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ARTICLE

Atmospheric Circulation in the Furnas Reservoir Region, MG: Sensitivity Experiments with RegCM5 in Convection-Permitting Mode

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ABSTRACT

In the 1950s, the Furnas reservoir was created, an artificial lake surrounded by hills, for the operation of the Furnas Hydroelectric Power Plant in southeastern Brazil. Along the shores of the Furnas reservoir, there are no meteorological stations, and only three are found at a distance greater than 10 km from the reservoir, which makes it challenging to assess the lake's influence on the local climate. To address this issue, the Regional Climate Model version 5 (RegCM5) was run in convection-permitting (CP) mode for two months, with a horizontal resolution of 1 km, to investigate the near-surface atmospheric circulation patterns around the reservoir. Three numerical experiments were conducted using RegCM5-CP nested in ERA5 reanalysis: a control simulation (CTRL), an experiment where the topography was assumed to be flat throughout the domain (expTOPO), and an experiment where the water body was replaced by vegetation (expVEG). The first month of simulation in each experiment was excluded from the analysis as it was considered a spin-up period. RegCM5-CP has good performance in simulating the diurnal cycle of the 2-m air temperature and reasonable performance for the 10-m wind intensity compared to observed data from three meteorological stations in the domain of simulation (but distant from the reservoir shore). Despite the geographic complexity of the Furnas reservoir, the experiments revealed coupling between lake and valley breezes during the daytime and land and mountain breezes during nighttime in different segments of the reservoir, such as in Guapé (near the dam). However, mountain-valley breezes are more dominant.

Keywords: Sensitivity experiments; Breezes; Furnas reservoir; RegCM5-CP

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1. Introduction

In the state of Minas Gerais (MG) is located the Furnas Hydroelectric Power Plant, which was created in 1957 with the aim of supplying energy to the southeastern region of Brazil, focusing on the states of São Paulo, Rio de Janeiro, and MG [1]. This power plant has an installed capacity of 1,216 MW and a reservoir with a flooded area of 1,440 km^2 [1,2]. The reservoir of the Furnas Hydroelectric Power Plant (hereinafter referred to as the Furnas reservoir) is an extensive artificial lake located between the municipalities of Guapé, Capitólio, São José da Barra, Areado, and Alfenas. Geographically, this reservoir has two segments in relation to the power plant (20.67°S and 46.39°W) located in São José da Barra (**Figure 1**): one to the east with 240 km along the Grande River and another to the south with approximately 170 km along the Sapucaí River [3]. Both segments are surrounded by high and complex topography (**Figure 1**).

Lakes/reservoirs, whether natural or artificial, can affect local meteorology by influencing the humidity and air temperature, as well as the near-surface winds. Briefly, reservoirs contribute to increased evaporation. Since water vapor is a greenhouse gas, it affects the nocturnal loss of terrestrial radiation and the daytime intake of solar radiation. Consequently, the daily minimum temperature may be higher over the water body and its surroundings, and the maximum temperature cooler compared to areas distant from the lakes/reservoirs [4]. In terms of atmospheric circulation, the difference between the thermal capacity of water and land can generate lake-land breezes [5,6], which is also influenced by the size of the reservoir. The lake breeze, an airflow from the water body region towards the land (**Figure 2a**), occurs during the daytime when the air temperature over the reservoir is lower than the surrounding land. The land breeze (**Figure 2b**), which occurs during the nighttime, is opposite to the lake breeze. Breezes are mesoscale phenomena, meaning they have a

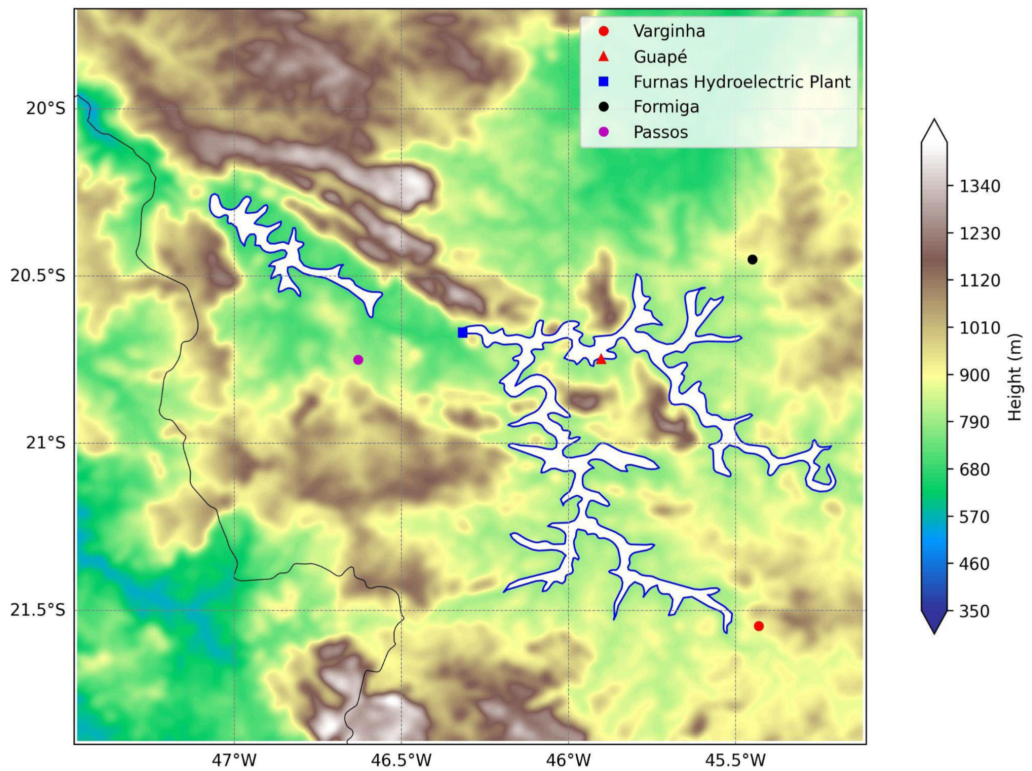

Figure 1. Simulation domain, topography (meters) and spatial representation of the Furnas reservoir (white). The location of the Furnas Hydroelectric Power Plant (blue square), surface meteorological stations—Varginha (red circle), Formiga (black circle), and Passos (purple circle), and a field campaign site—Guapé (red triangle) are also shown.

horizontal dimension of 10^2 km and a duration of less than a day [7]. Another mesoscale phenomenon is the mountain-valley breeze. As the sun rises, it heats mountain slopes more quickly than the air in the adjacent valley. Thus, there is a flow from the valley to the mountain slopes, characterizing the valley breeze (**Figure 2c**). As the sun sets, the air cools more rapidly on mountain slopes than in the adjacent valley. Cooler, denser air descends from the mountains and flows downhill into the valley, characterizing a mountain breeze (**Figure 2d**). Therefore, regions with both complex topography and a lake have mesoscale circulation associated with lake-land and mountain-valley circulation, which can often be difficult to understand the contribution of each in the total circulation; Furnas reservoir is in this context.

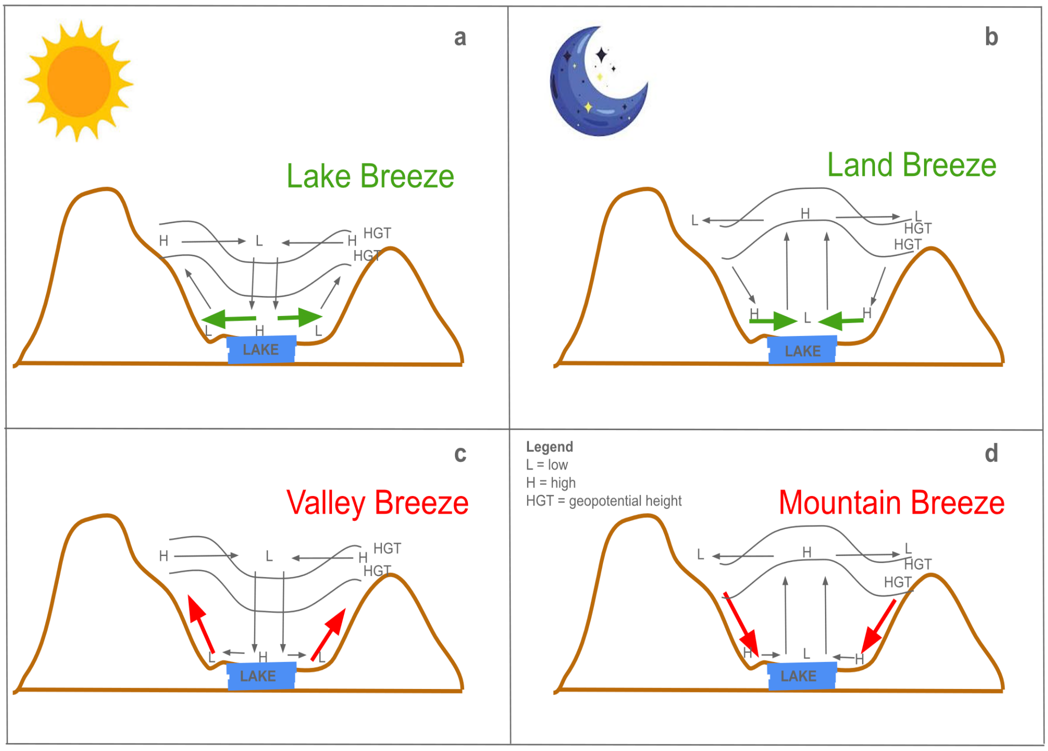

Figure 2. Schematic representation of (**a**) lake and (**b**) land breezes, and (**c**) valley and (**d**) mountain breezes. Arrows indicate the wind direction.

In Brazil, there are not many studies evaluating the impact of reservoir construction on local climate; some that can be mentioned are Guidon (1991) [8], Grimm (1988) [4]; Correia and Dias (2003) [9]; Stivari et al. (2003) [10], Saldanha (2003) [11], Gunkel (2003) [12], Freitas (2003) [13]; Freitas and Silva Dias (2004) [14], Czarnobai (2006) [15], Leite (2013) [16], Ekhtiari et al. (2017) [17] and Reis et al. (2018) [18]. Partly, this is due to the lack of historical data series. Furthermore, when there are measurement stations, they do not include data from pre- and post-construction periods of the reservoirs. One of the earliest studies on the topic is by Grimm (1988) [4]. With pre- and post-construction meteorological data of the Itaipu Hydroelectric Power Plant reservoir, this author identified an increase in evaporation and a decrease in daily thermal amplitude, the latter due to an increase in minimum temperature and a decrease in maximum temperature. Also considering the Itaipu reservoir, Stivari et al. (2003) [10] showed, through numerical experiments, that there are lake and land breezes in the Itaipu region and that there is a coupling between the lake breeze and the mountain-valley breeze contributing to the intensification of the former during the day. Additionally, the authors showed that the lake breeze sets up around 12 local time (LT) and reaches maximum intensity at 18 LT, with an intensity of ~3.5 m s^{-1} and a horizontal extent of ~50 km. The maximum thermal gradient between the lake and the land is around 15 LT with the vertical circulation extending to about 1500 meters altitude. Similar results for the time of maximum intensity of the lake breeze were also obtained by Czarnobai et al. (2006) [15] in the region of the Itá Hydroelectric Power Plant, located on the Uruguay River, between the states of Santa Catarina and Rio Grande do Sul.

Freitas (2003) [13] and Freitas and Silva Dias (2004) [14] studied the effect of the Guarapiranga and the Billings reservoir in São Paulo state on the local climate through numerical modeling. One experiment considered the specific characteristics of the locations, while in the other, the water bodies were replaced by the predominant vegetation around the Billings reservoir. The model used a high horizontal resolution (500 m). The land breeze at both reservoirs reaches maximum intensity at 02 LT and begins to decline around 09 LT, being practically absent at 10 LT. Around 12 LT, the lake breeze begins to set up and lasts until around 17 LT. At 22 LT, the land breeze comes back.

For the Furnas reservoir in MG state, there are few studies of its impact on local climate because of the absence of meteorological stations along the shores of the reservoir. There are only three meteorological stations (**Figure 1**) belonging to the Brazilian National Institute of Meteorology (INMET) close to the reservoir shores. Even though they are at a considerable distance from the reservoir (37, 17 and 10 km), this does not allow them to capture the influence of the reservoir on local climate. For these reasons, studies for Furnas reservoirs are based on data measured in field campaigns [18–20] and/or by numerical simulations [18]. Reis et al. (2018) [18] analyzed the performance of the Weather Research and Forecasting (WRF) and Brazilian developments on the Regional Atmospheric Modeling System (BRAMS) models in simulating atmospheric characteristics during two periods (June 20–24, 2014, and July 23–25, 2014). They found, in general, a better performance of the WRF model compared to BRAMS and a predominance of east winds at 10 m height in the eastern segment of the reservoir, and suggested the influence of the topography on these winds. According to the authors, at a latitude of 20.75°S (near the city of Guapé-MG), around 09 LT, there are convergence and upward movements over the water body, while at 14 LT, there are subsiding and diverging movements. In addition, Reis et al. (2018) [18] calculated the difference in air temperature between the surroundings (20.75°S) and the lake showing a well-defined diurnal cycle with a difference in module of 3 °C in the morning and 5 °C during the afternoon. The authors attributed these features to the thermal circulation of lake breeze. Here, in the present study, we suggest that the thermal circulation in the latitude of 20.75°S can be a combination of lake-land and mountain-valley circulation since the Furnas reservoir is in lower altitudes compared to the surroundings, and it will be focused in this study. Pellegrini et al. (2019) [19] evaluated the performance of WRF in simulating an intense and persistent wind episode in the Furnas reservoir near Guapé City, on September 22, 2016. The model was validated with measurements from a LIDAR and from a sonic anemometer during a field campaign. According to the authors, WRF had a good performance in simulating the wind intensity and direction, suggesting that this model can be used in the operational mode for the analysed region. The strong wind on September 22 was related to a low-level jet, positioned around 500 m above the surface. The same episode studied by Pellegrini et al. (2019) [19] was also analysed by Reis et al. (2023) [20], but focusing on the vertical mixing process caused by the strong winds in the Furnas reservoir.

Numerical models are excellent tools for studying physical mechanisms associated with atmospheric phenomena since they allow us to perform sensitive experiments. For instance, by including or excluding topography; by changing the land cover etc. A climate model that is in its fifth generation and with the option of convection-permitting (CP) is the Regional Climate Model—version 5 (RegCM5 [21]). Before the inclusion of the CP, which is solving the equations without including convection parameterization, it was not possible to use the model in studying local climate. In South America, the first studies using RegCM in CP mode date back to the year 2021 [22]. Based on the previous context, the present study aims to: a) verify the performance of the RegCM5-CP model in simulating atmospheric conditions in September 2016 within the simulation domain that covers the Furnas reservoir and surroundings, and b) through numerical sensitivity experiments (removing topography and replacing the reservoir's water cover with vegetation), verify the existence or non-existence of lake-land breeze in some sectors (including 20.75°S) of the Furnas reservoir, as well as the influence of the topography on the atmospheric circulation. September 2016 was chosen for the study because there were observations of wind intensity during a field campaign near Guapé [19,20]. Therefore, this is a useful data source for validating RegCM5-CP. The present study also differs from that of Pellegrini et al. (2019) [19] by conducting sensitivity experiments and simulations for a complete month.

2. Materials and methods

2.1 Study area

The study area is the Furnas reservoir region (**Figure 1**), located in the Rio Grande basin, in the southwest region of MG state (20.687°S, 46.326°W). The municipalities located on the shores of Furnas have tourism as their main economic source, due to the development of various recreational activities. Fishing is also a source of income for the local community due to the great diversity of aquatic fauna. The climate of the Furnas region is classified as tropical (Aw) and tropical altitude (Cwb) according to the Köppen classification [16,23,24]. Regarding vegetation, the predominant types are grassland, rocky grassland, and semideciduous seasonal forest [25].

2.2 Data

In this study, data from different sources are used as follows.

Meteorological station data: 2-m air temperature, precipitation, and 10-m wind intensity were obtained for September 2016 from meteorological stations belonging to the INMET. Unfortunately, there are only three stations near the Furnas reservoir (**Figure 1**): Varginha (21.57°S, 45.40°W) is 10 km from the lake shore, Formiga (20.45°S, 45.45°W) is 17 km away, and Passos (20.75°S, 46.63°W) at 37 km away.

Field campaign data: 10-m wind intensity from 1500 UTC September 21 to 0000 UTC 23, 2016 (where UTC means Coordinated Universal Time), were visually extracted from **Figure 5** by Pellegrini et al. (2019) [19]. These data were observed through a sonic anemometer installed at Guapé (20.72°S, 45.88°W).

Reanalysis: from the ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF [26]), hourly surface variables (2-m air temperature and 10-m horizontal wind components) and in vertical pressure levels (geopotential, horizontal wind components, temperature, and specific humidity) were obtained with a horizontal resolution of 0.25° × 0.25° from August to September 2016. Variables at vertical levels are used as boundary conditions in the RegCM5-CP. For an analysis of the near-surface mean atmospheric conditions over southeastern Brazil, surface variables from 1986 to 2016 were also obtained.

2.3 Numerical simulations

To study the climatic characteristics at a local scale in the Furnas reservoir region and to determine whether the reservoir contributes to the occurrence of lake-land breeze circulation or if topography is the main drive of local circulation, three numerical experiments were conducted using the RegCM5 in convective-permitting mode (RegCM5-CP [21]). The domain used in the simulations is shown in **Figure 1**.

The first experiment corresponds to the control simulation (CTRL), which uses the domain and topography shown in **Figure 1**; the second is a simulation where the topography of the entire domain was set to 850 meters altitude (expTOPO). In the third experiment, the topography was retained, but the Furnas reservoir was replaced by vegetation (expVEG).

The numerical experiments were performed with RegCM5-CP, which is a limited area model [21]. Due to this characteristic of the model, its lateral boundaries need to be constantly updated. Therefore, the boundaries were updated every 6 hours, as the model was nested with ERA5 reanalysis for atmospheric variables and sea surface temperature. The use of reanalysis as boundary conditions in CP climate models has been a common practice as shown in Dominguez et al. (2024) [27] and Torma and Giorgi (2024) [28]. For topography and land use, data from the United States Geological Service (USGS, https://www.usgs.gov/products/data/all-data) were used.

In all three numerical experiments, RegCM5-CP was integrated from August 1, 2016, to October 1, 2016 (a continuous run), with 1 km of horizontal resolution, 41 sigma-pressure vertical levels, and a model top at 5 hPa. MOLOCH [21] was used as the non-hydrostatical core of the model. In CP mode, cumulus parametrization scheme is not activated, so moisture convection is solved by microphysics parameterization; the experiments used the Explicit moisture Nogherotto/Tompkins scheme [29]. The representation of surface-atmosphere interaction processes in RegCM5-CP was performed using the Community Land Model scheme (CLM4.5 [30]). Other parameterization schemes included Holtslag [31] for solving planetary boundary layer processes, Zeng [32] for ocean fluxes, and the NCAR Community Climate Model (CCM3) [33] for radiative transfer. The first month of the simulation was not included in the analyses, as it is considered a spin-up period [34].

2.4 Analyses

Mean characteristics of September

The results section will begin by presenting the climatological patterns (average from 1986 to 2016) of September in the Furnas reservoir region for the variables of 2-m air temperature, and 10-m wind intensity and direction with ERA5 reanalysis. The September 2016 average of these variables obtained with ERA5 and the CTRL experiment is also presented, along with the difference between the September 2016 and climatological fields in the case of ERA5.

Simulations vs station observed data

To validate the RegCM5-CP model, 3-hour data (10-m wind intensity, 2-m air temperature and precipitation) from the three meteorological stations near the reservoir in September 2016 (**Figure 1**) are compared with the results of the simulations using statistical measures (root mean square error—RMSE, Pearson correlation, and bias). Simulated atmospheric variables are extracted by calculating an average around the coordinates of the meteorological stations in a box with 0.005° latitude by 0.005° longitude (25 grid points). In this analysis, we also compared ERA5 reanalysis with station data.

Additional comparison is made between the simulated 10-m wind intensity and that obtained in the Guapé region from 1500 UTC September 21 to 0000 UTC 23, 2016, as obtained by Pellegrini et al. (2019) [19].

Local atmospheric circulation

To emphasize the spatial pattern of mesoscale circulations on maps, we initially computed the average atmospheric fields every 3 hours in September 2016. Subsequently, we removed the synoptic background by subtracting the daily mean from the hourly data, as in Correia and Dias (2003) [9]. We will describe the atmospheric circulation pattern in the CTRL experiment and compare it with expTOPO and expVEG. More differences between CTRL and expTOPO are expected when replacing the complex topography with a flat one, as the thermal gradients essential for developing breezes are weakened. Conversely, in the experiment where the water body is replaced by vegetation, we expect similar results to CTRL because of the limited width of the Furnas reservoir, which results in weak temperature gradients with the surrounding areas.

3. Results and discussion

3.1 September climate characteristics

In this section, the comparison between Reg-

CM5-CP (whole simulated domain) and ERA5 is aimed at verifying if both sets have similar spatial patterns. Similarities in values are not expected, as the fields are smoother in ERA5 due to their lower resolution (topography is represented roughly) compared to RegCM5-CP.

Figure 3 shows the average of 2-m air temperature and 10-meter wind for September 2016 and for the period 1986–2016 (climatology) in MG state using ERA5 reanalysis, and just the average of September 2016 for the Furnas reservoir region obtained in CTRL simulation. Lower temperatures occur in regions of elevated topography in MG located in the southern and eastern parts of the state **(Figures 3a–3c)**. Comparing ERA5 September 2016 with the climatology, it was warmer throughout the state of MG. In the region of the Furnas reservoir, positive anomalies reached 1.5 °C (**Figure 3d**).

Focusing on the area around the Furnas reservoir, the spatial pattern of air temperature simulated by RegCM5-CP follows that from ERA5 but with a lot of details due to the better representation of the topography. As in ERA5, the model shows colder temperatures southward of the Furnas reservoir and warmer temperatures northeast of the reservoir (**Figure 3a**). In general, there is a higher amplitude of temperature in the model: warm (cold) areas are warmer (colder) in the model compared to ERA5. For instance, RegCM5-CP simulates temperatures about 2 °C warmer compared to the September 2016 reanalysis (**Figure 3a**).

The 10-m wind direction in September 2016 in MG (**Figure 3f**) was very similar to the climatological pattern (**Figure 3g**) with predominance of easterlies in most parts of the state and northeasterly winds in the south of MG. Additionally, anomalies are weak except in the western (negative anomaly) and eastern (positive anomaly) of the region (**Figure 3h**). Comparing the area of the Furnas reservoir in RegCM5-CP and ERA5 (highlighted by a black box), we can see that CTRL simulation, like ERA5, presents easterly winds over the southern part of the Furnas reservoir and northeasterly winds in the northern part, and the winds are more intense in the model (**Figure 3e**).

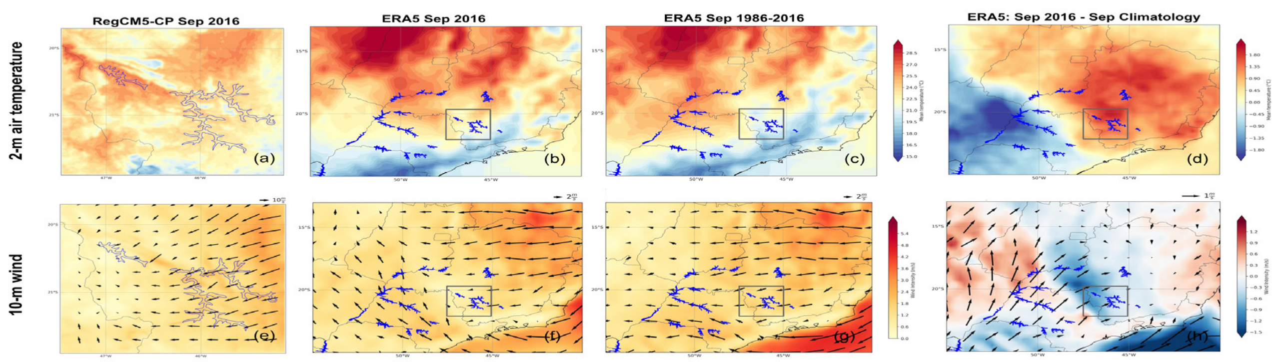

Figure 3. (**a**) average of 2-m air temperature (°C) in September 2016 obtained in CTRL experiment, (**b**) idem but for MG state with ERA5 reanalysis, (**c**) ERA5 2-m air temperature climatology (1986–2016) for September, (**d**) 2-m air temperature anomaly in September 2016, (**e**) average of 10-m wind intensity (m s^{-1}) and direction in September 2016 obtained in CTRL experiment, (**f**) idem but for MG state with ERA5 reanalysis, (**g**) ERA5 10-m wind climatology (1986–2016) for September, and (**h**) 10-m wind anomaly in September 2016. Black box represents the area of figures a and e.

3.2 RegCM5-CP validation

This section compares the 3-hour CTRL simulation with observed data from Varginha, Passos, and Formiga (**Figures 4–6**). Additionally, we also present the time series of expTOPO and expVEG, along with ERA5. For precipitation (**Figure 4a**), 0.2 mm was recorded at the Varginha station on September 6 and 12.8 mm on 25. The CTRL simulation overestimates the precipitation on September 25 and simulated rainfall on other days absent in the station data, thus indicating low performance for this variable.

ERA5 only outperforms the CTRL simulation on September 25, displaying a similar amount of precipitation as the station data. In Passos (**Figure 5a**), precipitation was not observed in September, but the experiments and ERA5 showed rainfall on some days. For instance, CTRL simulated approximately 8 mm on September 8. In Formiga (**Figure 6a**), in six days (1, 8, 15, 19, 20 and 26) low values of precipitation were observed in the station. CTRL simulates them but, in general, with overestimation. ERA5 shows precipitation on most of these days and also on some days without rainfall recorded at the station. One interesting result from the statistical measures is that RegCM5-CP shows a better correlation with the station data than ERA5, indicating that it can capture the variability of the time series. In terms of RMSE, ERA5 has better performance.

CTRL experiment accurately captures the phase of the diurnal cycle of 2-m air temperature measured in the three stations (**Figures 4–6b**), and temporal correlation exceeds 0.85 in all locations. However, the model shows a positive bias of 0.74 °C, 0.97 °C, and 2.29 °C, respectively, in Formiga, Varginha, and Passos. The higher warm bias in Passos is mostly due to an overestimation of the minimum temperature (**Figure 5b**). The diurnal cycle of air temperature is also well represented by the expTOPO and expVEG. ERA5 also shows a higher warm bias in Passos (0.32 °C). In Varginha, the bias is negative (–0.17 °C) and in Formiga it is positive (0.09 °C).

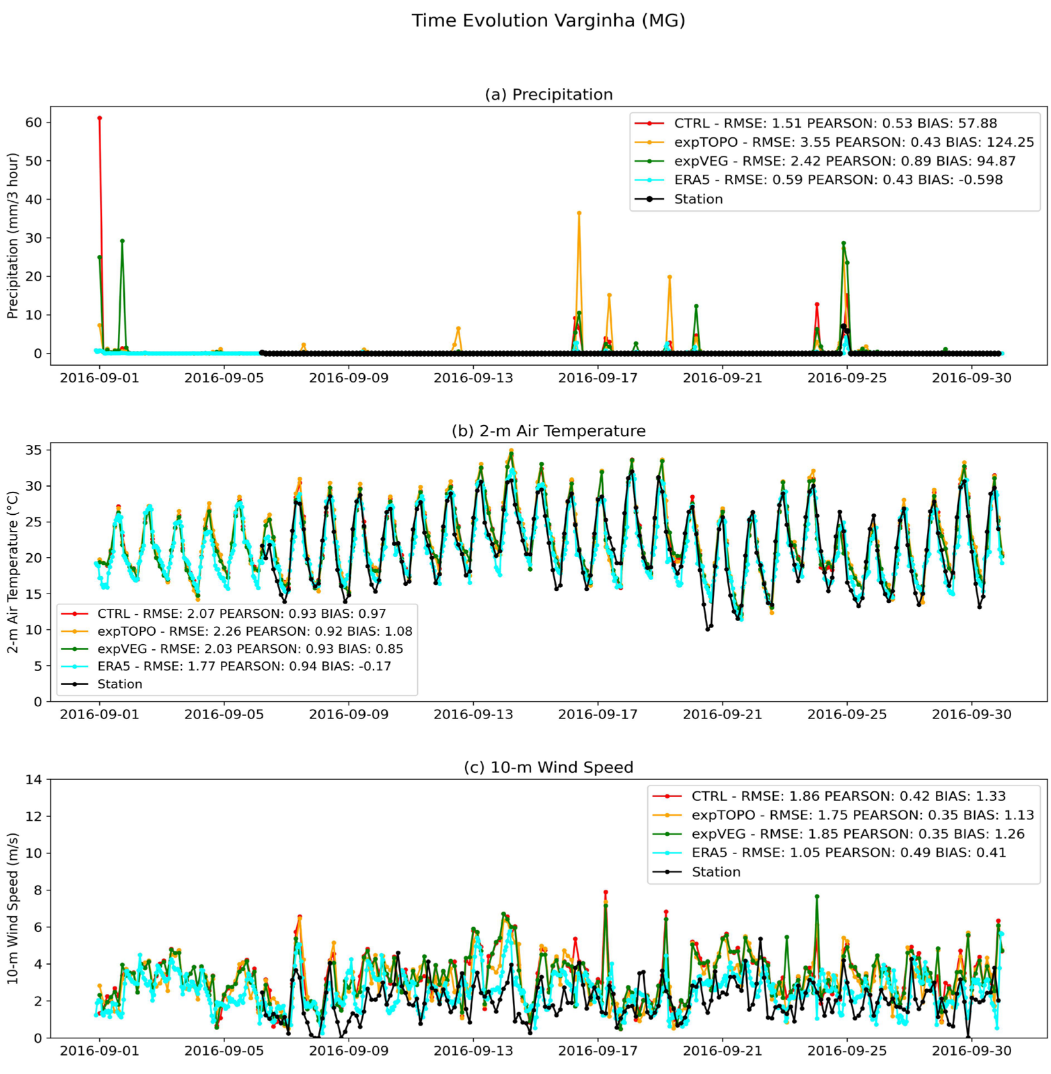

Figure 4. Hourly time series from September 2016 of the three simulations, ERA5 (blue), and observed station data (black) in Varginha, MG. All statistical measures were computed concerning the observed data (station).

The diurnal cycle phase of 10-m wind intensity is better represented by the CTRL experiment in Passos, with a temporal correlation of 0.63. In Varginha and Formiga, the correlation coefficients are lower: 0.42 and 0.39, respectively (**Figures 4–6c**). Passos, compared to the other locations, is in a region with less complex topography, which can contribute to the better performance of the CTRL simulation in this locality. Indeed, ERA5 also has better performance in this locality than in the other two, with correlation coefficients of 0.64, 0.55, and 0.49 in Passos, Formiga and Varginha, respectively. In expTOPO and expVEG the correlation coefficient is even lower compared to the station data, and it is expected because, with a flat topography, mountain-valley circulation will not occur. The same is expected without the Furnas reservoir. All experiments overestimate the wind intensity compared to the observations (**Figures 4–6c**). In the case of the CTRL simulation, there is a bias of 1.33, 1.45, and 1.83 m s^{-1}, respectively, in Varginha, Passos, and Formiga. The model's lower skill in simulating wind intensity compared to air temperature can be attributed to differences between the real topography and that described in the model (horizontal resolution of 0.01° that is ~1 km). Within a 1 km distance, there are significant variations in topography that cannot be represented by the horizontal resolution of the surface boundary conditions in the model. The biases obtained with the RegCM5-CP in this section are in line with those presented by Reboita et al. (2023) [35] focusing on meteorological stations in São Paulo state.

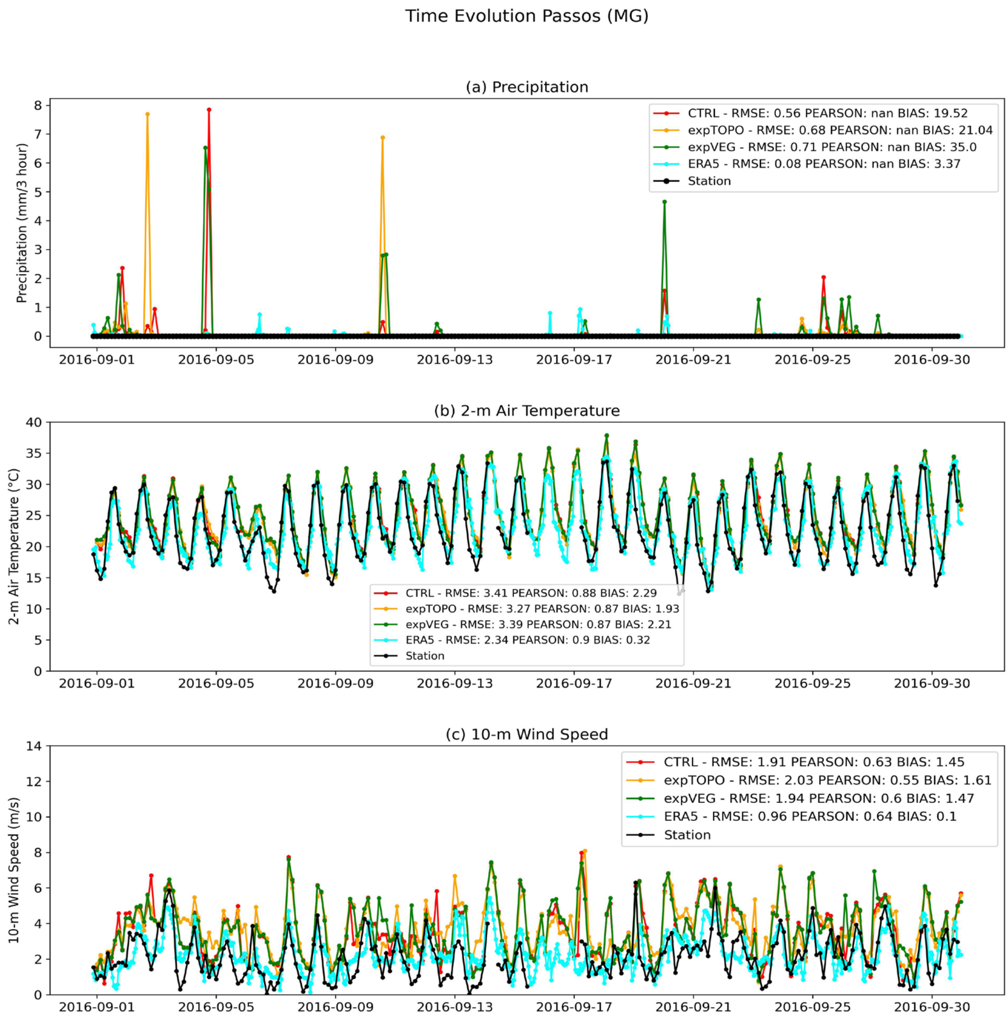

Figure 5. Hourly time series from September 2016 of the three simulations, ERA5 (blue), and observed station data (black) in Passos, MG.

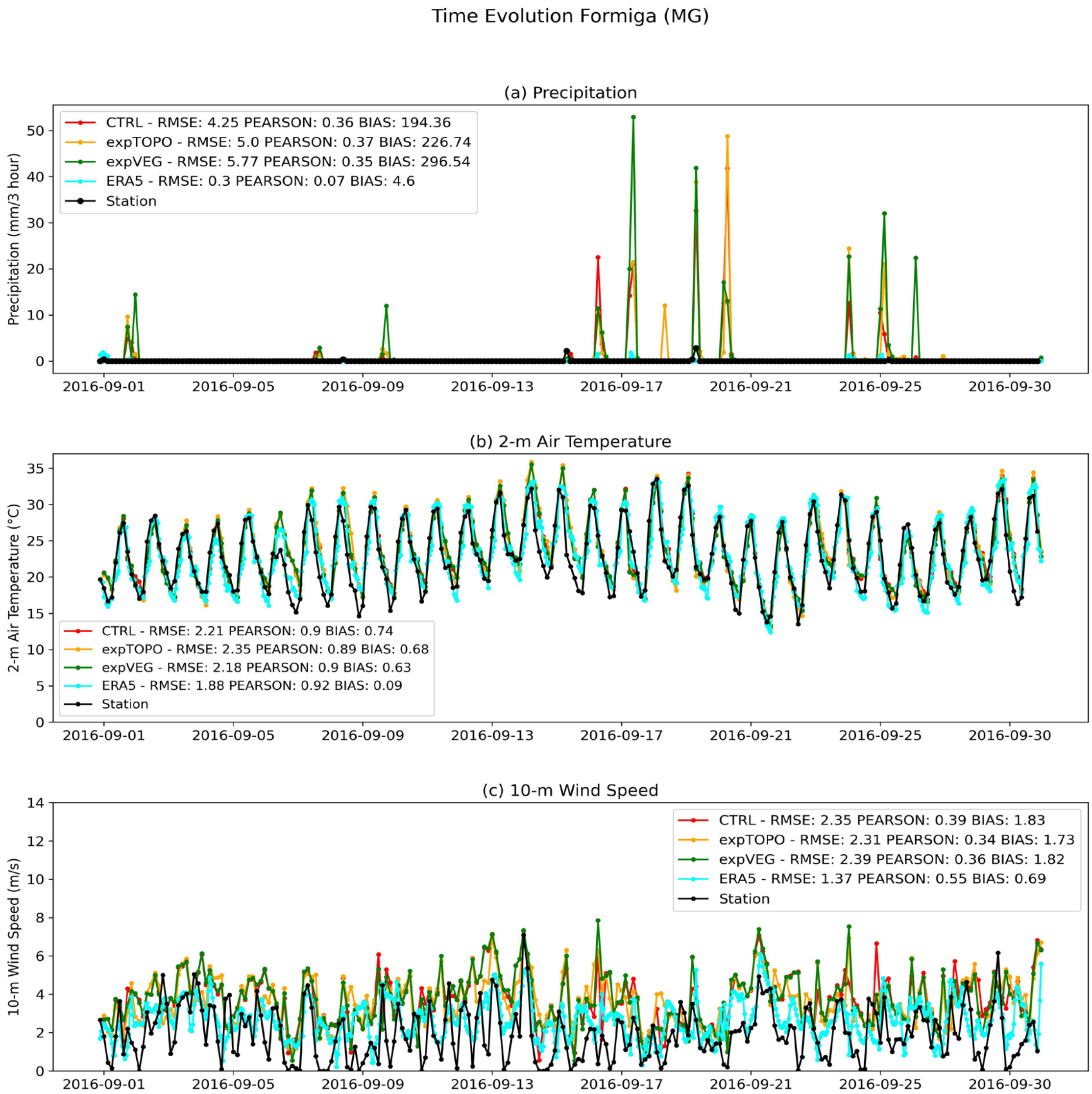

Figure 6. Hourly time series from September 2016 of the three simulations, ERA5 (blue), and observed station data (black) in Formiga, MG.

Figure 7 presents a comparison of the 10-m wind intensity from RegCM5-CP and ERA5 with observations obtained during a field campaign in Guapé on September 21–22 2016, when an episode of extreme wind was registered in the region [19]. The CTRL experiment reproduces the maximum intensity (~10 m s^{-1}) observed in Guapé, but with a 6-hour anticipation. ERA5 also anticipates the maximum wind and underestimates the wind intensity throughout the entire period. While the expTOPO shows wind intensity very similar to CTRL, the wind intensity is lower in expVEG, indicating that the Furnas reservoir affects Guapé's local circulation.

Considering that RegCM5-CP is a climate model and not a weather model, it performs well in simulating the diurnal evolution of 2-m air temperature and 10-m wind intensity in the domain of simulation compared to observed data. We emphasize that the lack of validation of the CTRL simulation on the shores of Furnas reservoir does not invalidate the numerical experiments presented in the next section. Instead, these experiments help us understand the physical processes in the surroundings of the Furnas reservoir. We highlight the necessity of investments in the region for the implementation of meteorological stations.

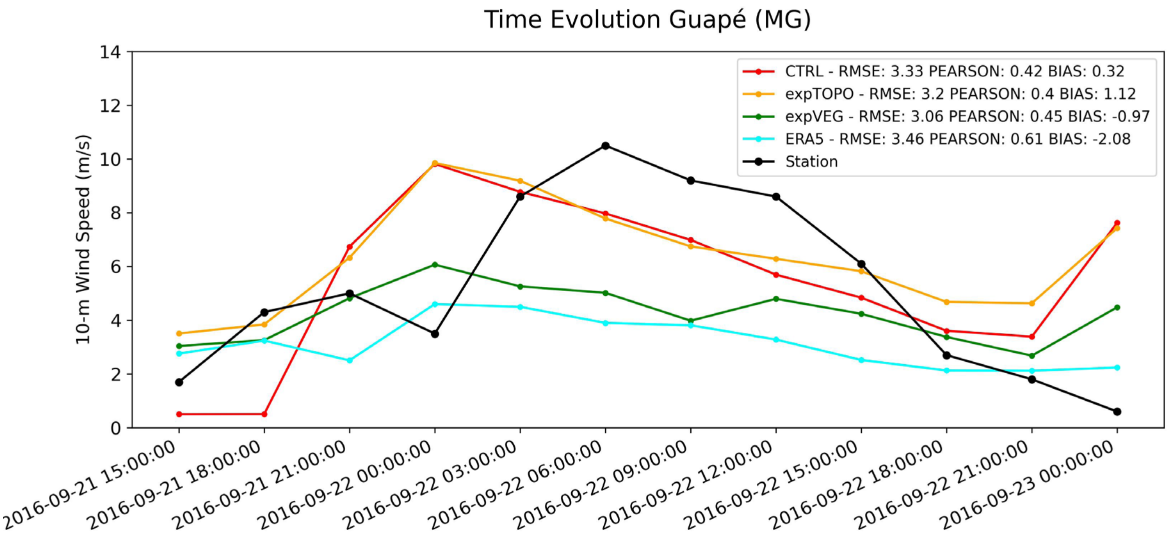

Figure 7. 10-m wind intensity (m s^{-1}) from 1500 UTC September 21 to 0000 UTC September 23, 2016, of the three simulations, ERA5 (blue), and the observed data (black) obtained by Pellegrini et al. (2019) [19]. All statistical measures were computed concerning the observed data (station).

3.3 Local atmospheric circulation

The area of the Furnas reservoir is considered a valley since it is surrounded by high topography (**Figure 1**). Therefore, it is expected that mountain-valley breezes can occur and become coupled with lake-land breezes, as a response to the differential warming between the valley/water body and the mountain/land. To verify these hypotheses, three numerical experiments were conducted (CTRL, expTOPO, and expVEG). In **Figures 8–10**, we converted UTC to local time (LT) to facilitate the analysis of the night and day thermal influence on the mesoscale circulation. The LT in the study area is UTC minus 3 hours (for instance, 1200 UTC is 09 LT). LT 00, 03, 06, and 09 represent nighttime, while 12, 15, 18, and 21 LT represent daytime.

The CTRL experiment can be considered representative of the real atmospheric conditions in the Furnas reservoir region (**Figure 8**). Following the thermal theory [36], this simulation shows warmer air during the night over the reservoir compared to the surrounding land (**Figures 8a-8b**) and colder air during the day (**Figures 8e–8g**). Additionally, since the Furnas reservoir is situated at a lower altitude in a valley surrounded by hills, 2-m air temperature indicates distinct temperatures between the valley (lake) and hills, with the hills being colder than the valley both at night and day (topography is acting as a climate control). Moreover, during nighttime, the spatial pattern of the air temperature is cool over the hills, cold in the valley and relatively warm over the reservoir (note that the shape of topography is reflected in the anomalies of the 2-m air temperature). This pattern is different during the daytime since the air over the reservoir is relatively colder than the surroundings.

The temperature difference between the water body and the land is strengthened in expTOPO, mainly during 15 and 18 LT (daytime; **Figure 9**) and smoothed in expVEG (**Figure 10**). In expTOPO (**Figure 9**), where the entire domain has the same altitude, the spatial pattern of air temperature becomes more uniform compared to the CTRL (**Figure 8**). With a flat topography, predominates an east-west gradient, with warmer temperatures in the west/northwest of the domain, which can be a response to the continentality effect (distance from the ocean, in this case, from the South Atlantic Ocean) and/or by influence of a large-scale circulation even removing the daily mean of the experiments. The zonal air temperature gradient is disturbed in the Furnas reservoir, where the water body influences the air temperature, for instance at 03 and 15 LT (**Figures 9b and 9f**).

ExpVEG confirms the impact of the Furnas reservoir on air temperature (**Figure 10**): when the water body is replaced by vegetation, the air temperature over the reservoir becomes similar to that of the surrounding land (valley), as depicted, for instance, in **Figures 10b and 10g**. Much of the spatial distribution of air temperature in expVEG is governed by topography being clear in **Figure 10** the temperature contrast between regions of lower elevation (warmer) and higher elevation (colder) (**Figure 10**).

In the thermal theory of mountain-valley breeze, the temperature contrast that develops breezes is related to the air over the slope of a hill (rather than the entire hill area) and the adjacent air layer at the same altitude but over the valley, and the result is a circulation cell. However, this particularity is challenging to discern in the figures since they represent the air temperature measured at 2-m above the ground and not standard vertical profiles of the atmosphere. Therefore, given the complexity of the Furnas reservoir region, explaining near-surface atmospheric circulation across the entire domain in **Figures 8–10** is difficult. Thus, we chose four small regions to investigate the hypotheses of this study.

The region indicated by the red box in **Figure 8** includes a hill in its north/northeastern sector and a small portion of the Furnas reservoir in its southeastern part. At 00 LT, the winds are weaker within the red box. From this time onwards, northeast winds (blowing from the hill to the valley) begin to appear and intensify, reaching maximum intensity at 09 LT. By 12 LT, the winds acquire a counterclockwise rotation, becoming from southwest (from the valley to the hill) by 21 LT. Thus, the reversal of wind direction throughout the day means a mountain-valley circulation, a characteristic confirmed in expTOPO. In this experiment, the circulation pattern during nighttime is different from CTRL. In expTOPO (**Figure 9**), weak winds blow from the southeast at night, moving from the colder to the warmer area, and the wind direction changes during the day, which may be aligned with the broader atmospheric pattern, as the entire domain exhibits a similar wind direction. The reservoir does have a noticeable impact on the wind direction in the red box since there is a similar pattern of winds in expVEG (**Figure 10**) compared to CTRL (**Figure 8**).

The yellow box represents one of the most studied areas in the Furnas reservoir because it includes the municipality of Guapé, which serves as a scenario for field campaigns [18,19]. The northern sector of this box includes part of the Furnas reservoir, while the southern sector comprises land area bounded by hills. Thus, the land is bounded to the north by the lake and to the south by the hills (**Figure 1**). During nighttime (00–03 LT; **Figures 8a and 8b**), there is a southeastern flow from the hills to the lake suggesting a coupling between mountain and land breezes. However, at 06 LT, the flow shifts from the east, and by 12 LT, during the daytime, it comes from the northeast. By 18 LT, the flow is from the northwest, and weaker winds are observed at 21 LT (**Figure 8h**). During the daytime, CTRL also indicates the coupling of lake and valley breezes, suggesting that the two types of breezes during night (land-mountain) and day (lake-valley) are likely coupled. Indeed, in expTOPO (**Figure 8**) the southeast winds at night (00 and 03 LT) and the northwest winds during the day, for instance at 18 LT, are weaker than in CTRL indicating the influence of the topography on the flow. When the water body is replaced by vegetation (**Figure 10**), the circulation pattern is very similar to the CTRL meaning that the topography may be the main control of the circulation in this analysed area. Our results are also consistent with those of Reis et al. (2018) [18], who showed through simulations that near the city of Guapé, wind convergence occurs over the water body at 09 LT, and wind divergence at 14 LT, as also observed in **Figures 8d and 8f**.

In the western and southern sectors of the cyan box there is a portion of the Furnas reservoir, and in the north and east sectors, a complex topography. During the nighttime (**Figures 8a–8d**), the circulation seems to be influenced by the hills, as the northeast winds blow from the high topography to the reservoir. In addition, this mountain breeze may be coupled with the land breeze. From 12 LT, the winds adopt a counterclockwise movement and strengthen, with west/southwest winds prevailing by 18 LT (**Figure 8g**). As this flow is from the reservoir to the high topography, we suggest the coupling of both lake and valley breezes. However, the numerical experiments indicate that the flow is more influenced by the topography than by the water body. Removing the topography (expTOPO), during nighttime the winds become weaker and from east quadrant (**Figure 9**). As the eastern flow accelerates near the lake at 09 LT, it can be an indicator of the land breeze. During the daytime, there are fewer differences between CTRL and expTOPO. As expVEG has the wind spatial pattern very similar to CTRL it also means that the effect of topography is dominant in this area. Indeed, changing the reservoir by vegetation, the area with warmer temperatures is more homogeneous in the valley and it can also help to organize the mountain circulation as shown in **Figures 10c–10d**.

The geography of the region represented by the pink box resembles that of the cyan box, with a section of the Furnas reservoir in the southern part and hills surrounding the other sectors. In addition, the circulation pattern presented by CTRL is also very similar to that in the cyan box (**Figure 8**). The higher difference between the two areas occurs at 21 LT when there is the absence of winds in the cyan box and southeastern winds in the pink box. In the region limited by the pink box, expTOPO (**Figure 9**) indicates that the topography contributes to modulating the wind direction mainly during nighttime. The absence of mountains causes a weaker eastern flow and at 09 LT (**Figure 9h**) it is clear that the eastern flow intensifies near the reservoir showing the influence of land breeze. As the circulation pattern of expVEG (**Figure 10**) and CTRL (**Figure 8**) are similar, it highlights the main contribution of the topography for the region.

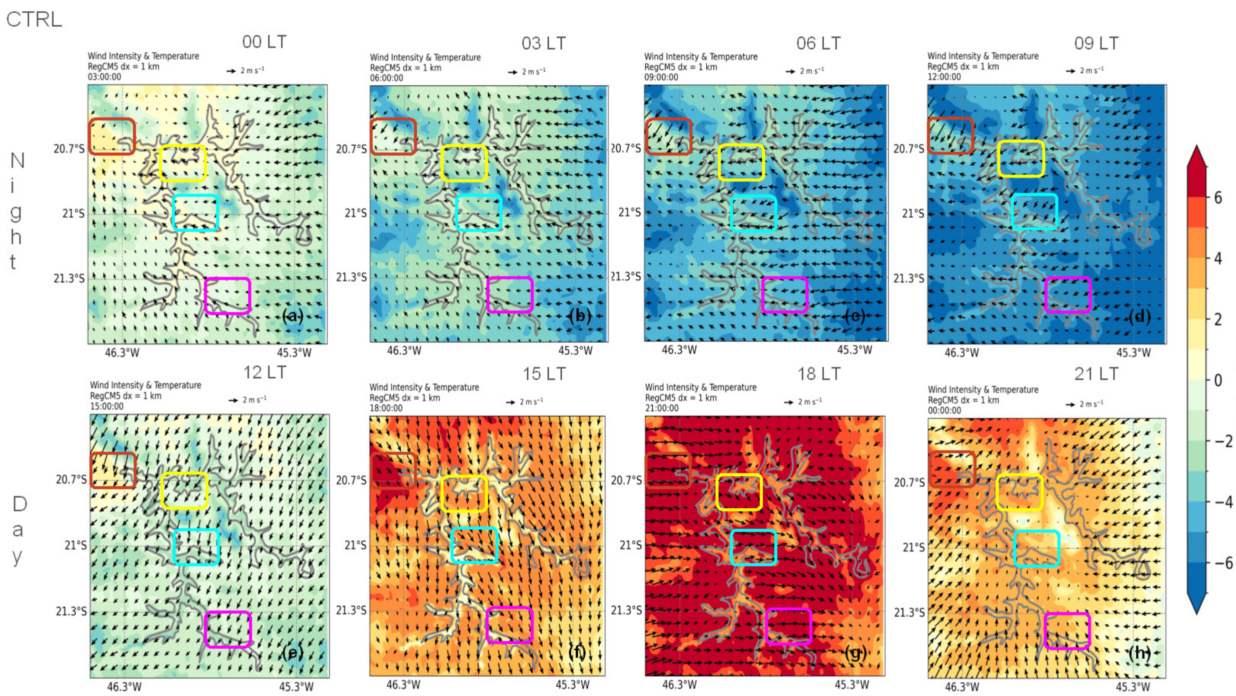

Figure 8. CTRL experiment: 3-hour anomalies of 2-m air temperature (°C) and 10-wind direction and intensity (m s^{-1}, arrows) in September 2016. The panels are organized by period of the day: (a–d) nighttime (00, 03, 06 and 09 local time) and (e–h) daytime (12, 15, 18 and 21 local time). Colored boxes indicate the selected areas for analyses.

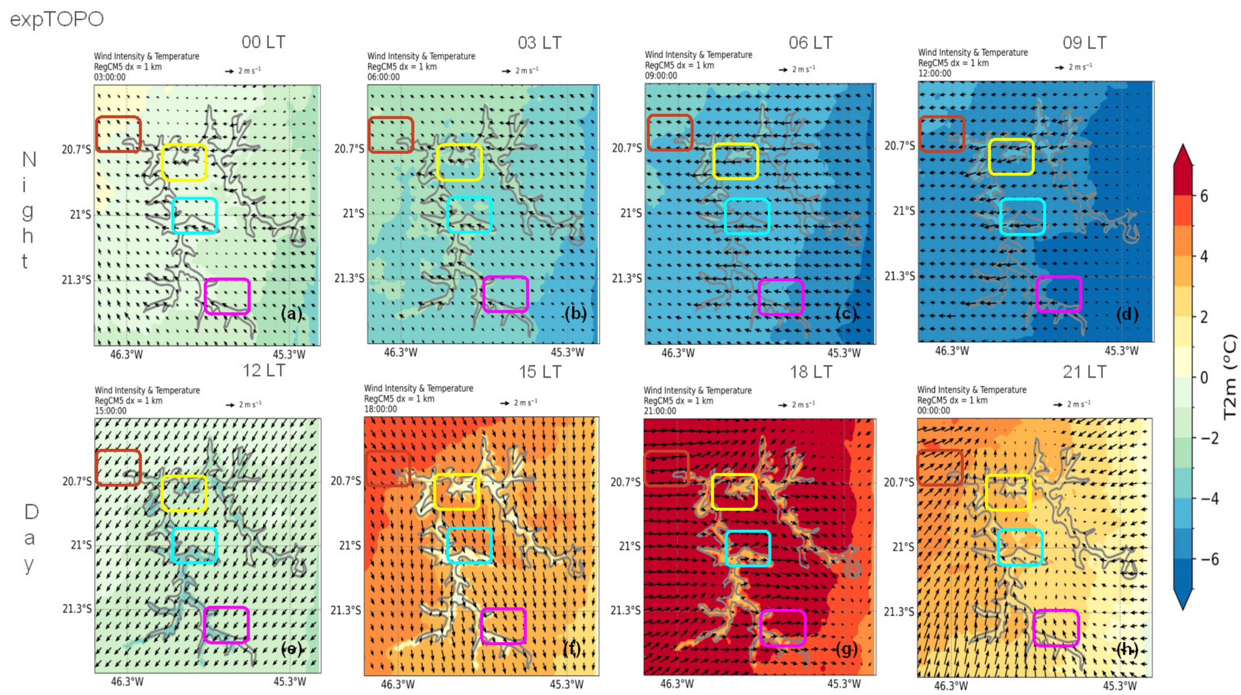

Figure 9. Similar to Figure 8 but for expTOPO.

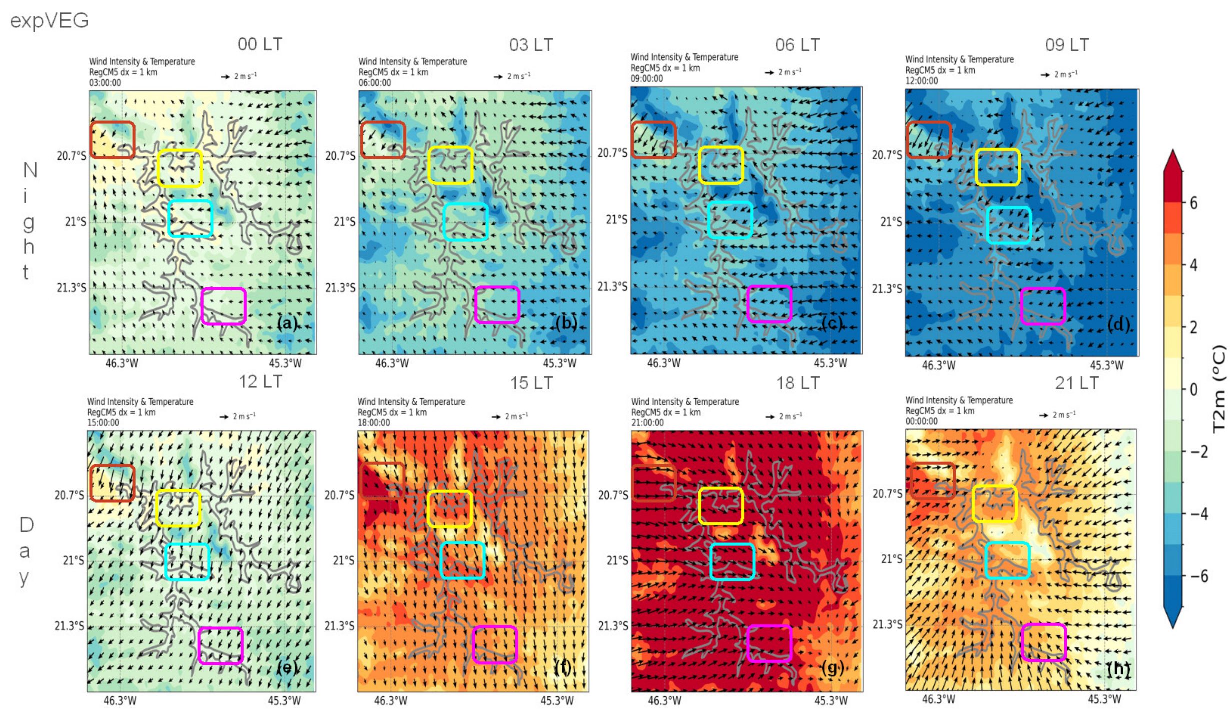

Figure 10. Similar to Figure 8 but for expVEG. The contours of the Furnas reservoir are kept to facilitate the comparison of this figure with Figures 8 and 9.

4. Conclusions

The Furnas reservoir plays a significant role in the local economy through tourism and transportation activities. Abrupt weather changes, such as those reported by Pellegrini et al. [19], can cause socio-economic injuries. Unfortunately, little is known about the climate conditions around the shores of the Furnas reservoir due to the absence of weather stations in the area. The nearest station is located in the southeast sector, 10 kilometers from the shore. In this sense, this study performed simulations with RegCM5-CP in the region of the Furnas reservoir to describe the near-surface atmospheric circulation.

For model validation, since there are no meteorological stations on the reservoir shore, we used data from the three closest stations. The climate model performed well in representing the diurnal cycle of 2-m air temperature in September 2016 when compared with observed data, but its performance decreased for the 10-m wind intensity. Comparing the 10-m wind intensity measured during a 2-day field campaign in Guapé, on the Furnas reservoir shore, the model showed good performance in representing the maximum wind and standing out in relation to ERA5. Model validation indicated that RegCM5-CP represents the main local features of the studied domain, making it very useful for studying physical processes. For this reason, we conducted two additional experiments (expTOPO and expVEG).

The experiments are very useful in describing the thermal features of the reservoir and surrounding areas. Important features, such as a colder water body during the daytime and warmer at night compared to the surroundings, and the temperature difference due to topography, are well captured by the model.

In the four analyzed regions, topography had a greater influence on modulating local circulation. However, in some of the analyzed time periods, the contribution of the thermal contrast between the reservoir and its surroundings to wind modulation was also evident. An interesting characteristic is that throughout the day, the wind direction changes follow a counterclockwise rotation. Another fact is that during the night, mesoscale circulations are better configured than during the day. During the day, diurnal heating may contribute to larger-scale patterns affecting circulation.

For a more detailed analysis of lake-land breezes in the Furnas reservoir region, we suggest long-term simulations (more than 3 years) with a resolution higher than 1 km. Additionally, nesting the RegCM5-CP model with our simulations could improve spatial resolution. However, this is one of the study's limitations because this type of simulation requires high computational performance, which is available only in large meteorological centers. Another limitation of the study is the absence of meteorological stations on the shores of the Furnas reservoir to validate the control simulation. Hence, this study highlights the necessity to implement meteorological stations around the Furnas reservoir and the need for a weather monitoring and forecast service in the region, particularly due to the intense winds that pose challenges to navigation and air transportation.

Author Contributions

FRB: figures plotting, analyses of the results and writing; MSR: conceptualization, figures plotting, analyses of the results and writing; NCON: Python script development; DWG, RGX and LGO: design of the experiments and model execution, and RPR: conceptualization and writing.

Conflict of Interest

The authors declare no conflict of interests.

Data Availability Statement

The data used in this study are freely available at https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5 and https://bdmep.inmet.gov.br/.

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