**# Abstract**

Ecosystems adapt differently to global warming through microclimate factors. Mires are sensitive habitats that strongly rely on local soil properties, which makes them a good model to understand how local climate parameters counteract the effects of climate change. We quantified the temperature buffering effect in waterlogged mire soils as compared with adjacent dry soils.

We buried dataloggers at 5 cm depth in waterlogged and dry points in 8 mires of the Cantabrian Mountains (Spain, Southwestern Europe) and recorded soil temperatures for c. 5 years. We also compared our local measures with air temperatures predicted by the CHELSA model.

Waterlogged soils had less diurnal thermal amplitude (-2.3 ºC), less annual thermal amplitude (-5.1 ºC), cooler summer maximums (-4.3 ºC) and warmer winter minimums (+0.8 ºC). CHELSA air temperatures only correlated significantly (p < 0.05) with the winter minimum temperatures (Pearson's r > 0.83), and CHELSA predictions were less accurate (higher RMSE) for waterlogged soils, except for the summer maximums.

We conclude that mire soils show a thermal buffer effect that insulates them from the surrounding landscape. This effect is stronger at the warm end of the climatic spectrum, i.e. during summer and at lower elevations. These results highlight the potential refugial character of mires under global warming, and the need to integrate microclimate measurements into climate change models.

**# Keywords**

bog, CHELSA, climatic model, datalogger, fen, peatland, soil temperature, wetland

**# Introduction**

Climate change [@RN3586] affects global biodiversity, from drylands [@RN4672] to forests [@RN4673] and oceans [@RN4674]. An accurate prediction of species responses requires to focus on physiologically-relevant variables related to critical plant growth periods [@RN4765]. Traditional models of species responses to global warming are based on macroclimatic data from weather stations. Recently, several authors have pointed out the need of complementing these models with \*in situ\* microclimatic measures [@RN4758; @RN4759; @RN4760; @RN4761]. As has been shown for European forests [@RN4763], ecosystems usually respond to broad climatic changes through local processes. Increasingly there are downscaling efforts based on atmospheric microclimate networks distributed in complex terrain that focus on topographic effects on air temperature [@RN3279], but hydrologic factors under edaphic control require more attention.

Mires are permanent semi-terrestrial peatlands whose soils remain waterlogged but not inundated during most of the year [@RN3161]. The term mire encompasses peatlands that are classified as either ombrotrophic (rain-fed bogs) or minerotrophic (groundwater-fed fens). These are azonal habitats whose existence depends on local soil properties rather than macroclimatic zonation [@RN3328]. It has been known for a relatively long time that groundwater can produce a buffer effect on soil temperature, keeping soils warmer than air during cold periods, and vice versa [@RN4940; @RN3344; @RN3201]. Root-zone temperature is a major determinant of plant ecophysiology [@RN3024], so the groundwater buffer effect is expected to allow mire plants to live in a wider range of air temperatures than they could otherwise. Indeed, mires have a relatively homogeneous flora across their range despite their broad distribution. In Europe, fens are distributed from the Iberian Peninsula to Fennoscandia and from low valleys to the alpine belt [@RN4678]. In the United States, fens are distributed across the glaciated Midwest and Northeast, as well as portions of the Appalachian Mountains and mountainous West [@RN4933].However, continued aridification is expected to significantly reduce the overall extent of wetlands as it has been shown in the Midwestern United States [@RN4934]. In the arctic, temperate-continental and suboceanic regions of boreal Russia mires make up an important part of the landscape, from 20 to 80 % of the surface of different regions stretching from Europe to the Pacific [@RN4937].

Clara M. Frederick [-@RN4940] showed the existence of a buffer effect comparing soil temperatures taken at Cedar Bog (Ohio, United States) with temperatures from a neighbouring agricultural station. Recently, more soil temperature measurements have become available for mires of North America [@RN3204], Western Europe [@RN2356] and Central Europe [@RN4675]. Their comparison with air temperatures derived from models has shown that mire soils are indeed warmer in winter and cooler in summer, thus giving support to the existence of the groundwater thermal buffer [@RN2356; @RN4675]. Furthermore, the effect has been linked to the composition of mire flora and fauna [@RN4675; @RN4679], the growth rings of mire trees [@RN3060] and the role of mires as glacial refugia [@RN2513; @RN4680].

Mires meet certain criteria that make them especially vulnerable to climate change [@RN4675]: (a) preponderance of species that evolved under a cold climate; (b) low productivity due to nutrient limitation, making them sensitive to increased nutrient cycling caused by warming [@RN4676]; and (c) scattered distribution pattern, which limits species dispersal and migration [@RN4677]. Therefore, mires are priority habitats for biodiversity conservation, harbouring high numbers of endangered species [@RN3122], and supporting highly adapted floras in spatially reduced areas [@RN2960]. Worryingly, mires retain high levels of methane and carbon which can be released due to global warming [@RN4764]. Habitat distribution models have predicted a loss of mire area as a consequence of ongoing climate change [@RN2937].

It is evident that the groundwater buffer effect will play a determinant role in the response of mire habitats to climate change [@RN4936]. Both bogs and fens are actively peat forming and are dependent on precipitation, whereas fens rely also on sources of telluric water from mineral ground. Moreover, they are composed from microreliefs and a specific plant cover zonation which makes them especially sensitive to small changes in wetness. Climate change affects the quantity, timing and spatial distribution of precipitation, leading to changes in surface wetness which alter the intensity or organic decomposition by disturbing the conditions for plant grow and the depth of air penetration [@RN4935]. Global warming would also result in warmer groundwater delivered to fens and in drier conditions, but there is a gap of knowledge about the rate of such changes and their ecological consequences within the mires [@RN4936].

As is the case for all azonal habitats, locally measured temperatures are essential to understand this response. Available references recorded temperatures only on waterlogged soils, using model-derived air temperatures for comparison [@RN2356; @RN4675; @RN4679]; or recorded temperatures in both wet and dry spots but for less than a year, lacking representation throughout the growth cycle of mire vegetation [@RN3204; @RN3060]. This article provides the first measurement of the thermal buffer against surrounding non-mire areas, based on soil temperatures recorded during a period of five years. These measures can be used to support previous evidence about the general effects of soil moisture on thermal buffering [@RN3204; @RN2356; @RN4675; @RN4936] and to determine the magnitude of this buffering within microrefugia habitats. Specifically, we tested the hypotheses that, when compared to adjacent dry soils, waterlogged mire soil are (i) warmer in winter and (ii) colder in summer; and have less thermal amplitude in (iii) daily and (iv) annual scales. In addition, we compare \*in situ\* measurements with data derived from the CHELSA climatic models [@RN4766].

**# Materials and methods**

This study took place in the temperate oceanic region of north-western Spain (43º N, 5º W) (Fig. \@ref(fig:fig1)a). Local geography and climate are dominated by the Cantabrian Mountains (> 1500 m above sea level), which run parallel to the coast and trap the prevailing NW Atlantic winds. In the study area, average annual precipitation ranges from 800 mm at the low elevations to 1800 mm at the high mountains, while average annual temperature ranges from 12.5 ºC to 5 ºC (source = Agencia Estatal de Meteorología, http://www.aemet.es/es/serviciosclimaticos/). Under the most extreme emissions scenario, the latest projection expects temperatures to increase by 4 ºC and precipitation to decrease by c. 10 % by the end of the century, although the precipitation projections are subjected to great uncertainty [@RN4939]. This humid climate harbours the south-western limit of mire communities in Europe [@RN2982; @RN3246]. Rain-fed raised bogs (https://eunis.eea.europa.eu/habitats/260) are very rare and appear locally on top of acid valley mires (https://eunis.eea.europa.eu/habitats/526) which be found from the coast to just below the treeline, in poorly drained valleys and former glacial lakes. Glacial lakes undergoing silting develop transition mires and quaking bogs communities (https://eunis.eea.europa.eu/habitats/1637) in the water-to-land transition. Spring fens appear in the mountains above 1000 m; they range from soft-water poor fens (https://eunis.eea.europa.eu/habitats/279) on acid bedrocks, to alkaline calcareous fens (https://eunis.eea.europa.eu/habitats/277) on limestone.

We selected `r length(unique(temperatures$Logger))/2` mire sites representing the regional elevation gradient of mire vegetation and the different mire types (Table 1). Although we classify two of these sites as rain-fed bogs based on their vegetation (\*Oxycocco-Sphagnetea\* Br.-Bl. et Tx. ex Westhoff et al. 1946), we must note that these bogs are very poorly developed over valley mires and in tight connection to the underlying water table coming from streams, therefore all of our sites have waterlogging feed by streams or springs. In each site, we buried two dataloggers (M-Log5W, GeoPrecision, Ettlingen, Germany; accuracy: +/- 0.1 ºC (at 0 ºC), resolution: 0.01 ºC) at a depth of 5 cm below the upper layer of the soil. In this ecosystem, it is at this depth that true soil begins to develop, under the porous upper layers made up of live mosses. We installed one datalogger in a flat waterlogged spot within the mire; the other one in the close vicinity, but in a flat and dry upland area outside the mire (Fig. \@ref(fig:fig1)b). The vegetation was always either mire or pasture, with no shrubs, trees or any other landscape features shading the measuring points. Dataloggers recorded temperature once every hour and stayed on site for approximately five years, after which we retrieved them and downloaded their records. At the moment of retrieval, the internal clock of all dataloggers had not deviated for more than four hours.

All data processing and analysis was performed in R [@RN2315]. The original data, R code for the analysis and creation of the manuscript can be accessed at the GitHub repository https://github.com/efernandezpascual/mires. To clean the logs we took the following steps: (i) removing records from the first week after installation, to account for the installation process and the settling of the soils; and (ii) keeping only time series with records for both the dry and waterlogged points, because some of the dataloggers had failed at different points in time. Afterwards, we calculated four bioclimatic variables for each datalogger: (1) the mean diurnal range; i.e. the average for the whole period of the daily differences between the maximum and the minimum temperatures recorded in the day; (2) the maximum temperature of the warmest month; i.e. the average of the daily maximum records, for the warmest month; (3) the minimum temperature of the coldest month; i.e. the average of the daily minimum records, for the coldest month; and (4) the annual range; i.e. the difference between the maximum temperature of the warmest month and the minimum temperature of the coldest month. These are classical bioclimatic variables that indicate the limiting factors (extreme temperatures) and seasonality (diurnal and annual range) that organisms must tolerate. To compare our measurements with model-based predictions of air temperature, we downloaded from CHELSA the same bioclimatic variables for our measuring coordinates.

To test if the differences between dry and waterlogged points were significant, we used paired t-tests (n = 8 paired sites per each of the four bioclimatic variables). Tests were one-tailed, according to the following hypotheses: the dry point would have a higher diurnal range, a higher maximum temperature, a lower minimum temperature, and a higher annual range. To compare our soil measurements with the CHELSA air temperatures we calculated Pearson's correlation between both sets of values, and we also calculated the root-mean-square error (RMSE) of the CHELSA values as a measure of their accuracy (n = 8 sites per combination of bioclimatic variable and dry/waterlogged condition) using the package \*Metrics\* [@RN4941].

**# Results**

Dataloggers recorded temperatures for five years in five of the sites, four years in two, and two years in one. Time series showed considerably less variation at waterlogged points, for all eight site comparisons (Fig. \@ref(fig:fig2)).

Bioclimatic variables (Table 2 and Fig. \@ref(fig:fig3)) supported this notion. The mean annual range was wider at dry points, as was the mean diurnal range. Maximum temperatures of the warmest months were usually higher at dry measuring points. The opposite was true for the minimums of the coldest months, in which case temperature was generally colder at dry points, although the difference was less pronounced than for the maximums (Fig. \@ref(fig:fig3)).

Patterns regarding the maximum temperatures and annual range were especially noticeable at both low (El Molinucu, La Malva) and high (La Recoleta) elevations. The pattern for the diurnal range, however, was more prominent just at the low sites (El Molinucu, La Malva), whereas the minimums of the coldest months showed no specific pattern (Table 2).

T-tests supported the original hypotheses; namely waterlogged measuring points had (a) smaller diurnal fluctuations (t = `r ttests %>% filter(Trait == "Diurnal range") %>% pull(t.statistic) %>% round(2)`, p = `r ttests %>% filter(Trait == "Diurnal range") %>% pull(t.p.value) %>% round(3)`, effect size = `r ttests %>% filter(Trait == "Diurnal range") %>% pull(t.estimate) %>% round(2)` ºC, 95 % CI = -∞, `r ttests %>% filter(Trait == "Diurnal range") %>% pull(t.conf.int.2.) %>% round(2)`); (b) lower maximums (t = `r ttests %>% filter(Trait == "Summer max") %>% pull(t.statistic) %>% round(2)`, p = `r ttests %>% filter(Trait == "Summer max") %>% pull(t.p.value) %>% round(3)`, effect size = `r ttests %>% filter(Trait == "Summer max") %>% pull(t.estimate) %>% round(2)` ºC, 95 % CI = -∞, `r ttests %>% filter(Trait == "Summer max") %>% pull(t.conf.int.2.) %>% round(2)`); (c) higher minimums (t = `r ttests %>% filter(Trait == "Winter min") %>% pull(t.statistic) %>% round(2)`, p = `r ttests %>% filter(Trait == "Winter min") %>% pull(t.p.value) %>% round(3)`, effect size = `r ttests %>% filter(Trait == "Winter min") %>% pull(t.estimate) %>% round(2)` ºC, 95 % CI = `r ttests %>% filter(Trait == "Winter min") %>% pull(t.conf.int.1.) %>% round(2)`, ∞), and (d) smaller annual fluctuations (t = `r ttests %>% filter(Trait == "Annual range") %>% pull(t.statistic) %>% round(2)`, p = `r ttests %>% filter(Trait == "Annual range") %>% pull(t.p.value) %>% round(3)`, effect size = `r ttests %>% filter(Trait == "Annual range") %>% pull(t.estimate) %>% round(2)` ºC, 95 % CI = -∞, `r ttests %>% filter(Trait == "Annual range") %>% pull(t.conf.int.2.) %>% round(2)`).

The CHELSA climatic model (Table 3 and Fig. \@ref(fig:fig4)) provided air temperatures that were significantly correlated (p < 0.05) with soil temperatures only in the case of the minimums of the coldest month, both at dry points (Pearson's r = 0.90) and waterlogged points (Pearson's r = 0.84). The correlation between CHELSA and soil values was marginally significant (p = 0.05) in the case of the maximums of the warmest month, but only at dry points (Pearson's r = 0.71). The values of CHELSA did not correlate with soil temperatures in the rest of the cases (p > 0.05). RMSE indicated that the predictions of CHELSA were more accurate at dry points for the cases of the annual range, the diurnal range and the winter min; the CHELSA values were more accurate at waterlogged points in the case of the summer max.

**# Discussion**

The results presented here quantify the size of the thermal buffer effect that takes place in waterlogged mire soils [@RN4940], when compared with adjacent dry soils. The mire thermal buffer had been compared previously with air temperatures derived from models, with generally similar results [@RN2356; @RN4675]. The mire buffer had also been compared to dry soils at 10 cm depth [@RN3204; @RN3060]; our results confirm those findings at 5 cm depth and extend them to the full year. Thus, the pattern is reproducible among years, out to five years. Therefore, there exists a thermal buffer effect in mire soils that makes their temperatures less extreme than the surrounding landscape. In our study, this effect seems stronger during warmer periods. This highlights the importance of using fine-scale microclimatic data to assess vegetation responses to climate change [@RN4683; @RN4758; @RN4763].

One important difference with previous studies is the importance of the buffer during winter. The articles that had used model air temperatures as a control concluded that the buffer effect was stronger at the cold end of the thermal gradient, i.e. in winter and at night [@RN2356; @RN4675]. In the case of this investigation, the situation was reverse: the effect was weaker when considering the minimum temperatures of the cold period. This indicates the importance of identifying root temperatures when working with plant communities. At high elevations of the study region, the soil can remain covered by snow for periods of winter, and this has its own insulating effect on soil temperatures [@RN2392]. Indeed, snow cover has being described as one of the vertical features that affects vegetation distribution in a local manner [@RN4760].Taking into account that the mentioned studies used a 5 cm depth for observation, it may be worth to use a deeper depth in winter to avoid this snow effect.

In concordance with our results, the air temperature measured at 0.5 m from the surface of boreal bogs is lower at the wetter zones, at least during the warmest months [@RN4761]. Thus, the water buffering effect seems to take place both at southern and northern latitudes and may affect not only the temperature in the soil but also the air temperature within certain height from the soil. Nonetheless, Philippov \*et al.\* did not record winter months, so more monitoring is needed at more northern latitudes, where the winter effect may be more relevant [@RN4675].

The buffering effect was much stronger during the summer. This was most noticeable in the two lowest elevations, El Molinucu and La Malva. La Malva showed especially high summer temperatures within the dry soils (> 40 ºC). It must be noted that this difference of > 15ºC between the dry and waterlogged points, separated by a few meters, is almost four times the warming expected in the study region at the end of this century (+ 4 ºC) under the more extreme emissions scenario [@RN4939]. Whereas the rest of the study sites are flat, La Malva is a calcareous spring in a southeast-facing slope on limestone, a place experiencing sub-Mediterranean conditions at the micro-scale [@RN4681], and surrounded by a forest of evergreen oaks (\*Quercus rotundifolia\* Lam., \*Quercus faginea\* Lam.). This suggests the importance of groundwater in the existence of mire vegetation in Mediterranean areas [@RN4682], not only from the water-availability aspect, but also providing cooling regulation during summer [@RN3344]. The buffering was also prominent at one of the highest elevations, La Recoleta, which may be explained by the high saturation of water in this kind of habitat, a quaking bog, i.e. a former glacial lake undergoing silting. However, more studies focusing on each kind of habitat are needed in order to understand the relation between hydrology conditions and microclimatic effects.

Most models currently employed to predict vegetation and species distribution use macroclimatic parameters, like the ones obtained from CHELSA [@RN4766]. This study revealed that CHELSA values correlate relatively well with soil temperatures in the case of the minimum temperatures at the coldest month, but not with the rest of the bioclimatic variables under study. Moreover, CHELSA predictions were less accurate for the waterlogged soils, except for the summer max, which might be the consequence of the noise introduced by sun-heated soil. In addition to the water buffering effect, other traits may explain the differences between our results and CHELSEA values like the height of temperature measurement, 5 cm below the upper layer of the soil in our study versus 2 m above the ground in CHESA; the temporal scale of observation, hourly based for a 5 years period in our study versus 30 arc sec resolution for a 34 years period; and the spatial scale, (AÑADIR). This brings out the importance of studying local factors as drivers of microclimatic changes [@RN4762]. These factors contribute to landscape heterogeneity, producing safe sites that can act as micro-refugees and buffer species from regional climatic warming.

In summary, this article shows that waterlogged mire soils have a thermal buffer when compared to adjacent soils, contributing to their behaviour as mild island habitats in a landscape that can be more thermally variable [@RN4936; @RN4675]. The effect occurs during cold and warm periods, but it is stronger during the summer, at least in the study area. However, the climatic buffering within microrefugia would strongly rely on the water regime, a key factor for their conservation. Long-term decreases in precipitation could reduce the groundwater discharge into the mires, with potentially fatal consequences if the mire dries out during warmer summers. For the study area, the latest projections for the end of the century [@RN4939] consider a decrease of c. 10 % in annual precipitation. Future recording schemes are needed to obtain local soil temperatures from other latitudes, and from more microtopographies within the same mire. We must consider that the microclimatic effect is not limited to mires as it can also be found in other habitats related with thawing snow like alpine and arctic-alpine slopes [@RN3279; @RN4938]. Our study provides useful microclimate parameters to improve the current models that predict the impact of global warming on specific ecosystems.

**# Data availability**

The original data, R code for the analysis and creation of the manuscript can be accessed at the GitHub repository https://github.com/efernandezpascual/mires. Upon publication, a version of record of the repository will be deposited in Zenodo.

**# Editor**

> Both reviewers found this to be an interesting study. There is room to expand on your results/discussion as highlighted by both reviewers to improve upon the rigor and impact of this work. One upshot of the study is that mire regions might be climate refugia. Figure 3 gets at this point for summer Tmax spatially. I wonder if one can also show how soil temperatures may vary at paired sites during exceptionally warm daily temperatures during the warm season (e.g., complementary temporal analysis).

We have included a new figure (Figure 5) showing the complementary variation in paired sites during exceptionally warm days (i.e. days in the 90th percentile of daily maximums for the site).

**# Reviewer: 1**

> This is a short and simple study comparing 5cm soil temperatures in mire habitats with adjacent drier microhabitats. It could be of interest to some readers, although it could use some polish and set in a broader context. L15 – I think a yes/no type hypothesis about climate variability is not very interesting given we already have a priori expectations in this regard (e.g. L61-65, Ashcroft & Gollan 2013 Agric. For. Meteorol. 176:77-89. I would focus more on a quantitative question like: how different are they? What are you finding that is different from what we already know?

We have changed the question as suggested.

> L25 – What do you mean by failed to predict? E.g. r2 < 0.5? RMSE > 2oC? Spatial pattern wrong? Consistent bias?

We have changed this sentence to comply with the new approach using correlation and RMSE (see below), and now indicate what we mean regarding p-value, r and RMSE.

> L42 – “has been”

Changed.

> L88-94: Like L15 above, we already have strong evidence that soil moisture acts as a buffer, so testing yes/no hypothesis about this make the research more trivial that it could be. I would focus more on how different they are etc.

We have changed the question as suggested.

> L142 – significantly? P<0.05?

We now indicate the p-value threshold whenever we use the word “significant”. In this case, we use the word “considerably” because we refer to a qualitative visual evaluation of the raw data shown in Figure 2.

> L155 – This is more like a results section with actual figures. Would be good to see 95% CI for the effect sizes. i.e. instead of just effect size = -2.29oC, you would give a range like -1.5 to -3.0.

We include the CI. Please note that since this is the result of a one-tailed t-test, one of the limits of the CIs is -∞/∞.

> Fig. 3 – Make the scales on the y and x axes the same and add a 1:1 line. R2 tells you the correlation between soil and air temps but not the bias. You could have a high r2 and still have a high RMSE indicating poor predictions.

We have changed the figure as requested. For the RMSE comment, please see below.

> L160-165 – building on above comment, note both the r2 and RMSE to capture both correlation and bias. These results will be affected by a number of factors: 1) the soil moisture effect you are interested in 2) the height of observation (2m air temperatures v 5cm soil temperatures) 3) the temporal scale of obvservation (the 1-5 years of your study is different to Chelsa) 4) The spatial scale – does Chelsa reflect the actual elevation of your sites.

We have followed the suggestion and now indicate RMSE to measure the accuracy of the CHELSA values in relation to our measurements. To indicate the correlation between CHELSA and our measurements, instead of a linear model we now use Pearson’s correlation. We have changed the text accordingly. We also note these considerations regarding the factors affecting the CHELSA/soil measure correspondence in the discussion.

> L167 – “Quantify the size of the thermal buffer effect” rather than “prove the existence”. We already know it exists.

Changed.

> Discussion: Where results are similar or different from other studies it would be nice to delve deeper into why. Were the observations at the same depth? E.g. We expect diurnal range to decrease with depth so studies at different depths are not necessarily comparable. What do the results tell us more generally about mires elsewhere, or where sites may vary along a moisture gradient rather than just be mire or non-mire?

We have expanded the discussion as suggested.

> 198-208 – Don’t read too much into individual sites. When you only have 8 sites each will be unique in one way or another and we expect some results to be different. What we are interested in is trends that are consistent across all 8 sites.

We agree with the reviewer on this point, we believe it is worthy to highlight some of the extreme cases among our sites for the purpose of discussion, but no firm conclusions can be made with 8 sites. We now note this limitation in the discussion.

**# Reviewer: 2**

> Very interesting datasets. More rigor in describing how analyses were performed and digging a little deeper into the results is needed. Peatland terms vary somewhat from N. America to Europe / Eurasia. Clearly defining hydrological terms like "mire" will be useful - is this a broad term for all peatlands or simply groundwater fed ones? You describe a groundwater buffer effect, but include wetlands in your study whose hydrology may be dominated moreso by precipitation inputs (bogs, raised bogs). While it may not be practical to fully describe source hydrology to your sites from in situ measurements, some more information on hydrology of these wetlands would be useful. Does a gradient in groundwater connection strength exist among your sites?

We have expanded the description of mire, including the definition of bogs and fens. We also describe the classification we use (based on EUNIS, we provide links to the EUNIS sheets for our habitat types) and give more details about the hydrology of our sites. Please note that our two bogs are classified as raised bogs because of their vegetation, but they are very poorly developed, with small isolated hummocks. Therefore, the are greatly influenced by soil water coming from streams (they develop in waterlogged valleys) and cannot be considered to be fed only by precipitation.

> A general comment is, you would expect to see a thermal buffer effect just from the presence of water at all compared to dry sites. Your data indicate that none of the waterlogged sample locations dried out, thus removing the thermal buffer effect during mreasurement (Figure 1). Do you have a hypothesis for what would happen if they dried based on your data? For your low elevation sites, it suggests any locations drying might be really susceptible to warming.

Partially changed at the end of discussion.

> Is it possible to compare/contrast sites based on sites with weaker vs. stronger groundwater inputs in your study sites? Yes there is an elevation gradient present, but do differences in source hydrology, stronger groundwater inputs explain the really pronounced buffering of some sites vs. others irrespective of elevation? Your methods section is really short and does not provide extensive detail on how you performed your analysis, what statistical platform you used, elsewhere R is referenced, but not in the methods directly.

We agree with reviewer one that, since we have eight sites, it is not possible to read too much on their individual character or perform any type of test considering their elevation or their source hydrology. This is something that can only be pointed out in the discussion. See also the previous comment, our two bog sites are very poorly developed as bogs and receive water inputs from a stream. Regarding the questions about the analyses, please see below.

> Your study might benefit from using a mixed model instead of a simple linear model. I could be convinced a more sophisticated analytical structure like linear mixed modeling (site random effect) is not needed - especially if you expect differences related to hydrology among sites, but those differences if they exist you may want to provide some justification for. If you think your sites have similar hydro-logical characteristics, then a site random effect grouping wet and dry locations by site may make sense to control for noise in the dataset from microclimate factors such as aspect etc. Please at include some justification as to why a mixed modeling approach is not needed or replace the simple linear model with a mixed model.

Following the comments of the previous reviewer, we have removed the linear model, and now use Pearson’s correlation.

> It looks as though some of the temperature variability in your dataset is due to differences in hydrology among sites. If you suspect that is the case as well, then you can pretty easily justify the existing linear model analytical structure, but need more interpretation of hydrological differences in your results and discussion.

As commented above, we do not believe we can study in more detail the effect of source hydrology because of the limited number of sites, and also because all of our sites receive some groundwater input either from springs or streams.

> Do any patterns emerge if you code sites by habitat type? Please include the habitat type labels presented in Table 1 in the figure panels for Figure 1.

We have included the labels as suggested.

> Can you clarify if dry sites are in fact adjacent dry uplands or dry raised hummocks (high spots) within the wetlands? A figure with a site-level inset map would also convey this information and would benefit the paper.

We have clarified that they are adjacent dry uplands, and also included the figure requested.

> It would be worth describing the >15 degree C differences between wet vs dry sites at low elevation (La Malva). That is very biologically significant! You should put that into perspective for the readers, that level of difference greatly exceeds IPCC projections for climate change in this region... Huge differences within site. Please provide some descriptive statistics on peak differences observed at some of your sites.

We have noted this comment about the comparison between the buffer at La Malva and the warming predictions, and also expanded the description of the special case of La Malva. We have also included a new figure (Figure 5) showing the peak differences in the eight sites during exceptionally warm days.

> This is a neat study, there seems to be some more interesting angles you can explore/present in your discussion that will make your paper more interesting to a wider array of readers.

# PDF

> The authors have collected compelling data in an understudied field. The study is relevant to biodiversity under climate change, and to assumptions of global carbon dynamics. The data collected has a lot of merit and pretty easily stands on its own without much help. However, additional descriptions of methodologies are needed. There are some interesting results here, and a nice temporal record from which to draw conclusions. The authors focus on the waterlogged nature of the soils – but the source of hydrology and how closely coupled groundwater in mires is linked with atmospheric conditions may have some bearing on whether these systems remain buffered from effects of atmospheric warming. More robust discussion on the atmospheric coupling of hydrology in these systems tied to other literature is needed. Do groundwater-fed mires persist in drying climates? The paper may benefit from discussion on changes in climate in the study region. Is this study region getting drier? What effect is that expected to have on the thermal buffer effect described? Some descriptions of the latitudinal and elevational distribution of mires in Europe from literature as well as precipitation range would be useful. One to two paragraphs with appropriate citations will help. There are a handful of N. American papers that discuss geographic distribution of groundwater-fed mires [fens] as well. Some literature on how extensive these peatlands are in temperate and boreal landscapes would be helpful to convey the relevance of this work.

We have expanded the sentences describing the distribution of mires in Europe, North America and Russia. For the questions related to hydrology and climate change in the study region, please see the responses to similar comments.

> Some more description on differences in source hydrology to the sites studied and implications for how that may translate to strength of thermal buffer is warranted. Strictly speaking source hydrology – dominated by groundwater flows vs. hydrology dominated moreso by precipitation should have an effect on the microclimate thermal buffer. Some of the variation among sites that is unexplained by elevation may be a result of stronger vs. weaker connection to groundwater. This is an angle you really don’t address in much detail and is a potentially really important area to explore in discussion. It’s possible that wetlands in similar elevation and latitude could have markedly differing responses to climate change. i.e., stronger buffer effects at certain sites vs. others at the similar elevations – explore and describe these results further.

Please see the previous response to the issue of hydrology.

> Including a table with shift in climate trend per decade for precipitation and temperature for the study area would be informative or a citation with similar information.

We have cited the data with the latest projections made by the national meteorology agency of Spain (AEMET).

> Some additional historical background on groundwater thermal buffer effect would improve the paper, and further support the notion that these effects have been “known” but little quantified. The authors will probably enjoy reading Clara May Frederick’s, 1974 A Natural History Study of the Vascular Flora of Cedar Bog, Champaign County, Ohio) Ohio Journal of Science who performed early temperature data collection work in such settings as far back as the 1960’s.

Thank you for this pioneering reference, we have integrated it into our manuscript.

> A Ph.D. dissertation chapter by Raney (2014) Identifying Potential Refugia from Climate Change in Wetlands: High Resolution Soil Climate Maps For Priority Conservation Areas: Hydrologic Processes Mediate Significant Microclimate Variation uses very similar field data collection methods to test the groundwater thermal buffer effect in wetlands as the authors, but focused on spatial coverage vs temporal length. That study includes 1-year worth of data. While the Raney study has not undergone formal peer-review and has some limitations, the soil temperature figures and data summaries in that study may be of particular interest to the authors as additional evidence of thermal buffer due to groundwater.

We have integrated this reference into our manuscript.

> Line 39 – increasingly there are downscaling efforts based on atmospheric microclimate networks distributed in complex terrain that focus on topographic effects on air temperature. So to a degree microclimate factors are increasingly considered, but not hydrologic factors under edaphic/soil control. It may be a distinction worth pointing out.

We have included this consideration.

> Lines 47-59 The term mire may vary somewhat in terms of meaning by region. Please clearly define the primary source of hydrology along with your definition of mire. This will help readers in other regions. If the authors have soil-pH or pore-water pH available for study sites that would be useful but not mandatory to include in Table 1.

We have included water pH and conductivity in the table. Please see also the response to a similar comment above.

> Line 56 – insert “across their range” after homogeneous flora.

Changed.

> Line 76 – and carbon

Changed.

> Line 78 – replace the word “surface” with “area”

Changed.

> Figures: Your first figure should be a site map showing regional context, and if possible topographic gradient of your sites.

We have created the suggested figure.

> Figure 1 Make all labels bold, and text larger. To reduce space, put Site name labels in the light gray plot space and reduce the resulting blank space between top and bottom panels. This figure will likely take up ½ the size when published, so labels need to be larger/darker to maintain legibility. Also you might add to your figure caption that the amplitude of diurnal temperature range in dry sites was reduced with increasing elevation, where the thermal buffer effect was also less apparent.

Changed as suggested.

> Any ideas why La Recoleta at higher elevation shows a really strong disparity between wet and dry locations moreso than your other high elevation sites? Do you think aspect or some other factor had an effect? May be worth exploring in your results section a little further.

A possible explanation is that La Recoleta is a quaking bog (a transition from aquatic to fen vegetation at the margins of a silting glacial lake) and therefore it is more waterlogged than other sites. We have expanded this explanation. However, we agree with reviewer 1 that we should not go too far into interpreting the results of single sites.

> Line 80 – Groundwater flows are somewhat decoupled from high frequency variation in precipitation, but are still linked to lower-frequency long-term changes in precipitation, groundwater recharge and flow to some degree. Focusing some attention on this phenomenon and possibly your discussion may be useful. Just because there is an observed thermal buffer effect now does not mean it will persist indefinitely, especially if climate becomes more arid – distribution of groundwater flows supporting mires may diminish in frequency, quantity, resulting in periodic drying and even potential loss of this buffer effect. For instance, regions that are wetting and expected to become wetter based on IPCC or other projections may have more stability in the thermal buffer effect vs. drying regions. It would be beneficial to focus some of your discussion on this topic.

We have noted in the discussion that the buffer effect is dependent on future changes on precipitation and described the latest projection for the study area (a decrease of 10 % by the end of the century).

> Line 86 change representativeness to representation for simplicity.

Changed.

> The materials and methods section needs to be much more robust in terms of explaining the statistical platform used to perform the analyses, the packages used, citations for those platforms and packages. Why the analyses are appropriate. There’s really not much of a description of how linear modeling was performed, assumptions etc. A linear mixed-model approach would make a lot of sense instead of a simple linear model, grouping wet and dry locations by a “Site” factor to control for latent processes.

We have included the information and citations about the use of R and the package Metrics. The linear model is no longer used, please see response to reviewer 1.

> Need details on sample sizes in your methods.

We have included the sample sizes.

> Lines 99-101 Also include quantitative descriptors of climate in the study area (mm precip/year min and max temp/year).

We have included this information.

> Line 110 – provide sampling resolution of loggers. A description of why was 5cm depth chosen is needed.

We have included this information, and the explanation for the sampling depth.

> Please include a map of the study sites with an inset to show regional/continental position.

We have included the map.

> Lines 123 – 133 – some discussion on why these are biologically or environmentally meaningful statistics is needed. Are species distributions controlled by winter minimums? Carbon dynamics by warm temperatures?

We have included a description of the biological meaning of the bioclimatic variables we chose.

> Statistical analysis: Some simple statistics on precipitation and temperature trends over the last ~hundred years in this study region would be helpful to broaden discussion regarding future uncertainty of microclimates. That would also help to put your study into perspective / macroclimatic context. Are the elevational trends we’re seeing shown for a warming region? A simple trend analysis would be useful. Mm precipitation shift/decade and °C/decade would be useful metrics to include as well as the significance of those shifts. It is a stronger argument if you can show that there’s a thermal buffer effect detectable in a warming or drying climate. Dendrochronology literature frequently includes analytical methods for such trend analyses.

We are sorry but we do not have access to the data necessary to make such analysis, since analysing the evolution of climate in the study region was not the goal of this project.

> Results: More interpretation of the results is needed. Line 155 If you’re only looking at wet vs dry sites, wouldn’t you expect wet sites to have less variability even if the source was not groundwater?

We interpret the results in the discussion.

> Line 167 – Delete the word prove. The evidence required to prove something is very high. Suggest changing to: The results presented provide strong evidence of...

Changed.

> Line 173 – Raney 2014 has similar findings from year-round data for a single year. Warmer in winter, cooler in summer. You should highlight that your findings were extended to a full year and the pattern is reproducible among years out to five years. The fact that your data possess a strong-elevational relationship, i.e., stronger under warming environment is worth more attention.

We have added these considerations.

> Line 194 – Replace “highness” with “height”

Changed.

> Line 200 – you elude to some topographic microclimate effects on your sites. That is fine as they influence both wet and dry locations equally, but may be worth including aspect measurements for your sites in Table 1. Neat datasets, I look forward to reading the final manuscript.

Only one of the sites (La Malva) is in a slope and thus has an aspect, the other sites are flat. We have changed the sentence to make this clear.