Breeze effects at a large artificial lake: summer case study

Authors' responses to the Reviewer 2 comments

Maksim Iakunin[1], Rui Salgado[1], Miguel Potes[1]
miakunin@uevora.pt

[1]Department of Physics, ICT, Institute of Earth Sciences, University of Évora, 7000 Évora, Portugal

Contents

Introduction. Document structure

This document contains authors' responses to the comments of the Reviewer. The document structure is the following:

- Reviewer's comments are numbered and given in *italic font*. General, specific, and technical comments come separately.
- Authors' response follows the comment and starts after **"Response:"** with normal font.
- The text from the article itself (if some changes were done, and if it is reasonable to provide it) is typed with `typewriter font` and separated from the response with an extra blank line.
- *Technical comments and mistakes* are not numbered, and authors' response follows immediately.

Reviewed manuscript with all the corrections is given after all responses. It contains the changes and proposals of **two** Reviewers and was prepared using LaTeXdiff package for better understanding of what was added or removed.

Anonymous Referee 2

General comments

This paper investigates changes in atmospheric variables in the area of Lake Alqueva, induced by the filling of this artificial lake in 2004. To identify the changes, two simulations were performed using a mesoscale atmospheric model, the Meso-NH model. In the first experiment, the lake is not present and in the second one, a lake model, Flake, is run in a coupled mode. The authors observed the formation of a lake breeze in the presence of the reservoir and identified impacts on the atmosphere.

This study is interesting as it quantifies the effects of a large lake on the weather of the region. The results are nice and innovative, in particular results presented in Fig. 11 and Fig. 13, but I think the author could go a bit further and relate their findings (in terms of simulations) with changes that have been observed at the weather stations. Did they also notice changes in the observed wind regime between 2010-2018 and year1990-2000 for instance? Otherwise, the paper looks more like a first draft, which makes the reading quite painful. Some explanations are too vague, some acronyms are not defined, and many sentences are awkward. I highly recommend that an English speaker reads the manuscript before resubmitting.

Response: The wind regimes between 2010-2018 and 1990-2000 were not studied. It would be very interesting to make that comparison, but the meteorological stations were installed in the lake shores only during two field campaigns. One in the summer of 2014 (ALEX) and more recently in February 2017 (ALOP — Alentejo Observation and Prediction systems) which is an ongoing experiment. Since the lake breeze is only detected nearby the lake shores and loses its intensity entering inland we have no chance to make that study because the closer stations operating continuously from our Institute (ICT) and from the Portuguese Institute for Sea and Atmosphere (IPMA) are Portel and Reguengos de Monsaraz (Fig. 1), where the lake breeze effect is not noticeable due to the distance to the lake. In a previous paper, Policarpo et al. (2017)

have studied the effect of the Alqueva reservoir on fog and for this purpose it was possible to use observational data.

Anyway, we try to go a little further in the analysis and introduce data observed in the summer of 2014.

The paper was carefully reviewed and explanations were added, acronyms defined, awkward sentences rewritten taking into account a better reading of the manuscript.

Specific comments

Comment 1

The formation of the lake breeze is not clearly explained.

Response: Corresponding paragraphs of section **6 Lake impact** were expanded to reflect more information about this effect. Also, some discussion was added to the **7 Conclusions** section.

Comment 2

Some acronyms are given but they first need to be explained. For instance, in the introduction, you mention NH3D. What king of model is it (ex: atmospheric model)? Same, when you mention Meso-NH model, SURFEX, Flake. As well, p.3: what is Csa? (Mediterranean climate) should appear in the text, and Csa should be in brackets (Csa according to the Köppen climate classification). Again, in p.6 ECOCLIMAP and SRTM. You need to clarify.

Response:

- NH3D — non-hydrostatic 3-dimensional mesoscale model;
- Meso-NH — non-hydrostatic mesoscale atmospheric model;
- SURFEX — Surface Externalisée, in French;
- SRTM — Shuttle Radar Topography Mission;
- ECOCLIMAP — is the name of a database, not an acronym. We could suppose that it came from ECOlogical and CLImate MAP, but the authors do not indicate it;
- FLake model — Freshwater Lake model

Corresponding corrections were made in various parts of the article.

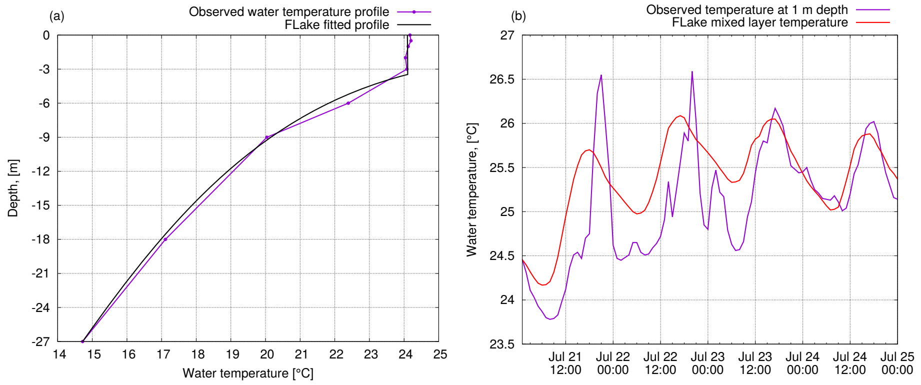
`Csa` as well as `Bsk` are categories of climate in Köppen climate classification. The sentence was rewritten:

`This region has Mediterranean climate with dry and hot summers (Csa according to the Köppen climate classification), with a small area within of the mid-latitude steppe (BSk) category.`

Comment 3

P7. L34: You mention Flake results based on 2-4 months simulations. Did you perform these simulations? Which period did you choose to run these simulations? What is the correlation between simulated and observed data? I would like to see how well the model reproduces the surface temperatures. This is very important to assess the intensity of a lake breeze and the accuracy of the results.

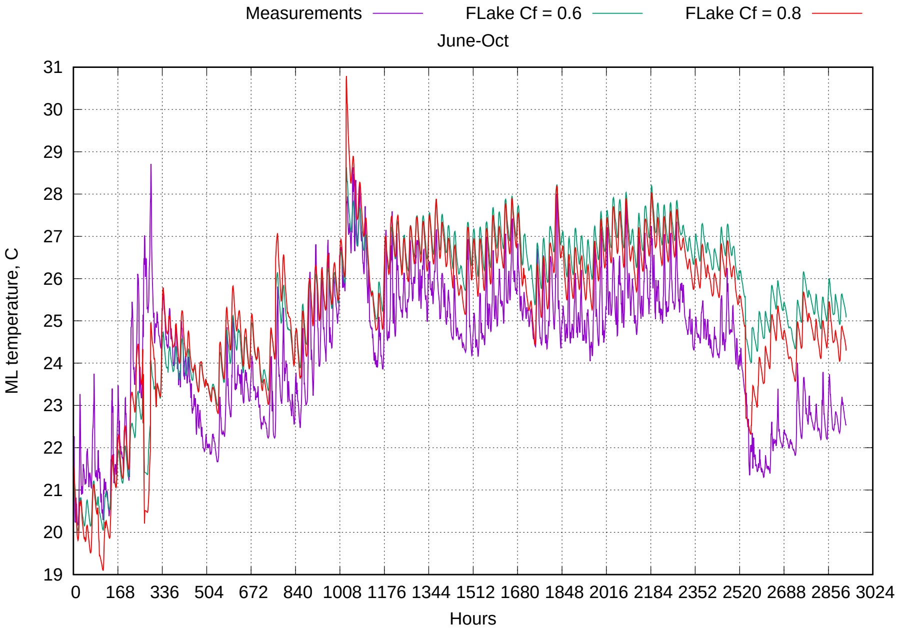
Response: Yes, these simulations were done, and FLake shows very realistic results both in short-term and long-term simulations. Example of the short-term simulations for the IOP was added to Fig. 2:



Corresponding text was added to the section **4.2 FLake model**:

The comparison between measurements of water temperature near surface (at 1 meter depth) and FLake simulated values of mixed layer temperature are shown in Fig. 2 (b). Sensor at 1 meter depth was chosen because it always stays in mixed layer and is not affected by surface "skin" effects. Modelled values are close to measurements which indicates that the initial conditions were realistically imposed.

Long-term simulations was performed for all ALEX data. It was not shown in the article because at the moment, another paper is being prepared on these results and FLake initial parameters. Example for this simulation for 4 months with different FLake shape factors is shown below:



Comment 4

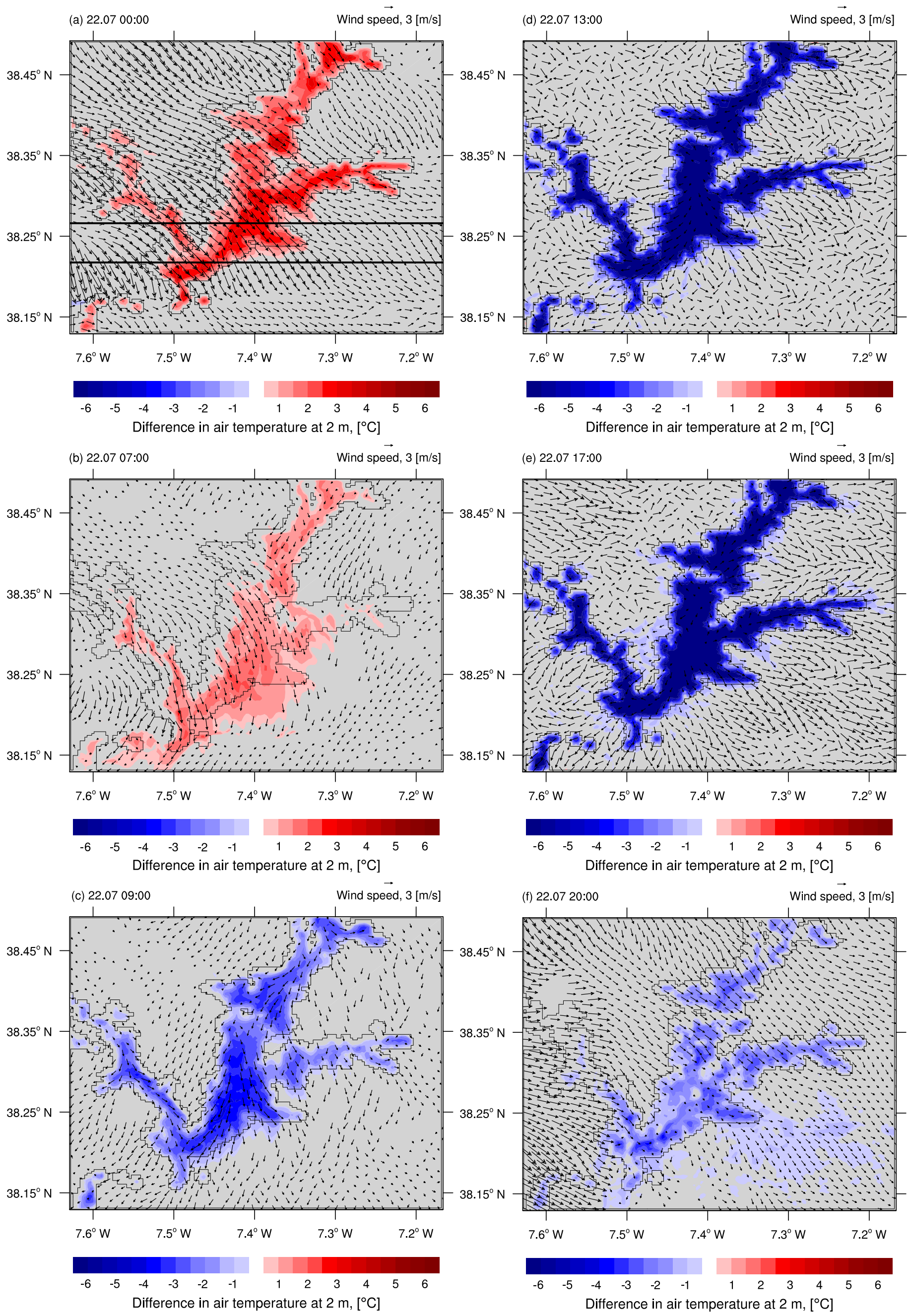
The discussion on the lake effects focuses on the southern part of the lake. Are the conclusions also valid in the northern part of the lake?

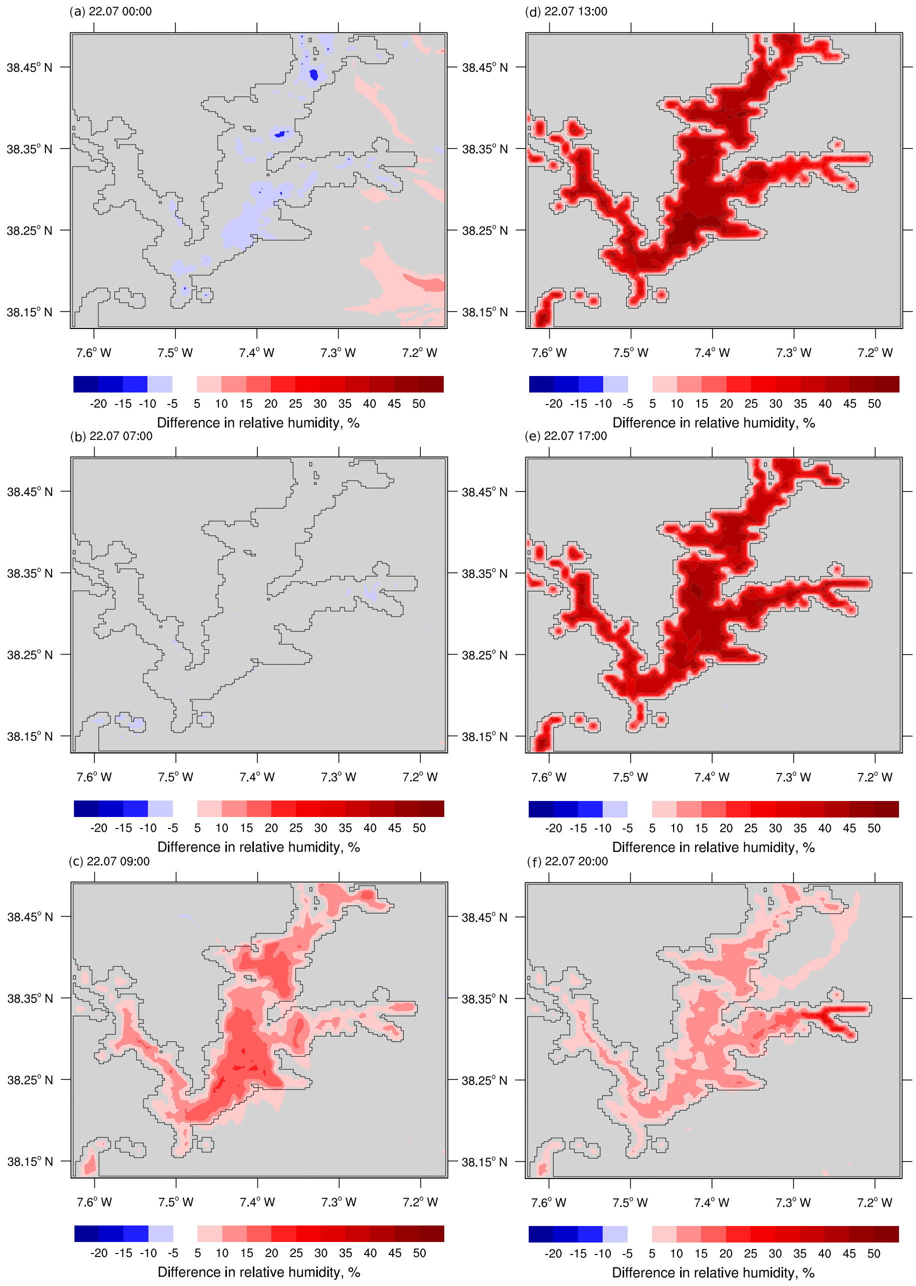
Response: Yes, most of the discussion is centered around the S1 cross-section because it crosses Montante floating platform — the source of measurement data. But S2 cross-section located more to the center of the lake, and the results there are similar. We also studied cross-sections of the middle of the lake in the most wide part (west to east direction) and came to the same results. Breeze effect is observed in the northern part of the lake as well (it is seen on the maps, Fig. 10), but its intensity is not so high due to the fact that the lake there is much more narrow. Maps of the differences of mater vapor mixing ratio provided in the response to the next comment also show that the same conclusions are valid for the central and northern parts of the lake.

Comment 5

You mention that changes in relative humidity are mostly related to change in temperature. However, looking at Fig. 10 and Fig. 12, differences do not appear at the same place. It is maybe related to the fact that the hours on each subplot of figures 10 differ from those on figure 12. It would make sense to have something more homogeneous. Also, wouldn't it be worth adding a map, such as Figs. 10 and 12, representing surface specific humidity? Are they several descending branches of dry air over the lake?

Response: Following the Reviewer comment, Fig. 12 was replotted with the same time of output as Fig. 10 (note, that one figure was removed from the section **6**, so the numeration was changed).

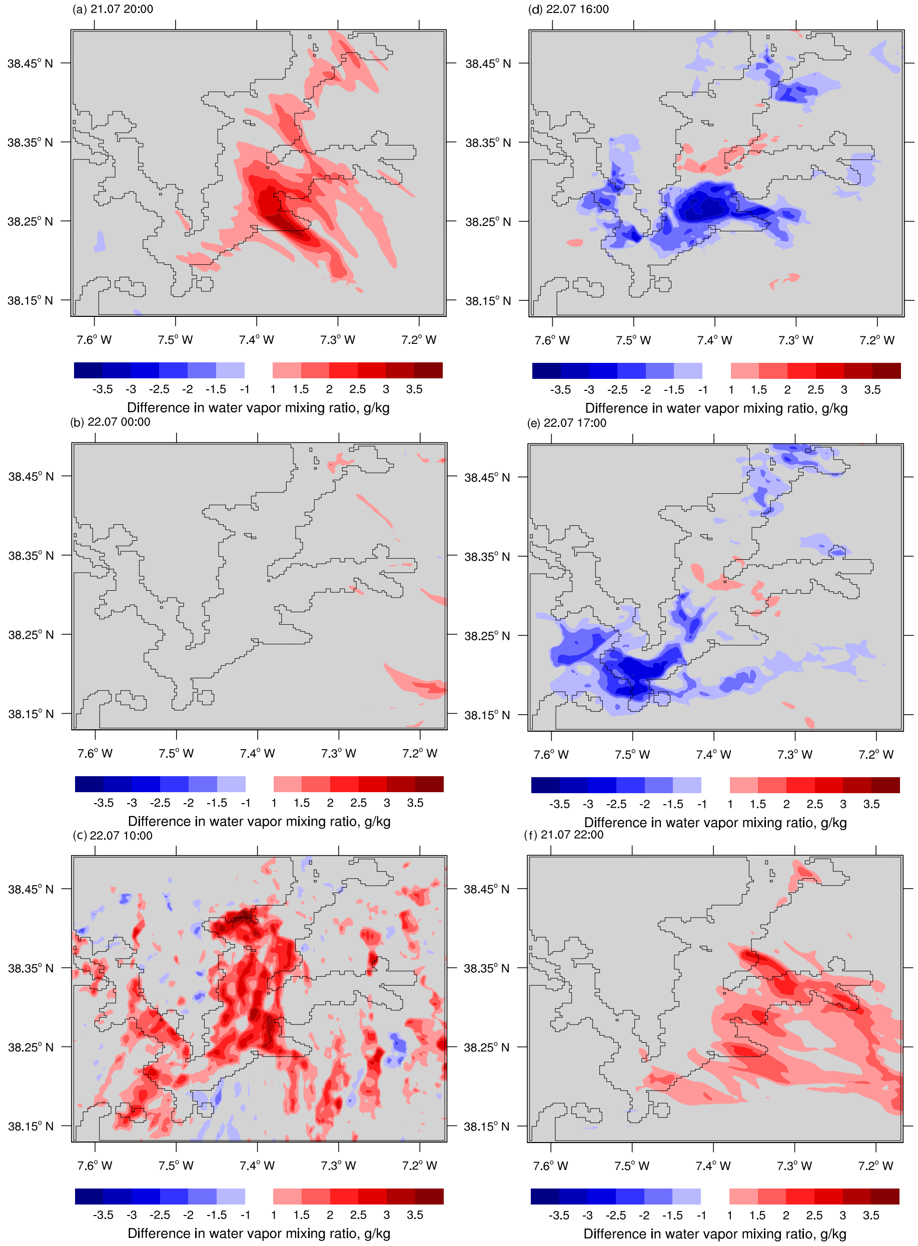

(a) 22.07 00:00
Wind speed, 3 [m/s]
(b) 22.07 07:00
(c) 22.07 09:00
(d) 22.07 13:00
(e) 22.07 17:00
(f) 22.07 20:00
38.45° N
38.35° N
38.25° N
38.15° N
7.6° W
7.5° W
7.4° W
7.3° W
7.2° W
-6 -5 -4 -3 -2 -1 1 2 3 4 5 6
Difference in air temperature at 2 m, [°C]



Night and early morning air temperature anomalies are not high enough to produce significant difference in relative humidity, but now it is easy to catch the relationship between these two variables at daytime.

Also, we add figures with the near surface water mixing ratio and a new paragraph.

Figure 14 illustrates this process in a horizontal plane. At midnight (Fig 14 (b)) the reservoir does not directly affect vapour mixing ratio in the air. In the morning hours, when the sun has risen, but the breeze system has not yet formed, a positive impact on the moisture over the lake can be seen due to the increase of the evaporation. This anomaly affects the air above central and southern part of the reservoir and is advected to other nearby areas (Fig 14 (c)). Later in the afternoon, with the formation of the lake breeze, a negative impact can be traced over the water surface due to the descending branches of the local circulation (Fig. 14 (d, e)). This explains the afternoon decrease of the water vapour mixing ratio observed at the Montante platform as seen in Fig 13. The localization of the area of this negative anomaly changes in time, but predominantly it is over the larger southern part of the reservoir. With the dissipation of the local lake breeze system and the arriving of the stronger large scale northwestern wind, the negative moisture anomaly over the reservoir disappears and a positive effect is visible on the downwind region (Fig. 14 (a, f)), due to the increase of evaporation (note that Fig. 14 (a) corresponds to the night of July 21 to 22, when the effect was more noticeable).



Comment 6

P.12 You indicate the maximum error in terms of temperature. My feeling is that a bias of 5° is quite a lot and especially when it last for several hours. I would a discussion on the impact of this bias on the turbulent fluxes or some hypothesis in order to explain why the fluxes are so well reproduced considering this bias. This could affect modelled lake surface temperature and the intensity of lake breezes.

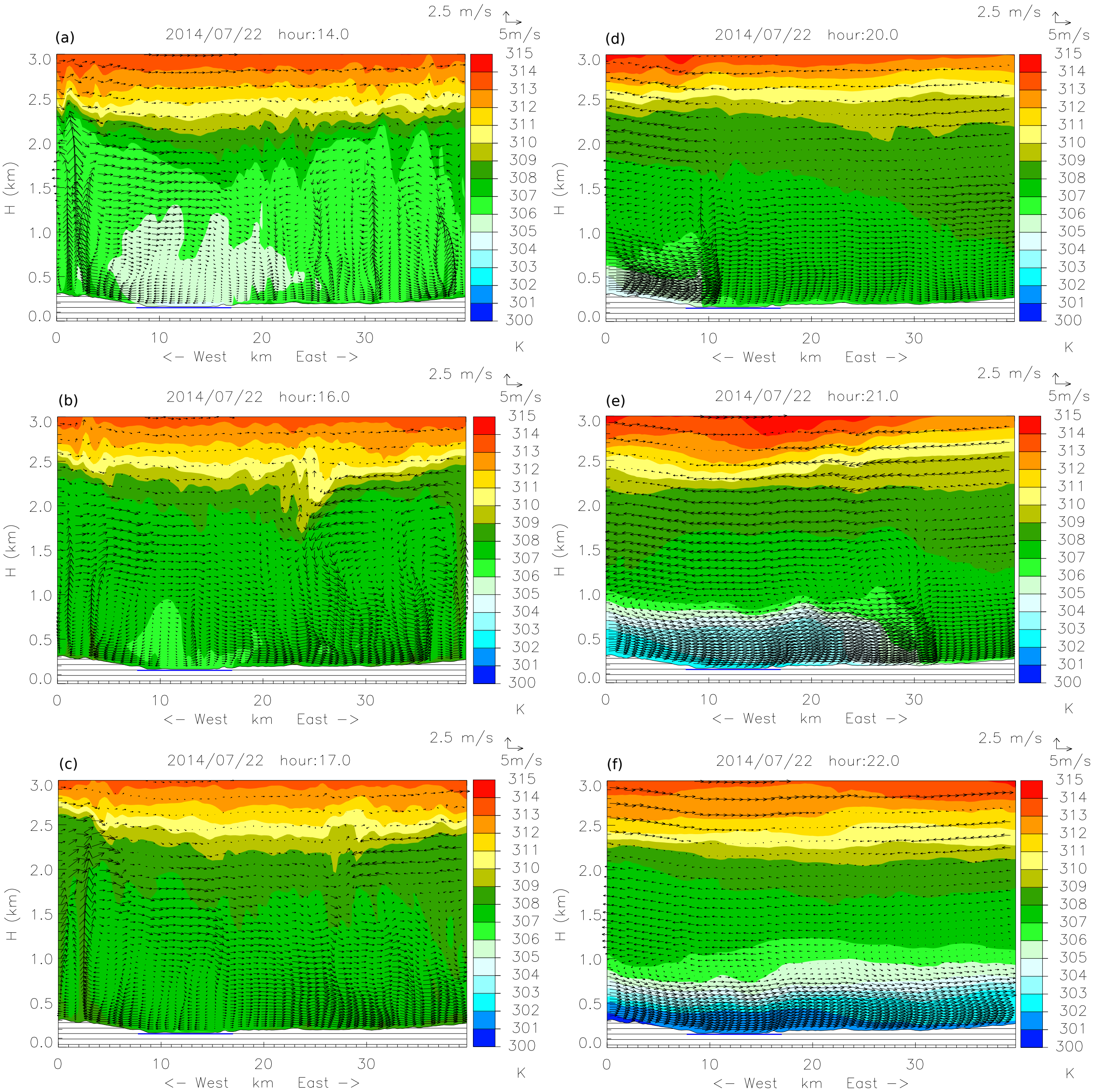
Response: Indeed, maximum error of 5 °C seems to be huge. But in fact, such difference can be observed only during very short time period (at 1 or 2 timesteps, see Fig. 6). More important parameter here that describes the whole period of validation is average bias which value for Cid Almeida station is 0.5 °C (and root mean square error is 1.57 °C). Single relatively big differences, if they occur, do not lead to critical errors in subsequent conclusions.

Latent and sensible heat fluxes were measured at Montante platform, where maximum difference bias was 3.2 °C at late afternoon of July 22. At that time there is a gap in flux measurements, but as it can be seen on Fig. 7, the difference between the model and assumed measured values is the highest. At other intervals of time the biases of air temperature and fluxes are much smaller. Corresponding corrections were added to the article.

Comment 7

The lake effect part is very interesting, but it is hard to follow the mechanism you describe. On Figure 11, you should draw circle where you identify "the upper-level convergent return circulation". The figure needs to be bigger.

Response: Figure 11 (now Figure 10) was enlarged and font size was changed so now it looks better. Wind speed vectors do not merge into one and the circulations are seen much clearer.



Comment 8

In the conclusion, I would expect some general comments on your findings. Are the conditions on July 22-24, representative of the conditions that prevail in this area in summer? What kind of experiments should be done in the future or is there anything you would like to investigate further? What are the limits to your conclusion? There are some biases in the atmospheric variables between modelled and observed data. How confident are you in your results?

Response: **Conclusions** section was expanded and more comments were added to the discussion:

This work is dedicated to the studies of the formation and magnitude of the summer lake breeze at the Alqueva reservoir, South Portugal, one of the impacts of the artificial lake on the local weather. The study was based on Meso-NH simulations of a well documented case study of 22-24 July 2014. This period was taken for several reasons. First, a large volume of meteorological data was collected during these days, which allowed for a validation of the simulation results. Secondly, this period was hot and dry, which is typical for most summer days in this region.

The model allowed to conduct the simulation with horizontal resolution of 250 meters which is fine enough to resolve such relatively small scale lake breeze and to spot the impact of the reservoir on the detailed local boundary layer structure. Due to the "youth" of the Alqueva reservoir it is possible to run atmospheric model with the surface conditions prevailing before the filling of the reservoir. Two simulations, one with Alqueva and another one without it, allow to evaluate the raw impact of the lake on the local weather regime.

Formation and dissipation of the daytime breeze system induced by the reservoir are described in the work. On hot summer mornings the difference between air temperatures above water and neighbouring land surfaces induces the radial movement of air from the lake. The breeze system starts to form in the morning and the peak of the wind speed reaches 6 m/s in the late afternoon. Simulation results show that the lake breeze could be detected at a distance of more than 6 km away from the the shores and on altitudes up to 300 m above water surface. In late afternoon the dissipation stage of the lake breeze system anticipated with the arrival of the larger scale sea breeze from the Portuguese west Atlantic coast. In early evening (19:00 – 20:00 UTC) the local lake breeze system can not be detected anymore. No reverse land breeze is detected during the night.

During daytime, the simulation testify the observed very low evaporation from water surface (0 – 120 Wm^{-2} in terms of sensible heat flux), due to weak winds and the stable stratification of the internal atmospheric surface layer. A night-time, the strong winds associated with the Peninsular larger-scale circulation induced by the sea-land contrasts, induce a very high evaporation rate (200 – 250 Wm^{-2}).

The cooling effect of the reservoir can decrease the air temperature up to 7 °C, nevertheless is limited by the lake borders and normally can not be seen farther than few kilometers away from the shore mostly in southeast direction. The cooling can be found up to 1200 m above the lake surface.

Lake breeze system brings dry air from upper atmospheric layers (2-2.5 km) to near surface levels above the reservoir. This effect leads to the fact that the air above the surface of the lake becomes more dry in terms of water vapor mixing ratio, in spite of its relative humidity can increase up to 50% due to the decrease in air temperature.

Further work implies two directions. The first is tuning the lake model and its initialization in order to obtain more accurate results and reduce validation biases. The second is to carry out a longer experiment, which would cover a 12-month period. Such simulation could reveal seasonal aspects of the impact of Alqueva on local weather.

Comment 9

The units are not systematically the same. Temperatures unit are for instance in °C in Fig. 5 but in K in Table 2.

Response: True, it was corrected, now in the **Table 2** temperature units are °C. Also, the units are °C everywhere if it is referred to air temperature. In the cross-sections, when we discuss potential temperature, the units are Kelvins.

Comment 10

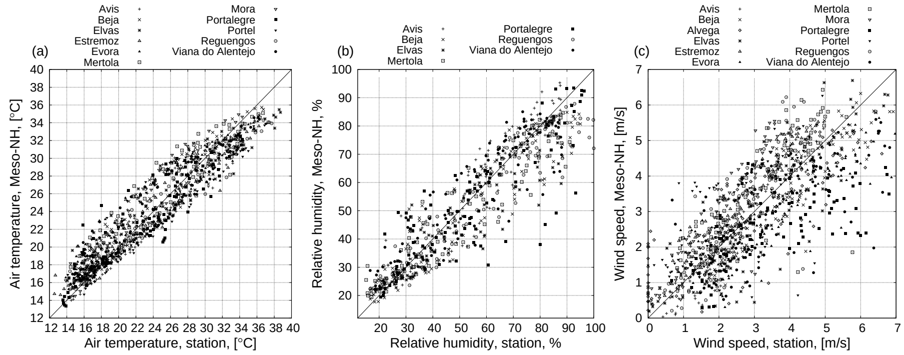
P5: you mention 3 domains, A, B, and C, why don't you use these terms later in the text? For instance on P6: Domaine B required deep convection. . . It would make the manuscript easier to read.

Response: Thank you for noticing that. Indeed, several times we named domains for their resolution, skipping the notation that we introduced. Now it was corrected throughout the whole article.

Comment 11

Some figures are too small. For instance, Figure 5. Also use the same symbol for corresponding stations on each subplot. Figure 11 needs to be bigger.

Response: Agree, elements of some figures are unreadable — they were enlarged and corrected. Also now the same symbols are used for corresponding stations in the legend on Fig. 5:



Comment 12

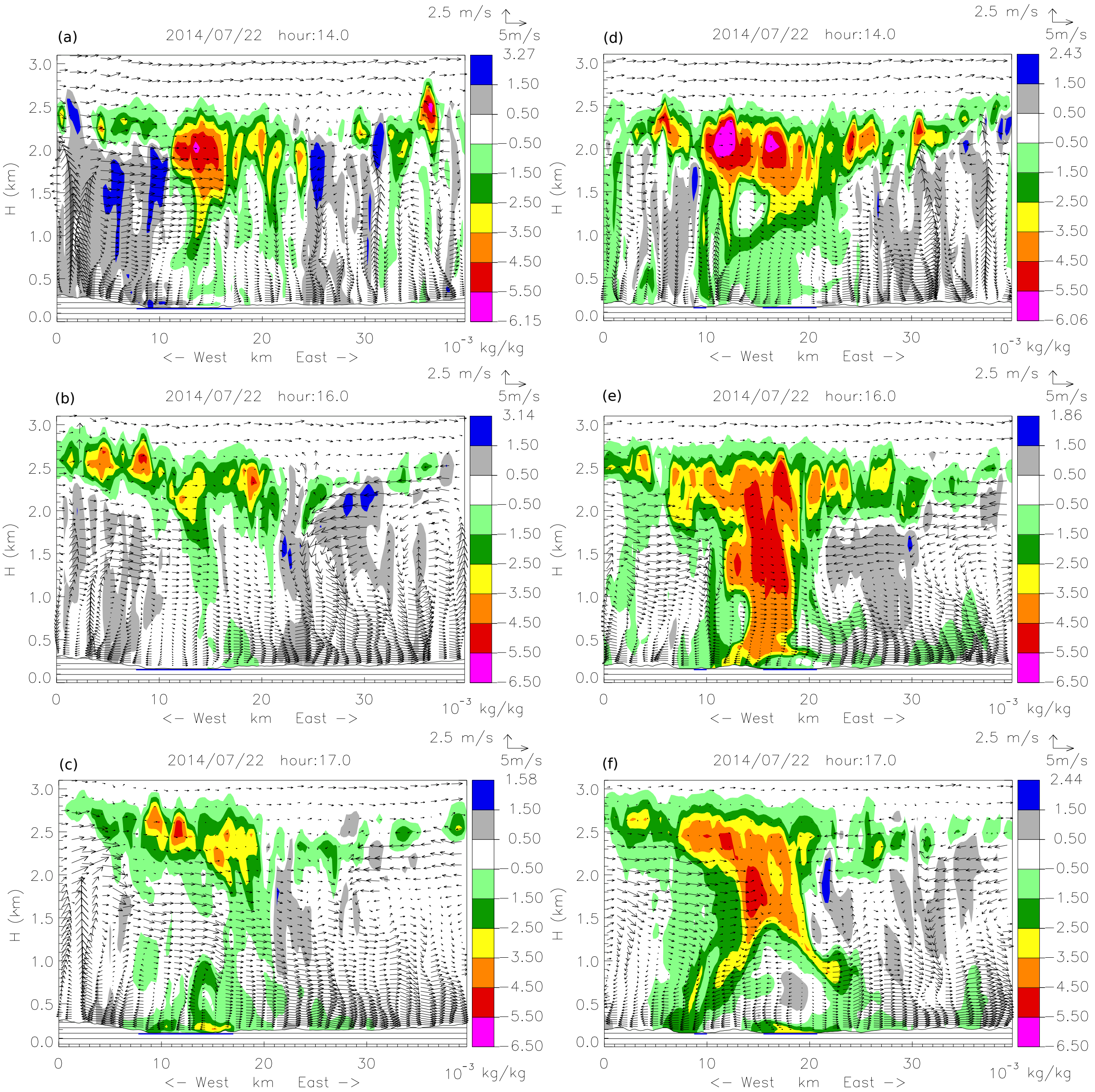
Figure 10: you should name the cross section. For instance S1 and S2 and refer to them in the text. That would ease the reading.

Response: Yes, this can help to improve the section. Cross-sections named S1 and S2, corresponding references and corrections are made in **6 Lake impact**.

Comment 13

Figure 13 and others: it is weird to have different scales for the windspeed. It is then difficult to assess the evolution of the windspeed throughout the day.

Response: The figures were replotted with the same reference vector length and value (See *Comment 7* and Figure below).



Comment 14

P8. You say twice that the domain B is used for validation with radiosondes.

Response: Indeed. The sentence

> This comparison is done in 1-km horizontal resolution domain

was removed.

Comment 15

In the dataset section, try to gather the information per station. Also later in the text (p.11), you define the coordinates of the stations.

Response: Agreed, coordinates of the stations and the platform should be in the Measurement data section. It was moved there and the first paragraph of the 5.2 section was rewritten:

In addition to the validation against the IPMA synoptic stations, comparisons were made with data obtained at ALEX stations (Barbosa, Cid Almeida and Montante platform). Their coordinates were used to locate corresponding grid points on the C domain output.

Comment 16

P1. Abstract: you say that two simulations have been done with the meso-NH model coupled to Flake. Only one was coupled, no?

Response: No, the meaning here is the following: version of atmospheric model Meso-NH that we use is coupled to FLake model. It is this combination was used in all simulations.

Comment 17

P1: L 25: daily air temperature near the surface is decreased in lake shore areas -> and above the lake?

Response: Thank you for pointing this out, the sentence was corrected:

Normally, near surface relative humidity is increased while daily air temperature is decreased above lake and shore areas.

Comment 18

P1. L26: lake surface balances the atmosphere above ->clarify

Response: The sentence was rewritten:

During the warm summer periods relatively colder lake surface interacts with the atmosphere above, which leads to a reduction of clouds and precipitation.

Comment 19

P2. L3: In autumn and winter it has the opposite effect due to the warmer air above lake surface: increase of evaporation and cloud formation -> not warmer air above the lake in summer?

Response: Agree, the phrase is incorrect. The sentence was rewritten:

In autumn and winter it has the opposite effect: due to the fact that water is warmer than the air above, increase of evaporation and cloud formation can be observed (Ekhtiari et al., 2017).

Comment 20

P2. L32: Simulation has been done for. . . -> which simulation are your talking about? A simulation performed within the ALEX2014 experiment?

Response: Indeed, this sentence was unclear. Rewritten:

In this work simulations have been done for the Intensive Observation Period (IOP) of ALEX project (ALqueva hydro-meteorological EXperiment, http://www.alex2014.cge.uevora.pt/).

Comment 21

P4, L24: 3 stations of Instituto de Ciencias etc. . . -> what kind of stations? What kind of variables?

Response: Weather stations (added to the text).

Comment 22

ALEX and ALEX2014, is it the same database?

Response: Yes, it is one database from one experiment. To avoid further confusions we changed ALEX2014 to ALEX throughout the text.

Comment 23

P4. The two land stations your refer to, are they the weather stations you mentioned earlier? Gather the information and be consistent. Alqueva Montante and Montante, the same?

Response: Yes, the main point here is about land weather stations (named Barbosa and Cid Almeida) and floating platform named Montante. Several corrections were made in these paragraphs to make it clearer.

Comment 24

You say that the choice of your study period is based on atmospheric conditions. But you also say that the project lasted for 3 days. Wasn't the choice more based on the availability of data?

Response: Not exactly. ALEX lasted from June to October 2014 and included an Intensive Observation Period (IOP) — these three days (22-24) in July. Atmospheric data from stations and floating platform are available for the whole ALEX period. IOP period was chosen for case study because **a:** this period reflects a typical summer weather in the region, and **b:** additional data from radiosondes was available for validation.

Comment 25

P. 9: the worse values are in the lower lever. What do you mean? Extremely bad?

Response: No, just relatively worse. The paragraph was rewritten to be more clear:

`The principal features of the profiles trend are well represented by the model. During daytime, air temperature and relative humidity curves indicate that the model tends to well represent the height of the boundary layer at 2-2.5 km altitude (around 2 km in Fig. 4 (a), (b)). Overall, Meso-NH reproduces the air temperature above the surface layer (over 500 m) very well. Near surface, the Meso-NH tends to anticipate the development of the unstable boundary layer in the morning (9:00 and 12:00 UTC), simulating higher temperatures in the lower levels. In the late afternoon (18:00 and 21:00 UTC) the model also tends to anticipate the decrease of the temperature in the surface layer (see the supplementary material, Fig. S1).`

Comment 26

p. 9: patterns look similar. Are they similar or do they just look similar?

Response: In fact, we should admit that modelled curves reflect only principal changes in these variables, e.g. low level jet, and, in general, more smooth than measured curves. That is why we say that, in general, patterns of modeled and measured curves look similar. However profile validation showed good results.

Comment 27

P.16: The first level of air above the lake is the most affected by its impact- > impact of what?

Response: The sentence was rewritten for better understanding:

`The lower layers of air are the first to be affected by the presence of water.`

Comment 28

P16: Need to clarify where you mention positive or negative anomalies. Over the lake?, over the land surface?.

Response: To avoid a confusion the following sentence was added:

`By positive and negative anomalies here we mean the differences between LAKE1 and LAKE0 simulations.`

We do not consider it over the land or lake surface, in general it is the area where the difference is not zero.

Comment 29

P.18, legend: what do you mean with projection of wind, same for figure 13.

Response: By projection of wind we mean the component of the wind vector in the plane of the cross-section.

Comment 30

P.18: the fact RH is decreasing due to change in temperature is an important point. Remove "it should be noted"

Response: Agree, "it should be noted" was removed from this sentence.

Technical corrections

Sentences that need to be rephrased

P.2 the using of coarse spatial resolution observations data
Rewritten:

`...inexistence of observational data at sufficiently fine spatial resolution.`

On many pages: meteorological variables instead of parameters
Agree, in many places we abused the word "parameters". We replaced it with the "variable" in the proper places.

p.2, L20. Remove "in his PhD thesis also in Portuguese", not relevant
Removed. Updated sentence:

`The studies were continued and improved by Salgado (2006) who did the first attempt to quantify the direct effect of the reservoir on the local climate, in particular on winter fog.`

p2, L 27. Surface models Masson et al used among atmospheric models by Meso-NH
This paragraph was removed from the article.

p2. L 29: allows to gain the results
The sentence was rewritten:

Mesoscale atmospheric models, such as Meso-NH, allow to obtain results with sufficient horizontal resolution (250 m in present study) for studying the local effects of air temperature changes and the generation of small-scale circulations under different large-scale atmospheric situations.

Many times, you use ":", make a sentence that includes what follows. For instance, you could replace the ":" by "such as "
Yes, colons were used way too many times. In the places where it was not necessary it was removed from text or replaced with "such as" construction.

P4: L3: "on the surface level? –> at the surface
Rewritten:

The incident solar radiation at the surface is…

P5: L10: For that, ->remove.
Removed. Two sentences were merged into one:

The intensive observation period of the ALEX project lasted 3 days (22-24 July) and included launches of meteorological balloons every 3 hours.

P. 6:Longwave and shortwave radiative transfer equations are solved for independent air columns
Rewritten:

Longwave and shortwave radiative transfer equations are solved for independent air columns…

P6: A set of two numerical simulations were performed. . .
Corrected:

To track the impact of the reservoir on the weather conditions two numerical simulation were performed…

P.9, L15: Temperature average bias is -0.13 K, RMSE 1.49 K, and correlation coefficient is 0.99. Humidity average bias is 0.59% RMSE of 11.26 % and 0.87 correlation coefficient.
The sentence was rewritten:

Statistical results for them are the following: temperature average bias is -0.13 °C, RMSE is 1.49 °C, and correlation coefficient is 0.99; relative humidity average bias is 0.59%, RMSE is 11.26%, and correlation coefficient is 0.87; and for the wind speed average bias is 0.05 m/s, RMSE is 2.07 m/s, and correlation coefficient is 0.90.

P10. Scatter plots of air temperature, relative humidity, and wind speed shown on Fig. 5 -> verb missing
Corrected:

Scatter plots of air temperature, relative humidity, and wind speed are shown in Fig. 5

P.10: The worse result are observed in comparison against Portalegre data
The sentence was rewritten:

The worst results are observed in Portalegre data…

P.11; Legend needs to be clarified. Comparison of modelled air temperature. . .with
The legend was rewritten:

Scatter plots of the comparison between Meso-NH sumulation LAKE1 and measured values at synoptic stations. Air temperature (a), relative humidity (b), and horizontal wind speed (c).

p.11. L 7-8, suggestion: In the case the meteorological stations were located in a lake grid cell, the nearest land . . .
Thank you for this suggestion. The sentence was rewritten:

In the case of land stations with grid point associated to water fraction, the nearest land grid point was chosen.

P12. L2-3: Meso-NH underestimation of air temperature in the afternoon time is opposite of wind speed overestimation at the same period.
The part was rewritten:

Overall, the simulation results are slightly more conservative (except wind speed over the Montante platform), but in general, the patterns are well represented. The model could not represent well the maximum and minimum temperatures, especially in land stations where the temperature range is larger. Regarding wind speed, the model underestimates the maximum values at land stations and at Montante platform (Fig. 6 (d)), on the contrary, the wind speed is overestimated by the model, but the principal features of the curve is represented.

P15, L3: is a 3 sets of -> consist of
There was no need in this sentence in the article, and it was removed. The rest of the paragraph was rewritten:

To analyse the impact of the Alqueva reservoir on local area the changes of the following atmospheric variables, such as air temperature and potential temperature, relative humidity and water mixing ratio, and vertical and horizontal wind speed, were considered. In this section only B and C domain datasets were used.

P15, L3: (for each horizontal resolution) > (one set per domain)
See the comment above.

P16, L14: which depth decrease (very clear seen on Fig.11). I don't know what you mean.
This part was rewritten:

The highest impact on the air temperature can be observed in the early afternoon (12:00

– 14:00 UTC). The boundary layer is cooling down and its height decreases from more than 2 km above the land outside to values close to 1 km over the lake surface (Fig. 10 (a)).

Typing errors and other mistakes

p2. L20: a first attempt were done

The sentence was rewritten:

…who did the first attempt to quantify…

p3. L7: "if" instead of "of"

Corrected.

p3, L8: 92 m instead of 92.0 m

Corrected.

p4. L31: locaton

Corrected.

p6. Table: convction

Corrected.

p7: Flake were used

Corrected.

p9, L5: accurace

Corrected.

p9. L11 et L15: supplementary

Corrected.

p.9 Statistical results are following

Corrected:

Statistical results for them are the following: …

p. 11: meteostation

Replaced by weather stations.

p. 12, L19: minimums

Corrected.

p.12, L22: are tend to

Corrected.

p.20, L1: this zone -> This zone

The sentence rewritten:

On the other hand, Fig. 12 also shows that outside the reservoir there are zones of low-level convergence and upward motion that increase the moisture of the boundary layer and form some kind of lake breeze fronts.

p.20, L4: midle
Corrected: middle

P.10 L14: lesser
Corrected: less

P.10 L13. Verb missing
The end of the sentence changed to:

…with bias always less than 1 degree.

P.16, L29: the teservoir
Corrected.

P.16, L31: intensifes
Corrected.

P.21: more wet
This paragraph was rewritten:

Lake breeze system brings dry air from upper atmospheric layers (2-2.5 km) to near surface levels above the reservoir. This effect leads to the fact that the air above the surface of the lake becomes more dry in terms of water vapor mixing ratio, in spite of its relative humidity can increase up to 50% due to the decrease in air temperature.

P.18: Legend: cross-sectons, at different times-> hours
Corrected.

Breeze effects at a large artificial lake: summer case study

Maksim Iakunin[1], Rui Salgado[1], and Miguel Potes[1]

[1]Department of Physics, ICT, Institute of Earth Sciences, University of Évora, 7000 Évora, Portugal

Correspondence to: Maksim Iakunin (miakunin@uevora.pt)

Abstract. Natural lakes and big artificial reservoirs ~~could~~ can affect the weather regime of surrounding areas but~~usually it is difficult to track~~ , usually, consideration of all aspects of this impact and ~~evaluate its magnitude~~their quantification is a difficult task. Alqueva reservoir, the largest artificial ~~lakes~~ lake in Western Europe located on the ~~South-East~~ southeast of Portugal, was filled in 2004. This makes it a large laboratory and allows to study the changes in ~~hydrological and geological structures~~ the surface and in the landscape and how they affect the weather in the region. This paper is focused on a case study of ~~the~~ a 3 days intensive observation period of 22-24 July 2014. In order to quantify the breeze effects induced by Alqueva reservoir, two simulations with the mesoscale atmospheric model Meso-NH coupled to FLake freshwater lake ~~scheme~~ model has been done. The principal difference of ~~this~~ these two simulations is in the presence of the reservoir in the input surface data. Comparing two simulations datasets: with and without the reservoir, net results of the lake impact were obtained. Magnitude of the impact on the air temperature, relative humidity, and other atmospheric ~~parameters~~ variables is shown. Clear effect of a lake breeze (5-7 m/s) can be observed during the daytime on the distances up to 6 km away from the shores and up to 300 m over the lake surface. ~~Breeze~~ Lake breeze system starts to form at 9:00 UTC and dissipates at 18:00-19:00 UTC with the arrival of ~~major Atlantic breezesystem. It induces specific air circulation that captures the~~ a larger scale Atlantic breeze. The descending branch of the lake breeze circulation brings dry air from ~~the upper atmosphere~~ higher atmospheric layers (2-2.5 km) ~~which follows the downstream and redistributes~~ and redistributes it over the lake. It is also shown that ~~the although the impact can be relatively intensive, its area is limited by several~~ despite its significant intensity the effect is limited to a couple of kilometers away from the lake borders.

1 Introduction

Human ~~activity~~activities, such as urbanization, deforestation or water reservoirs building ~~, changes surface properties~~ change the properties of the surface (vegetation cover, emissivity, albedo) which ~~determine~~ rule the surface energy fluxes (Cotton and Pielke, 2007). As a consequence, changes in surface energy fluxes affect local weather and climate. Lakes and reservoirs contains about 0.35% of global freshwater storage (Hartmann, 1994) and cover only 2% of continental surface area (Segal et al., 1997). ~~However, they play a huge societal role.~~ Thermal circulations triggered by lake/land thermal contrast have an impact on dispersion of air pollution and lake catchment transport (Lee et al., 2014). Big lakes being a significant source of atmospheric moisture can intensify storm formation (Samuelsson et al., 2006; Zhao et al., 2012). Lakes and reservoirs~~can be characterized by increased~~ , compared to land surfaces, have higher thermal inertia and heat capacity, ~~small~~ and lower albedo and roughness length~~compared to vegetated land surfaces~~ (Bonan, 1995). They can affect meteorological conditions and atmospheric processes at meso and synoptic scales (Pielke, 1974; Bates et al., 1993; Pielke, 2013).

Normally, ~~surface moisture~~ near surface relative humidity is increased while daily air temperature ~~near the surface is decreased in lake~~ is decreased above lake and shore areas. During the warm summer ~~period~~ periods relatively colder lake surface ~~balances~~ interacts with the atmosphere above, ~~forcing~~ which leads to a reduction of clouds and precipitation. Formation of the local high pressure areas over the lake surface in summer season supports atmospheric circulation, which can be observed as a lake breeze (Bates et al., 1993). In autumn and winter it has the opposite effect: due to the ~~warmer air above lake surface:~~ fact that water is warmer than the air above, increase of evaporation and cloud formation can be observed (Ekhtiari et al., 2017). These ~~lake effects on the regional climate regime find confirmation~~ regional lake effects have been seen in previous studies, e.g. Elqui Valley reservoir in Chile (Bischoff-Gauß et al., 2006) and the great African lakes (Thiery et al., 2014).

~~Despite the fact that~~ Although the theoretical aspects of formation of the lake breezes are clear, in practice, they remain not well documented. Difficulties in studies of lake breeze are due to the diversity and complexity of lake shapes and surrounding landscapes, and the ~~using of coarse spatial resolutionobservations data~~inexistence of observational data at sufficiently fine spatial resolution (Segal et al., 1997).

Lake breezes are mainly determined by ~~geophysical variables~~ the landscape and weather conditions. Formation and intensity of the breeze depend on the set of parameters such as large scale winds, sensible heat flux, geometry of the lake ~~,~~ and terrain types of the surrounding area~~, and others~~ (Segal et al., 1997; Drobinski and Dubos, 2009; Crosman and Horel, 2012).

In this work, the focus is on the study of the lake ~~of Alqueva~~ breeze at the Alqueva reservoir and its impact on atmospheric parameters of the surrounding area. This large artificial reservoir has been filled in 2004 which makes it a big natural laboratory for studying physical, chemical, and biological effects. Few studies about the influence of Alqueva on atmosphere and climate were published. ~~A~~ The first report, in Portuguese, was published even before the construction of the dam by Miranda et al. (1995), as a part of the environmental impact study of the reservoir ~~. They concluded,~~ on the basis of numerical simulations performed with the NH3D ~~model Miranda and James (1992)~~ (non-hydrostatic 3-dimensional) mesoscale model from Miranda and James (1992). It was concluded that the climate impact of the ~~the~~ multi-purpose Alqueva project should be ~~essentially~~ merely due to the ~~projected irrigation area and pay little attention to~~ irrigation of surrounding area. The influence of the reservoir itself ~~as at the~~ was unclear as at that time it was not possible to perform high resolution simulations. The studies were continued and improved by Salgado (2006) ~~in his PhD thesis, also in Portuguese, in which a~~ who did the first attempt to quantify the direct effect of the reservoir on the local climate, in particular on winter fog~~, were done~~. Using the Meso-NH (non-hydrostatic mesoscale atmospheric model) model, the author concluded that the introduction of the reservoir should increase slightly the winter fog in the ~~neighborhood~~surrounding area, but decrease over the filled area. Later on, Policarpo et al. (2017)~~used observations for two periods~~ , used observations data from two periods of ten years (before and after Alqueva ~~)~~ ~~and also~~ reservoir) combined with Meso-NH simulations, ~~showing~~ and showed a slight increase in the average number of days with fog during the winter (~~DJF), of~~ about 4 days per winter after 2003 in a downwind site~~and reinforcing previous findings.~~).

~~On the other hand, data collected in and above the Alqueva reservoir allowed the characterization of energy and mass transfers between the water and the air (Salgado and Le Moigne, 2010; Potes et al., 2012) and were used to calibrate the FLake~~

~~model (Mironov, 2008) and to validate its integration in the SURFEX platform of surface models Masson et al. (2013) used among other atmospheric models by Meso-NH.~~

~~Using a mesoscale atmospheric model~~ Mesoscale atmospheric models, such as Meso-NH~~allows to gain the~~, allow to obtain results with sufficient horizontal resolution (~~up to~~ 250~~m) to track~~ m in present study) for studying the local effects of air temperature changes and the generation of small-scale ~~winds on the background of~~ circulations under different large-scale atmospheric ~~motions. Simulation has~~ situations. In this work simulations have been done for the Intensive Observation Period (IOP) of ~~an in-situ measurement field campaign on the lake area (ALEX2014 —~~ ALEX project (ALqueva hydro-meteorological EXperiment, http://www.alex2014.cge.uevora.pt/)~~, so it allowed~~. Data collected during this experiment were used to validate the ~~acquired results with different datasets~~numerical simulations.

The article outline is the following. Section 2 provides a brief description of the Alqueva reservoir~~, the object of current study~~. Section 3 reveals information about ~~ALEX2014 experiment and dataset~~ ALEX experiment and the measurement data used in this paper ~~:~~ such as meteorological stations, observations, and measurements. Section 4 contains a brief description of the numerical models ~~: Meso-NH and FLake,~~ used in this work: Meso-NH and FLake. Sections 5 and 6 are dedicated to the case study on 22-24 July 2014: validation of simulation results using in-situ measurements and the studies of the lake effects respectively, with an illustration and discussion of the magnitude of the impact and intensity of a lake breeze. Section 7 summarizes the results and conclusions.

2 Object of study

Alqueva reservoir established in 2002 is an artificial lake located in the ~~South-East~~ southeast part of Portugal. It spreads along 83 km over the Guadiana river valley covering~~the total~~, when completely filled, an area of 250 km^2 with ~~the total capacity if~~ a capacity of 4.15 km^3, which makes it the largest artificial lake in Western Europe (Fig. 1 (a)). The maximum and average depths of the reservoir are ~~92.0~~92 m and 16.6 m respectively. The dam is located in the southern part of the reservoir (Fig 1 (c)).

Alqueva reservoir is mainly used to provide water supply, irrigation, and hydroelectric power. ~~Surrounding region~~ The region where it is located is known for the irregularity of its hydrological resources, with ~~the~~ long periods of drought that could last for more than one consecutive year (Silva et al., 2014). This region ~~is characterised as Csa according to the Köppen climate classification (~~has an Mediterranean climate with dry and hot summers (Csa according to the Köppen climate classification), with a small area within of the mid-latitude steppe (BSk) category. During summer, the maximum air temperature ranges between 31 and 35 °C on average (July and August), often reaching values close to 40 °C, or even higher. The incident solar radiation ~~on the surface level~~ at the surface is of the highest in Europe, with mean daily values (integrated over 24 hours) of about 300 $\mathrm{W m^{-2}}$ and the daily maximum of July often can reach 1000 $\mathrm{W m^{-2}}$. Rainfall periods are seasonal and last from October to April~~, an~~. The normal (1981-2010) average annual precipitation ~~registered~~ in the city of Beja (40 km from Alqueva reservoir) ~~over 1981-2010~~ is 558 mm (www.ipma.pt).

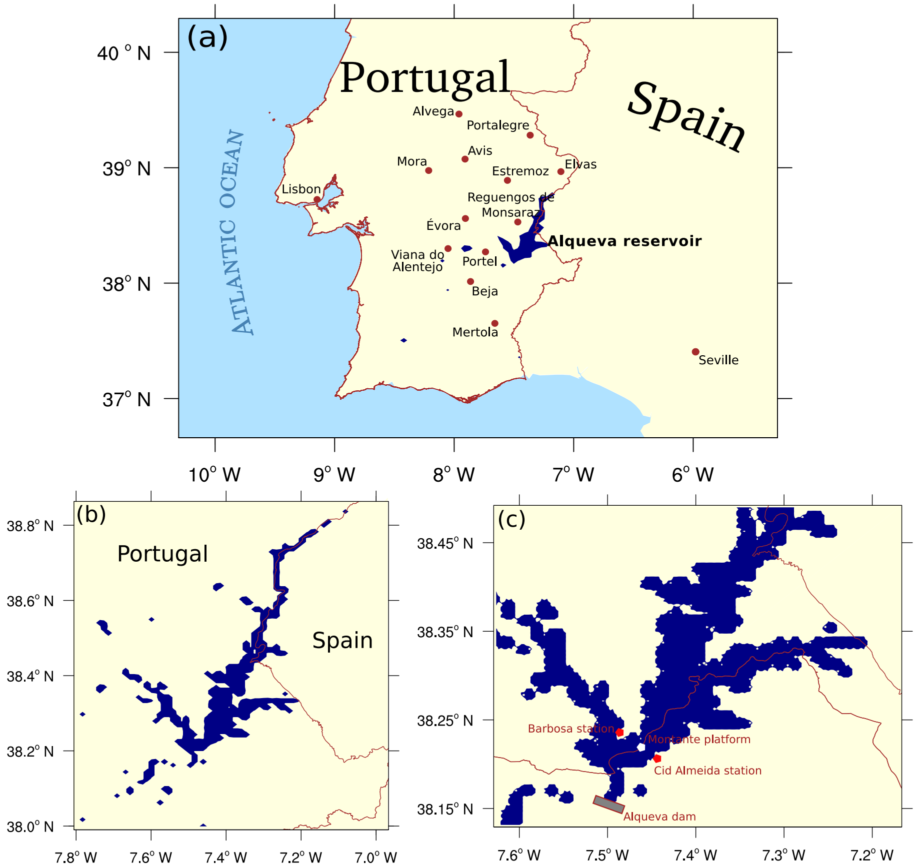


Figure 1. ~~Maps of the nesting~~ Nested domains used in the simulations: **(a)** Father domain at 4 km horizontal resolution ~~, 100×108 pixels~~with 100 × 108 grid points, with location of the 12 IPMA synoptic stations used for validation~~process~~ , **(b)** intermediate 1 km horizontal resolution domain, ~~96×72 pixels~~96 × 72 grid points, **(c)** finer 250~~m horizontal~~ m resolution domain comprising 160 × 160 grid points, ~~160×160 pixels,~~ together with ~~ALEX2014~~ the location of the ALEX land stations~~and~~ , the Montante floating platform ~~Montante location~~and the dam.

Two major factors determine synoptic circulations over the region during the summer period: the shape and location of the Azores anticyclone, and the frequent establishment of a low-pressure system over the Iberian Peninsula~~inside it~~, induced by the ~~the~~ land-ocean thermal contrasts. The sea breeze system controls the transport of the maritime air masses from the Atlantic ~~coast of the peninsula to its internal areas~~ to Iberian Peninsula, on distances more than 100 km reaching the Alqueva region in the late afternoon. This phenomenon is known as the Iberian thermal low (Hoinka and Castro, 2003) and is characterized by a westward change of the wind direction (prevailing wind directions are from the ~~North-West~~ northwest quadrant). As a result, this effect is observed in the local increase in wind intensity and in its rotation (Salgado et al., 2015).

3 ~~Dataset~~Measurement data

The ~~main dataset for this work has been~~ measured data used in this work were obtained during the ~~ALEX2014~~ ALEX campaign — a multidisciplinary observational experiment at the Alqueva reservoir which ~~has last~~ lasted from June to October 2014. ~~The aim~~ One of the aims of this project ~~included~~ was to perform a wide set of measurements of chemical, physical, and biological parameters in the water, air columns, and over the water-atmosphere interface. To reach this goal the project operated the following facilities:

- 7 sites with meteorological measurements: 2 ~~Platforms~~ platforms (Montante and Mourão); 1 permanent weather station ~~in the island~~ located in a small island nearby the dam (Alquilha), 2 dedicated weather stations (Barbosa and Cid Almeida), two compact weather stations in the Solar Park and Amieira;
- 4 floating platforms where water quality and biological sampling were done: Montante, Mourão, Captação, and Alcarrache;
- 3 weather stations of Instituto de Ciências da Terra (ICT), located in Mitra, Portel, and at the University of Évora;
- 2 Air quality mobile units: Amieira and ~~at~~ Solar Park;
- 3 Atmospheric Electricity stations: Amieira, Solar Park, and Beja.

Also, data from 42 IPMA (Portuguese Institue of Sea and Atmosphere) meteorological stations located ~~over all nearby regions~~ in the region were integrated into ALEX database. They provided ~~basic set of parameters~~typical set of variables, e.g. air temperature, relative humidity, pressure, horizontal wind speed.

Two land weather stations (Barbosa and Cid Almeida) were ~~located on the opposite shores and~~ installed on opposite shores (38.2235° N, 7.4595° W and 38.2164° N, 7.4545° W, correspondingly) while the floating platform Montante is situated in the middle (38.2276° N, 7.4708° W, Fig. 1 (c)). This ~~locaton allowed to monitor~~ locations allowed the characterization of the lake effects ~~in real time during the observations~~on a fine scale. Land stations collected ~~the following data with~~ data with an 1-minute time resolution ~~:~~ including horizontal wind speed, relative humidity, air temperature, and downwelling short-wave radiation~~, and precipitation. The floating platform Alqueva Montante~~. Montante floating platform was the principal experimental site inside the reservoir. The following equipment was installed there ~~and collected data since~~ on 2 June 2014 and data has been collected until the end of the campaign:

- ~~Irgason~~ an eddy-covariance system which provides data for ~~:~~ pressure, temperature, water vapor and carbon dioxide concentrations, 3D wind components, momentum flux, sensible and latent heat fluxes (with 30 minutes timestep), carbon dioxide flux, evaporation;
- one albedometer and one pirradiometer in order to measure upwelling and downwelling shortwave and total radiative fluxes;
- 9 thermistors to measure water temperature profile.

The ~~most intensive observational part~~ intensive observation period of the ALEX project ~~has last~~ lasted 3 days (22-24 July) and included launches of meteorological balloons every 3 hours. ~~For that TOTEX meteorological balloons (600) were used.~~ In total, 18 radiosondes ~~have been~~ were launched: 2 from the boat over the lake and 16 from the land. Atmospheric profiles of air temperature, relative humidity, wind, and pressure were obtained~~with the use of Vaisala Radiosondes model RS92-SGP~~. This period, 22-24 July, was chosen for a case study in the this work,~~because it was a period with mostly atmospheric stability and anticyclonic conditions~~as it is an well documented period with typical anticyclonic conditions, hot, dry and low near surface wind speed.

Data collected during the ~~ALEX2014~~ ALEX field campaign have already been used to study: lake-atmosphere interactions, including the heat and mass ($\mathrm{H_2O}$ and $\mathrm{CO_2}$) fluxes in the interface water-air (Potes et al., 2017); the effects of inland water bodies on the atmospheric electrical field (Lopes et al., 2016); and the evolution of the vertical electrical charge profiles and its relation with the boundary layer transport of moisture, momentum and particulate matter (Nicoll et al., 2018).

4 Simulation setup

4.1 Meso-NH atmospheric model

~~For the study of the breeze effects of the~~ To study the lake breeze effects in Alqueva reservoir the Meso-NH model (Lac et al., 2018) was used.

Meso-NH is a non-hydrostatic mesoscale atmospheric research model. It ~~has a complete set of physical parameterizations, which are particularly advanced for the representation of clouds and precipitation, incorporates a non-hydrostatic system of equations, for dealing with~~ can simulate the evolution of the atmosphere on scales ranging from large (synoptic) to small (large eddy)~~scales while calculating budgets~~, and has a complete set of physical parametrizations. Meso-NH is coupled with SURFEX ~~(Masson et al., 2013) platforms~~ (Surface Externalisée, Masson et al. (2013)) platform of models for the representation of surface-atmosphere interactions by considering different surface types (vegetation, city, ocean, ~~lake), and~~ inland waters).

Meso-NH allows a multi-scale approach through a grid-nesting technique (Stein et al., 2000).

~~Three nesting levels were usedin Meso-NH runs~~In this work, three nesting domains were used: $400 \times 432\,\mathrm{km}^2$ domain with $4\,\mathrm{km}$ ~~spatial~~ horizontal resolution to take into account the large scale circulations, namely the influence of the sea breeze (Fig. 1 (a)), an intermediate $96 \times 72\,\mathrm{km}^2$ domain with $1\,\mathrm{km}$ ~~spatial~~ horizontal resolution centered at the Alqueva reservoir (Fig. 1 (b)), and a ~~small~~ finer $40 \times 40\,\mathrm{km}^2$ domain with $250\,\mathrm{m}$ spatial resolution to track the ~~minor~~ small scale effects of the lake (Fig. 1 (c)). Hereinafter we denote this three domains A, B, and C correspondingly. The two-way nesting technique used in Meso-NH allows to conduct simulations on different horizontal resolutions at the same time. Domain A is a "father" domain for B, which means that simulation results on domain A are interpolated and used as initial and boundary conditions for domain B. Same scheme applies for domains B/C. European Centre for Medium-Range Weather Forecast (ECMWF) operational analyses, updated every six hours, were used for Meso-NH initialization and domain A boundary forcing.

For ~~the~~ surface and orography, ECOCLIMAP II (Faroux et al., 2013) and SRTM ~~(Jarvis et al., 2008)~~ (Shuttle Radar Topography Mission, Jarvis et al. (2008)) databases were used, respectively, both updated with the ~~presence~~ inclusion of Alqueva reservoir

Table 1. Summary of the Meso-NH physical schemes used in the simulations.

Schemes and parameters	~~4-km domain~~ A	~~1-km domain~~ Domains B	~~250-m domain~~ C
Deep ~~convetion~~ convection	KAFR	NONE	NONE
Shallow convection	EDKF	EDKF	NONE
Turbulence	BL89 1 dimension	DEAR 3 dimensions	DEAR 3 dimensions
Radiation transfer	ECMW	ECMW	ECMW
Advection	WENO	WENO	WENO
Clouds	ICE3	ICE3	ICE3
Timestep	20 s	5 s	1 s

by Policarpo et al. (2017). All model domains had 68 vertical levels starting with 20 m and up to 22 km~~at the top~~, including 36 levels for the lower atmospheric level (2 km). The model configuration included ~~the~~ a turbulent scheme based on a one-dimensional 1.5 closure (Bougeault and Lacarrere, 1989). ~~Mixed~~ A mixed-phase microphysical scheme for stratiform clouds and explicit precipitation (Cohard and Pinty, 2000; Cuxart et al., 2000) which ~~distinguish 6~~ distinguishes six classes of hydrometeors (water vapor, cloud water droplets, liquid water, ice, snow, and graupel) was used. Longwave and shortwave radiative transfer equations are solved for independent air columns (Fouquart and Bonnel, 1980; Morcrette, 1991). Atmosphere-surface ~~flux exchange controlled by physical parametrisations~~exchanges are taken into account through physical parametrizations: the surface soil and vegetation are described by the Interface Soil Biosphere Atmosphere (ISBA) model (Noilhan and Mahfouf, 1996); the town energy balance was handled according to Masson (2000). Basic parameters for each model domain are shown in the Table 1. ~~4-horizontal resolution in the first domain is coarse enough to use deep~~ Deep and shallow convection ~~schemes in simulation~~parametrization schemes were activated in the coarser domain A. 1-km ~~resolution of the second domain already required deep~~and 250-m resolutions of domains B and C are high enough for the deep/shallow convection to be ~~resolved explicitly. 250-resolution is fine so both schemes can not be applicable. Used schemes~~ represented explicitly. The following schemes were used (see Table ~~are the following~~1): KAFR (Kain and Fritsch, 1990; Bechtold et al., 2001), EDKF (Pergaud et al., 2009), WENO (Lunet et al., 2017), and ICE3 (Pinty and Jabouille, 1998).

~~European Centre for Medium-Range Weather Forecast (ECMWF) operational analyses data files were used for Meso-NH initialization and lateral boundary forcing, updated every six hours.~~

To track the ~~direct~~ impact of the reservoir on the weather conditions, ~~a set of~~ two numerical simulation were performed: ~~the~~ one with the surface input files updated to ~~Alqueva reservoir presence~~ include the Alqueva reservoir (ECOCLIMAP database version updated by ~~Policarpo et al. (2017)~~Policarpo et al., 2017) and another ~~—~~with the previous version of this database where the reservoir does not exist yet. In order to distinguish these simulations hereinafter we denote them LAKE1 and LAKE0, correspondingly. Both simulations ~~have~~ covered the case study period, 22-24 July 2014, with 1 hour output. To reproduce the atmospheric conditions more ~~realistic the simulation included~~ realistically the simulations included the previous 24 hours (21 July), so ~~, overall the model covered~~ the model was integrated for 96 hours. The differences between these two simulations were then computed, with the aim of evaluating the direct influence of the ~~presence of the~~ lake on the ~~environment~~atmosphere.

4.2 FLake ~~scheme~~model

In order to ~~represent the presence and~~ better represent the evolution of the lake ~~more realistically, freshwater lake model FLake (Mironov, 2008) were~~ surface temperature and therefore the water-air heat fluxes, FLake (Freshwater Lake) model (Mironov, 2008) was used. FLake is a bulk-type model capable to predict the evolution of the lake water temperature at different depth on time scales from a few hours to many years. For ~~the~~ an unfrozen lake it uses a two-layer approach: upper mixing layer with ~~the~~ a constant water temperature ~~from the surface~~ and the thermocline ~~level~~ beneath it where the temperature decreases with depth. Parametrization of the thermocline ~~layer~~ profile is based on the concept of self-similarity assuming that such approach could be applied to all natural and artificial freshwater lakes.

~~The following parameters are required to runthe FLake model~~FLake model requires at least the following sets of variables and parameters to run: four initial parameters ~~of~~ to describe the lake temperature structure, six atmospheric ~~parameters for each calculation~~ input variables for each timestep, and two ~~constants~~ parameters — lake depth and the attenuation coefficient of light ~~into~~ in the water. This coefficient ~~represents~~ is used to compute the penetration of the solar radiation in the water body. In this work, the attenuation coefficient was set to 0.85 ~~corresponding the~~ based on in-situ measurements carried out in Alqueva by Potes et al. (2017).

~~Initial parameters~~ The FLake prognostic variables that need to be initialized are: water temperature at the bottom, temperature and depth of the mixing layer, and shape factor C_f — ~~specific~~ a parameter that describes the shape of the the thermocline curve. In the parametrization proposed by Mironov (2008) for the normalized temperature profile ~~and depth~~ it varies from 0.5 to 0.8. The initial values of the shape factor C_f, ~~temperature of the~~ a water mixing layer ~~and its~~ temperature, and depth were determined using ~~fitting technique of real~~ a fitting technique applied to the observed water temperature profile ~~data from~~ at a given time in Montante platform (Fig. 2 ~~). FLake model is~~ (a)). Short term FLake model runs are very sensitive to initial parameters~~, and this~~ . The fitting technique is based on the assumption that the bottom temperature is fixed and given by the value of the lowermost sensor. Thereby, the other three parameters could vary within some range until the best set ~~of them~~ is found. The ~~set of parameters for this case study is~~initial conditions for our simulations were obtained following this technique: $C_f = 0.8$, mixed layer temperature is 23.8 °~~,~~ C and depth is 3.4 m. ~~Water temperature profile on July 21, 00:00 at Montante platform.~~ Test simulation with these set of inputs was done using stand-alone version of FLake model (not in couple with Meso-NH). The results of the comparison of water mixing layer temperature is shown in Fig. 2 (b). The maximum difference does not exceed 0.8 °C which is a very good result for such short-term simulation.

~~In view of the fact that the~~ The observed daytime temperature profiles showed strong skin effects (higher temperatures ~~of the upper (up to~~ in first 10 cm) ~~water layer)~~ and could not be ~~correctly fitted ,~~ well fitted by a FLake type temperature profile, which

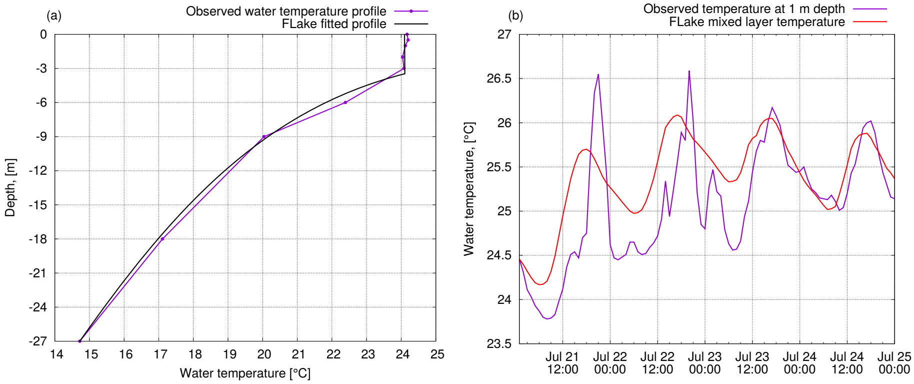


Figure 2. Water temperature observed and fitted profiles on July 21, 00:00 at the Montante platform (a) and comparison of upper level water temperature between measurements and FLake results (b)

assumes a constant temperature in the mixed layer. Thus, the midnight profile was used as an initial one and the simulation started at midnight, 21 July 2014.

~~Required atmospheric parameters: horizontal wind speed, air temperature, special humidity, longwave and shortwave downwelling radiation, and atmospheric pressure were taken directly~~ The required atmospheric variables were taken interactively from Meso-NH simulation since FLake was implemented in SURFEX model ~~(Salgado and Le Moigne, 2010)~~by Salgado and Le Moigne (2010)

~~Typically, the~~ The depth of the artificial lakes ~~characterized by strong spatial variability~~varies decreases rapidly from the center to the shore, because the ~~lake bottom of these lakes~~ bottom of the reservoirs used to be ~~a valley~~valleys. In case of Alqueva, when completely filled, the mean depth is of about 17 m (http://www.edia.pt/). On the other hand, the local depth at Montante platform can reach 70 m. As an 1D bulk model, FLake has only one depth value which should be seen as an effective depth and is not easy to assess. Moreover, FLake ~~scheme~~ model is not capable to represent deep lakes, ~~the scheme~~ it works well for depths from 20 to 50 m with the sediments routine ~~switched off~~switched-off. After a series of a sensitivity tests of short-term (2-4 days) and long-term (2-4 months) simulation it was found that the best simulations results can be obtained with the bottom depth value of 20-30 m. Thus, since the ~~last profile sensor was~~ deepest temperature probe was installed at the depth of 27 m, this value was chosen for the effective lake depth in this work. The comparison between measurements of water temperature near surface (at 1 meter depth) and FLake simulated values of mixed layer temperature are shown in Fig. 2 (b). Sensor at 1 meter depth was chosen because it always stays in mixed layer and is not affected by surface "skin" effects. Modelled values are close to measurements which indicates that the initial conditions were realistically imposed.

5 Validation

The simulation LAKE1 results were validated against radiosondes data (vertical profiles) and meteorological ~~stations data :~~ data from ALEX and IPMA ~~synoptic stations and~~ stations located on land and in the floating platforms. ~~In this process all~~ All three domains were ~~used. Size~~ considered in the validation. The size of the domain A was enough to consider 12 ~~meteorological~~

~~stations~~ synoptic stations located in the region, domain B was used to track the radiosondes trajectory, and domain C ~~data was used for the validation against stations at~~ results were validated against stations installed on the lake shores and on the Montante floating platform. The ~~parameters to compare are:~~ variables under analysis were air temperature, relative humidity, wind speed, sensible and latent heat fluxes.

5.1 Comparison with radiosondes data

The ALEX ~~2014 IOP of~~ IOP took place between 22 ~~–~~ and 24 of July 2014 ~~took place~~ at the Alqueva reservoir. ~~They included balloon launches~~ It included the launch of 18 meteorological balloon every 3 hours~~, and overall 18 launches have been done. Balloons radiosonde data provided~~ . The radiosondes took measurements of air temperature, humidity, pressure, and wind speed.

~~Due to the fact that the trajectory of the balloons was not vertical but resembled a spiral and balloons~~ As the balloons did not ascent vertically and flew several kilometers away from the launching point~~it was decided to make~~ , a trajectory profile comparison was performed. Each balloon had a GPS-tracker to register its coordinates every 2 seconds, which was used to build a corresponding ~~trajectory inside~~ numerical trajectory on the simulation domain. Radiosondes ~~have~~ reached the altitude of ~~≈ 35 km, but since the upper layer~~ the top of the model ~~is limited to~~ (about 22 km~~, the profiles were built up to this altitude. For sondes it took~~) in about 2.5 hours~~to reach 22 height so to build a corresponding profilethree consecutive timestep arrays of the model data~~ . Therefore in order to build the simulated profile, three consecutive hourly outputs from the model were used. ~~This comparison is done in 1-horizontal resolution domain.~~

Figures 3 (a, b, c) represent examples of the daytime profiles ~~for~~ of air temperature, relative humidity, and horizontal wind speed. Examples of ~~corresponding~~ night profiles can be found ~~on~~ in figures 3 (d, e, f). ~~All night profiles demonstrate~~ In general, the night simulated profiles show slightly better accordance with model results~~because atmosphere is more stable during the nighttime.~~ .

Figure 4 ~~represents~~ shows the same profiles, but for the lower ~~atmospheric~~ troposphere level (3000 m altitude). Simulation ~~results~~ are in good accordance with ~~measured values under the radiosonde accurace~~ observations. The simulation results are within the confidence interval of the measurements as given by the radiosonde accuracy (±0.5° ~~-~~C, ±5% relative humidity, and ±0.15 m/s wind speed with 2-sigma confidence level (95.5%)).

The principal features of the ~~curve profiles as well as the dynamics~~ profiles trend are well represented by the model. ~~On air temperature curves (and , to a lesser extent, on the relative humidity and wind speed curves), one can observe a characteristic fracture~~ During daytime, air temperature and relative humidity curves indicate that the model tends to well represent the height of the boundary layer at 2-2.5 km altitude ~~during daytime, which denotes the top of the boundary layer~~(around 2 km in Fig. 4 (a), (b)). Overall, Meso-NH ~~better represents air temperature in the layer from 2.5 to 10-12 , while the worst values are in the lower lever near the surface during the period of 06~~reproduces the air temperature above the surface layer (over 500 m) very well. Near surface, the Meso-NH tends to anticipate the development of the unstable boundary layer in the morning (9:00 ~~–~~ and 12:00 UTC~~(presented in suplementary material~~), simulating higher temperatures in the lower levels. In the late afternoon (18:00

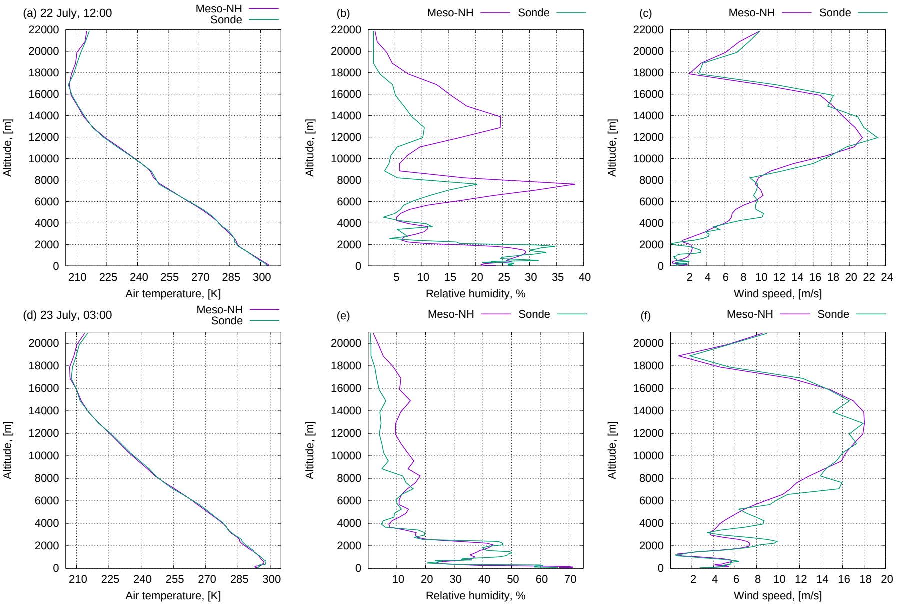


Figure 3. Examples of observed and simulated vertical profiles for July 22, 12:00 and July 23, 3:00 of air temperature (a, d), relative humidity (b, e), and wind speed (c, f).

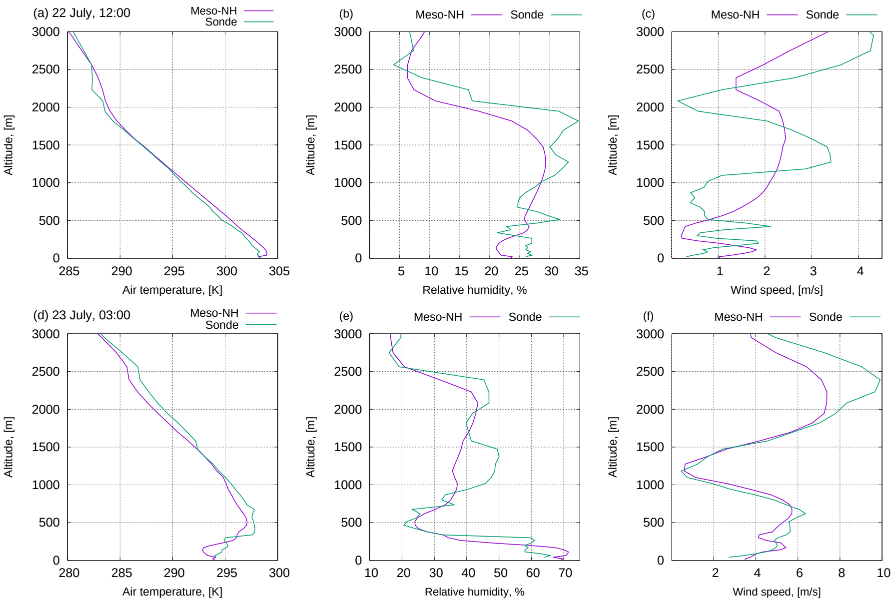


Figure 4. ~~Lower atmospheric level profiles for~~ Profiles of air temperature, relative humidity, and wind speed ~~.~~in low atmosphere on 22 July 12:00 and 23 July 03:00.

and 21:00 UTC) the model also tends to anticipate the decrease of the temperature in the surface layer (see the supplementary material, Fig. S1).

~~Patterns~~ The patterns of relative humidity and wind speed are good, as observed and modelled curves look similar, nevertheless simulations tend to be more conservative and their values do not change so quick. ~~For example,~~ Nocturnal low level jets ~~can be found on night profiles~~ at the edge of the boundary ~~level (Fig. 4 (f)). These jets~~ layer are represented by the model~~as well~~, but their magnitude ~~are~~ is slightly weaker than the observed~~values. All 18~~. All the profiles can be found in the ~~suplementary material .~~ supplementary material (Fig. S3). The moisture vertical profile in the boundary layer is well reproduced by the model, as can be seen in the graphs of the relative humidity (Fig. 4 (b), (e), and S2 in the supplementary materials). Above the boundary layer the radiosondes show a dry layer, which is also well simulated. From July 23 the observations show the appearance of a moist layer close to the troposphere, which magnitude is overestimated by the model. On July 24 at dawn the radiosondes and the model indicate the existence of a very moist layer close to the surface, with the formation of low clouds that were not formed in the simulations.

Statistical results for them are ~~following. Temperature~~ the following: temperature average bias is -0.13~~, RMSE~~ °C, RMSE is 1.49 °C, and correlation coefficient is 0.99~~. Humidity~~; relative humidity average bias is 0.59%~~RMSE of~~, RMSE is 11.26%~~and 0.87 correlation coefficient . For wind speed these values are:~~, and correlation coefficient is 0.87; and for the wind speed average bias is 0.05 m/s~~average bias~~, RMSE is 2.07 m/s, and correlation coefficient is 0.90. ~~All these values show~~ These values testify that the simulation is in a good ~~accordance~~ accord with the observations, ~~and~~ in line with similar studies of Meso-NH validation against radiosondes data (e.g., Masciadri et al., 2013).

5.2 Comparison with IPMA stations data

~~We also validated the model data~~ The model was also validated against 12 IPMA automatic meteorological stations. For this comparison ~~data of 4-domain~~ the output of the bigger domain A were used. Geographical positions of the stations can be found ~~on~~ in Fig. 1 (a). Scatter plots of air temperature, relative humidity, and wind speed ~~shown on~~ are shown in Fig. 5. ~~Not~~ It should be mentioned that not all stations provided the same set of ~~parameters. These scatter plots represent~~ variables. The scatter plots show the intercomparison of the model data (X axis) and the measured values (Y axis) over ~~the case study period~~ all the simulated period and all the stations. The model tends to overestimate lower values of air temperature (14-24 °C) and slightly underestimate higher values (>30 °C), ~~visible in~~ as can be seen from Fig. 5 (a).

~~For relative humidity the model shows lower values~~ Over some stations and in several times, the model simulates lower values of relative humidity within the range from 40 to 100% ~~. Wind speed is overestimated~~ (Fig. 5 (b)). Fig. 5 (c) indicates that the wind speed is slightly underestimated by the model~~as the output is set to 10 above the surface and measurements are at 2~~.

Statistical parameters (~~biases~~bias, mean absolute ~~errors~~error, root mean ~~square~~squar, and correlation ~~coefficients) of this comparison~~ coefficient) for each station are shown in Table 2. ~~Comparison of air temperature showed high correlation~~ Simulated and observed air temperature are highly correlated (correlation coefficient is higher that 0.91) with ~~biases absolute values lesser~~ bias always less than 1 degree. The ~~worse result~~ worst results are observed in ~~comparison against Portalegre data (see for~~

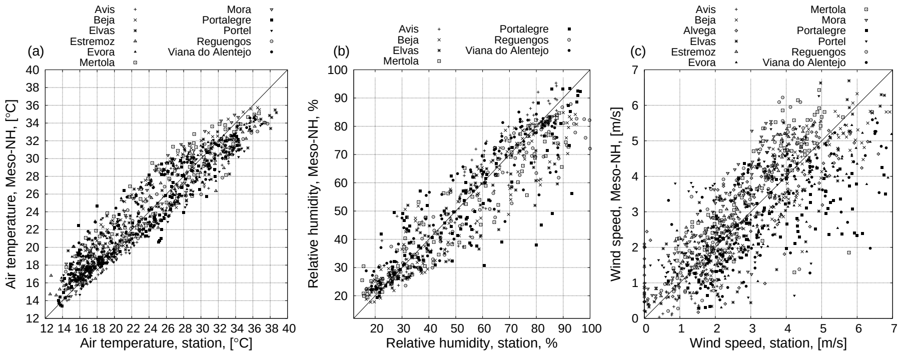


Figure 5. Scatter plots of the comparison ~~with~~ between Meso-NH sumulation LAKE1 and measured values at synoptic stations. Air temperature **(a)**, relative humidity **(b)**, and horizontal wind speed **(c)**.

Table 2. Statistics for the hourly values of the station validation.

Stations:		Alvega	Avis	Beja	Elvas	Estrem.	Évora	Mert.	Mora	Portal.
Temp.,	Bias:	—	-0.08	0.68	-0.39	0.00	0.56	0.85	0.9	-0.08
°C	MAE:	—	1.49	1.60	1.76	1.65	1.60	1.71	1.54	1.82
	RMS:	—	1.84	1.96	2.18	2.02	1.96	2.20	1.93	2.38
	Corr:	—	0.95	0.96	0.96	0.96	0.96	0.95	0.96	0.91
Rel.	Bias:	—	0.53	-2.98	-3.42	—	—	-1.29	-4.19	-2.79
hum.,	MAE:	—	5.80	7.48	5.87	—	—	6.61	6.88	7.83
%	RMS:	—	7.41	9.49	8.61	—	—	8.49	8.43	11.91
	Corr:	—	0.93	0.93	0.93	—	—	0.94	0.94	0.86
Wind	Bias:	~~0.49~~ -0.46	~~0.31~~ -0.34	~~0.17~~ -0.16	~~0.07~~ -0.09	~~0.89~~ -0.91	~~-0.36~~ 0.27	~~1.08~~ -1.11	~~1.19~~ -1.09	~~-0.66~~ 0.53
speed,	MAE:	~~0.91~~ 2.33	~~0.60~~ 0.26	~~0.60~~ 0.22	~~0.74~~ 0.88	~~0.97~~ 1.28	~~0.80~~ 0.44	~~1.25~~ 0.74	~~1.30~~ 1.19	~~1.05~~ 0.68
m/s	RMS:	~~1.15~~ 1.01	~~0.77~~ 0.73	~~0.77~~ 0.74	~~0.99~~ 1.01	~~1.11~~ 0.69	~~1.01~~ 0.94	~~1.42~~ 0.93	~~1.52~~ 0.93	~~1.36~~ 1.12
	Corr:	0.85	0.92	0.91	0.86	~~0.93~~ 0.92	0.82	~~0.82~~ 0.81	~~0.84~~ 0.85	~~0.65~~ 0.68

~~example the~~ Portalegre (square points in relative humidity plot ~~on~~ in Fig. 5 (b))~~: this station is located~~, and a possible reason for this relies on the location of the station which is installed in small mountain area~~which makes the meteorological situation more difficult to predict. Validation of~~. Regarding the wind speed~~shown the~~, Table 2 shows small biases, in general lower than 1 m/s, and relatively high correlation coefficients for wind simulations (0.68 - 0.92). The lowest correlation coefficient ~~(0.65 in Portalegre, 0.82 average) due to its high variability over time~~is also obtained in Portalegre. Overall, simulation results are in good agreement with synoptic stations data~~. Other works represent the similar results of~~, and the statistical parameters are similar to other published works done with Meso-NH~~validation against data from meteostations~~ (e.g., Lascaux et al., 2013, 2015).

5.3 Comparison with data from ALEX ~~Lake platform and stations~~database

In addition to the validation against the IPMA synoptic stations, comparisons were made with data obtained at ~~ALEX2014 dedicated stations : Montante platform (38.2235° N, 7.4595° W) and two stations: Cid Almeida~~ ALEX stations (~~38.2164° N, 7.4545° W) and Barbosa (38.2276° N, 7.4708° W) (Fig. 1 (c)). These~~ Barbosa, Cid Almeida and Montante platform). Their coordinates were used to locate ~~the stations on the 250-output. Another criteria which was used for this was water fraction variable: land stations can not be found over the water , so the nearest land grid-point was used~~corresponding grid points on the C domain output. In the case of land stations with grid point associated to water fraction, the nearest land grid point was chosen.

Figure 6 ~~represents the evolution in time of~~ shows the time evolution of simulated and observed air temperature and wind speed ~~for these stations and the comparison to the corresponding simulated parameters. Meso-NH underestimation of air temperature in the afternoon time is opposite of wind speedoverestimation at the same period.Values of wind speed show higher amplitude which may can be partlially explained by the same fact that modelwind corresponds to the 10 height while sensors at the station are at a height of 2 .~~ at Cid Almeida, Barbosa, and Montante sites. Overall, the simulation results are slightly more conservative (except wind speed over the Montante platform), but in general, the patterns are well represented. The model could not represent well the maximum and minimum temperatures, especially in land stations where the temperature range is larger. Regarding wind speed, the model underestimates the maximum values at land stations and at Montante platform (Fig. 6 (d)), on the contrary, the wind speed is overestimated by the model, but the principal features of the curve is represented. Statistical values for this validation are the following. For Barbosa: air temperature ~~maximum absolute error (MAE) is 3.6 with RMSE of~~ average bias is 0.23 °C, RMSE is 1.37 °C and correlation coefficient is 0.98, ~~and~~ for wind speed ~~: 4.4 is maximum absolute bias , 2.13~~ these values are: average bias is 0.55 m/s~~RMSE, and 0.67 correlation coefficient~~, RMSE is 1.08 m/s, and correlation coefficient is 0.73. For Cid Almeida: ~~MAE 4.9 , RMSE~~ temperature average bias is 0.5 °C, RMSE is 1.57~~,~~ °C, and correlation coefficient is 0.98, wind speed ~~MAE is 5.9~~ average bias is -0.36 m/s, RMSE is ~~1.56~~ 1.24 m/s~~wid the correlation coefficient of 0.63~~, and correlation coefficient is 0.69. For Montante platform~~these values are following. Air temperature MAE is 3.2 , RMSE~~: air temperature average bias is -0.1 °C, RMSE is 1.22 °C, correlation is 0.98, wind speed ~~MAE 4.95~~ average bias is -0.97 m/s, RMSE ~~1.76~~ is 1.55 m/s, and correlation coefficient is ~~0.63. Wind speed in the simulation input is given at 10 meters high while the stations are installed to measure it at 2 meters. Interpolation of the model results for 2 meters can reduce biases and improve the comparison. All maximums of the biases can be found on the peaks of the temperature or wind speed which is explained by the fact that the model is more conservative.~~ 0.61.

~~Dynamic of~~ The temporal evolution of simulated and observed latent and sensible heat fluxes at Montante platform is shown ~~on~~ in Fig. 7 (a, b). Overall patterns of ~~these~~ the curves are similar but ~~simulated results are more smoothwhile observed values changes more quickly~~the simulated one is more smooth. Comparison between measurements and simulated results demonstrates that for latent heat the RMSE is 57.34 $\mathrm{W\,m^{-2}}$ with correlation coefficient of 0.47, and for sensible heat the RMSE is 13.39 $\mathrm{W\,m^{-2}}$ with the correlation of 0.82. ~~It should be noted here~~

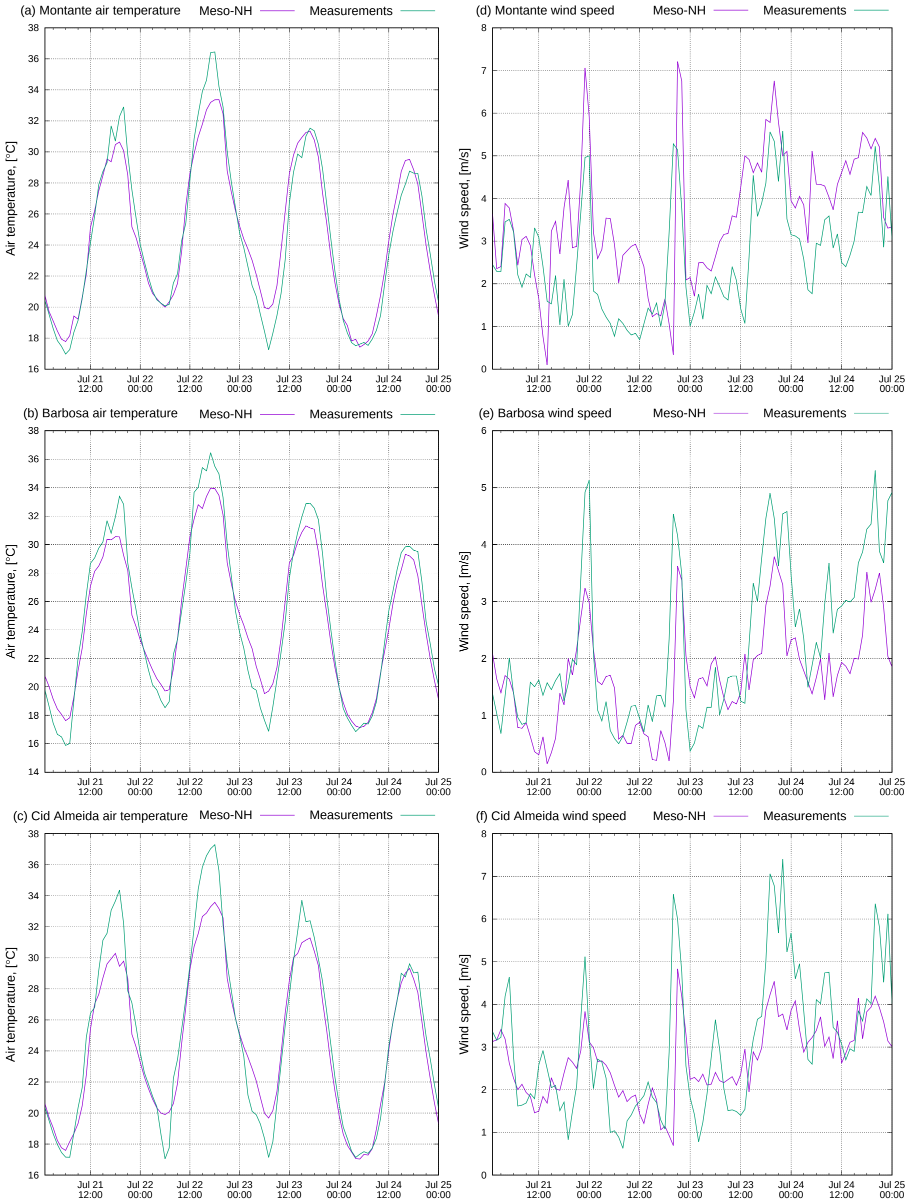


Figure 6. ~~Comparison of~~ Observed and simulated air temperature and wind speed at 2 meters for ALEX stations: Montante platform (a, d), Barbosa (b, e), and Cid Almeida (c, f) sites.

Both observed and simulated curves of Fig. 7 (a) reveal that sensible heat flux has two different periods during the day, positive when air-water temperature difference is negative, and vice-versa, showing that during daytime the water gets energy from the air and during night-time the water warms the nearby air. The transition between the two regimes is well captured by the model. Fig. 7 (b) also shows that the magnitude of the sensible heat flux is relatively small when compared with the other

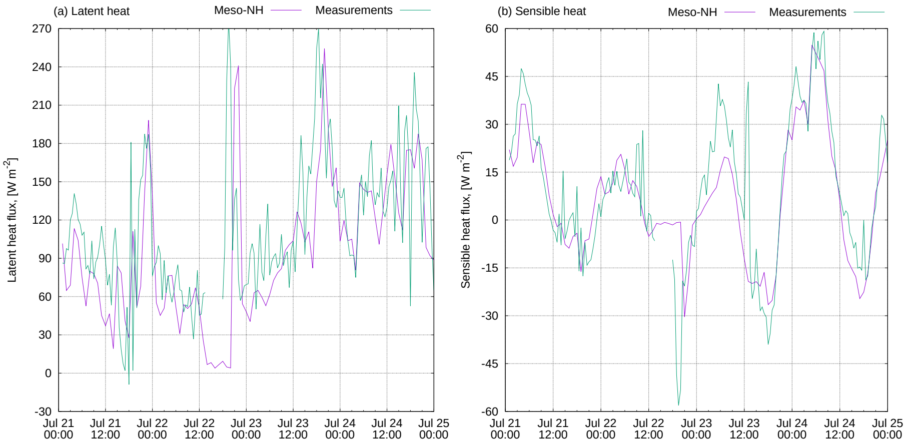


Figure 7. Observed and simulated latent (a) and sensible (b) heat fluxes at Montante floating platform.

terms of the energy balance. Daily maximum positive (negative) fluxes between 30 and 60 $\mathrm{Wm^{-2}}$ (-15 and -30 $\mathrm{Wm^{-2}}$) are well reproduced by the model. An apparently strange behavior appears on July 22 afternoon, with the sensible heat flux being almost zero. This effect, unfortunately not documented due to the lack of data, will be discussed later and is linked to the fact that the wind is very weak during this period (see Fig. 6 (d)).

More detailed analysis of ~~these curves shows that measurements have minimums of latent heat in the daytime~~ Fig 7 (a) shows that the lowest heat flux values usually occur during the afternoon (12:00 – 18:00 UTC), under windless conditions, and high peaks in the early evening (20:00 – 21:00 ~~). Simulation~~ UTC). The simulation reproduces these peaks with 1-2 hour delay which are related to the delay on the simulated wind speed. ~~Unfortunately, there is no data about fluxes for~~ The magnitude of the latent heat flux daily maximum (order of 200 – 250 $\mathrm{Wm^{-2}}$) is well captured by the model. The delay in the simulation of the peaks reduces the value of the correlation coefficient and is a manifestation of the so-called double-penalty that penalize high-resolution model scores. As seen in the Fig. 7 (b) the simulated latent heat flux is almost zero between 14:00 ~~–~~ and 16:00 ~~, 22 of July , but according to the model results both fluxes are tend to be around 0~~ ~~$^{-2}$~~ UTC of July 22. As pointed before, there is a gap in the measurements of the flux during this period, but data from the day before indicates that the results are realistic. This effect of almost zero evaporation from water on a very hot day is contrary to common sense and will be discussed later.

~~Wind direction on Barbosa and Cid Almeida stations.~~

Wind direction at ALEX stations is represented ~~on the~~ in Fig. 8. ~~Measurements show how wind direction changes to the opposite due to the lake breeze effect during the daytime between~~ Different behaviour in wind direction between the two station from 21 ~~and~~ to 23 of July ~~, not clearly seen on the simulation results on the grid-points near the ALEX stations. The structure of the simulated breeze will be discussed later.~~ is clearly seen from measurements data (green dots). In Barbosa station the wind changes from northwest to south regime during daytime while in Cid Almeida this effect is not observed. In the simulations this difference is not so clear, but is still visible during the afternoon on July 22. Barbosa station, located on the ~~North-West~~ northwest shore of the lake, indicates the presence of the lake breeze because its direction is the opposite to the

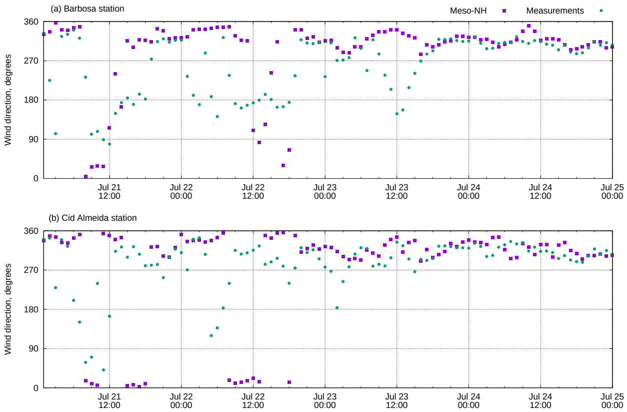


Figure 8. Observed and simulated wind direction on Barbosa and Cid Almeida stations.

dominant wind~~in this area~~. However, at Cid Almeida station on the ~~South-East~~ southeast shore breeze is co-directed with the dominant wind in the area, so, its appearance is difficult to track.

6 Lake ~~effects~~impact

To ~~study how the Alqueva lake affects the~~ analyse the impact of the Alqueva reservoir on local area the ~~following atmospheric parameters were used in this work:~~ changes of the following atmospheric variables, such as air temperature and potential temperature, relative humidity and water mixing ratio, and vertical and horizontal wind speed~~. Overall, simulation result is a 3 sets of 96 output files (for each horizontal resolution) of 1-hour timestep consisting of required atmospheric parameters. Only 1-and 250-resolution~~ , were considered. In this section only B and C domain datasets were used~~in this section.~~

~~During daytime water temperature is lower than air temperature, which is associated to a very weak air circulation over the water surface which leads to very low evaporation from the lake (refer to low latent heat flux values on Fig. 7 (a)). At this time period evaporation over the land is even higher that over the water. By late afternoon when the dominant sea breeze system reaches the region, smooth water surface significantly enhances the North-West wind. As the result, evaporation from the lake becomes very intensive.~~

~~Figure ?? shows an example of wind regime on the 1 domain in the morning (07:00 UTC). Dark blue color represents the lake area over the orography. At this time of the day before the establishment of the lake breeze, North-West wind prevails in the area with the magnitude of 3-5~~. ~~Simulated 10 wind (vectors) over orography (color scale) at 07:00 UT 22 July 2014; results from the 1 resolution domain.~~

6.1 Impact on air temperature and relative humidity

The ~~first level of air above the lake surface is the most affected by its impact. Fig. 9 illustrates the air temperature difference caused by~~ lower layers of air are the first to be affected by the presence of ~~the reservoir~~ water. Differences in air temperature at 2 meters ~~height~~ during 22 July ~~2014. We focus on this day because air temperature was the highest and the lake breeze expected to be strong and well distinguishable~~are shown in Fig. 9, the warmest day of the IOP and the one when the breeze was stronger. Positive anomaly (up to 3-4~~K~~ °C) can be traced during the period from 1 hour after the sunset (21:00 UTC) ~~until~~ to 1 hour after the sunrise (07:00 UTC). ~~Examples of this~~ By positive and negative anomalies here we mean the differences between LAKE1 and LAKE0 simulations. Examples of the positive night anomalies are illustrated in Fig. 9 (a, b). Night ~~North-West~~ northwest wind transports warm air from the lake to the ~~South-East~~ southeast part of the reservoir for up to 2~~km~~ km away from the shore. Daytime period is characterized by the negative temperature anomaly up to 7 °C (Fig. 9 (c-f)). This effect is essentially limited by the lake borders. When the large-scale sea breeze system arrives~~to the Alqueva area~~, temperature trace of the lake impact ~~are followed~~ is advected by the wind and can be found in 10-12 km away from the ~~South-East~~ southeast part of the reservoir (Fig. 9 (f)).

Vertical cross-sections ~~can~~ help to illustrate the processes in the atmosphere on different altitudes. ~~Such East-West~~ Two different cross-sections ~~along 38.215 °N (Fig. 10, position of this cross-section is indicated by a lower horizontal line on~~ S1 and S2 (the first one crosses the lake near Montante platform and the second in the middle, exact locations are indicated in Fig. 9, (a)) are shown to provide a better visualization of the three-dimensional structure of air circulation above the lake. Cross-sections S1 along 38.215 °N (Fig. 10) show the evolution of wind and the potential temperature during the 22 July in the

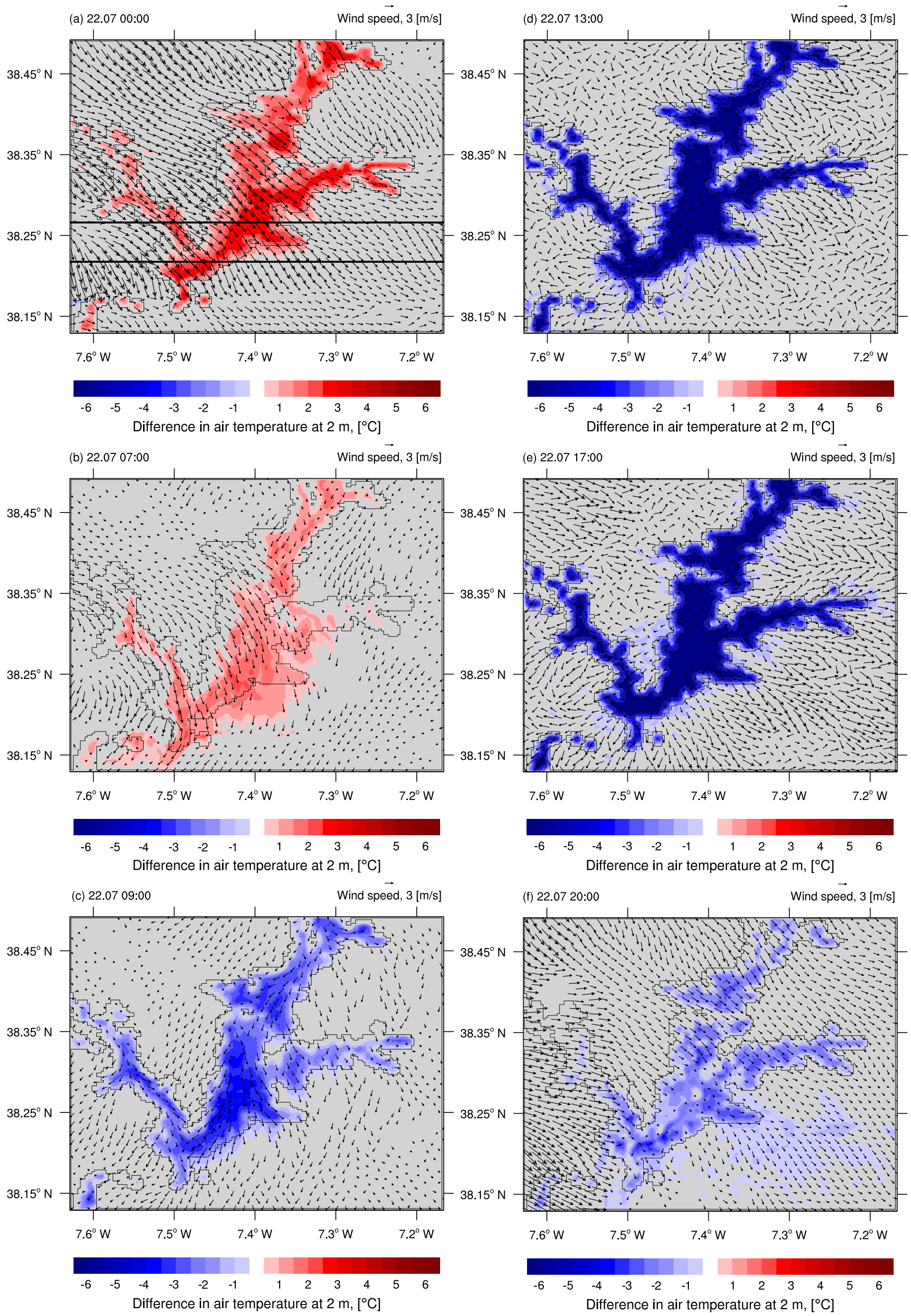


Figure 9. Anomalies in air temperature at 2 m ~~temperature anomaly~~ (~~difference between LAKE1 and LAKE0 experiments)~~ in filled contours) and horizontal wind in LAKE1 experiment (arrays, the scale is indicated in the upper rigth corner of each figure) of the reservoir on 22 of July 2014 on ~~the 250 resolution~~ domain C. Horizontal lines on (a) indicate the location of cross-sections S1 (southern) and S2 (northern).

experiment with the reservoir (simulation LAKE1). ~~Maximum of the temperature impact of the lake can be found~~ The highest impact on the air temperature can be observed in the early afternoon ~~, at~~ (12:00 – 14:00 ~~on the altitudes up to 1-1.2 , cooling all the boundary layer , which depth decreases (very clear seen on Fig. 10 (a))~~ UTC). The boundary layer is cooling down and its height decreases from more than 2 km above the ~~surface outside the zone of influence of Alqueva,~~ land outside to values close to 1 km over the ~~water reservoir~~lake surface (Fig. 10 (a)). The thermal anomaly induced by the presence of the reservoir seems to affect an area greater than ~~that~~ what was identified at the surface, especially in the middle of the boundary layer. Later on, at 19:00 – 20:00 UTC the powerful ocean breeze system reaches the area and cools the lower (1~~km~~ km) layer of air by 6-7 K. The progression of the sea breeze front is impressively well shown ~~on~~ in Fig. 10 (d) (20:00 ~~UT~~UTC), when it reaches the border of the reservoir, and ~~on~~ in Fig. 10 (e), (f) (21:00 ~~UT~~- 22:00 UTC), when it is already beyond the east bank of the Alqueva ~~lake~~reservoir.

Alqueva causes a similar anomaly on 2 m relative humidity which is shown in Fig. 11. At night when the temperature impact is negative some small negative differences in relative humidity can be seen over the lake surface (Fig. 11 (a)). There are also traces of daytime positive impact, essentially due to the decrease of air temperature, advected by the sea breeze in the southeast direction. In the morning, however, the difference of relative humidity can not be detected because the thermal impact is not strong enough (Fig. 11 (b)). Figures 11 (c), (d), and (e) show how relative humidity increases during the daytime over the water surface. The peak of the difference can reach 50% in the afternoon (Fig. 11 (f)). In general, lake impact on relative humidity is limited by the area of the reservoir and does not spread over the surrounding land.

6.2 Breeze effects

Differences in near surface sensible heat fluxes and ~~consequentely in air temperature~~ contrast of the air temperature over the land and water surfaces during the daytime ~~induces~~ induce the formation of the lake breeze system. The development of the lake breeze is illustrated ~~on~~ in Fig. 9 ~~. Wind arrows corresponding to~~ (arrows that corresponds to the wind speed lesser than 0.5 m/s are not ~~ploted. During nighttime~~ plotted). During the night, the large-scale circulation (Fig. 9 (a), (b)) ~~large-scale circulation, driven by the peninsular scale sea breeze system~~ is dominant in the area~~but after the sunrise when the temperature anomalies near surface changes to negative, winds blowing out of the the lake shores can be observed.~~ . After the sunrise (07:00 – 08:00 UTC) the air temperature over the water surface becomes lower than the air temperature over the surrounding areas, which induce a thermal circulation directed from the center of the lake to its shores. The breeze intensifies during the afternoon reaching 6 m/s in some areas (Fig 9 (d), (e)).

Daytime cross-sections ~~on~~ S1 in Fig. 10 (a, b, c) indicates that the direct lake breeze can be found on ~~the~~ altitudes up to 300 meters above ~~lake surface. Breeze wind speed in that case can reach 5-7 . Spreading of the lake breeze in horizontal plane~~ the lake, with a divergent flow over the water surface. The lake breeze intensity and pattern depends on the local orography, but usually the traces ~~of it~~ can be found ~~in~~ 4-6 km away from the lake shores (Fig. 10 (c)). ~~An~~ In altitude, a return flow is visible in the eastward wind component over the west shore and a westward component in the east of the reservoir which causes an upper-level ~~convergent return circulation can be noticed (~~convergence which can be seen in Fig. 10 (a, b, c)~~) by an increase of eastward component over the west shore, and an westward motion to East of the reservoir~~. We will return to this features

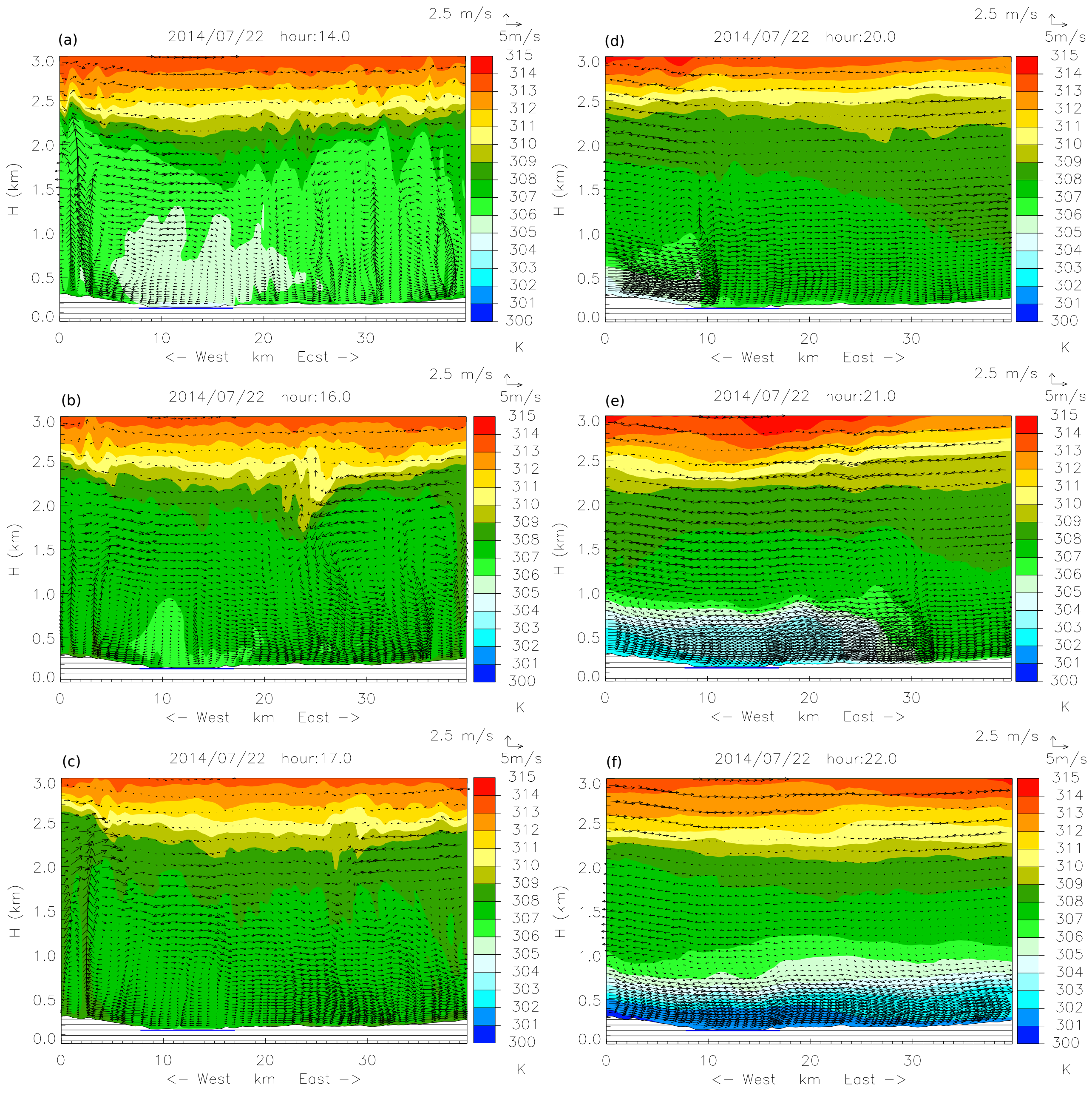


Figure 10. ~~East-West~~ East-west direction cross-sectons along 38.215 °N (S1, crosses the lake near Montante platform, ~~southernmost straight line in~~ Fig. 9 (a)) of potential temperature (filled contours) and ~~projection of~~ wind vectors in the plane of the cross-section (~~arrays~~arrows), at different ~~times~~ hours (indicated in the top of each figure) in LAKE1 experiment at 250 m horizontal resolution. The wind vertical and horizontal scales are indicated in the upper right corner of each figure. Blue line on the surface level indicates the location of the reservoir.

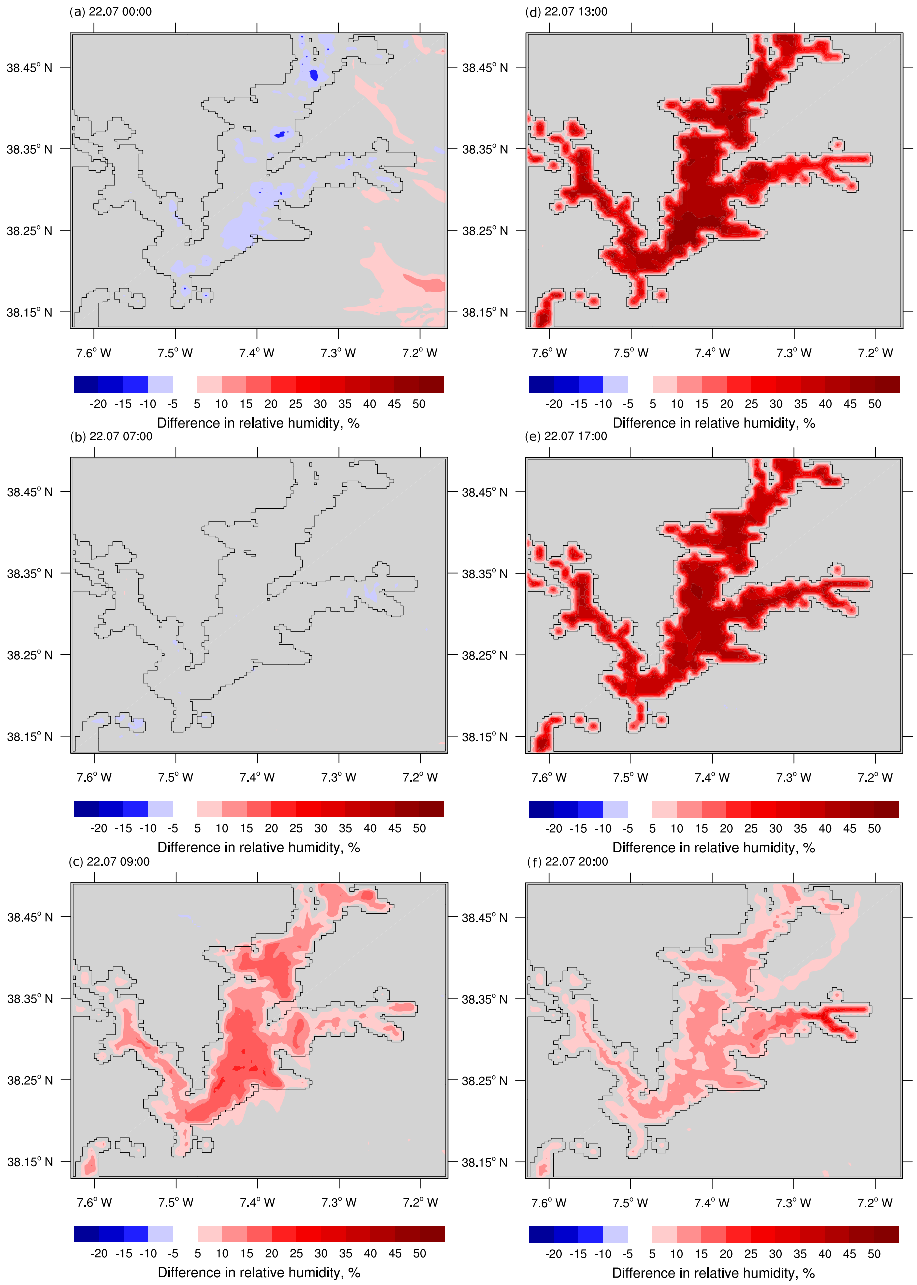


Figure 11. 2 m relative humidity anomalies (in filled contours) on 22 of July 2014 on domain C.

later ~~, during~~ together with the discussion of the ~~impacts of the teservoir~~ effects of the reservoir on the moisture field, ~~showing another cross-section,~~ in which the structure of the lake breeze system is more visible.

~~This breeze wind intensifes until~~ In the late afternoon (~~Fig. 9 (e)) when the wind speed can reach 7 . When~~ 18:00 UTC) the negative temperature anomaly due to the presence of the ~~mass body~~ lake is getting weaker, and breeze system starts to wane and dissipate. At 19:00 – 20:00 ~~when~~ the ocean breeze arrives to the area ~~, lake breeze already can not be traced~~ and overlaps the local circulations (Fig. 10 (d, e, f)).

~~Alqueva impact on the relative humidity at 2 height is shown on Fig. 11. 2 relative humidity anomaly (difference between LAKE1 and LAKE0 experiments) in filled contours on 22 of July 2014 on 250 resolution domain. The lake increases relative humidity up to 50% during the daytime while at night its influence is insignificant. The positive anomaly is limited by the area of the lake and does not spread over the surrounding land. It should be noted that the increase in the relative humidity is mainly due to the decrease in air temperature.~~

~~In fact, cross-sections presented on~~ Cross-sections S1 and S2 presented in Fig. 12 ~~(the position of the cross-sections are indicated with horizontal lines on Fig. 9 (a))~~ show that the lake breeze system includes a descending branch over the ~~lake area~~ reservoir that carries dry air from a height of about 2-2.5 km and redistribute it over the lake surface. ~~Two different locations of cross-sections (the first one is near Montante platform and the second one is in the middle of the lake) are shown to provide a better vizualization of the three-dimensional structure of air circulation above the lake.~~ This dry downstream ~~effect~~ is confirmed by the ~~results of measurement~~ measurements of water vapor mixing ratio at ~~Montante platform as~~ the Montante platform. As can be seen in Fig. 13 ~~, in which simulation results are compared with observations: it decreases to a minimum of about 7-8~~the observed and the simulated mixing ratio of water vapor have a daily minimum with average values of about 8-8.5 g kg^{-1} ~~every day after noon~~ around 14:~~00-15:00 and reaches a minimum~~ 00-16:00. During the afternoon of July 22, the day with a strong lake breeze, the minimum reached a value lower than 6 g kg^{-1}~~during the afternoon of the day of stonger lake breeze (July 22)~~. Out of the period in which the air ~~subside~~ over the lake ~~, the~~ subsides, the water vapor mixing ratio returns ~~to previous values of~~ beck to 9-10.5 g kg^{-1}. The presence of this dry downstream was proposed as a hypothesis by Potes et al. (2017) and is proved through the ~~simulations done in this study.~~ performed simulations. In the same Fig. 13 it is clearly seen that the model tends to overestimating the mixing ratio, except in the afternoon of July 22.

On the other hand, Fig. 12 also shows that outside the reservoir there ~~exist~~ are zones of low-level convergence and upward motion ~~which~~ that increase the moisture of the boundary layer ~~. this zones correspond to~~ and form some kind of lake breeze fronts. The complex shape of the reservoir implies an also complex 3D structure of the breeze system. Towards the ~~Southernmost~~ southernmost part, near the dam, the low level divergent breeze circulation is very clear, but the convergence upper-level return current is weaker (Fig. 12 (a, b, ~~and~~ c)). In contrary, near the ~~midle~~ middle of the reservoir (cross-section S2 in Fig. 12 (d, e, ~~and~~ f)) where two water branches exist, the circulation near the surface is more complex due to the presence of a land ~~band~~ area inbetween, but the subsidence motion is more ~~proeminent~~prominent, inducing a decrease in mixing ratio through the boundary layer, which reaches a magnitude of about 4 g kg^{-1} at 16:00 (Fig. 12 (f)).

Figure 14 illustrates this process in a horizontal plane. At midnight (Fig 14 (b)) the reservoir does not directly affect vapour mixing ratio in the air. In the morning hours, when the sun has risen, but the breeze system has not yet formed, a positive impact on the moisture over the lake can be seen due to the increase of the evaporation. This anomaly affects the air above central and southern part of the reservoir and is advected to other nearby areas (Fig 14 (c)). Later in the afternoon, with the

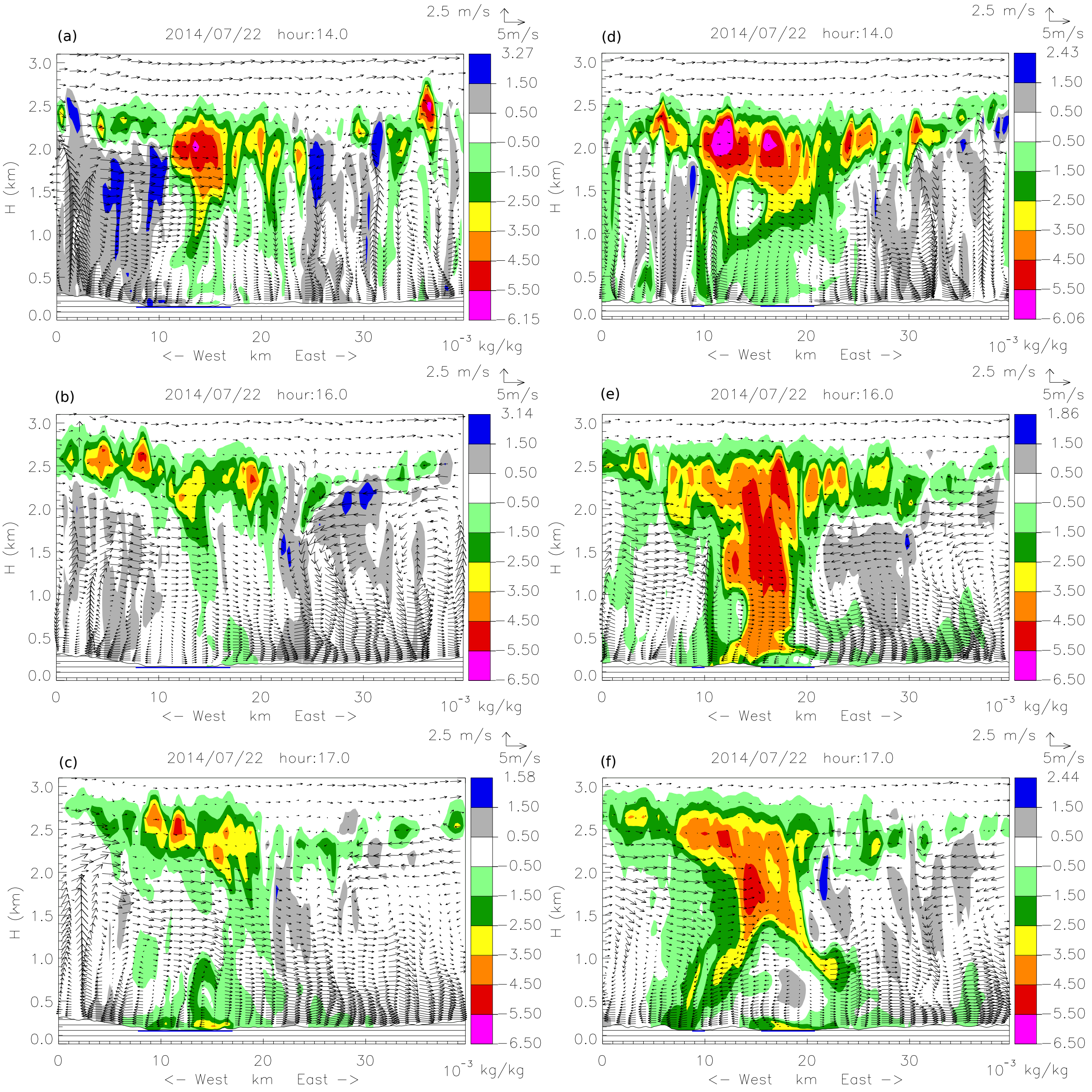


Figure 12. ~~East-West~~ East-west direction cross-sections S1 along 38.215 °N (a,b,c) and S2 along 38.274 °N (d, e, f) ~~(horizontal lines on Fig. 9 (a))~~ with the difference (LAKE1 and LAKE0 simulations) of water mixing ratio (filled contours), and ~~projection of~~ wind vectors in the plane of the cross-section (~~arrays~~arrows) in LAKE1 experiment at 250 m horizontal resolution at different times (indicated in the top of each figure). Blue line on the surface level indicates the location of the reservoir.

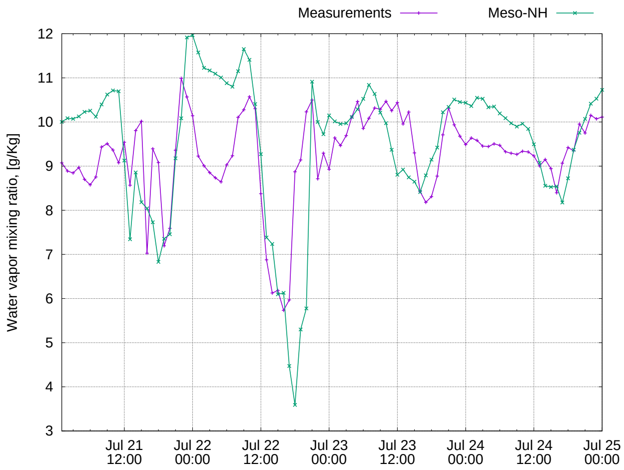


Figure 13. ~~Water~~ Observed and simulated water vapor mixing ratio over the Montante platform.

formation of the lake breeze, a negative impact can be traced over the water surface due to the descending branches of the local circulation (Fig. 14 (d, e)). This explains the afternoon decrease of the water vapour mixing ratio observed at the Montante platform as seen in Fig 13. The localization of the area of this negative anomaly changes in time, but predominantly it is over the larger southern part of the reservoir. With the dissipation of the local lake breeze system and the arriving of the stronger large scale northwestern wind, the negative moisture anomaly over the reservoir disappears and a positive effect is visible on the downwind region (Fig. 14 (a, f)), due to the increase of evaporation (note that Fig. 14 (a) corresponds to the night of July 21 to 22, when the effect was more noticeable).

During daytime, the water temperature is lower than the air temperature, which is associated to a very weak air circulation over the water surface which leads to very low evaporation from the lake (refer to low latent heat flux values in Fig. 7 (a)). At this time period evaporation over the land is even higher that over the water. By late afternoon when the dominant sea breeze system reaches the region, the northwestern wind accelerates significantly, passing over the smooth surface of the lake. As result, evaporation from the lake becomes very intense.

7 Conclusions

~~In this work we studied~~ This work is dedicated to the studies of the formation and magnitude of the summer lake breeze at the Alqueva reservoir, South Portugal, ~~and the impact~~ one of the impacts of the artificial lake on the local weather. The study was based on Meso-NH simulations of ~~an~~ a well documented case study of 22-24 July 2014. This period was taken for several reasons. First, a large volume of meteorological data was collected during these days, which allowed for a validation of the simulation results. Secondly, this period was hot and dry, which is typical for most summer days in this region.

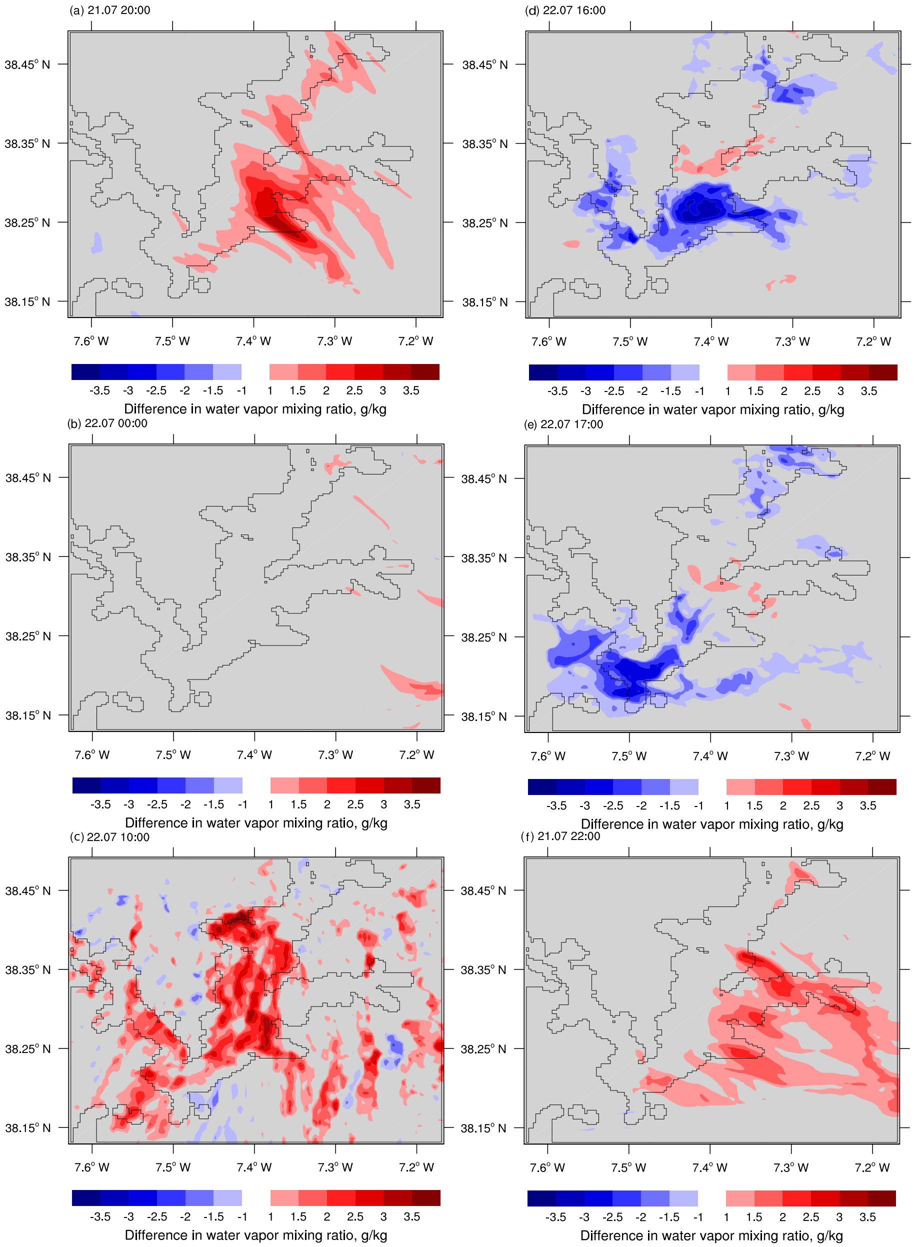


Figure 14. Observed and simulated water vapor mixing ratio anomalies in filled contours on 22 of July 2014 on domain C for selected hours

The model allowed to conduct the simulation with horizontal resolution of 250 meters which is fine enough to ~~figure out~~ resolve such relatively small scale lake breeze and to spot the impact of the reservoir on the detailed local boundary layer structure.

Due to the “youth” of the Alqueva reservoir it is possible to run atmospheric model with the surface conditions prevailing before the filling of the reservoir. Two simulations, one with ~~the~~ Alqueva and another one without it, allow to evaluate the ~~impact~~raw impact of the lake on the local weather regime.

~~We described the formation of~~ Formation and dissipation of the daytime breeze system induced by the reservoir are described in the work. On hot summer mornings the difference between air temperatures above water and neighbouring land surfaces induces the radial movement of air from the lake. The breeze system starts to form in the morning and the ~~lake breeze system during the daytime and its dissipation in late afternoon anticipated by the arrival of the larger scale sea breeze generated at the Portuguese west Atlantic coast. The magnitude of~~ peak of the wind speed reaches 6 m/s in the late afternoon. Simulation results show that the lake breeze ~~can reach 6 . It can be traced at about~~ could be detected at a distance of more than 6 km away from the ~~lake shore~~ the shores and on altitudes up to 300 m above ~~the lake surface. Daytime lake regime can be characterized by~~ water surface. In late afternoon the dissipation stage of the lake breeze system anticipated with the arrival of the larger scale sea breeze from the Portuguese west Atlantic coast. In early evening (19:00 – 20:00 UTC) the local lake breeze system can not be detected anymore. No reverse land breeze is detected during the night.

During daytime, the simulation testify the observed very low evaporation ~~rate~~ from water surface ~~, while at nighttime major sea breeze induces~~ (0 – 120 $\mathrm{Wm^{-2}}$ in terms of sensible heat flux), due to weak winds and the stable stratification of the internal atmospheric surface layer. A night-time, the strong winds associated with the Peninsular larger-scale circulation induced by the sea-land contrasts, induce a very high evaporation rate (200 – 250 $\mathrm{Wm^{-2}}$).

~~Cooling~~ The cooling effect of the ~~lake expressed in lower air temperatures (~~reservoir can decrease the air temperature up to 7~~) but~~ °C, nevertheless is limited by the lake borders and normally ~~not~~ can not be seen farther than few kilometers away from the shore mostly in ~~South-East direction. Altitude effect of the~~ southeast direction. The cooling can be found ~~at the~~ up to 1200 m above the lake surface.

~~The lower layer of the air over the lake usually are more wet during the daytime, but the presence of the lake makes a negative impact on the humidity at higher altitudes. Downward circulation induced by the lake breeze~~ Lake breeze system brings dry air from ~~the upper atmospheric layer~~ upper atmospheric layers (2-2.5 km) to near surface levels above the reservoir. This effect leads to the fact that the air above the surface of the lake becomes more dry in terms of water vapor mixing ratio, in spite of its relative humidity can increase up to 50% due to the decrease in air temperature.

Further work implies two directions. The first is tuning the lake model and its initialization in order to obtain more accurate results and reduce validation biases. The second is to carry out a longer experiment, which would cover a 12-month period. Such simulation could reveal seasonal aspects of the impact of Alqueva on local weather.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The work is co-funded by the European Union through the European Regional Development Fund, included in the COMPETE 2020 (Operational Program Competitiveness and Internationalization) through the ICT project (UID / GEO / 04683/2013) with the reference POCI-01-0145-FEDER-007690 and also through the ALOP project (ALT20-03-0145-FEDER-000004). Experiments were accomplished during the field campaign funded by FCT and FEDER-COMPETE: ALEX ~~2014~~ (EXPL/GEO-MET/1422/2013) FCOMP-01-0124-FEDER-041840.

References

Bates, G. T., Giorgi, F., and Hostetler, S. W.: Toward the Simulation of the Effects of the Great Lakes on Regional Climate, Monthly Weather Review, 121, 1373–1387, https://doi.org/10.1175/1520-0493(1993)121<1373:TTSOTE>2.0.CO;2, 1993.

Bechtold, P., Bazile, E., Guichard, F., Mascart, P., and Richard, E.: A mass-flux convection scheme for regional and global models, Quarterly Journal of the Royal Meteorological Society, 127, 869–886, https://doi.org/10.1002/qj.49712757309, 2001.

Bischoff-Gauß, I., Kalthoff, N., and Fiebig-Wittmaack, M.: The influence of a storage lake in the Arid Elqui Valley in Chile on local climate, Theoretical and Applied Climatology, 85, 227–241, https://doi.org/10.1007/s00704-005-0190-8, 2006.

Bonan, G. B.: Sensitivity of a GCM Simulation to Inclusion of Inland Water Surfaces, Journal of Climate, 8, 2691–2704, https://doi.org/10.1175/1520-0442(1995)008<2691:SOAGST>2.0.CO;2, 1995.

Bougeault, P. and Lacarrere, P.: Parameterization of Orography-Induced Turbulence in a Mesobeta–Scale Model, Monthly Weather Review, 117, 1872–1890, https://doi.org/10.1175/1520-0493(1989)117<1872:POOITI>2.0.CO;2, 1989.

Cohard, J.-M. and Pinty, J.-P.: A comprehensive two-moment warm microphysical bulk scheme. I: Description and tests, Quarterly Journal of the Royal Meteorological Society, 126, 1815–1842, https://doi.org/10.1002/qj.49712656613, 2000.

Cotton, W. R. and Pielke, R. A. S.: Human Impacts on Weather and Climate, Cambridge University Press, 2nd edn., 2007.

Crosman, E. T. and Horel, J. D.: Idealized Large-Eddy Simulations of Sea and Lake Breezes: Sensitivity to Lake Diameter, Heat Flux and Stability, Boundary-Layer Meteorology, 144, 309–328, https://doi.org/10.1007/s10546-012-9721-x, 2012.

Cuxart, J., Bougeault, P., and Redelsperger, J.-L.: A turbulence scheme allowing for mesoscale and large-eddy simulations, Quarterly Journal of the Royal Meteorological Society, 126, 1–30, https://doi.org/10.1002/qj.49712656202, 2000.

Drobinski, P. and Dubos, T.: Linear breeze scaling: from large-scale land/sea breezes to mesoscale inland breezes, Quarterly Journal of the Royal Meteorological Society, 135, 1766–1775, https://doi.org/10.1002/qj.496, 2009.

Ekhtiari, N., Grossman-Clarke, S., Koch, H., Souza, W. M., Donner, R. V., and Volkholz, J.: Effects of the Lake Sobradinho Reservoir (Northeastern Brazil) on the Regional Climate, Climate, 5, https://doi.org/10.3390/cli5030050, 2017.

Faroux, S., Kaptué Tchuenté, A. T., Roujean, J.-L., Masson, V., Martin, E., and Le Moigne, P.: ECOCLIMAP-II/Europe: a twofold database of ecosystems and surface parameters at 1 km resolution based on satellite information for use in land surface, meteorological and climate models, Geoscientific Model Development, 6, 563–582, https://doi.org/10.5194/gmd-6-563-2013, 2013.

Fouquart, Y. and Bonnel, B.: Computations of Solar Heating of the Earth's Atmosphere — A New Parameterization., Beitrage zur Physik der Atmosphare, 53, 35–62, 1980.

Hartmann, D. L.: Global physical climatology, International geophysics, 1994.

Hoinka, K. P. and Castro, M. D.: The Iberian Peninsula thermal low, Q. J. Roy. Meteorol. Soc., 129(590), 1491–1511, 2003.

Jarvis, A., Guevara, E., Reuter, H. I., , and Nelson, A. D.: Hole - filled SRTM for the globe : version 4 : data grid, published by CGIAR-CSI on 19 August 2008., 2008.

Kain, J. S. and Fritsch, M. J.: A One-Dimensional Entraining/Detraining Plume Model and Its Application in Convective Parameterization, Journal of the Atmospheric Sciences, 47, 2784–2802, https://doi.org/10.1175/1520-0469(1990)047<2784:AODEPM>2.0.CO;2, 1990.

Lac, C., Chaboureau, J.-P., Masson, V., Pinty, J.-P., Tulet, P., Escobar, J., Leriche, M., Barthe, C., Aouizerats, B., Augros, C., Aumond, P., Auguste, F., Bechtold, P., Berthet, S., Bieilli, S., Bosseur, F., Caumont, O., Cohard, J.-M., Colin, J., Couvreux, F., Cuxart, J., Delautier, G., Dauhut, T., Ducrocq, V., Filippi, J.-B., Gazen, D., Geoffroy, O., Gheusi, F., Honnert, R., Lafore, J.-P., Lebeaupin Brossier, C., Libois, Q., Lunet, T., Mari, C., Maric, T., Mascart, P., Mogé, M., Molinié, G., Nuissier, O., Pantillon, F., Peyrillé, P., Pergaud, J., Perraud, E., Pianezze, J., Redelsperger, J.-L., Ricard, D., Richard, E., Riette, S., Rodier, Q., Schoetter, R., Seyfried, L., Stein, J., Suhre, K., Thouron, O., Turner, S., Verrelle, A., Vié, B., Visentin, F., Vionnet, V., and Wautelet, P.: Overview of the Meso-NH model version 5.4 and its applications, Geoscientific Model Development Discussions, 2018, 1–66, https://doi.org/10.5194/gmd-2017-297, 2018.

Lascaux, F., Masciadri, E., and Fini, L.: MOSE: operational forecast of the optical turbulence and atmospheric parameters at European Southern Observatory ground-based sites — II. Atmospheric parameters in the surface layer 0-30 m, Monthly Notices of the Royal Astronomical Society, 436, 3147–3166, https://doi.org/10.1093/mnras/stt1803, 2013.

Lascaux, F., Masciadri, E., and Fini, L.: Forecast of surface layer meteorological parameters at Cerro Paranal with a mesoscale atmospherical model, Monthly Notices of the Royal Astronomical Society, 449, 1664–1678, https://doi.org/10.1093/mnras/stv332, 2015.

Lee, X., Liu, S., Xiao, W., Wang, W., Gao, Z., Cao, C., Hu, C., Hu, Z., Shen, S., Wang, Y., Wen, X., Xiao, Q., Xu, J., Yang, J., and Zhang, M.: The Taihu Eddy Flux Network: An Observational Program on Energy, Water, and Greenhouse Gas Fluxes of a Large Freshwater Lake, Bulletin of the American Meteorological Society, 95, 1583–1594, https://doi.org/10.1175/BAMS-D-13-00136.1, 2014.

Lopes, F., Silva, H. G., Salgado, R., Potes, M., Nicoll, K. A., and Harrison, R. G.: Atmospheric electrical field measurements near a fresh water reservoir and the formation of the lake breeze, Tellus A: Dynamic Meteorology and Oceanography, 68, 31 592, https://doi.org/10.3402/tellusa.v68.31592, 2016.

Lunet, L., Lac, C., Auguste, F., Visentin, F., Masson, V., and Escobar, J.: Combination of WENO and Explicit Runge–Kutta Methods for Wind Transport in the Meso-NH Model, Monthly Weather Review, 145, 3817–3838, https://doi.org/10.1175/MWR-D-16-0343.1, 2017.

Masciadri, E., Lascaux, F., and Fini, L.: MOSE: operational forecast of the optical turbulence and atmospheric parameters at European Southern Observatory ground-based sites — I. Overview and vertical stratification of atmospheric parameters at 0-20 km, Monthly Notices of the Royal Astronomical Society, 436, 1968–1985, https://doi.org/10.1093/mnras/stt1708, 2013.

Masson, V.: A Physically-Based Scheme For The Urban Energy Budget In Atmospheric Models, Boundary-Layer Meteorology, 94, 357–397, https://doi.org/10.1023/A:1002463829265, 2000.

Masson, V., Le Moigne, P., Martin, E., Faroux, S., Alias, A., Alkama, R., Belamari, S., Barbu, A., Boone, A., Bouyssel, F., Brousseau, P., Brun, E., Calvet, J.-C., Carrer, D., Decharme, B., Delire, C., Donier, S., Essaouini, K., Gibelin, A.-L., Giordani, H., Habets, F., Jidane, M., Kerdraon, G., Kourzeneva, E., Lafaysse, M., Lafont, S., Lebeaupin Brossier, C., Lemonsu, A., Mahfouf, J.-F., Marguinaud, P., Mokhtari, M., Morin, S., Pigeon, G., Salgado, R., Seity, Y., Taillefer, F., Tanguy, G., Tulet, P., Vincendon, B., Vionnet, V., and Voldoire, A.: The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes, Geoscientific Model Development, 6, 929–960, https://doi.org/10.5194/gmd-6-929-2013, 2013.

Miranda, P., Abreu, F., and Salgado, R.: Estudo de Impacte Ambiental do Alqueva, Tech. rep., Instituto de ciencia aplicada e tecnologia, Faculdade de Ciências, Universidade de Lisboa, 1995.

Miranda, P. M. and James, I. N.: Non-linear three-dimensional effects on gravity-wave drag: Splitting flow and breaking waves, Quarterly J. Royal Meteorological Society, 118, 1057–1081, 1992.

Mironov, D.: Parameterization of lakes in numerical weather prediction. Description of a lake model. COSMO Technical Report, Deutscher Wetterdienst, 11, Pp. 41, 2008.

Morcrette, J.-J.: Radiation and cloud radiative properties in the European Centre for Medium Range Weather Forecasts forecasting system, Journal of Geophysical Research: Atmospheres, 96, 9121–9132, https://doi.org/10.1029/89JD01597, 1991.

Nicoll, K. A., Harrison, R. G., Silva, H. G., Salgado, R., Melgâo, M., and Bortoli, D.: Electrical sensing of the dynamical structure of the planetary boundary layer, Atmospheric Research, 202, 81–95, https://doi.org/https://doi.org/10.1016/j.atmosres.2017.11.009, 2018.

Noilhan, J. and Mahfouf, J.-F.: The ISBA land surface parameterisation scheme, Global and Planetary Change, 13, 145 – 159, https://doi.org/10.1016/0921-8181(95)00043-7, soil Moisture Simulation, 1996.

Pergaud, J., Masson, V., Malardel, S., and Couvreux, F.: A Parameterization of Dry Thermals and Shallow Cumuli for Mesoscale Numerical Weather Prediction, Boundary-Layer Meteorology, 132, 83, https://doi.org/10.1007/s10546-009-9388-0, 2009.

Pielke, R. A.: A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida, Monthly Weather Review, 102, 115–139, https://doi.org/10.1175/1520-0493(1974)102<0115:ATDNMO>2.0.CO;2, 1974.

Pielke, R. A. S.: Mesoscale Meteorological Modeling, Academic Press, 3rd edn., 2013.

Pinty, J.-P. and Jabouille, P.: A mixed-phase cloud parameterization for use in mesoscale non-hydrostatic model: simulations of a squall line and of orographic precipitations., Proc. Conf. of Cloud Physics, Everett, WA, USA, Amer. Meteor. soc., pp. 217–220, 1998.

Policarpo, C., Salgado, R., and ao C., M. J.: Numerical Simulations of Fog Events in Southern Portugal, Advances in Meteorology, 2017, 16, 2017.

Potes, M., Costa, J. M., and Salgado, R.: Satellite remote sensing of water turbidity in Alqueva reservoir and implications on lake modelling, Hydrol. Earth Syst. Sci., 16, 1623–1633, https://doi.org/doi:10.5194/hess-16-1623-2012, 2012.

Potes, M., Salgado, R., Costa, M. J., Morais, M., Bortoli, D., Kostadinov, I., and Mammarella, I.: Lake–atmosphere interactions at Alqueva reservoir: a case study in the summer of 2014, Tellus A: Dynamic Meteorology and Oceanography, 69, 1272 787, https://doi.org/10.1080/16000870.2016.1272787, 2017.

Salgado, R.: Interacção solo-atmosfera em clima semi-àrido, Ph.D. thesis, Universidade de Èvora, 2006.

Salgado, R. and Le Moigne, P.: Coupling of the FLake model to the Surfex externalized surface model, Boreal Environ. Res., 15, 231–244, 2010.

Salgado, R., Miranda, P. M. A., Lacarrère, P., and Noilhan, J.: Boundary layer development and summer circulation in Southern Portugal, Tethys, 12, 33–44, https://doi.org/10.3369/tethys.2015.12.03, 2015.

Samuelsson, P., Kourzeneva, E., and Mironov, D.: The impact of lakes on the European climate as simulated by a regional climate model, Boreal Environment Research, 15, 113–129, http://www.borenv.net/BER/pdfs/ber15/ber15-113.pdf, 2006.

Segal, M., Leuthold, M., Arritt, R. W., Anderson, C., and Shen, J.: Small Lake Daytime Breezes: Some Observational and Conceptual Evaluations, Bulletin of the American Meteorological Society, 78, 1135–1147, https://doi.org/10.1175/1520-0477(1997)078<1135:SLDBSO>2.0.CO;2, 1997.

Silva, A., De Lima, I., Santo, F., and V., P.: Assessing changes in drought and wetness episodes in drainage basins using the Standardized Precipitation Index, Bodenkultur, 65 (3-4), 31–37, 2014.

Stein, J., Richard, E., Lafore, J. P., Pinty, J. P., Asencio, N., and Cosma, S.: High-Resolution Non-Hydrostatic Simulations of Flash-Flood Episodes with Grid-Nesting and Ice-Phase Parameterization, Meteorology and Atmospheric Physics, 72, 203–221, https://doi.org/10.1007/s007030050016, 2000.

Thiery, W., Martynov, A., Darchambeau, F., Descy, J.-P., Plisnier, P.-D., Sushama, L., and van Lipzig, N. P. M.: Understanding the performance of the FLake model over two African Great Lakes, Geoscientific Model Development, 7, 317–337, https://doi.org/10.5194/gmd-7-317-2014, 2014.

Zhao, L., Jin, J., Wang, S.-Y., and Ek, M. B.: Integration of remote-sensing data with WRF to improve lake-effect precipitation simulations over the Great Lakes region, Journal of Geophysical Research: Atmospheres, 117, https://doi.org/10.1029/2011JD016979, d09102, 2012.