognostic equations are carried for the temperature at the snow upper surface and for the snow thickness. Since the snow module has not been thoroughly tested yet, the recommended choice at present is to account for snow above the lake-ice implicitly, namely, through the changes of the ice surface albedo with respect to shortwave radiation. Details of the FLake physics are given in Mironov (2008).

The ability of FLake to predict the temperature structure in lakes of various depths on diurnal to seasonal time scales has been successfully tested against data through single-column numerical experiments. Off-line sensitivity experiments (Kourzeneva and Braskavsky 2005) have indicated some characteristic features of FLake performance. In many instances, the mixed layer depth tends to be underestimated. The sensitivity of the model results to the wind fetch and to the optical parameters of the lake water is not high. There is virtually no sensitivity to the bottom sediments module switched on or off except for long-term simulations of shallow lakes. The mean lake depth is the main parameter to which the model is sensitive. Numerical experiments suggest that the lake depth should be limited to 40 m (perhaps 50 m). That is, an artificial lake bottom should be set at a depth of 40 m where the actual lake depth is larger. The use of such device is justified since FLake is actually not suitable for deep lakes (because of the assumption that the thermocline extends from the bottom of the mixed layer down to the lake bottom). As no appreciable temperature changes typically occur in deep zones of freshwater lakes, the use of false bottom should not lead to a degradation of FLake performance.

As a lake parameterization scheme, FLake is implemented (or on the way) into a number of NWP and climate models. Further information about FLake can be found at http://lakemodel.net.

The RCA-FLake coupling

RCA uses a tiled surface scheme where any water within a given grid box is treated independently of other sub-grid surfaces. The energy fluxes from each individual tile are area weighted to form grid-averaged fluxes. In RCA all types of inland water (natural lakes, man-made reservoirs and rivers, from hereon collectively referred to as lakes) are modelled by FLake. If the information is available there is a possibility to distinguish between three different lake categories with respect to depth in each grid box; shallow (0–4 m), medium (4–8 m) and deep lakes (> 8 m). The fractional area of the lakes and their area-weighted depth for each category are specified by combing the information on the lake depth from the database developed by Kourzeneva (2010) and the lake fraction information from ECOCLIMAP (Masson *et al.* 2003). The first version of the lake-depth database used in this study was developed in May 2006. It provides reasonable coverage for most of Europe (Kourzeneva 2010). When no information on the lake depth is available but the ECOCLIMAP data indicates that lakes are present within a grid box, a default depth of 10 m is used. Any fraction of inland water less than 1% is replaced by land.

RCA and FLake are flux coupled, implying that the system is energy consistent. In the tiled surface scheme we distinguish between different 2m air temperatures (T2m) over the individual tiles. We recognise T2m over lakes, over open land, and over forest areas. A grid-box mean T2m is simply an area-weighted value of these individual values of T2m.

Methodology

To quantify the impact of lakes on the European climate we have analysed two 30-year simulations with RCA (1961–1990). In the first simulation (S-lake) lakes are present and RCA is coupled to FLake. In the second simulation (S-nolake) all lakes in the RCA domain are replaced by land using the distribution of forest and open land as already present in the grid box. This replacement is done to preserve the character of the existing landscape. If the lake fraction is 100%, which is the case only for two grid boxes over Lake Ladoga, we chose to replace the lake by open land only, using constant leaf area index = 2, roughness length = 0.05 m, albedo = 20% and vegetation cover = 95%. By comparing the results of the two simulations we identify geographical regions where the effect of lakes is most important in terms of climate conditions. We quantify the effect of lakes on some meteorological parameters, such as 2-m temperature, precipitation and thermal energy fluxes. In simulation S-lake the bottom-sediment module of FLake is switched on. Snow over lake is not treated explicitly; the effect of snow is accounted for parametrically through the changes in the surface albedo with respect to shortwave radiation. The ice albedo is increased from the original FLake value of 60% to 75% and the heat transfer coefficient for ice is decreased from 2.29 J m^{-1} s^{-1} K^{-1} to 1.5 J m^{-1} s^{-1} K^{-1}. The maximum lake depth used in the simulations is 40 m as suggested by earlier sensitivity studies.

Considering the density of lakes over Europe it is obvious that the largest influence of lakes should be expected in northern Europe (Fig. 1). The percentage of lakes, accounting for their fractional area coverage, found in different depth intervals shows that the deep category totally dominates when all lakes are considered (Table 1). However, the percentage of lakes whose depth is unknown and is therefore set to a default value of 10 m in the simulations may be high. Excluding lakes with depth of 10 m gives quite a different distribution which is probably closer to the real depth distribution for European lakes (Table 1). The true distribution is likely to be shifted even more towards shallow and medium lakes as many lakes with unknown depth are probably quite small and also shallow. In spite of these findings we still apply 10 m as depth for lakes with unknown depth. This is for a very practical reason; RCA is applied globally and we believe that 10 m may be a more globally appropriate value than a value smaller than 10 m. In a global perspective the northern latitudes are probably dominated by shallow lakes for morphological reasons.

The atmospheric model domain is resolved by 102 × 111 grid points (the average horizontal

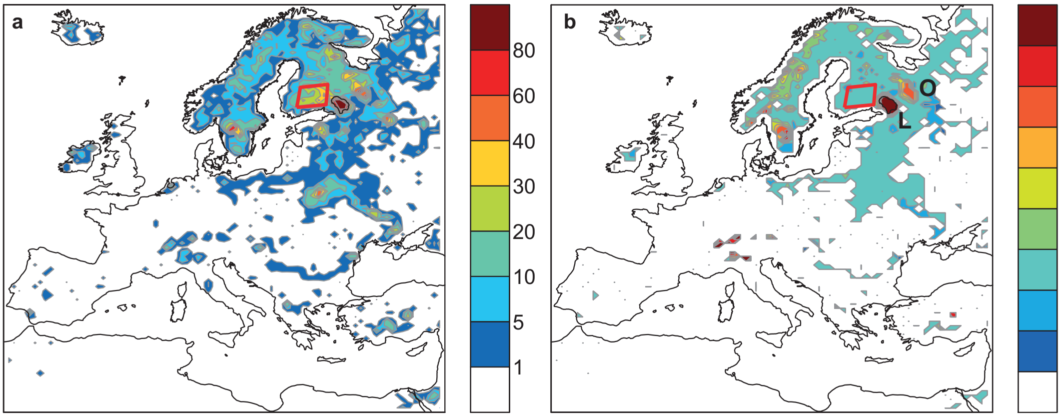

Fig. 1. (**a**) Total fraction of lakes (%) and (**b**) depth of lakes (m) in the model domain. A relatively large fraction in southern Finland (indicated by the red rhombus) is due to many small and moderately deep lakes (these lakes are 10 m deep in the S-lake simulation). Two large and deep lakes, Lake Ladoga (40 m) and Lake Onega (30 m) in western Russia, are indicated with **L** and **O**, respectively.

mesh size is about 0.4°, that is about 50 km) and 24 levels in the vertical are used. The model uses semi-Lagrangian dynamics and is hydrostatic. The time step is 30 minutes. The ECMWF 40-year reanalysis data (ERA40, *see* Uppala *et al*. 2005) are used to specify the lateral and the sea-surface temperature boundary conditions.

Comparison of model results with observations

Seasonal averages of T2m over open land from S-lake show deviations of mostly less than 2 °C from observed climatology (Fig. 2). Note that we evaluate the open land temperature and not the grid-averaged temperature as is often the case in similar model evaluations. The reason for this choice is that most observations represent open land conditions. The observed T2m climatology is a mean value of monthly averaged two-meter temperatures from Climate Research Unit (CRU, Mitchell *et al*. 2005), Willmott (Willmott and Matsura 1995) and ERA40 (Uppala *et al*. 2005) gridded data sets. Winter and autumn show a slight warm bias (model minus observation), in the order of 1–2 °C, over the central and eastern parts of the domain while the summer shows a warm bias in the Mediterranean area, locally in excess of 2 °C. The precipitation reveals a wet bias of 10–20 mm month^{-1} over the central and northern parts of Europe as compared with that in the CRU and Willmott data. Over southern Europe, the wet bias was in the range 0–15 mm month^{-1}. These biases in temperature and precipitation are well within reported biases in similar RCM studies (Hagemann *et al*. 2004). They are small and should not violate the results and conclusions of the present sensitivity study.

Monthly mean values of the simulated lake surface temperature (LST) from simulation S-lake are also compared with data from observations taken in four lakes (Fig. 3 and Table 2). The simulation results are taken from the grid squares, including correct lake category (shallow, medium, deep), where the lakes are located (Table 2). The simulated LSTs for Võrtsjärv and Pääjärvi show a good agreement with observations (Fig. 3a and b). There is a tendency for an

Table 1. Percentage of lakes in different depth intervals. The three categories of lakes as used in the model are indicated by shallow, medium and deep, respectively. The rightmost column gives the percentage distribution when excluding lakes with the default lake depth of 10 m.

Depth interval (m)	All	Excluding 10 m
0–4 (shallow)	1.4	3.9
4–8 (medium)	7.8	21.8
8–40 (deep)	85.2	74.3
25–40 (deep)	5.6	15.6

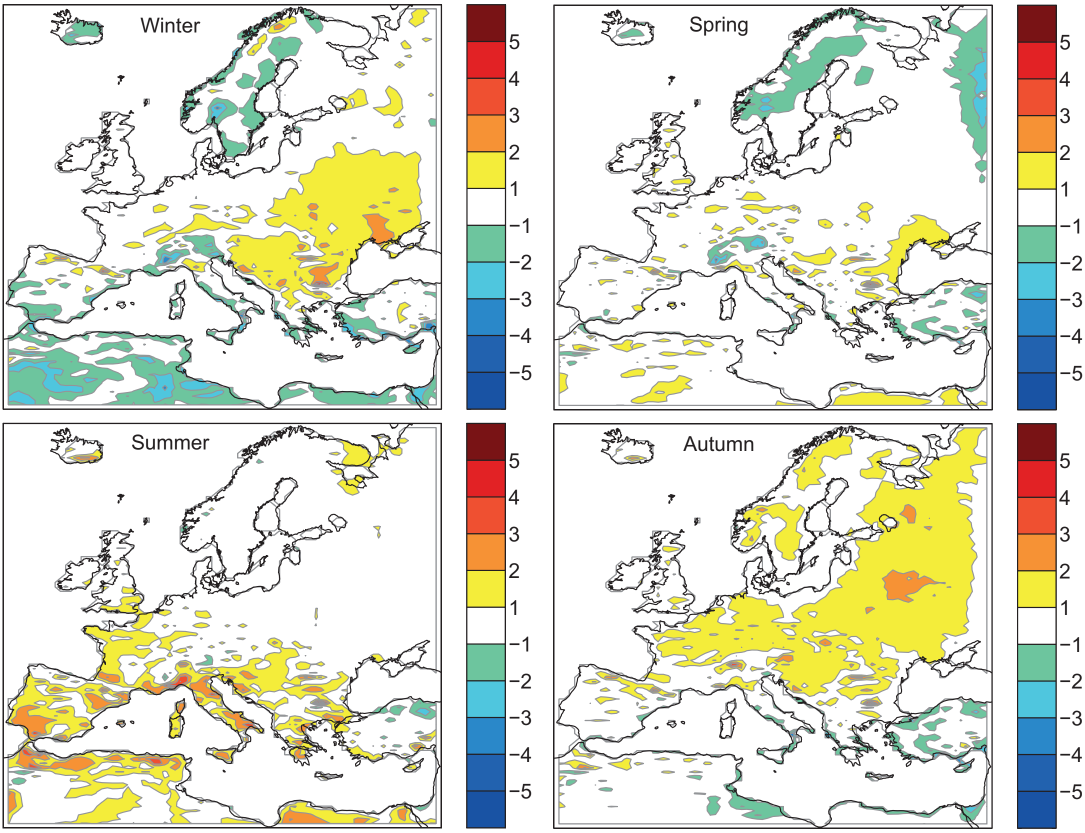

Fig. 2. Difference in T2m over open-land (°C) between the S-lake simulation and a climatological mean of the CRU, Willmott and ERA40 data sets for the four seasons.

overestimation of the LST during the summers of 1984 and 1985. However, this overestimation does not seem to be related to any deficiency of FLake since the T2m over open land is also overestimated as compared to observations. Although the timing of observed lake freezing and of ice break-up is based on climatology only (not on the real measurements for the considered years), it lends support to the simulated ice cover. Note that the summer T2m over the lakes is generally slightly higher than the T2m over the surrounding open land areas. The reason for this, as will be shown in more details further on, is the difference in nighttime conditions between lakes and open-land areas.

For deep Lake Ladoga, the 2-m air temperature over lake clearly lags behind the surrounding open-land temperature (Fig. 3c). As inferred from the plot, the observed air temperature climatology, although gridded (i.e. point observations taken as representative for an area and thus interpolated to specific grid points), is chiefly based on open land values. As compared with the observations, the simulated LST shows a warm bias. The warm bias during autumn reflects a general picture around this area of the model domain (Fig. 2). In spring and summer, the simulated T2m over open land is very close to observations. The climatology of the observed LST in May is just above 0 °C while the simulated temperature is almost 5 °C. Still, the simulated timing of ice break-up compares quite well with the observations. Thus, there seems to be a mismatch between the LST and the ice break-up observations as used here. The reason for this mismatch is not quite clear although the sources of information on LST and ice conditions are different (Table 2). For a large lake it is probably nearly impossible to specify particular dates for ice on/off. Large lakes remain partially covered

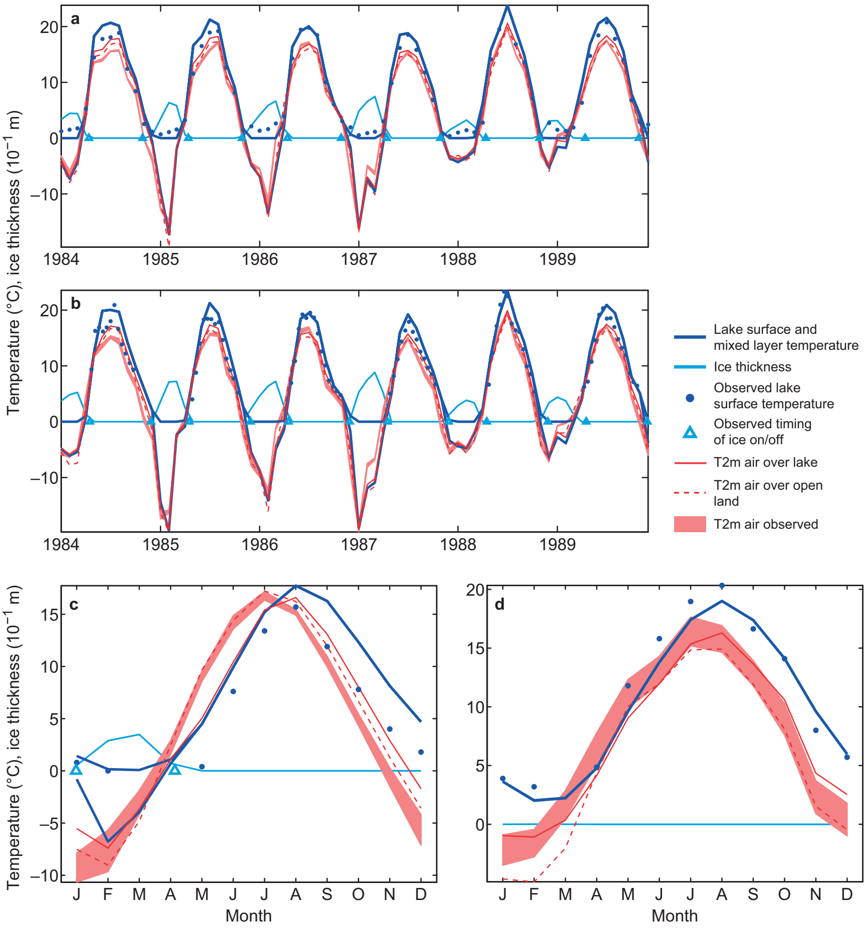

Fig. 3. Simulated and observed temperatures and ice conditions (*see* also Table 2) for four lake sites: (**a**) Võrtsjärv, Estonia, (**b**) Pääjärvi, Finland, (**c**) Lake Ladoga, Russia, and (**d**) Ammersee, Germany. The observed T2m band embraces the individual observational data sets ERA40, CRU and Willmott, respectively.

Table 2. Characteristics of the lakes as used in the evaluation study and references to evaluation data sources for lake surface temperature and ice on/off dates. The observed depth refers to mean depth. The RCA depth means the depth used for the specific lake category in the grid square where the lake is located. The given time periods represent both time series (T) and mean climate (C).

Lake (location)	Lake depth		Surfface temp. period, source	Ice on/off period, source	RCA period
	Obs.	RCA			
Võrtsjärv (Estonia, 58.1°N, 26.2°E)	3 m	3 m	1984–1989 (T), http://clime.tkk.fi/	unknown, http://www.ilec.or.jp/	1984–1989
Pääjärvi (Finland, 60.8°N, 25.0°E)	15 m	10 m	1984–1989 (T), http://clime.tkk.fi/	1961–2002 (C), Blenckner *et al.* (2004)	1984–1989
Ammersee (Germany, 47.6°N, 11.4°E)	38 m	35 m	1985–1986 (C), http://www.ilec.or.jp/	– –	1984–1989
Ladoga (Russia, 61.2°N, 31.5°E)	51 m	40 m	1959–1988 (C), http://www.ilec.or.jp/	1948–1988 (C), http://nsidc.org/data/lake_river_ice/	1961–1990

by ice over certain period, and the water surface temperature during that period may be quite different from the ice surface temperature. It is, therefore, difficult to say which value of LST is representative of Lake Ladoga during the period of partial ice cover.

The simulated LST over Ammersee (Fig. 3d) fits the observed climatology better than the Lake Ladoga LST. Ammersee is located in an area with complex terrain which is manifested in the relatively broad spread in observed T2m climatology. This is probably also the reason for the discrepancy between the simulated T2m over open land and the climatology. The T2m over the lake lags the corresponding open land temperature but the lag is not as pronounced as for Lake Ladoga.

Comparison of simulations with and without lakes

In the following much of the discussion is related to a region in southern Finland and to a grid square over the northern part of Lake Ladoga (31.5°E, 61.2°N). The region in southern Finland (Fig. 1) is represented by 38 grid squares in the model domain and has on average 25% water (21% deep lakes with mean depth 10.4 m and 4% medium deep lakes with mean depth 2.8 m), 62% forest and 13% open land in the S-lake simulation. In the S-nolake simulation the fractions are 83% forest and 17% open land. The grid square over Lake Ladoga has 88% water (only deep lake with mean depth 40 m), 10% forest and 2% open land in the S-lake simulation and 83% forest and 17% open land in the S-nolake simulation.

The differences between the simulations are, among other things, related to the difference in surface properties between land (depending on snow conditions) and lake (depending on ice conditions), e.g. albedo and surface roughness. Given the fractions of forest and open land the snow-free land albedo becomes 12%. The albedo for water is specified to 7% and for lake ice to 75%. During the snow season the land albedo depends on simulated snow fraction and age of snow but reaches a monthly mean value of 34% in February. The momentum roughness length, z_0, for a snow-free land surface is 0.2–1 m depending on the fractional coverage of forest, z_0 for snow on open land is 5×10^{-3} m, z_0 for water is based on a Charnock formulation (Charnock 1955) and z_0 for lake ice is 8×10^{-4} m.

Two-meter air temperature

In general, the presence of lakes had a warming effect on the T2m climate for all seasons (Fig. 4). Considering that this result is based on differences in the open-land T2m (*see* above), the effect of lakes should have been communicated to the surrounding land through the atmospheric boundary layer whose structure and transport properties are modified if lakes are present in the model domain. The presence of lakes also affects cloudiness, thus modifying the surface radiation budget and hence the near-surface temperature. In autumn, the warming effect of lakes is certainly expected since lakes are relatively warm as compared to the surrounding land. The thermally active soil layer has a lower inertia than the water column of most lakes and does therefore cool more quickly. The warming effect during winter is mainly explained by the fact that the ice season usually extends from mid winter until mid spring. During the first half of the winter lakes are still warmer than the land surface would be if lakes are replaced with land. Another contributing factor to the winter warming could be heat transfer through the ice. Using satellite remote sensing data Jeffries *et al*. (1999) estimated the heat flux through lake ice in Alaska to be about 10 W m^{-2} higher than the heat flux from the soil.

The warming effect due to lakes during summer is less obvious. The reason for this warming can be explained by a relatively high LST during nighttime (Fig. 5). For the area in southern Finland the T2m over lakes is on average higher than the T2m over surrounding open land from 15 UTC to 6 UTC. Then, the lakes heat the atmospheric boundary layer which manifests itself in the increase of the temperature at the lowest model level above the surface (located at approximately 90 m in these simulations) and in the increase of T2m (Figs. 4 and 6).

The inclusion of lakes decreases the amplitude of the temperature diurnal cycle in summer

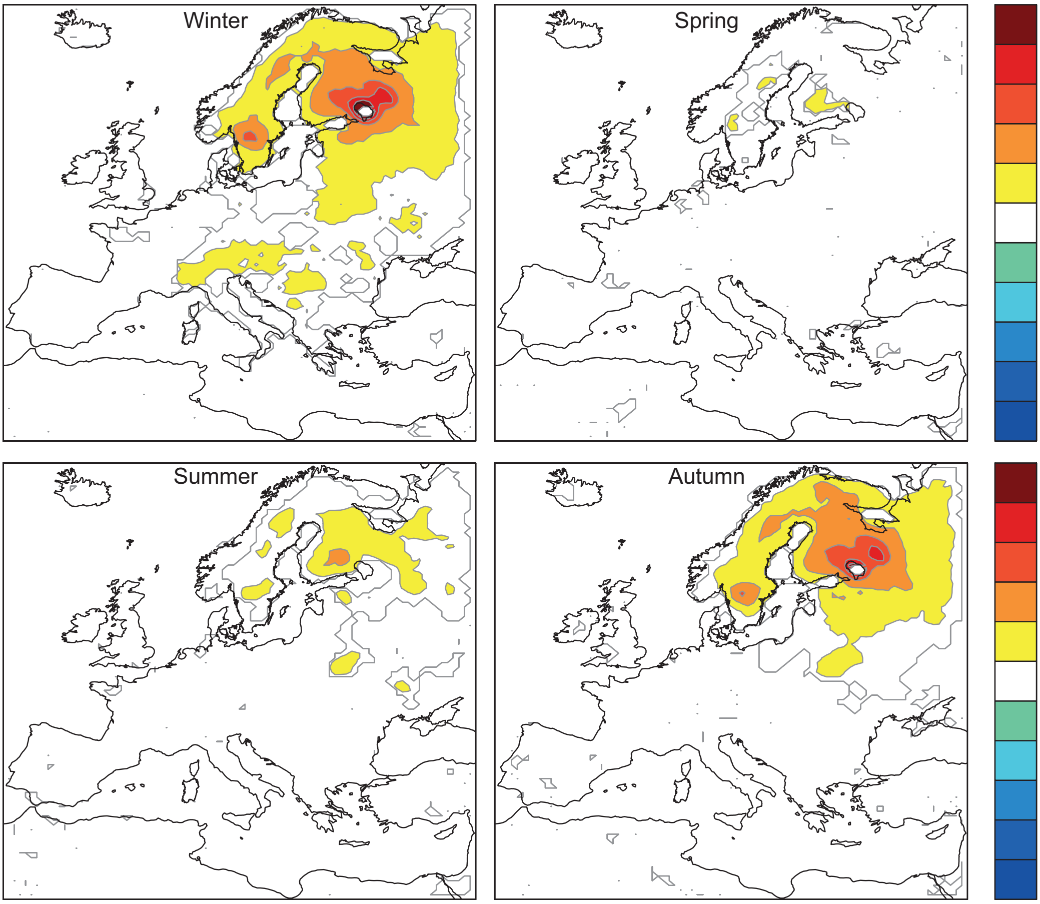

Fig. 4. Differences between the simulations S-lake and S-nolake for the four seasons winter, spring, summer and autumn. The differences concern T2m over open land (°C). The grey lines indicate areas for which $p = 0.05$ (*t*-test). Thus, the null hypothesis is rejected and mean differences for areas within grey lines do not contain 0 at a 95% confidence interval level. Note that $p \leq 0.05$ for all coloured areas.

(Fig. 5). The effect is actually seen all around the year but it is most pronounced during summer when the diurnal cycle amplitude is reduced by more than 0.5 °C. Notice that both the daily minimum two-metre temperature $T2m_{min}$ and the daily maximum two-metre temperature $T2m_{max}$ are increased for all seasons (Figs. 7–8). The increase in $T2m_{min}$ is, however, larger than the increase in $T2m_{max}$, leading to a reduced amplitude of the diurnal cycle. The increase in $T2m_{max}$ during summer is probably due to a slight decrease in cloudiness and a corresponding slight increase in the downward shortwave radiation (not shown). The presence of lakes also increases the downward longwave radiation in the morning hours during spring, hence a slight increase in $T2m_{min}$ for this season. However, the reason for the increased downward longwave radiation is not clear.

For all seasons except spring the temperature at the lowest model level is found to be higher in the presence of lakes (Fig. 6). The only noticeable difference at this level during spring is a local cooling over Lake Ladoga. Due to high thermal inertia of large lakes, their surface temperature remains low during spring, leading to a colder boundary layer over lakes than over land. The open land T2m during spring shows an increase over southern Finland (Fig. 4). The reason is probably a decrease in cloudiness and, as a consequence, an increase in downward shortwave radiation (not shown).

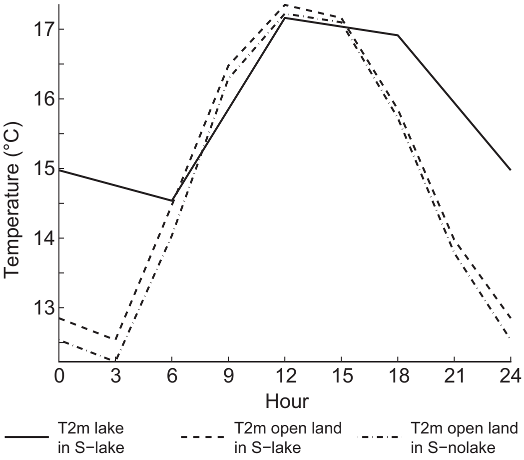

Fig. 5. Simulated summer-season (JJA) mean diurnal cycle of two-metre air temperatures as area averaged over a region in southern Finland (Fig. 1). The T2m lake temperature cycle is calculated from six hourly model output while the T2m open land cycles are calculated from three hourly output.

Precipitation

The major differences in precipitation between the simulations with and without lakes are seen in the convective component (Fig. 9). Differences are shown only if they exceed 5 mm month^{-1}. The differences are, however, restricted to only a few regions of Europe and to only two seasons, *viz.*, summer and autumn (Fig. 10). The lake district in southern Finland and the large and deep Russian lakes, Lake Ladoga and Lake Onega, are the areas where the difference in precipitation is most pronounced. Over southern Finland, the convective precipitation in August is increased by more than 20%. Over Lake Ladoga the effect is even stronger; convective precipitation is decreased by more than 70% in July and is increased by nearly 40% in September. A possible reason for the increase in convective precipitation is an addi-

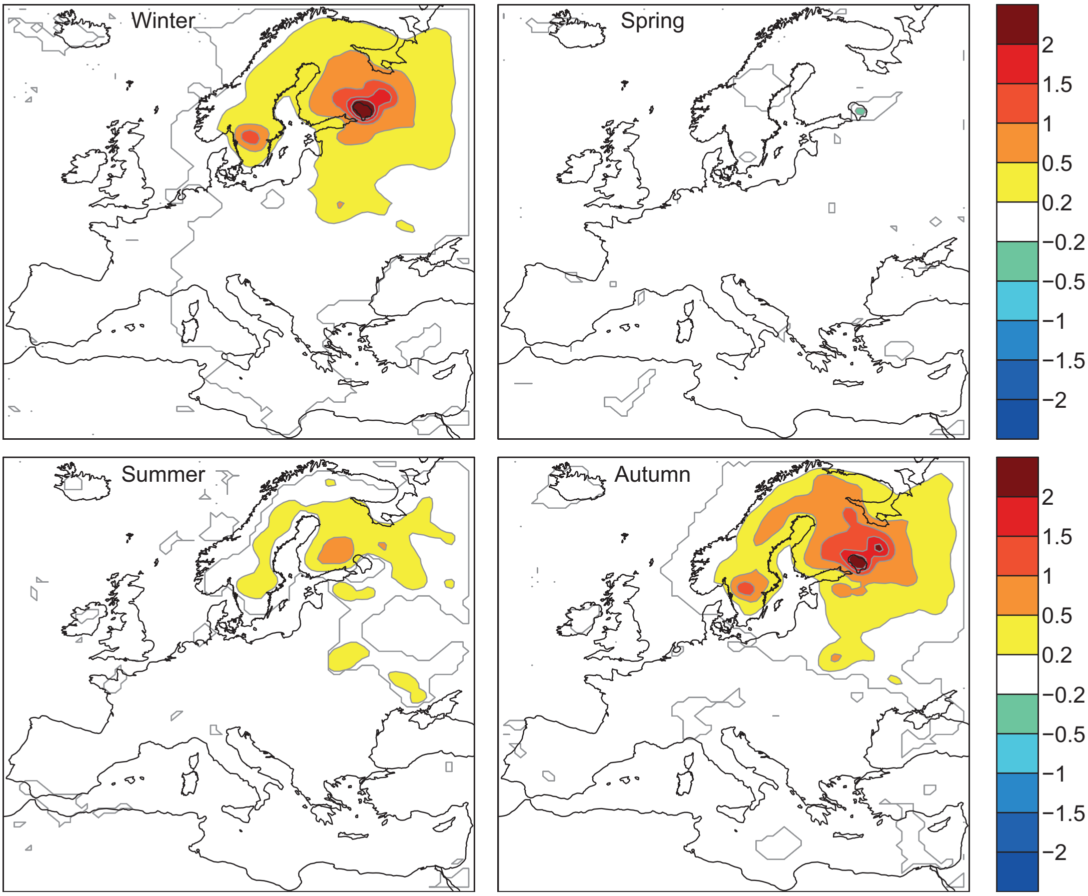

Fig. 6. As Fig 4 but for temperature (°C) at the lowest model level (at 90 m).

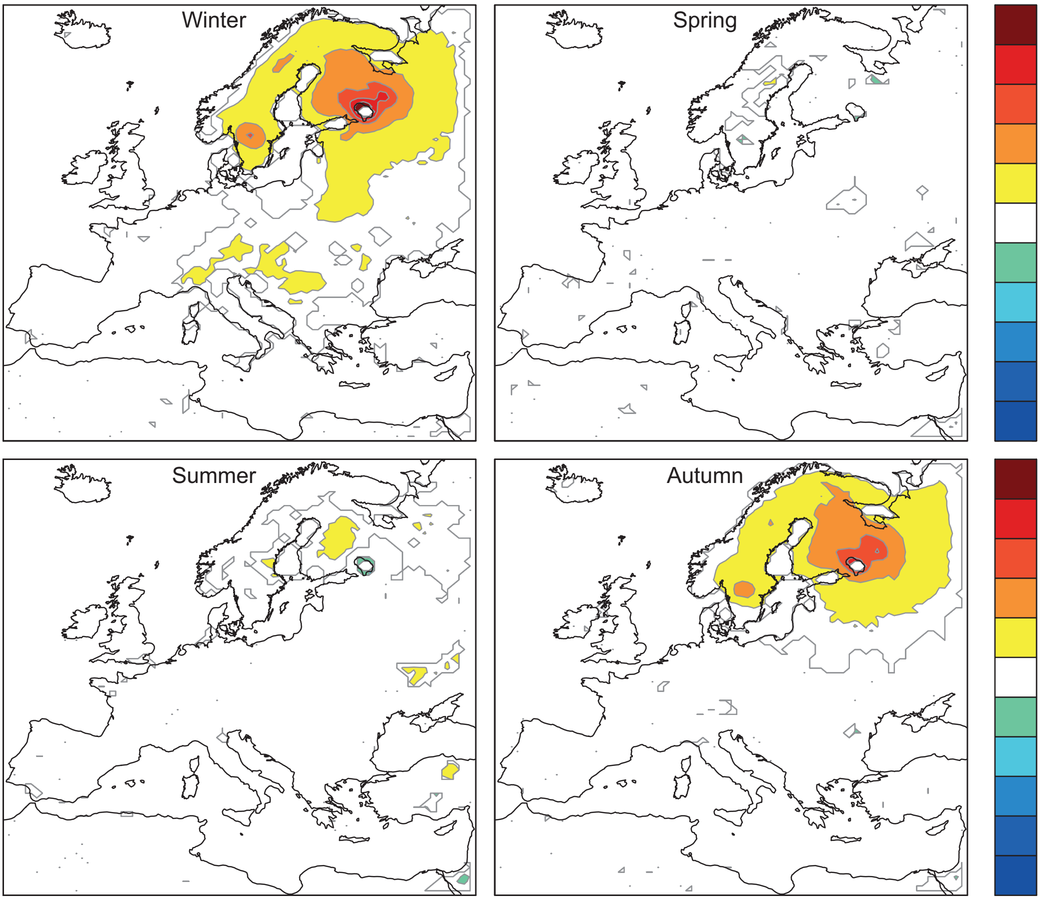

Fig. 7. As Fig 4 but for differences in daily maximum of T2m over open land (°C).

tional heating and moistening of the atmospheric boundary that facilitate the triggering of convection. This situation takes place when the lake surface is warm (summer over southern Finland and autumn over Lake Ladoga). A stable boundary layer that develops over a relatively cold lake surface (summer over Lake Ladoga) suppresses the vertical heat and moisture transport and hence suppresses convection.

One should bear in mind that the partitioning between large-scale and convective precipitation is usually very dependent on the convection scheme used in the atmospheric model. A similar study performed with a different convection parameterisation may give different results. However, we only look at the differences between the two simulations using the same convection parameterisation. It is then expected that the result is more generally valid than only for the particular model using a particular convection parameterisation scheme.

Thermal energy fluxes

For the grid square over Lake Ladoga, the differences in thermal energy fluxes (Fig. 11d) between the two simulations are quite large as compared with the magnitude of the fluxes themselves (Fig. 11b). These differences reflect the replacement of a large and deep lake area (S-lake) by land only (S-nolake). The lag in latent heat flux between the two simulations (Fig. 11b) is in accordance with the effect on convective precipitation as discussed earlier (Fig. 9b). As expected, the replacement of a smaller fractional area of more shallow lakes by land only, as in southern Finland, does not show as large

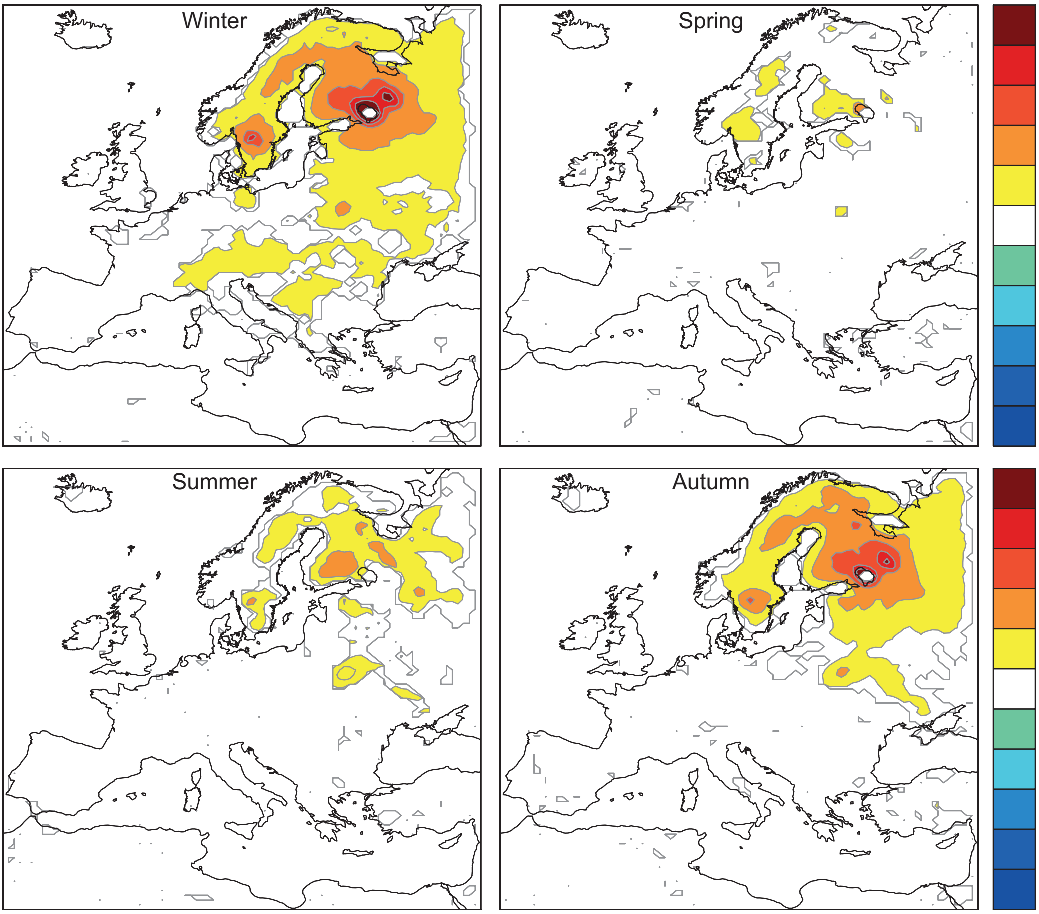

Fig. 8. As Fig 4 but for differences in daily minimum of T2m over open land (°C).

differences in fluxes (Fig. 11c) as compared to the fluxes themselves (Fig. 11a).

The difference in total net thermal energy flux shows a positive peak in May and in June for the region in southern Finland (Fig. 11c) and for Lake Ladoga (Fig. 11d), respectively. Thus, the surface in the S-lake simulation, including the lakes, gain heat energy with respect to the S-nolake simulation. The main contributions to this difference are differences in shortwave net radiation (which is larger in the simulation S-lake due to the lower albedo of water as compared to land) and evaporation (which is strongly suppressed in S-lake mainly due to cold lake surface temperature). The effect of the albedo difference between lake and land is also seen in the change of the sign of the net shortwave radiation difference from April to May over southern Finland; the albedo decreases in both simulations but the decrease in S-lake is more dramatic as snow covered ice is replaced by water. The suppressed evaporation over lakes in early summer is not only explained by the forming of a stable boundary layer over the cold lake surface but a lower roughness of the water surface, as compared to the land surface, also contributes to a reduced latent heat flux. During autumn, the evaporation loss from the warm lake surface appears to be much larger than from a cold (and drier) land surface, a reduction of fluxes due to a small water-surface roughness being a second order effect.

The difference in total net thermal energy flux shows a negative peak in November and in December for the two locations, respectively. The main contributing components are differences in the longwave radiation, evaporation, and sensible heat flux. Lake Ladoga acts as a source of sensi-

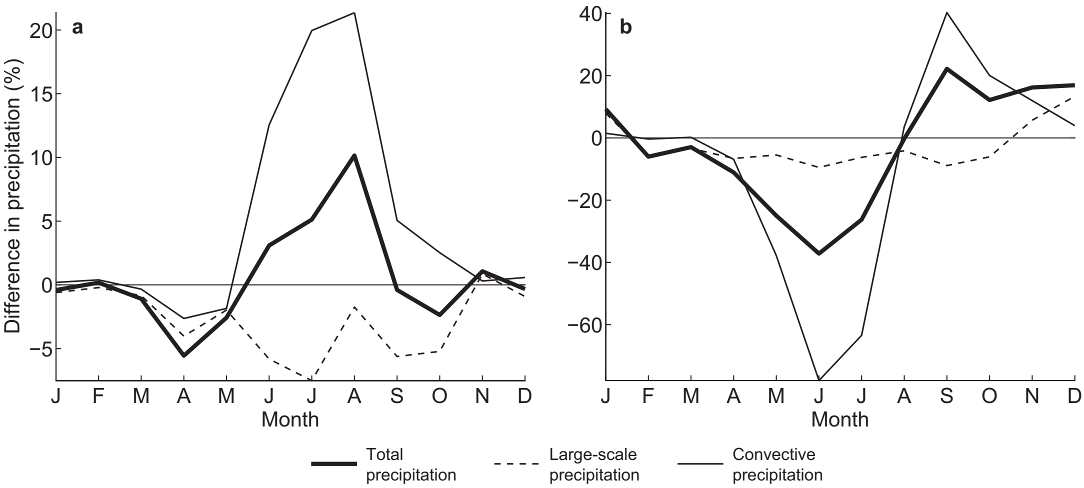

Fig. 9. Annual cycle of difference in precipitation (S-lake – S-nolake)/(S-nolake) (**a**) for the area in southern Finland (as marked in Fig. 1), and (**b**) for a point over Lake Ladoga.

ble heat flux for the atmosphere during August–January (Fig. 11b) in contrast to the lake area in southern Finland where the surface (grid-averaged flux) in both simulations acts as a source during summer but as a sink during winter.

Discussion and conclusions

The purpose of this study was to investigate and quantify the impact of lakes on the European climate. For this purpose, two 30-year climate simulations are set up and analyzed with the aid of the regional climate model RCA3.5. In the simulation S-lake, all lakes are modelled applying a two-layer bulk model FLake, whereas in the simulation S-nolake, all lakes are replaced by land. Off-line sensitivity studies with FLake suggest that FLake is most sensitive to the lake depth and that a mean depth to the bottom of the lake in question yields the best results in terms of the lake surface temperature and the ice characteristics. For this reason we used, probably the best available, information on observed lake depth covering Europe provided by the lake depth data set by Kourzeneva (2010). Unfortunately, the mean depth of many inland water bodies is still unknown. In the present study, all those water bodies are given a “default” depth of ten metres. This value is perhaps an overestimation for a number of regions in Europe but is taken to be a reasonable zero-order estimate globally. A default lake depth will be replaced with the actual depth as the lake depth data set gets updated (the work is underway).

Generally, a comparison of S-lake and S-nolake shows that lakes induce a warming effect on the European ambient air temperature two meters above the surface (T2m) over open land, particularly over northern Europe where many lakes are located and the fractional area coverage of lakes is substantial. Thermal inertia of shallow lakes is larger than thermal inertia of a thermally active soil layer. This enables lakes to damp the variability in temperature and lag the response to atmospheric forcing as compared with a land surface. It is then not surprising that lakes induce a warming effect during the cooling period of autumn and winter. Over southern Finland and around the large Russian lakes, Lake Ladoga and Lake Onega, the warming effect of lakes is shown to be over 1 °C, close to the large lakes even over 1.5 °C, on a seasonal basis during autumn and winter. Areas in southern Sweden and large parts of Finland and of western Russia show significant warming of more than 0.5 °C. These numbers are comparable to the bias found in climate modelling and in NWP (Hagemann *et al*. 2004, Kjellström *et al*. 2005). In this regard, the results indicate that the effects of lakes should be accounted for in atmospheric models, at least in regions with many lakes.

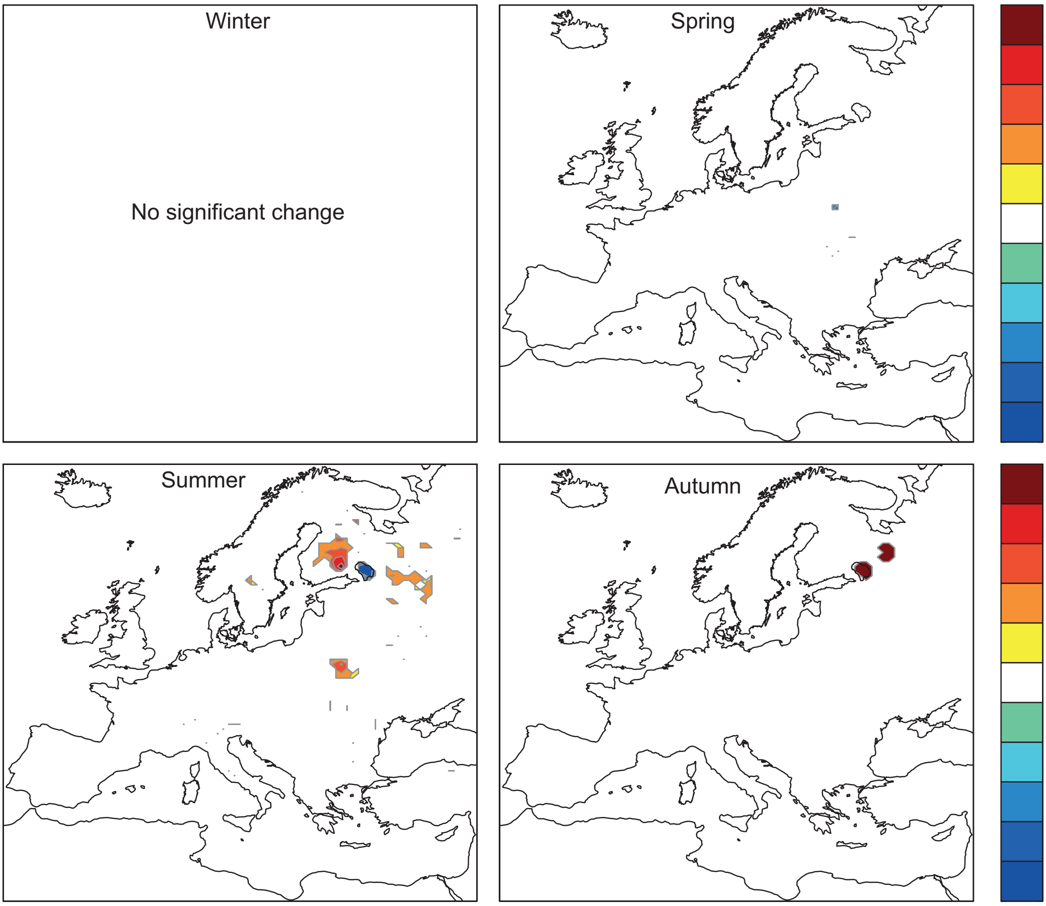

Fig. 10. As Fig 4 but for convective precipitation (percentage).

Lakes have less of an influence on the spring and summer climates. During summer, there is still a warming effect that is explained by the relatively warm surface water of lakes at night. Even in spring, there is a warming tendency over southern Finland that is small but still statistically significant. In contrast to the other seasons, the spring warming is only induced by indirect effects related to reduced cloudiness and the ensuing increased downward shortwave radiation. Please recall that all these results refer to the T2m over open land. The T2m averaged over the entire atmospheric-model grid box which includes both land and lakes experiences a cooling effect of lakes not only during spring time, but also during summer time for the deepest lakes. Bonan (1995) and Krinner (2003) used a lake depth of 50 meters for all lakes present in their GCM domains. This depth is close to the actual mean depth of Lake Ladoga. These authors came to the conclusion that lakes induce a cooling effect on the summer climate. Our results support this conclusion when considering summer grid-box mean T2m over Lake Ladoga, where the fractional area coverage of lake water is large in the RCA domain. However, for the majority of European lakes the mean depth is less than 50 m and the fractional area coverage is quite small. Then, the cooling effect of lakes is less pronounced (if at all), and the warming effect is seen if the T2m over land part of the model grid box is considered.

Krinner (2003) also looked at the impact of wetlands on climate. He came to the conclusion that wetlands act to increase the evaporation during summer and to warm the climate during winter. Interestingly, the influence of wetlands on the climate according to Krinner (2003) is

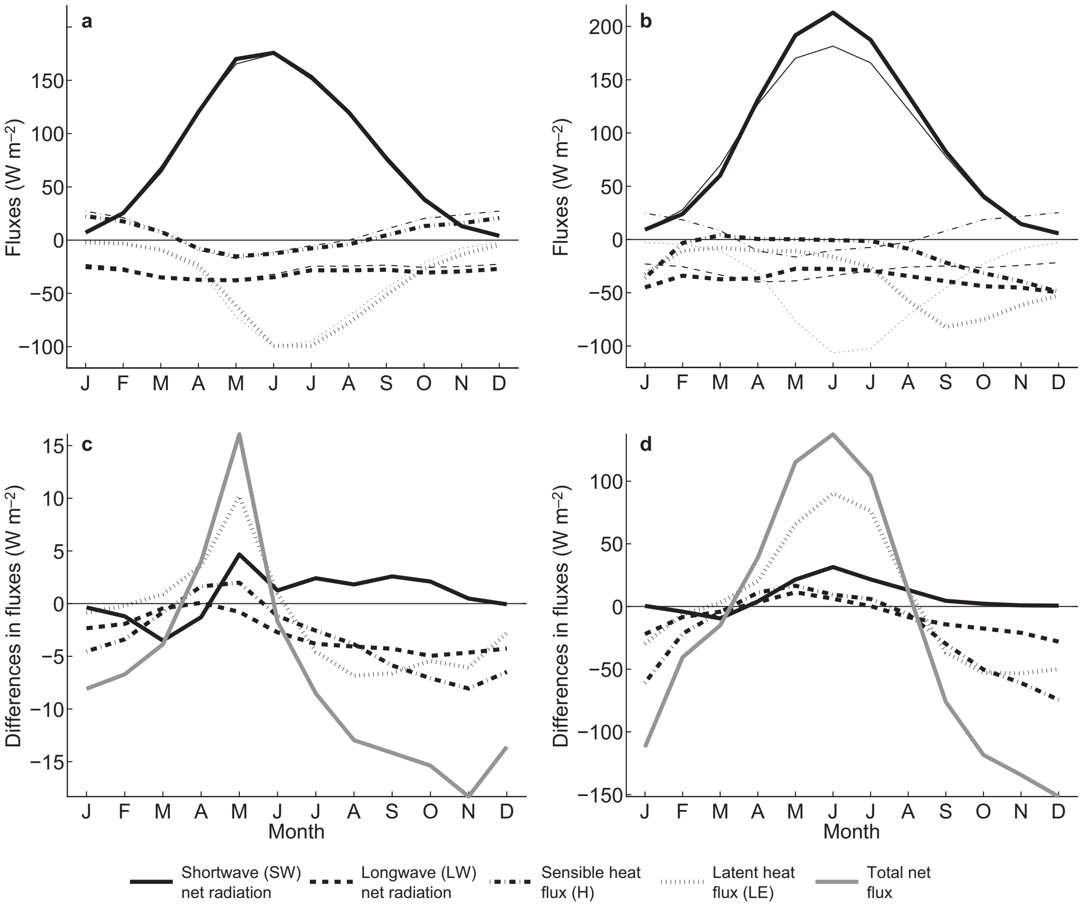

Fig. 11. Annual cycle of (**a**–**b**) thermal energy fluxes and (**c**–**d**) difference in fluxes (S-lake – S-nolake) for (**a**, **c**) the area in southern Finland (as marked in Fig. 1) and (**b**, **d**) a point over Lake Ladoga. Thick lines in panels **a** and **b** represent S-lake while thin lines represent S-nolake. The total net thermal energy flux is SWnet + LWnet + H + LE. Note that all fluxes are positive downwards, thus positive LE difference means less evaporation in S-lake.

very similar to the influence of shallow and medium-depth lakes in the present study.

The impact of lakes on the precipitation is only very locally significant as compared with the impact on the temperature. The strongest signal is seen in the convective precipitation component. In southern Finland, there is an increase of convective precipitation of about 20% in July and August, whereas over Lake Ladoga the increase reaches 40% in September. Over southern Finland there is no significant decrease of precipitation due to lakes at any time over the year, but over Lake Ladoga there is a reduction of convective precipitation of more than 70% in June due to a suppressed evaporation. This effect on precipitation around deep and large lakes was also found by Krinner (2003). He showed that the summer precipitation around Laurentian Great Lakes decreases, a result which is also supported in numerical simulations by Lofgren (1997).

In closing it is stated that results of regional climate modelling are sensitive to the presence of lakes. Excluding the effect of lakes from the atmospheric-model physics leads, among other things, to seasonal bias in near-surface temperature of the order of 1 °C. In regions with many small to medium size relatively shallow lakes and around large and deep lakes, lakes also induce considerable changes in convective precipitation and in evaporation rates. The present study is restricted to Europe but similar results are expected for the northern parts of Asia and of North America. The impact of lakes on regional climate is dependent on the mean lake depth used in the simulations. Since the mean depth of many lakes in Europe and all over the world is unknown a default depth is used as a zero-order approximation. In this regard, further development of the lake depth data set (Kourzeneva 2010) is of great importance for climate studies.

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