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Article

# Effects of the Lake Sobradinho Reservoir (Northeastern Brazil) on the Regional Climate

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**Abstract:** This study investigates the effects of Lake Sobradinho, a large reservoir in Northeastern Brazil, on the local near-surface atmospheric and boundary layer conditions. For this purpose, simulations with the regional climate model COSMO-CLM are compared for two different scenarios: (1) with the lake being replaced by the average normal native vegetation cover and (2) with the lake as it exists today, for two different two-month periods reflecting average and very dry conditions, respectively. The performance of the simulation is evaluated against data from surface meteorological stations as well as satellite data in order to ensure the model's ability to capture atmospheric conditions in the vicinity of Lake Sobradinho. The obtained results demonstrate that the lake affects the near-surface air temperature of the surrounding area as well as its humidity and wind patterns. Specifically, Lake Sobradinho cools down the air during the day and warms it up during the night by up to several °C depending on the large-scale meteorological conditions. Moreover, the humidity is significantly increased as a result of the lake's presence and causes a lake breeze. The observed effects on humidity and air temperature also extend over areas relatively far away from the lake.

**Keywords:** regional climate modeling; COSMO-CLM; artificial reservoirs; near-surface air temperature; humidity; wind; lake breeze

## 1. Introduction

Human induced land use and land cover changes (like deforestation, water reservoirs, urbanization) modify important land surface properties such as albedo, roughness length, emissivity and vegetation cover. These characteristics are important determinants for the partitioning of surface energy fluxes [1,2]. Depending on the type and scale of these modifications, local weather and climate can be affected to different degrees due to the resulting changes in surface fluxes.

Lakes are characterized by an elevated heat capacity and thermal inertia, small roughness length and albedo [3]. Several studies have demonstrated that the presence of lakes can affect near-surface meteorological conditions as well as meso or synoptic scale processes [4–6]. Typically, in the vicinity of lakes, surface moisture is increased and the daily and annual range of near-surface air temperature is reduced. In fall and winter of temperate climates, cold dry air moves over warmer lake surfaces causing high evaporation rates and subsequently cloudiness and precipitation. This situation is reversed in summer, when the cooler lake surface stabilizes the overlying atmosphere leading to a reduction in clouds and precipitation. Local high pressure centers over lakes in the summer can influence atmospheric circulation and cause lake breezes [4]. Previous studies on the effects of tropical lakes on the regional climate, such as the Elqui Valley reservoir in an arid region of Chile [7] and the great African lakes [8] confirm the aforementioned findings for lakes in temperate climates regarding their effects on near-surface air temperature and its diurnal cycle as well as increased precipitation.

With respect to the region of interest in this work (Northeastern Brazil), Melo et al. [9] used the numerical model RAMS (Regional Atmospheric Modeling System, version 8) to assess the environmental impact of agricultural expansion on the natural Caatinga dominated landscape in the basin of the São Francisco River. They found that the spatial variability of turbulent flows is highly influenced by the surface characteristics, topography, soil moisture and vegetation type. In periods of intense convective activity and precipitation, the influence of irrigation is not evident in turbulent flows. In contrast, the simulated flows on dry days (without precipitation) are strongly affected by the availability of water in the soil and irrigated perimeters, highlighting the importance of distinguishing between different climatological situations when studying regional climate dynamics of Northeastern Brazil.

In a previous case study on Lake Sobradinho [10,11], the RAMS model was applied (at 2 km and 6 km resolution, respectively) for one-day simulations with and without the lake and irrigated crops. These simulations indicated that the lake causes thermally induced circulation patterns and a lake breeze that is influenced by crop irrigation. The area affected by the lake breeze is characterized by a drop in air temperature and an increase in precipitation. However, these results have been restricted to a single regional climate model (RCM) and a very short integration time, raising concerns regarding the general validity of the obtained results. To further address this problem, this work systematically expands the original case study by Correia et al. [10,11] by conducting additional high-resolution ($\sim$2 km) simulations with a different RCM, COSMO-CLM (COSMO (COnsortium for Small-scale MOdeling) in CLimate Mode), or short CCLM [12,13], for the entire months of April and May of the two years of 1998 and 2002. The year 1998 has been characterized by very high air temperatures and low amounts of rainfall. Therefore, the lake effects are expected to be particularly strong in this arid region. On the other hand, during the year 2002, the observed air temperatures and rainfall represent the long-term average climatic conditions of the lake basin.

The CCLM model has already been successfully applied to the specific climate conditions of South America by Lange et al. [14]. The latter study revealed that the model captures common tropical features such as the high vertical extent of the planetary boundary layer (i.e., the lowest part of the atmosphere the behavior of which is directly influenced by its contact with the Earth surface) and deep convection rather well. For the understanding of lake–atmosphere interactions, a good representation of the lake temperatures is required. This can be challenging, especially for large and deep lakes with three-dimensional circulations. Here, we apply the one-dimensional lake model FLake (Freshwater Lake model) [15,16] (see Section 2.1) together with CCLM. In order to provide highly resolved climate simulations, we first conduct long-term simulations (1979–2004) of the area with and without the lake at a spatial resolution of 11 km. The highly resolved 2 km runs are then simply nested for the two selected periods of interest, implying that these short-term fine-grid simulations are initialized and driven by long-term coarser-grid simulations with the same RCM. This strategy ensures that the model is in long-term equilibrium for our two study periods. Therefore, we capture possible long-term effects, even though we analyze only shorter episodes. In turn, we emphasize that analyzing climatological effects instead of effects at the weather scale would require simulations over 20–30 years on the finer grid, which would increase the numerical effort tremendously. However, a corresponding investigation is beyond the scope of the present study.

The remainder of this paper is organized as follows: Section 2 describes CCLM and its setup together with the observational data used for model validation. Our results are presented and further discussed in Section 3, including an evaluation of CCLM's performance by inter-comparison with observations and a study on the effects of Lake Sobradinho on surface meteorology and circulation. The paper concludes with a summary of our main findings in Section 4.

## 2. Materials and Methods

### *2.1. CCLM Model Description and Setup*

The non-hydrostatic RCM CCLM has been developed based on the "Local Model" of the German Weather Service (DWD). CCLM's numerical routines solve the hydro-thermodynamical equations for three-dimensional wind components, pressure, air temperature, specific humidity and cloud water content. Physical parameterizations consider sub-grid scale turbulence [17], grid-scale clouds and precipitation [12], delta-two stream radiation transfer [18] and shallow and moist convection (IFS scheme, [19]). Lower boundary conditions over land (i.e., land surface and soil processes) are simulated by means of the multi-layer soil model TERRA-ML [20]. The soil-vegetation water balance is modeled according to the biosphere-atmosphere transfer scheme (BATS) [21]. The Richards and heat conduction equations are solved in order to simulate the vertical soil moisture transport and heat flow. Note that only vertical fluxes are represented in TERRA-ML, as the horizontal displacement can be neglected at the presently used grid sizes. This also holds for the runoff which is formed within a grid cell and not transported to any of the adjacent cells. TERRA-ML provides a stability and roughness length dependent formulation of the surface turbulent fluxes which constitute the lower boundary conditions for the atmosphere. Surface runoff is formed by summarizing contributions from the interception store, the surface snow store, and water due to a limited infiltration rate into the soil. Furthermore, contributions from the hydrologically active soil layers in case of over-saturation are added to form the subsurface runoff. Soil types are based on the UNESCO/FAO (Food and Agriculture Organization of the United Nations) soil map of the world [22]. Here, the number of soil levels is set to 10, with the layer thickness increasing with soil depth from 0.005 m to 11.5 m, following an exponential law, and representation of the hydrology stops at 8 m depth.

The one-dimensional FLake model is applied for the computation of the lake's vertical temperature profile and the energy stored [15]. In FLake, a top mixed layer with a uniform water temperature profile as well as a thermocline layer at the bottom of the lake are assumed. The temperature of the thermocline layer is parameterized according to the concept of self-similarity [23]. FLake provides simulations of the mean temperature of the water column, the mixed-layer temperature and depth and the thermocline layer temperature profile. The default downward light attenuation coefficient for incoming solar radiation is $3\,\mathrm{m}^{-1}$. The global bathymetry data set [24] is used to determine Lake Sobradinho's depth for each modeling grid cell (maximum 50 m).

Here, we use CCLM version 4.25.3 with domains of 0.1° (about 11 km) and 0.02° (about 2 km) spatial grid spacing (enclosed areas in Figure 1). In a rotated longitude/latitude geographical coordinate system (rotated North Pole at $\phi = 80^\circ$ N, $\lambda = 41.8^\circ$ W), the higher resolution modeling domain extends from 2.26° S to 2.25° N and 2.26° W to 2.24° E and is covered by $226 \times 226$ grid cells. 50 vertical levels and internal time steps of 25 s are used. The initial six-hourly boundary conditions are provided by the ERA-Interim reanalysis [25]. In order to exclude lateral boundary effects from the analysis, we discard the sponge zone which has a width of 10 grid points. This zone doesn't really represent model dynamics; it is unphysical as it tries to smooth out any pathological effects due to discontinuities at the boundary between two completely different grids.

In this work, we carry out simulation studies without and with the lake. When the lake is excluded from the simulations, it is replaced by solid ground with the characteristics of representative grid cells from the surrounding land surface.

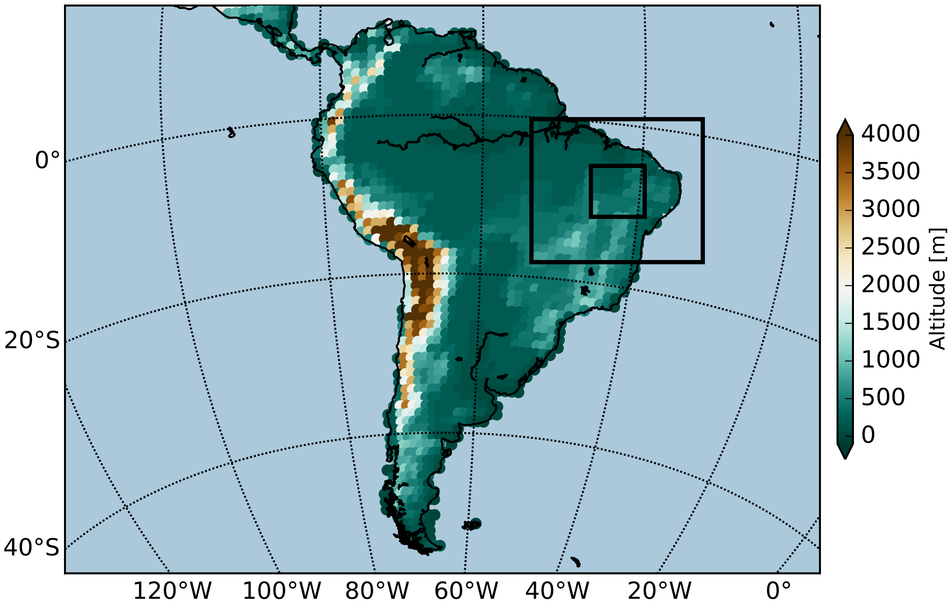

**Figure 1.** Schematic view of our nesting steps. The larger enclosed area corresponds to a 0.1° resolution and the smaller one to a 0.02° resolution of CCLM in the respective regions (in rotated coordinates as described in the text).

### *2.2. Climatological Setting*

The Northeast of Brazil (Nordeste do Brasil), comprising the federative states of Alagoas, Bahia, Ceará, Maranhão, Paraiba, Pernambuco, Piaui, Rio Grande do Norte and Sergipe, represents 18% of the national territory of Brazil. With a total area of almost 1.6 million km$^2$, it is among the regions most vulnerable to impacts of climate change. This is due to its semiarid climate in combination with a high population density [26]. The region Semiárido brasileiro represents approximately 58% of the surface of of Nordeste do Brasil [27] (excluding the State of Maranhão) plus the northernmost part of the State of Minas Gerais, extending from about 3° S to 17° S. Principal characteristics of this region are an annual precipitation fluctuating between 400 and 800 mm, mean air temperatures above 23 °C, and evapotranspiration above 2000 mm/year. The living conditions of the population and the region's potential for agricultural production are directly connected to the availabilty of water [28]. Specifically, the São Francisco river basin is of key importance in this context.

In this study, we investigate the effects of the Lake Sobradinho reservoir on the regional meteorological conditions. Lake Sobradinho is located in the semi-arid sub-middle São Francisco river basin (near Petrolina, State of Pernambuco). The reservoir was installed in 1982 and replaced the natural Caatinga vegetation cover, a mix of shrubs, low trees and cactuses. Precipitation mainly occurs from November to April. With a length of 280 km and a varying width of 5 km to 50 km, Sobradinho's water storage capacity is 34 billion m$^3$. Its surface area is large enough to potentially influence regional weather and climate, particularly in combination with large areas of irrigated agricultural land to which the natural Caatinga was converted as a result of a governmental irrigation program.

For choosing an extremely dry year and an "average" (non-extreme) year, we analyzed 2 m air temperature data from the meteorological station at Petrolina (9°22′ S, 40°28′ W, see below for details) for the years 1981 to 2004. Observational data for precipitation for the years 1998 to 2004 were obtained from the Tropical Rainfall Measuring Mission (TRMM) data set [29]. We calculated the mean air temperature and precipitation values for April and May for each of these years. From that, we determined the median and maximum values of the April/May air temperatures and precipitation taken over all these years. The median values coincide very well with the values obtained for the year 2002, 25.06 °C and 0.024 mm/day, respectively, which is therefore considered as a prototypical normal year. In turn, extremely warm and dry conditions have been observed in 1998 for which average air temperature and rainfall amount to 27.07 °C and 0.006 mm/day, respectively. As mentioned in a previous study on Lake Sobradinho [30], the long-term mean of the surface lake temperature is 26 °C. It is noteworthy that 1998 was rated an extremely dry year in Submédio San Francisco by the rainfall anomaly index (IAC), very likely affected by the strong El Niño event during that year, which caused a decrease in rainfall and rising air temperatures in the Northeast of Brazil [31].

### *2.3. Observational Data for Model Evaluation*

For the evaluation of modeled air temperature and wind speed, we use observational data from surface weather stations. The data were collected at a total of seven meteorological stations located in the surroundings of the lake (Figure 2), covering the westernmost part of the State of Pernambuco (PE) northeast of the lake as well as the northern part of the State of Bahia (BA): Petrolina-PCD/PE (9°9′ S, 40°22′ W; here, PCD stands for Plataforma de Coleta de Dados) and Araripina-PCD/PE (7°27′ S, 40°24′ W) belong to INPE (Instituto Nacional de Pesquisas Espaciais) [32], the National Institute for Space Research, which is a unit of the Brazilian Ministry of Science and Technology. Bebedouro–Petrolina/PE (9°9′ S, 40°22′ W) and Madacarú-Juazeiro/BA (9°24′ S, 40°26′ W) are operated by EMBRAPA/CPATSA [33], the Tropical Semi-Arid Research Center of the Brazilian Agricultural Research Corporation. Finally, we use data from three stations operated by INMET (Instituto Nacional de Meteorologia) [34], the National Institute of Meteorology: Petrolina/PE (9°22′ S, 40°28′ W), Barra/BA (11°05′ S, 43°10′ W) and Remanso/BA (9°38′ S, 42°1′ W). The data include daily values of maximum and minimum air temperature, humidity and wind velocity. For 1998, we used data from all stations except Petrolina-PCD/PE, while for 2002, data from the Araripina-PCD/PE station were not available.

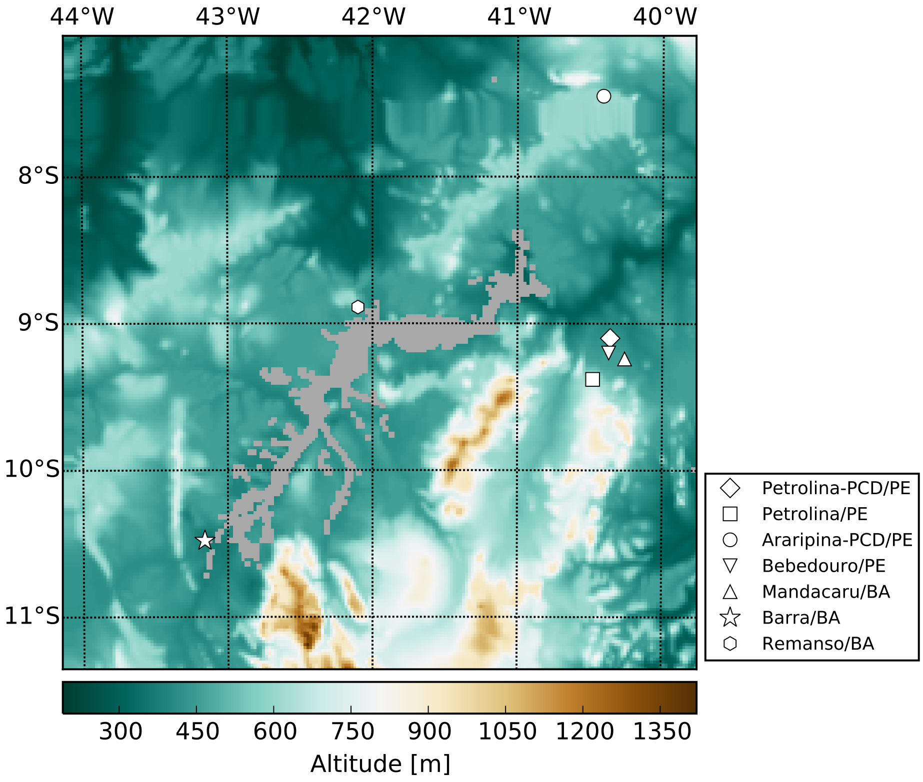

**Figure 2.** Geographical setting and meteorological stations used for model evaluation. The gray area represents the geographical extent of Lake Sobradinho.

## 3. Results

### *3.1. Model Evaluation*

We applied CCLM to simulate the evolution of various meteorological variables during the two periods of interest. At the coarser spatial scale, we utilized a long simulation starting back in 1979 and covering the whole period of interest of this work. In turn, the two nested simulations at the finer grid started at 1 January 1998 and 1 January 2002, respectively, resulting in a sufficiently long spin-up time of the model (i.e., the simulation period after which transient effects due to imperfect initial conditions can be neglected) of four months each prior to our analysis periods.

We first evaluate our simulation results by comparing the simulated average bi-monthly diurnal cycles of 2 m air temperature ($T_{2m}$) and 3 m wind speed ($V_{3m}$) with the corresponding three-hourly observations for each of the two two-month study periods. For this purpose, the model results at the grid points closest to the respective reference station are averaged for each hour of the day for the months of April and May. For the years 1998 and 2002, data from the Araripina/PE and Petrolina/PE stations were used, respectively, which have a temporal resolution of 3 hours (as opposed to the other stations where only daily data have been available). The results are shown in Figure 3. For the year 2002, CCLM approximately reproduces the diurnal cycles of $T_{2m}$ and $V_{3m}$ in the station data. In turn, for 1998, the shapes of the cycles are reproduced well, but the magnitudes are overestimated by CCLM. For air temperature, we have around 4 °C overestimation and for wind speed, the results are about 1.5 times larger than the observation data.

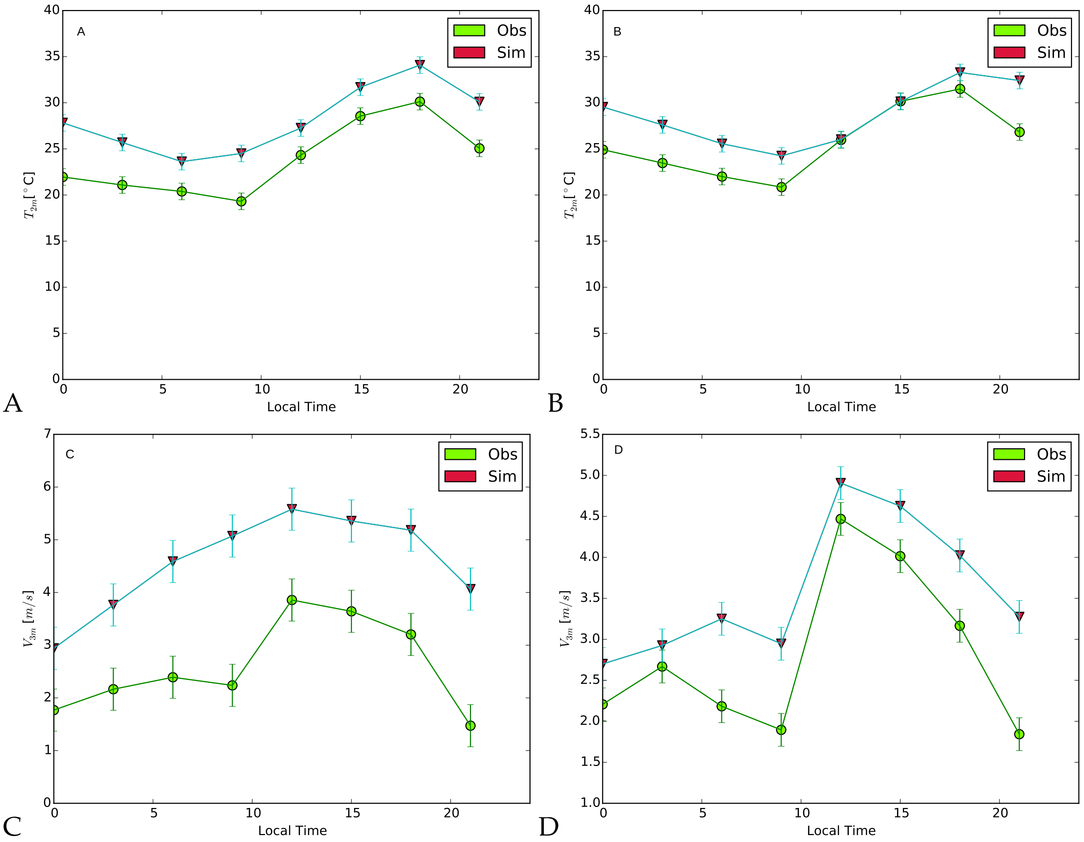

**Figure 3.** Average diurnal cycles of observed and simulated (**A**,**B**) 2 m air temperatures ($T_{2m}$) and (**C**,**D**) 3 m wind speeds ($V_{3m}$) for (**A**,**C**) 1 April–31 May 1998 (Araripina/PE station) and (**B**,**D**) 1 April–31 May 2002 (Petrolina/PE station).

In order to handle this overestimation, one should note that in climate modeling, one generally assumes that model errors are approximately constant across simulations. Therefore, it is customary to regard anomalies from simulations as valid output, even though the simulated baselines might be somewhat off. Considering only variations around the baseline and ignoring the systematic offset can be considered as the simplest possible strategy of bias correction, which is often referred to as the *delta change method* [35–37].

Another relevant factor is that we have only point observations and only simulated regional atmospheric conditions for a period of a few months. We tried to exclude influences of initial conditions as much as possible by using a long spin-up (see above), but some uncertainties remain. These facts already imply a possible mismatch between the observations and simulation results. Furthermore, we have chosen an extreme period, which is typically harder to be reproduced by an RCM than an average period. The missing shading effect could also be a reason for the discrepancy. TERRA-ML does not account for the shading effect of the vegetation. This can easily produce biases of the observed order, depending on the specific station's setup. In summary, we emphasize that the study region is known to be challenging for climate modeling in general [30]. In this regard, our results can be considered as in line with the state of the art.

Table 1 lists the root mean square error (RMSE) and bias (i.e., the root mean squared and mean differences, respectively, between all daily values in the model and observations for the respective periods of time) of the simulated daily mean, maximum and minimum values of 2 m air temperature as well as the 3 m wind speeds in comparison with observed data for the period of 1 April–31 May of the years 1998 and 2002.

**Table 1.** Root mean squared error (RMSE) and bias of simulated daily mean, minimum and maximum 2 m air temperatures and 3 m wind speeds in comparison with observed data for the period of 1 April–31 May of the years 1998 and 2002.

| **Year** | | **1998** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Station** | | **Petrolina/PE** | | **Mandacarú/BA** | | **Bebedouro/PE** | | **Barra/BA** | | **Remanso/BA** | |
| **Month** | | **April** | **May** | **April** | **May** | **April** | **May** | **April** | **May** | **April** | **May** |
| $T_{2m,mean}$ [°C] | RMSE | 1.61 | 0.92 | 1.53 | 1.06 | 2.29 | 1.52 | – | – | – | – |
| | Bias | −1.22 | −0.52 | −1.16 | −0.77 | −2.04 | −1.28 | – | – | – | – |
| $T_{2m,min}$ [°C] | RMSE | 1.59 | 1.0 | 2.36 | 3.32 | 1.82 | 1.40 | 4.7 | 4.33 | 3.67 | 2.67 |
| | Bias | −1.13 | 0.01 | −1.99 | −2.77 | −1.2 | −0.45 | −4.5 | −4.13 | −3.21 | −2.01 |
| $T_{2m,max}$ [°C] | RMSE | 2.58 | 2.03 | 1.87 | 3.2 | 2.48 | 2.15 | 2.32 | 1.28 | 2.02 | 3.02 |
| | Bias | −1.98 | −1.42 | −1.18 | −2.3 | −1.82 | −1.3 | −1.84 | 0.01 | −1.88 | −2.7 |
| $V_{3m}$ [ms$^{-1}$] | RMSE | – | – | 2.56 | 2.7 | 2.02 | 1.75 | 0.96 | 0.87 | 3.47 | 3.38 |
| | Bias | – | – | 2.37 | 2.5 | −1.91 | −1.62 | −0.5 | −0.22 | −2.97 | −2.82 |
| **Year** | | **2002** | | | | | | | | | |
| **Station** | | **Petrolina/PE** | | **Mandacarú/BA** | | **Bebedouro/PE** | | **Barra/BA** | | **Remanso/BA** | |
| **Month** | | **April** | **May** | **April** | **May** | **April** | **May** | **April** | **May** | **April** | **May** |
| $T_{2m,mean}$ [°C] | RMSE | 1.56 | 1.58 | 1.65 | 1.57 | 2.81 | 3.09 | – | – | – | – |
| | Bias | −0.27 | −1.15 | −0.54 | 1.3 | −2.27 | 2.08 | – | – | – | – |
| $T_{2m,min}$ [°C] | RMSE | 1.05 | 1.45 | 2.73 | 2.8 | 4.29 | 4.41 | 4.7 | 5.17 | 1.28 | 1.49 |
| | Bias | −0.5 | −0.56 | −2.42 | −2.41 | −4.03 | −4.05 | −4.19 | −5.01 | −0.93 | −1.12 |
| $T_{2m,max}$ [°C] | RMSE | 2.66 | 1.89 | 2.79 | 1.65 | 3.08 | 2.08 | 2.09 | 1.73 | 4.8 | 3.61 |
| | Bias | −0.02 | −1.3 | 0.36 | −0.97 | −0.51 | −1.56 | −0.57 | −1.29 | −4.4 | −1.17 |
| $V_{3m}$ [ms$^{-1}$] | RMSE | – | – | 1.98 | 1.44 | 2.11 | 2.36 | 0.81 | 0.77 | 2.67 | 3.05 |
| | Bias | – | – | 1.57 | 1.11 | −1.72 | −2.25 | 0.08 | 0.02 | −2.27 | −2.81 |

### *3.2. Lake Effects on Near-Surface Meteorological Conditions*

In the following, we present the results of our CCLM-based study regarding the effects of Lake Sobradinho on the near-surface meteorological conditions and surface energy fluxes. For all considered variables, mean values over the two entire simulation periods (1 April–31 May 1988 and 1 April–31 May 2002) are presented.

### 3.2.1. Warm and Dry Conditions: April/May 1998

We start with considering the more extreme conditions of the year 1998. Figure 4 shows the spatial patterns of the simulated daily minimum, maximum and mean 2 m air temperatures ($T_{2m,min}$, $T_{2m,max}$, $T_{2m,mean}$) for the simulations without the lake (Figure 4A,E,I) and the difference plots for the simulations with lake minus without lake (Figure 4B,F,J). The presence of Lake Sobradinho with its large heat capacity causes $T_{2m,min}$ to increase by up to 2 °C during night. As will be shown later, this is accompanied by an increase in the nighttime sensible heat fluxes. Additionally, we find that the values of $T_{2m,min}$ over the lake are higher than those in the surrounding natural area by about 1.5 °C. This can be understood by the fact that the study area is an arid region with dry soils that are characterized by small heat storage capacity and the resulting differential cooling at nighttime. Lake Sobradinho also affects $T_{2m,max}$ in the simulations (Figure 4E,F) by reducing the corresponding values by up to 7 °C. Cooler air is advected towards the region northwest of the lake, cooling this area by up to 3 °C. Taken together, the presence of the lake leads to a reduction in daily mean air temperatures, $T_{2m,mean}$ (Figure 4I,J) by up to 2 °C and also to lower $T_{2m,mean}$ values in its surrounding.

Analogously to Figure 4, Figure 5 shows the results for the daily minimum, maximum and mean specific humidity at 2 m above the ground ($qv_{2m,min}$, $qv_{2m,max}$, $qv_{2m,mean}$). As expected, the specific humidity over the lake is increased in comparison with the surrounding arid area during the whole day. This is especially pronounced during nighttime. With cooler air over the lake surface, humidity is advected in northeastern direction during daytime (Figure 5A,B), while the moister air is more confined to the lake area during nighttime (Figure 5E,F). The reasons for this are lower wind speeds and less mixing during nighttime, when the planetary boundary layer reaches its minimum height.

Figures 6 and 7 show the simulation results for the latent and sensible heat fluxes ($lE$ and $H$), respectively. Here, the fluxes are positive when directed away from the lake and land surface and negative when directed towards the surface. During the day (Figure 6E,F) and nighttime (Figure 6A,B), Lake Sobradinho's simulated $lE$ are about 250 $\mathrm{W{\cdot}m^{-2}}$ and 200 $\mathrm{W{\cdot}m^{-2}}$, respectively, and larger than the $lE$ of the arid surrounding. Since the lake has a large heat capacity and natural moisture availability, most of the absorbed solar radiation is released as latent heat flux during the day. On the other hand, the surrounding natural land surface heats up more quickly and subsequently sensible heat flux leads to higher air temperature over the arid area than over the lake. In Figure 6I,J, it can be seen that the average amount of latent heat flux for the whole period of simulation is 250 $\mathrm{W{\cdot}m^{-2}}$ over the lake, which is much larger than over the surrounding area (50 $\mathrm{W{\cdot}m^{-2}}$).

Regarding the simulated sensible heat fluxes (Figure 7), we recall that during the day the lake produces mostly latent heat flux, whereas the arid area without a lake would produce mostly sensible flux (Figure 7E,F). As a result, if there were no lake, the amount of sensible heat flux would increase in comparison with the case of the lake being present. It is noteworthy that, in the latter case, the arid area around the lake still produces more sensible heat flux than the lake area. In turn, during the night (Figure 7A,B), the lake produces a stronger sensible heat flux than the arid area without the lake. The arid land surface cools down more rapidly than the lake and, hence, the sensible heat flux above the lake increases. In Figure 7I,J, the average sensible heat flux for the whole period of simulation is 50 $\mathrm{W{\cdot}m^{-2}}$ over the lake, which is smaller than in the surrounding area (100 $\mathrm{W{\cdot}m^{-2}}$).

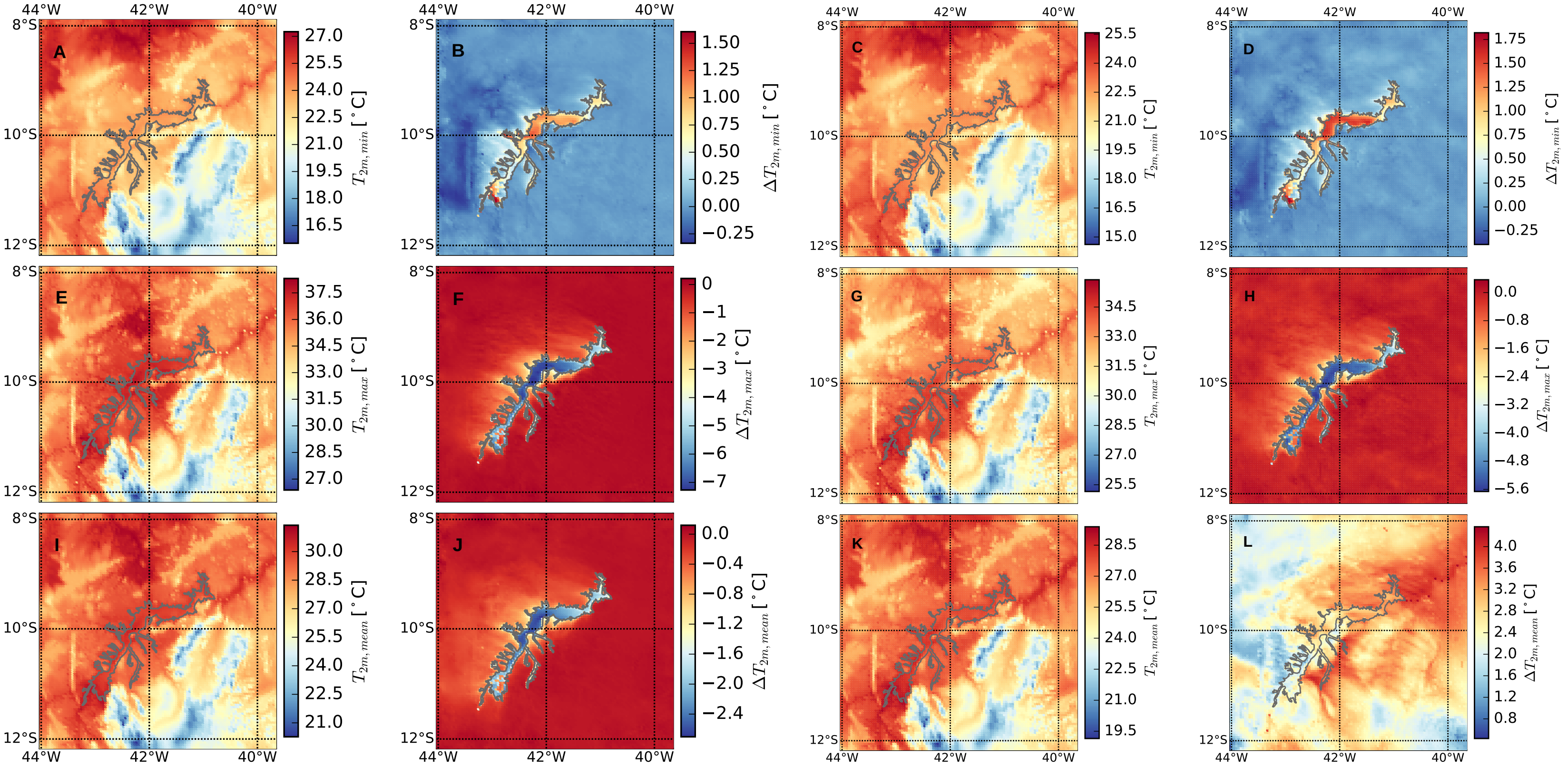

**Figure 4.** Simulated air temperatures at 2 m above ground: (**A**,**B**,**C**,**D**) daily minimum, (**E**,**F**,**G**,**H**) daily maximum and (**I**, **J**,**K**,**L**) daily mean values for the periods (**A**,**B**,**E**,**F**,**I**,**J**) 1 April–31 May 1998 and (**C**,**D**,**G**,**H**,**K**,**L**) 1 April–31 May 2002, respectively. (**A**,**C**,**E**,**G**,**I**,**K**) Results for simulations without the lake; (**B**,**D**,**F**,**H**,**J**,**L**) differences between the results including the lake with respect to the control runs without the lake. The lake's position is indicated by gray lines.

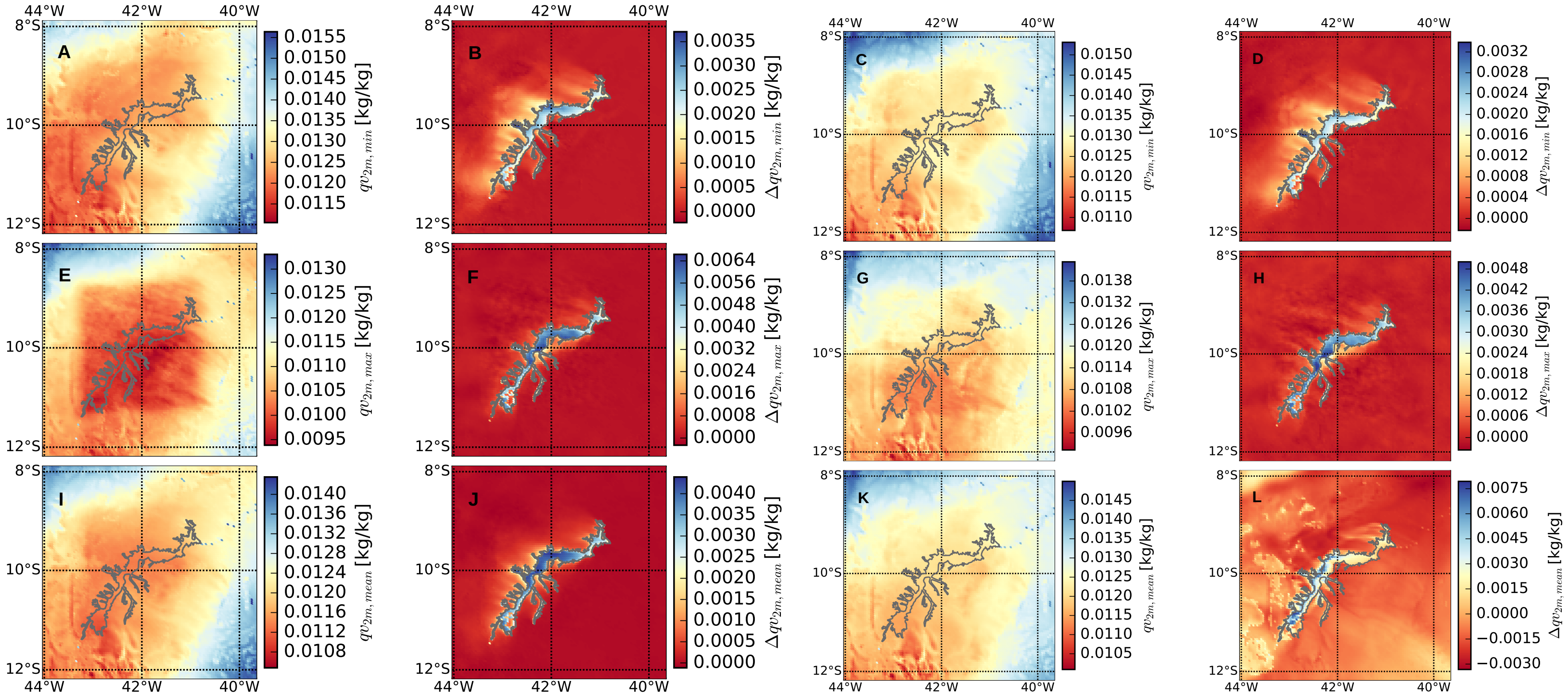

**Figure 5.** Same as in Figure 4 for specific humidity.

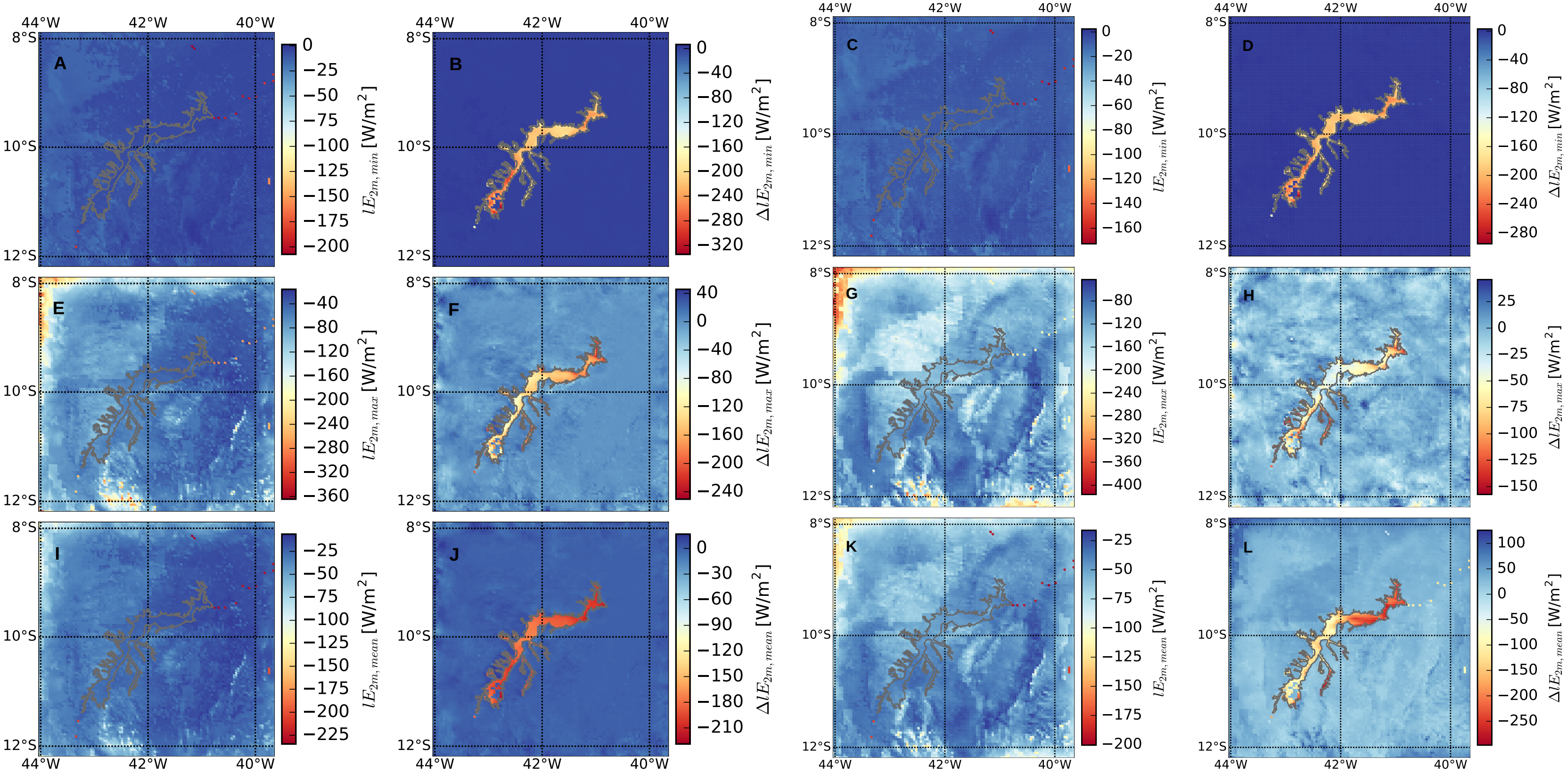

**Figure 6.** Same as in Figure 4 for the latent heat flux.

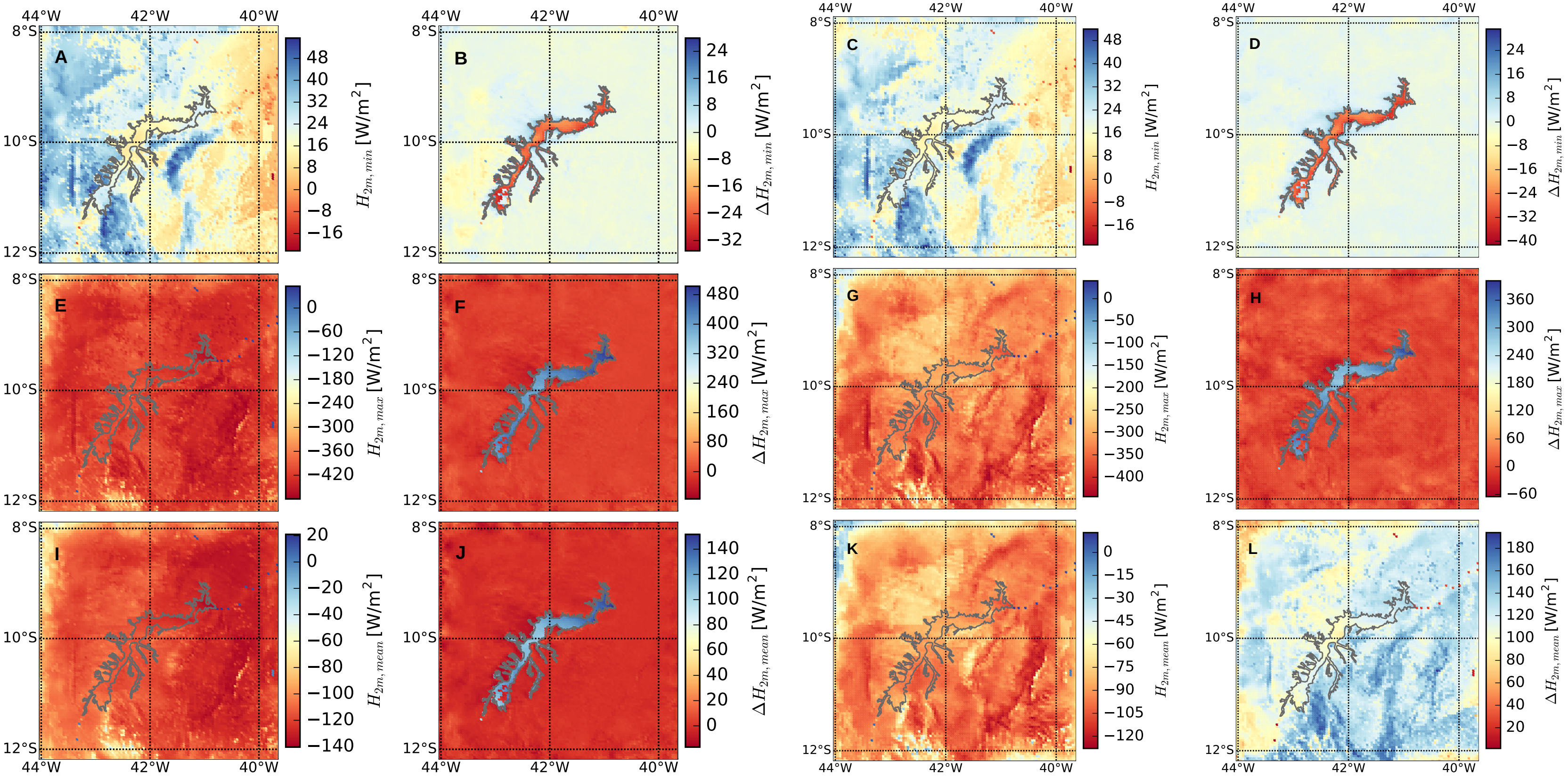

**Figure 7.** Same as in Figure 4 for the sensible heat flux.

#### 3.2.2. Average Conditions: April/May 2002

We now turn to the case of average conditions as exemplified by our simulations for the year 2002. Regarding the daily minimum, maximum and mean air temperature, the spatial patterns displayed in Figure 4 are qualitatively similar to those in 1998. Especially during daytime (Figure 4C,D), the situation closely resembles that observed for the year 1998, whereas during the night (Figure 4G,H), the general impact of the lake (expressed in the differences between both simulations with and without the reservoir) are smaller than in 1998. Under the average conditions present in 2002, during the night the areas near the lake also release more latent heat than during the more extreme conditions of 1998. As a result, the differences between the lake and its surrounding area are less obvious than during 1998. Because of the generally milder climate in 2002, the average effect of the lake on the air temperatures taken over the whole simulation period is not as pronounced as in the year 1998. The lake cools the air by just about 1 °C in comparison to the case without the lake.

Comparing the daily minimum, maximum and mean values of the specific humidity at 2 m above the land surface with the results for 1998 (Figure 5), we observe little differences between both years. Note again that the area around the lake is semi-arid, so that the amount of humidity in this region is small. The only significant difference between both years can be seen in Figure 5I–L. In 1998, we had an extremely hot season. Hence, the average difference in humidity between the two cases with and without lake was much larger than in the year 2002. In the latter, the surrounding areas were not as arid as in 1998.

Regarding the latent heat and sensible heat fluxes, respectively (Figures 6 and 7), we identify strong differences between the situations in 1998 and 2002. As mentioned above, during 2002, there was more humidity in the surroundings of the lake, which could elevate the soil moisture level near the lake in comparison with the values in 1998. Because of the same characteristic behavior of lake and soil water, during the day, we also observe latent heat fluxes over the lake's surroundings, so that the overall amount of latent heat flux in the year 2002 was larger than in 1998. On the other hand, the sensible heat flux also increased for the same reason as for the latent heat flux. Consequently, in the bottom panels of Figures 6 and 7, the lake's effect on the average amount of latent and sensible heat fluxes is less obvious than during 1998. As expected, orography is the most crucial factor controlling the horizontal and vertical distributions of the flows of energy and water, as can be seen from the predominant SE/NW direction of the flows.

### *3.3. Lake Effects on Atmospheric Circulation*

Figure 8 shows the characteristic wind fields for the simulation without the lake, as well as the associated differences if the lake is present, at 3:00 a.m. and 3:00 p.m. local time for both simulation periods.

In 1998, the wind velocities have been mostly unaffected by the presence of Lake Sobradinho. One key aspect related to this observation is the presence of a significant orographic effect that controls wind speed and direction in the study area. Specifically, anabatic winds in the region can affect the local circulation around the lake. There is also a pressure gradient as a result of air temperature differences between the lake and its surroundings, which causes a local thermal circulation (lake breeze). The difference plots in Figure 8B,F highlight this effect. In summary, there are a multitude of factors, including the surface temperature of the lake and its surrounding land surface, vegetation cover and orography, all of which do potentially affect the magnitude and direction of the lake breeze.

From a process-based perspective, in an area with low humidity, the surface evaporation would be high initially. Therefore, most of the energy absorbed by the surface would be emitted as latent heat. However, as the surface becomes progressively dryer during the day, the evaporation rate decreases and the air temperature increases, so most of the energy will be emitted as sensible heat flux. The intensity of thermally induced circulation can be affected by the amount and intensity of surface energy fluxes [38].

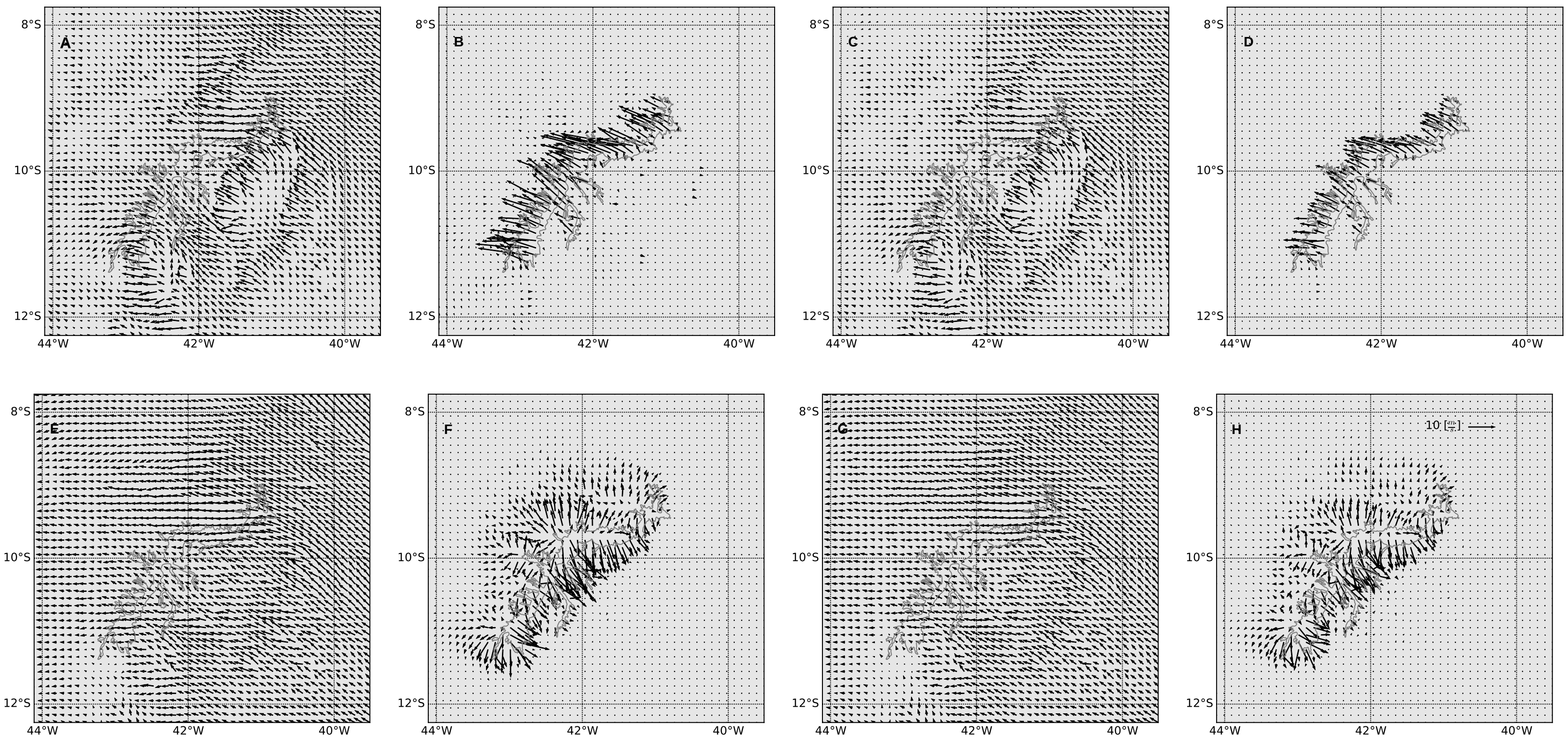

**Figure 8.** Characteristic wind velocities at 3 m above the ground at (**A**,**B**,**C**,**D**) 3:00 a.m. and (**E**,**F**,**G**,**H**) 3:00 p.m. for (**A**,**C**,**E**,**G**) the situation without the lake and (**B**,**D**,**F**,**H**) differences for the simulations with the lake in comparison with the control run without the lake. The results correspond to the periods (**A**,**B**,**E**,**F**) 1 April–3 May 1998 and (**C**,**D**,**G**,**H**) 1 April–31 May 2002, respectively.

During daytime, the lake produces large amounts of latent heat flux. Therefore, the air temperature above the lake is lower than in its surrounding areas. As a consequence, the air pressure above the lake is higher than above the nearby land surface, which causes a pressure gradient and creates a lake breeze towards the area close to the lake.

The situation is vice versa during the night. Here, the air temperature over the lake is higher than in the area surrounding the lake, and most of the available energy is redistributed by sensible heat flux. The pressure above the lake is reduced, which causes again a pressure gradient and a resulting breeze, but this time towards the lake.

As could be expected, the situation for the year 2002 is qualitatively similar. However, as one can see in Figure 8C,D,G,H, the lake breeze during the day is weaker than for 1998. To understand this difference, recall that in 1998, the air temperature has been higher than in 2002, associated with the much drier conditions. In such an extreme situation, the presence of the lake has stronger effects than in years with average meteorological conditions.

## 4. Conclusions

In this study, we have investigated the effects of the artificial freshwater reservoir Lake Sobradinho on the regional climate of its surrounding areas. For this purpose, we have used the regional climate model COSMO-CLM (CCLM). Our analyses have focused on air temperature, humidity, energy fluxes and wind. We have studied two representative periods in different years, one (1998) representing an extreme situation while the other one (2002) corresponds to the average climatic conditions of the region. By comparing the model simulations with station data, we have demonstrated that CCLM is able to reproduce the overall situation qualitatively, but exhibits substantial biases in air temperature and wind velocity.

Based on the simulations for the two considered years, we have demonstrated the emergence of a lake breeze during daytime. As a consequence, the air temperature in the lake's surrounding decreases whereas humidity increases. The latent heat flux increases as well, while the sensible heat flux decreases. The situation is reversed during the night. Here, the presence of the lake decreases the latent heat flux and increases the sensible heat flux, so the humidity over the lake increases. Because of lower wind speeds, reduced mixing and the lower planetary boundary layer height during nighttime, the humidity remains confined near the lake and advection to the surrounding area is reduced in comparison to daytime. The land areas near the lake cool faster than the lake itself, so during the night cooler winds blow towards the lake. The comparison between the more extreme year and the average climate demonstrates that the regional climatic effect of Lake Sobradinho is more pronounced during extreme years. More specifically, the presence of the lake has stronger effects on near-surface meteorological variables in a drier situation rather than under the normal mean climatology.

The present study underlines the existence of non-negligible effects of artificial reservoirs on local climate. Future studies should address in more detail the longer-term climate situations with and without the lake and additionally investigate the effect of land use change and greenhouse gas emissions on the regional climate of Northeastern Brazil.

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