Dear Editor and Reviewers,

The manuscript has undergone considerable changes and extensions. We think that the manuscript has improved very much and we would like to draw your attention to the major changes accomplished:

- As indicated by a comment in the interactive discussion, some of the newer in directly related papers are not cited in the Introduction. We added some text in the Introduction and cited the latest literature dealing with ET0 estimation and calibration procedures.
- One major concern of both reviewers where statements in the manuscript indicating that the presented dataset would be applicable to climate change impact studies. We decided to avoid these kinds of statements, since all agents driving evapotranspiration (e.g. wind speed) are not covered by the presented dataset.
- Reviewer #1 raised the concern whether the final gridded ET0 values are indeed better than the original HM ET0 values since the polynomial fitting introduces some uncertainties. We added a new Figure and Paragraph to the Discussion section showing that the final gridded dataset has clearly reduced biases all over the year and at different levels of altitude.
- Reviewer #2 commented on the lacking discussion on the altitude dependence of Cadj. We accomplished new analysis, adding two more Figures to the Discussion section and extended the text of this section considerably. This better justifies now a separate Discussion and Conclusion section, which was also a concern of Reviewer #2.

We put much effort in the improvement of the manuscript and hope for a positive feedback.

The Authors,
Klaus Haslinger
Annett Bartsch

**Anonymous Referee #1**

This manuscript constructs daily 1-km fields of reference evapotranspiration (ET0) over all of Austria from 1961-2013, by cleverly improving the Hargreaves method and dynamically calibrating it against Penman-Monteith. It is a very nice procedure and product, and I recommend full publication. However, the verification of the final product could be more thorough (comment 1), and the product is implicitly claimed to be suitable for trend analysis when it is not (comment 2), so these concerns need to be addressed first. The writing was also occasionally quite difficult to understand; these spots are detailed after the two major comments.

Major comments:

1) It is very nice to see the verification against Penman-Monteith, in Figure 6. However, Figure 6 just plots the ET0_h.c using *station* derived C. Your final gridded product does not use the station C, but an interpolation from the station C using the types of elevation curves in Figure 8. Critically, the black points (stations) in Figure 8 can be quite far from the red curve-fits, especially in winter at lower elevations. This introduces additional error in your final product, since ET0_h.c using the red curve to get C will be different from ET0_h.c using the station-based C (black dot) and thus somewhat different from ET0_p at the station. So, I highly recommend also comparing your final, *gridded* ET0_h.c to the stationbased ET0_h.c and ET0_p. You could do this by adding a fourth curve to each panel of Figure 6 (for the gridded ET0_h.c at the gridbox containing the station) or by making an additional figure or two of your own design. This will clarify the degree of confidence in your product and in statements like p5065 li27. Similarly, the comparison in Fig. 12 could also involve the station estimates... you could show that at your stations, Fig. 12a is closer to station-measured Penman-Monteith than Fig. 12b is. Right now Fig. 12 doesn't convince me about that, because of this additional error introduced by the imperfect curve-fitting illustrated in Fig. 8.

**This is a good suggestion. We will add a new Figure where we show the gridded versus the station based ET0 estimates compared to Penman-Monteith. We think, that adding a fourth line in Figure 6 might be too confusing. Additionally we will plot the station based estimates in Figures 12a and 12b which might show the improvements more clearly, but also indicates uncertainties due to the curve fitting.**

**We added one new plot (Figure 15) in the Discussion section which shows boxplots of the original and final, gridded ET0 estimates, stratified monthly and also by classes of altitude. Furthermore we added the station based PM ET0 values to plots (a) and (b) in Figure 12.**

2) I disagree with your suggestion at the end of the paper (bottom of 5067 and top of 5068) that your product is suitable for thinking about long-term trends or climate change. This is because a temperature-based method like Hargreaves may match Penman-Monteith just fine for overall magnitude and for year-to-year variability (e.g. in Fig 6a and 6b), but greatly disagree with Penman-Monteith about the long-term trend. There are several ways this could happen. One is that the Penman-Monteith ET0 may have a large long-term trend due to a windspeed trend (like those in McVicar et al. 2012, J. Hydrol., doi:10.1016/j.jhydrol.2011.10.024). In this case there's no hope that your product could catch it, since there is no windspeed input to Hargreaves. Another way is if the long-term increase

in greenhouse gases has caused a decrease in Tmax-Tmin that is *not* due to decreasing sunshine-hours, but is solely because of the greenhouse effect. In this case, your dataset will have a spurious downward trend, because Hargreaves will think the climate is getting less sunny (when actually it is not.) You can see this problem in the case of future greenhouse warming by comparing the Hargreaves-based result of Zhang and Cai, 2013, Geophys. Res. Lett., doi:10.1002/grl.50279 (which I think is spurious, for the reason just given) to the more usual Penman-based analysis of e.g. Feng and Fu, 2013, Atmos. Chem. Phys. (doi:10.5194/acp-13-10081-2013) or Scheff and Frierson, 2014, J. Clim. (doi:10.1175/JCLI-D-13-00233.1).

So, I would not include such language about long-term trends or climate change (and I would even include a caution *not* to put much belief in any trend in this dataset!) However, the dataset could still be useful for long-term studies if it is well known that the main change-agent is something other than ET0 (e.g. precipitation or land-use change.) In this case, you could de-trend this dataset and then use it for the ET0 input to such a study. So perhaps long-term uses could be mentioned, but more cautiously. (Is it possible to calculate Penman-Monteith for your entire 50-year study period, instead of just 2004-2013? If so, then the trends in your product could actually be verified. But I am guessing the required input data is only available after 2004. However, if this is possible, you should definitely do it, and compare the ET0_p trend with the ET0_h.c trend at each station where this is possible. If the trends strongly disagree, you could fix the problem by allowing C to have a long-term linear trend, in addition to its dependence on time-of-year and elevation. Then you would have a very useful product.)

**The statement on climate change applicability may indeed be too far-fetched. Unfortunately you are right on the station data availability for calculating Penman-Monteith ET0 (ET0_p). We calculated it, but only a handful of stations had sufficient data to go back to 1984 which would cover 30 years. Comparing the trends of this period (1984-2013) with calibrated Hargreaves estimates (ET0_h.c) we found that the ET0_p trends are generally higher compared to ET0_h.c, for one station twice as high. This analysis additionally showed, that the ET0_p estimation are also afflicted with a high amount of uncertainty due to inhomogeneous input data, which is particularly the case for the wind data. At one station the trend of ET0_p is even lower than the ET0_h.c trend, which mainly emerges from a strongly negative wind trend, which is not very realistic, since it is not apparent at other, nearby stations.**
**These results indicate that it is not reasonable to add a trend to the C values. We will change the text, avoiding statements like the applicability of the dataset to climate change analysis.**

**Since climate change applicability of the given data set is not valid we deleted these statements.**

Writing suggestions:

p5056 li7: Since this is the very first use of "FAO", it should be written out as "Food and Agriculture Organization (FAO)". After this, just "FAO" is OK, except perhaps at p5057 li10 (the first use of "FAO" in the body.)

**Thanks, we will write it out in the Abstract as well as in the Introduction.**

**Done.**

p5056 li12: "conduction" is an odd and confusing word choice here... "use" would be much simpler and easier to understand. Also, since you are *only* using surface elevation to interpolate (i.e. you are not using the horizontal dimensions), it might be good to highlight this by saying "the sole predictor" rather than "a predictor". (Or adding "alone" after "surface elevation.") Similarly, at p5067 li3, you should write "using" rather than "conducting."

**Thanks for these suggestions; we will revise the text following these comments.**

**We re-wrote these passages accordingly.**

p5056 li13: Your fits are not splines - they're just simple polynomials (not piecewise.) So should probably say "third order polynomial" or "cubic polynomial" instead of "third order spline."

**That´s true, the wording is wrong. We will correct that for "third order polynomials".**

**We corrected the sentence for "third order polynomials".**

p5059 li6: What is meant by "As for"? Do you mean that SRTM DEM is used in SPARTACUS, so you are also using SRTM DEM in this study? If so, it's much clearer to say "As *in* SPARATACUS, the SRTM ... (DEM) is used in this study." Even clearer would be "SPARTACUS uses the SRTM ... (DEM), so the SRTM DEM is also used for the present study." (If you actually mean something else, please make your meaning clear.) "As for" in English is very unclear... it can mean "As in" but it can also mean you're changing to a different subject.

**Thank you for your writing suggestion, we will change the text as suggested.**

**We corrected this sentence as indicated.**

p5059, bottom (beginning of 3.1): Much of this was already explained in the introduction.
So you can probably delete much of this, or preface it with "As explained above, ..."

**Yes, we will preface this passage with "As explained above…", thank you.**

**Done.**

p5061 li11: "noticeably" should be "noticeable" - it should be an adjective here, not adverb.
p5062 li17: "For sakes of" should be "For the sake of". Actually, just "For simplicity..." is simpler and better. And on li18 "respectively" is not needed, it's quite clear anyway.

**We will correct these two suggestions accordingly.**

**These writing suggestions have been implemented.**

p5064 li7: Does this mean that you determine a separate polynomial fit for each day of the year? That is OK to do, but the meaning is not quite clear from the sentence.

**Yes, we do the fitting for every day of year. We will rewrite this text passage to make this statement more clearly.**

**We changed the sentence to: “The polynomial fit is applied for every day of the daily interpolated station-wise Cadj values, since these are changing day by day as well.”**

p5066 li16: "unfolded" makes no sense in English here - maybe this is a direct translation from German? How about "Going to higher elevations in the warm season, Cadj decreases until roughly 1000 m.a.s.l."

**Thank you for the suggestion, we will change the text as recommended.**

**We changed the text as recommended.**

p5066 li20: Similarly, what is the meaning of "relativized by this relationship being affected by latitude"? I could not guess what you mean... just re-state in simple English please.

**We will rephrase this sentence to: “This altitude dependency of the calibration parameter in HM is mentioned in Samani (2000), but the authors also claimed that this relationship may be affected by different latitudes.”**

**Done.**

p5067 li1: "Alternating" means going repeatedly back and forth between two states... oscillating or vibrating. I think you mean "altering" here (or "adjusting", "changing" or similar.)

**This is true, “altering” is meant.**

**Correction was applied.**

Typos:

p5062 li18: "where" should be "were"
p5067 li3: "lower the" should be "lower than"

**Typos will be corrected accordingly.**

**All typos were corrected.**

**Anonymous Referee #2**

General comments: This study is interesting since not too many data and knowledge exists about evapotranspiration in Alpine environments. The authors worked hard and made a good job to generate new results from few available data. However, I do not see sufficient novelty and innovative potential in the analysis in order that it should be published in an international, highly ranked journal. The main drawbacks of this study are: (a) There already exist evapotranspiration maps for Austria and other countries in the European Alps, some of them including greater detail than the study presented here (b) Applications of the Hargreaves method and its adjustment with respect to accepted, physically based methods already exist (c) The physical background of the presented methodology does not exist or is questionable.

Questions and comments to item (a): Why was a new mapping of evapotranspiration necessary for Austria? Why didn't the authors compare their results with data from existing studies? There are evapotranspiration maps available for Austria: **-** Hydrological Atlas of Austria: Plate 3.2 (Mean annual potential evapotranspiration) and Plate 3.3 (Mean annual areal actual evapotranspiration using water balance data) Besides, there is an evaporation map for Switzerland which is based on the Penman-Monteith equation (reference period 1973-1992): **-** Hydrological Atlas of Switzerland: Plate 4.1 (Mean annual actual evaporation).
It is strongly recommended to analyse and to explain existing agreements or differences with the Austrian and possibly the Swiss map (e.g., different elevation gradients, mean annual data of evapotranspiration for different elevation zones etc.). Based on these analyses the authors should explain why a new product was necessary for Austria. What is the real novelty and in which fields was new knowledge generated with regard to the existing products? Why was a modified version of the Hargreaves equation applied when products exist which are based on more accepted methods?

**There are two main reasons for the compilation of a new ET0 dataset:**
**(i) to create a long-term dataset of reference evapotranspiration from 1961 onwards on a DAILY time step. The intention of this study was not to calculate new maps of climatological mean values. There are of course maps of ET0 in the hydrological atlases of Austria and Switzerland. Hence, they are compiled based on more physically representations of ET0 (for Austria based on Penman-Monteith). But it is much easier to get gridded climatological mean values of all the input data needed for calculating Penman-Monteith ET0 than it is for daily mean fields. Daily fields of wind speed, humidity, and radiation are unfortunately not available before the 1980s or 1990s, so there is no chance for calculating daily Penman-Monteith ET0 before the 90s.**
**(ii) We intended to compile a dataset with high spatial and temporal resolution stretching back as far as possible. Since daily fields of Tmin and Tmax are now available from 1961 onwards, we decided to use the Hargreaves method. This method is of course not physically based, it is a parameterization. But it is widely used and, as is shown by the references cited in our manuscript, there are approaches to calibrate this method to physically meaningful formulations (Gavilán et al. 2006, Pandey et al. 2014, Aguilar and Polo 2011, Bautista et al. 2009). The reasons for these attempts are always lack of data to calculate e.g. Penman-Monteith ET0 and the intention to stretch further into space and/or time by using a simpler method.**

Comments to items (b) and (c): The authors apply the simple Hargreaves method (HM) with a standard correction factor C (0.0023) to 42 stations in Austria. They compare the performance of the HM method with the modified Penman-Monteith method (PM) to express the reference evapotranspiration ET0. Then, “in order to achieve a meaningful representation of ET0 by HM” (page 5061, line 25) they adjust the calibration parameter Cadj to optimize the agreement between HM-derived ET0 estimates with those calculated with PM. The authors apply a simple method which was developed earlier, thus this step is not new. The results show that Cadj at individual stations varies over the time. Finally, the monthly Cadj parameters are first linearly interpolated to daily data which are then interpolated on a daily 1x1 km grid over Austria. The interpolation from 42 stations to the individual grid cells is carried out through monthly fitting of a third-order polynomial curve against altitude (the monthly shapes of the curves greatly differ). Result is a gridded dataset of Cadj for every day of a year. In a final step, ET0 is computed for the individual grid cells by use of the HM method and the Cadj values. All the steps described above lack conceptual clarity, the procedure just consists of a number of optimization steps which introduce fuzziness regarding any physical meaning. Therefore, any physically-based explanation regarding the temporal and spatial variation (including altitude dependencies) of Cadj or the HM-derived ET0 estimates is not given.

**Thanks for your comments; we actually we don´t actually know where this temporal and altitude dependence is emerging from. We will add an additional paragraph to the Discussion section where we will address this feature in detail, since this might be also be relevant for a broader audience and will raise the significance of the paper.**
**The whole approach is indeed an optimization and merging of existing methods. But we still think that this new optimization method is valuable, since it is worldwide applicable, not only for the Eastern Alpine Area.**

**We put a lot of effort into extending the Discussion section around that topic. We investigated the relation of the altitude and the correlation between Diurnal Temperature Range (DTR) and global radiation, which revealed the crucial point of the altitude dependence of Cadj. We were able to show, that the DTR - radiation connection is different at changing altitudes.**

Hence, analysis given in section 4 (results) remains obscure. Moreover, time series analysis with respect to climate change impacts on evapotranspiration seems not trustworthy and should be avoided.

**True. We will avoid these kinds of analysis and also statements on the usage of the dataset to assess climate change impacts on reference evapotranspiration evolution.**

**Since climate change applicability of the given data set is not valid we deleted these statements.**

As ET0 refers to the evapotranspiration from a well-watered grass cover neglecting the impact of soil properties how would you rate the applicability of this concept to high alpine areas? What is the meaningfulness of the ET0 concept for such conditions? Is ET0 a realistic approach for e.g. dwarf shrub communities on shallow initial soils, bare rock or snow/ice cover? Don’t you think that ET0 overestimates evapotranspiration for such conditions?

**The meaningfulness of ET0 is of course shrinking going to higher elevations where bare rock and snow/ice is dominating. However, the concept of ET0 serving as a reference**

**(well-watered grass cover), is that there is a “starting point”, from which actual evapotranspiration can be derived by using hydrological or land surface models. These models consider the “real” land surface cover, may it be forest, agricultural land or pasture, the soil conditions and actual soil wetness.**

Specific comments:
The article requires English language editing. There occur quite a number of spelling and grammatical errors and there are ways to say things more clearly or using fewer words. Some sections, including the abstract, read complicated.

**English language editing will be accomplished, as well as clearer formulations throughout the manuscript.**

**Editing and clearer formulations throughout the manuscript have been applied.**

Confusing notations: In the first sections of their article, the authors term the reference evaporation as ET0. In section 3.1 they term the ET0 following the (modified) PM method as E (equation 1) which they also define as reference evapotranspiration. Then, in the same section they apply the terms ET0_p for the reference evapotranspiration based on the (modified) PM equation and ET0_h for the ET0 derived from the original HM equation. In section 3.2 (equation 3) EH is “the original ET0 from HM” and EP “is the ET0 from PM” (page 5062, lines 3/4). This change in terminology is really confusing.

**We will change the terminology of the different ET0-types to be consistent throughout the manuscript.**

There are several repetitions in the text regarding the statement that the modified PM method is seen as the reference (see e.g., page 5058, line 6 or page 5061, line 6)

**We will go through the manuscript and change/delete redundant parts of the text.**

**We deleted all redundant parts of the text.**

Repetitions of ET0 definition: There are at least two definitions of ET0, and they seem quite different which confuses the reader. See for example page 5057, lines 6/7 and page 5059, lines 21/22

**In principle these two text passages state the same thing, but in rather different words. It is true that these contradicting formulations may confuse the reader, so we will change the passages to be more coherent.**

**We changed the second statement to match more closely to the first one:**
**“As explained above, numerous methods exist for the estimation of ET0, which is defined as the maximum moisture loss from a standardized, vegetated surface, determined by the meteorological forcing.”**

Page 5060: line 2 says that the PM method requires global radiation. In equation (1) however and on line 6 net radiation is mentioned as necessary input.

**The global radiation is used to calculate the net radiation. We will add some text to clarify that issue.**

**We changed net radiation for global radiation as the necessary input for PM ET0. Net radiation is calculated from global radiation as described in Allen et al. 1998.**

Regarding the formulation of the PM equation on page 5060 please mention that this is a modified version of PM, with the original form (to calculate actual evapotranspiration) including a resistance network.

**We will add some text on the differences between the original and the FAO Penman-Monteith formulation. Thank you for your suggestion.**

**We added the following sentence:**
**"It should be mentioned, that the original Penman-Monteith equation contains a "surface resistance" term, expressing the response of different vegetation types, which is set constant for FAO PM, since it uses a standardized vegetated surface."**

Page 5060, lines 11/12: It is simply not practicable / physically allowable to set the soil heat flux to zero on a daily time step! Please see standard textbooks on micrometeorology about the radiation balance. Or would you set the change in daily soil water storage to zero as well?

**In the FAO Penman-Monteith method, the soil heat flux on a daily time step (not on a shorter time step) is set to zero based on the following statements extracted from Allen et al. 1998:**

***Complex models are available to describe soil heat flux. Because soil heat flux is small compared to Rn, particularly when the surface is covered by vegetation and calculation time steps are 24 hours or longer, a simple calculation procedure is presented here for long time steps, based on the idea that the soil temperature follows air temperature.***

***For day and ten-day periods:***

***As the magnitude of the day or ten-day soil heat flux beneath the grass reference surface is relatively small, it may be ignored and thus:***
***Gday ≈ 0***

**For us it seems appropriate to follow this guideline, since it is a worldwide accepted and widely used framework.**

Page 5060: please explain how you calculated Ra for the Austrian stations / the individual grid cells from extra-terrestrial radiation and give an example (in water equivalent). Don't you think that this involves high uncertainty in the whole calculation process?

**Ra (extra-terrestrial radiation at the top of the atmosphere given in MJ $m^{-2}$ $day^{-1}$) can be calculated for every station by using latitude and Julian day as input variables. By**

**multiplying the result by a conversion factor of 0.408 the Ra [MJ $m^{-2}$ $day^{-1}$] is converted to Ra [mm $day^{-1}$]. The calculation steps are given in Allen et al. 1998 in detail.**

***Example:***

***Station at latitude 48° North, 22nd of April which is 112th day of year.***

***J = 112***
***lat = 48°***
***latr = 48/ 57.2957795 -> latitude in Radians***

***delta = 0.409 * sin(0.0172 * J - 1.39)***
***dr = 1 + 0.033 * cos(0.0172 * J)***
***omega = acos(-tan(latr) * tan(delta))***

***Ra = 37.6 * dr * (omega * sin(latr) * sin(delta) + cos(latr) * cos(delta) * sin(omega))***

***Ra = 34.01004 [MJ $m^{-2}$ $day^{-1}$]***
***Ra = 34.01004 * 0.408 = 13.87609 [mm $day^{-1}$]***

**There is of course uncertainty in the calculation, since this conversion factor applies to water at 20°C. Nevertheless, we followed the FAO guidelines in all of the calculation steps and think that this is an appropriate way of calculating ET0.**

Why are there separate Discussion and Conclusion sections? In the Discussion, any critical analysis is missing, while the Conclusion is just another summary of the work.

**From your previous comment we will add some critical analysis regarding the altitude dependence of the calibration parameter and the uncertainty involved in the calculation process. This will additionally justify a separate Discussion and Conclusions section.**

**As stated above we extended the Discussion section considerably. We added three new Figures and provide some in depth Discussion on the altitude dependence and the overall performance of the final gridded product which should now justify a separate Discussion section.**

Figure 5: They grey shaded area as well as the black line in Fig. 5a seems to be identical with the ones in Fig. 3b. Please avoid redundancy

**We thought it would support the reader if the original RMSE is added to the graph, to actually see the improvements.**

Page 5057, line 10: why “also recommended by FAO”?

**We will delete “also” for clarification.**

**Done.**

# Creating long term gridded fields of reference evapotranspiration in Alpine terrain based on a re-calibrated Hargreaves method

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## Abstract

A new approach for the construction of high resolution gridded fields of reference evapotranspiration for the Austrian domain on a daily time step is presented. ~~Forcing fields of gridded~~Gridded data of minimum and maximum temperatures are used to estimate reference evapotranspiration based on the formulation of Hargreaves. The calibration constant in the Hargreaves equation is recalibrated to the Penman-Monteith equation ~~, which is recommended by the FAO,~~ in a monthly and station-wise assessment. This ensures on one hand eliminated biases of the Hargreaves approach compared to the formulation of Penman-Monteith and on the other hand also reduced root mean square errors and relative errors on a daily time scale. The resulting new calibration parameters are interpolated in time to a daily temporal resolution for a standard year of 365 days. The overall novelty of the approach is the ~~conduction~~ use of surface elevation as ~~a~~ the sole predictor to estimate the re-calibrated Hargreaves parameter in space. A third order ~~spline~~ polynomial is fitted to the re-calibrated parameters against elevation at every station ~~and~~ which yields the statistical model for assessing these new parameters in space by using the underlying digital elevation model of the temperature fields. Having newly calibrated parameters for every day of year and every grid point, the Hargreaves method is applied to the temperature fields, yielding reference evapotranspiration for the entire grid and time period from 1961-2013. With this approach it is possible to generate high resolution reference evapotranspiration fields starting when only temperature observations are available but re-calibrated to meet the requirements of the recommendations defined by the ~~FAO~~Food and Agricultural Organisation (FAO).

## 1 Introduction

The water balance in its most general form is determined by the fluxes of precipitation, change in storage and evapotranspiration (Shelton 2009). Particularly for the latter, measurement is rather costly, since it requires sophisticated techniques like eddy correlation methods or lysimeters. In hydrology as well as agriculture the actual evapotranspiration as part of the water balance equation is mostly assessed from the potential evapotranspiration (PET). PET refers to the maximum moisture loss from the surface, determined by meteorological conditions and the surface type, assuming unlimited moisture supply (Lhomme 1997). Since surface conditions determine the amount of PET, the concept of reference evapotranspiration (ET0) was introduced (Doorenbos and Pruitt, 1977). ET0 refers to the evapotranspiration from a standardized vegetated surface (grass) under unrestricted water supply, making ET0 independent of soil properties. Numerous methods exist for estimating ET0; differences arise in the complexity and the amount of necessary input data for calculation.

A standard method, ~~also~~ recommended by the Food and Agricultural Organisation (FAO; ~~(~~Allen et al. 1998), is the Penman-Monteith (PM) formulation of ET0. There are of course countless other methods as thoroughly described in McMahon et al. (2013), but~~This~~ the PM equation is considered the most reliable estimate and serves as a standard for comparisons with other methods (Allen et al. 1998). PM is fully physically based and requires four meteorological parameters (air temperature, wind speed, relative humidity and net radiation). It utilizes energy balance calculations at the surface to derive ET0 and is therefore considered a radiation based method (Xu and Singh 2000).

On the contrary, much simpler methods which use air temperature as a proxy for radiation (Xu and Singh 2001) have been developed to overcome the shortcoming of PM of not having sufficient input data. In this paper, the method of Hargreaves (HM, Hargreaves et al. 1985) is used. It requires minimum and maximum air temperature and extra-terrestrial radiation, which can be derived by the geographical location and the day of year. Though much easier to calculate, as temperature observations are dense and easily accessible, one has to be aware that the HM, among most temperature based estimates, are developed for distinct studies and/or regions, representing a rather distinct climatic setting (Xu and Singh, 2001). To avoid large errors, these methods need to undergo a recalibration procedure to make them applicable to different climatic regions than they were originally designed for (Chattopadhyay and Hulme 1997, Xu and Chen 2005).

In this paper the method for constructing a dataset of ET0 on a daily time resolution and a 1 km spatial resolution based on the method of Hargreaves is presented. The HM is calibrated to the PM ~~as the standard for estimating ET0~~ on a station-wise assessment. ~~Numerous~~ Many studies describe re-calibration procedures for ET0 estimations in general (Tegos et al., 2015; Oudin et al. 2005) and for the HM in particular (Pandey et al. 2014; Tabari and Talaee, 2011; Bautista et al., 2009; ~~,~~ ~~Pandey et al. 2014,~~ Gavilán et al. 2006) in order to achieve similar results ~~to the~~compared to PM~~, which serves as a reference~~. There are also some studies describing methods for creating interpolated ET0 estimates (e. g. Aguila and Polo, 2011; Todorovic et al, 2013). However, two main methodological frameworks emerged for the interpolation of ET0 (McVicar et al., 2007): (i) interpolation of the forcing data and then calculating ET0, or (ii) calculating ET0 at every weather station and the interpolating ET0 onto the grid. In this paper we follow the first approach and combine it with methods proposed by Tegos et al. (2015) and Mancosu et al. (2014) which use spatially interpolated ET0 model parameters. ~~Spatially interpolated~~Gridded data of ~~daily temperature measurements (minimum and maximum temperature)~~minimum and maximum temperatures are used as forcing fields for the application of the Hargreaves formulation of ET0. The novelty of this study is the application of elevation as a predictor for the interpolation of the re-calibrated HM calibration parameter. Furthermore, these new calibration parameters are also variable in time, by changing day-by-day for all days of the year. This approach goes a step further than the method of Aguilar and Polo (2011) which derived one new calibration parameter for the dry and one for the wet season of the year.

The presented dataset aims to use the ~~best~~better of two worlds by (i) using a method for estimating ET0 that is calibrated to the standard algorithm as defined by the FAO and (ii) being applicable to a comprehensive, long-term forcing dataset and on a high temporal and spatial resolution.

## 2 Forcing Data

The foundation of the ET0 calculations ~~are~~ is a high resolution gridded dataset of daily minimum and maximum temperatures calculated for the Austrian domain (SPARTACUS, see Hiebl and Frei 2015), whereas the actual data stretches beyond Austria to entirely cover catchments close to the border. SPARTACUS is an operationally, daily updated dataset starting in 1961 and reaching down to the present day. For the conduction of the ET0 fields, the SPARTACUS temperature forcing is used for the period 1961-2013. The interpolation algorithm is tailored for complex, mountainous terrain with spatially complex temperature distributions. SPARTACUS also aims to ensure temporal consistency through a fixed station network over the whole time period, providing robust trend estimations in space. ~~As for the SPARTACUS dataset the SRTM (Shuttle Radar Topography Mission, Farr and Kobrick 2000) version 2 Digital Elevation Model (DEM) is used in this study.~~SPARTACUS uses the SRTM (Shuttle Radar Topography Mission, Farr and Kobrick 2000) version 2 Digital Elevation Model (DEM), so the SRTM DEM is also applied in the present study.

SPARTACUS provides the input data for calculating ET0 following the Hargreaves method (HM, Hargreaves and Samani 1982, Hargreaves and Allen 2003). However, a recalibration of the HM is necessary to avoid considerable estimation errors. This is carried out in a station wise assessment. Data of 42 meteorological stations (provided by the Austrian Weather Service ZAMG) is used to monthly calibrate the HM to the Penman-Monteith Method (PM). Figure 1 shows the location of these stations, which are spread homogeneously among the Austrian domain and also comprise rather different elevations and environmental settings (Table 1). Data of daily global radiation, wind speed, humidity, maximum and minimum temperatures covering the period 2004-2013 are used to calculate ET0 simultaneously with HM and PM.

# 3 Methods

## 3.1 Estimating reference evapotranspiration

As explained above, ~~N~~numerous methods exist for the estimation of ET0, which is defined as the maximum moisture loss from a standardized, vegetated surface, determined by the meteorological forcing~~the land surface limited only by energy endowment~~ (Shelton, 2009). They can roughly be classified as temperature based and radiation based estimates (Xu and Singh, 2000, Xu and Singh, 2001, Bormann, 2011). Following the recommendations of the FAO (Allen et al. 1998) the radiation-based Penman-Monteith Method (PM) provides most realistic results and generally outperforms temperature based methods. The overall shortcoming of the PM is the data intense calculation algorithm which requires daily values of

~~global~~ net radiation, wind speed, humidity, maximum and minimum temperatures. Data coverage for these variables is usually rather sparse, particularly if gridded data is required. ET0 following the PM is calculated as displayed in Equation 1:

$$ET0\_p = \frac{0.408\Delta(R_N - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (1)$$

where E is the reference evapotranspiration [mm day$^{-1}$], $R_N$ is the net radiation at the crop surface [MJ m$^{-2}$ day$^{-1}$], G is the soil heat flux density [MJ m$^{-2}$ day$^{-1}$], T is the mean air temperature at 2 m height [°C], $u_2$ is the wind speed at 2 m height [m s$^{-1}$], $e_s$ is the saturation vapour pressure [kPa], $e_a$ is the actual vapour pressure [kPa]; giving the vapour pressure deficit by subtracting $e_a$ from $e_s$; Δ is the slope of the vapour pressure curve [kPa °C$^{-1}$] and γ is the psychrometric constant [kPa °C$^{-1}$]. Given the time resolution of one day the soil heat flux term is set to zero. The calculation of the other individual terms of Equation 1 is described in Allen et al. (1998). It should be mentioned, that the original Penman-Monteith equation contains a "surface resistance" term, expressing the response of different vegetation types, which is set constant for FAO PM, since it uses a standardized vegetated surface.

In contrast to the radiation based PM, the HM is based on daily minimum and maximum temperatures ($T_{min}$, $T_{max}$). Hargreaves (1975) stated from regression analysis between meteorological variables and measured ET0 that temperature multiplied by surface global radiation is able to explain 94 % of the variance of ET0 for a five day period (see Hargreaves and Allen 2003). Furthermore, wind and relative humidity explained only 10 and 9 % respectively. Additional investigations by Hargreaves led to an assessment of surface radiation which can be explained by extra-terrestrial radiation at the top of the atmosphere and the diurnal temperature range as an indicator for the percentage of possible sunshine hours. The final form of the Hargreaves equation is given by:

$$ET0\_h = C(T_{mean} + 17.78)(T_{max} - T_{min})^{0.5} R_a \qquad (2)$$

where ET0_h is the reference evapotranspiration [mm day$^{-1}$], $T_{mean}$, $T_{max}$ and $T_{min}$ are the daily mean, maximum and minimum air temperatures [°C] respectively and $R_a$ is the water equivalent of the extra-terrestrial radiation at the top of the atmosphere [mm day$^{-1}$]. C is the calibration parameter of the HM and was set to 0.0023 in the original Hargreaves et al. (1985) publication.

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Following these formulations the ET0 for all stations was calculated for the period 2004-2013. ~~As PM is declared by the FAO as the preferred ET0 estimation model, it serves as the reference for the following comparison between both methods.~~ Figure 2a shows, as an example, the daily time series of ET0 as derived by PM (ET0_p) and HM (ET0_h) in the year 2004 at the station ~~Wien_Hohewarte~~Grossenzersdorf. The differences between those two are obvious as ET0_p shows clearly higher variability, with ET0_h underestimating the upward peaks in the cold season and downward peaks in the warm season. This feature is more noticeable~~noticeably~~ in Figure 2b, which shows the monthly averages over all stations, indicating the spread among all 42 stations. Here, an underestimation of the ET0_h compared to ET0_p from October to April is counteracted by an overestimation between May and September. On the other hand, ET0_h shows higher spread among stations compared to ET0_p except for November to January.

These features are also reflected in the bias of ET0_h compared to ET0_p as can be seen in Figure 3a. The average monthly bias over all stations is negative in the cold season with largest deviations in February of 0.3 mm day$^{-1}$, compared to the peak average positive bias in June of 0.4 mm day$^{-1}$. The annual cycle of the Root Mean Squared Error (RMSE) of ET0_h as displayed in Figure 3b shows peak values in summer mainly due to the higher absolute values in the warm season compared to wintertime. The RMSE in December is around 0.5 mm day$^{-1}$ compared to 1.1 mm day$^{-1}$ in July, showing some more spread in wintertime compared to summer.

## 3.2 Calibration

In order to achieve a meaningful representation of ET0 by HM, an adjustment of the calibration parameter ($C_{adj}$) of HM is necessary, with respect to ET0 derived from PM. This is carried out on an average monthly basis for every station by the following equation, as also proposed by Bautista et al. (2009):

$$C_{adj} = 0.0023 / (E_H / E_P) \quad (3)$$

where $C_{adj}$ represents the new calibration parameter of the HM, $E_H$ is the original ET0_h from HM, using a C of 0.0023 and $E_P$ is the ET0_p from PM. As a result, a new set of C values for every month and every station is available.

Figure 4 shows the adjusted C values for three exemplary stations. $C_{adj}$ is generally higher in winter and autumn compared to the original value indicated by the dashed line at 0.0023. It is also obvious that at station Grossenzersdorf the original value is matching rather well to the $C_{adj}$ from April to October, in the other months the adjusted values are clearly higher. On the contrary, at station Weissensee_Gatschach $C_{adj}$ is lower than 0.0023 except for the months from November to February. At station Rudolfshuette-Alpinzentrum the adjusted values are above the original ones all time of the year, reaching rather high values in wintertime of about 0.007. These results clearly underpin the necessity for a re-calibration of C in order to receive sound ET0 from temperature.

After determining the values for $C_{adj}$ the ET0 was re-calculated with these new calibration parameter values (ET0_h.c). For ~~sakes of~~ simplicity for this first assessment the monthly values of $C_{adj}$ ~~where~~ were used for all days of the month ~~respectively~~, no temporal interpolation was conducted. As a result, the monthly mean bias, as was shown in Figure 4a, is reduced to zero at every station. Furthermore, the RMSE has also slightly decreased by 0.1 to 0.2 mm day$^{-1}$, as can be seen in Figure 5a. The Relative Error (RE) has also decreased, from around 50 % to fewer than 40 % in January for example (cf. Figure 5b). The improvements regarding RE in summer are lower due to the higher absolute values of ET0 in the warm season.

The complete monthly mean time series from 2004 to 2013 of ET0_p, ET0_h and ET0_h.c for three stations are shown in Figure 6. At station Grossenzersdorf the underestimation of ET0_h in winter is reduced as well as the overall underestimation at station Rudolfshuette-Alpinzentrum. On the other hand, the overestimation in summer at station Weissensee-Gatschach is considerably reduced with ET0_h.c. These features in combination with the information on the altitude of the given stations provide some information on more general characteristics of $C_{adj}$ and the effects of the calibration. It seems that there is an altitude-dependence of $C_{adj}$, which is displayed in more detail in Figure 7. It shows the monthly average $C_{adj}$ for stations which where binned to distinct classes of altitude ranging from 100 to 2300 m in steps of 100 m. As already seen in Figure 4 as an example for three stations, $C_{adj}$ is clearly higher in winter than the unadjusted value. From April to September $C_{adj}$ is lower than 0.0023 up to altitudes of 1500 m.a.s.l., lowest values are visible in May to August between altitudes of 400 to 1000 m.a.s.l.

### 3.3 Temporal and spatial interpolation of the Hargreaves calibration parameter $C_{adj}$

The monthly adjusted calibration parameters are now interpolated in space and time in order to receive a congruent overlay of $C_{adj}$ over the SPARTACUS grid for every day of year. As a first step, the monthly $C_{adj}$ values at every station are linearly interpolated to daily values to avoid stepwise changes and therefore abrupt shifts of $C_{adj}$ between months. This is carried out for a standard year with length of 365 days. The result is a time series of daily changing values of $C_{adj}$ over the course of the year, available for every station, stretching over different altitudes and therefore yielding 42 different annual time series of $C_{adj}$.

Subsequently the daily, station-wise values of $C_{adj}$ are interpolated in space. As was shown in the previous section, $C_{adj}$ changes with altitude. Figure 8 shows the adjusted calibration parameters plotted against altitude for the monthly means of $C_{adj}$. From this Figure it comes clear that this relationship is not linear. $C_{adj}$ is decreasing from the very low situated stations until altitudes between 500 and 1000 m.a.s.l. Going further up $C_{adj}$ increases and one could say it might be a linear increase, particularly in winter. On the other hand, looking at the summer months the station with the highest elevation (Sonnblick, 3106 m.a.s.l.) shows somewhat lower or at least equal values of $C_{adj}$ compared to the cluster of stations between 2000 and 2400 m.a.sl. This feature indicates that the relationship above 1000 m.a.s.l. might not be linear. Taking all this characteristics into account, a higher order polynomial fit was chosen to describe the $C_{adj}$-altitude relation. As shown in Figure 8 a third order polynomial fit, indicated by the red line, is applied. Using the underlying DEM of the SPARTACUS dataset it is possible to determine adjusted calibration parameters for every grid point in space by this relationship. ~~This procedure is applied~~The polynomial fit is applied for every day of the daily interpolated station-wise $C_{adj}$ values, since these are changing day by day as well. The result is a gridded dataset of $C_{adj}$ for the SPARTACUS domain for 365 time steps from January 1$^{st}$ to December 31$^{st}$. Figure 9 shows two examples of $C_{adj}$ distribution in space on January 1$^{st}$ (a) and July 1$^{st}$ (b). Particularly in January the altitude dependence of the calibration parameter is clearly standing out, showing rather high values of $C_{adj}$ ~~at the main Alpine crest~~in the mountainous areas. In contrast to winter the spatial variations in summer are smaller, only some central Alpine areas between 1000 and 3000 m.a.s.l. are appearing in somewhat different shading than the surrounding low lands.

Having these gridded $C_{adj}$ values the ET0_h.c is calculated for every grid point and day since 1961 to 2013. In the case of leap years the $C_{adj}$ grid of February 28$^{th}$ is also used for February 29$^{th}$.

## 4 Results

Figure 10a shows the climatological mean (1961-2013) of the ~~annual sum of~~daily ET0 fields over the whole domain. ~~Altitude as a main control on surface temperature, and therefore consequently on ET0, clearly stands out.~~ Lowest ~~mean daily~~daily mean values of ~~around 1.4~~below 1.5 mm day$^{-1}$ are apparent on the highest mountain ridges of the main Alpine crest. Highest values of ~~up to~~ 2.4 mm day$^{-1}$ and above are found ~~on the inner Alpine valley floors and~~in the eastern and southern low lands. Other spatial features are visible as well, for example the higher ET0 in the valleys in the far western part of Austria. It is driven by the higher sunshine hours in these areas, which are also termed as “inner alpine dry valleys”, because rainfall approaching from the west is often screened by the mountain chains in the Northwest. In the ET0 estimate it is reflected in the higher Diurnal Temperature Range (DTR), yielding larger values in that particular area. A similar characteristic is apparent in the very south of Austria. Here the ET0 is higher as well, compared to topographically similar regions on the northern rim of the Alps. This is again connected to the higher proportion of sunshine hours which enhances indirectly ET0 through higher DTR values. ~~Interestingly, the northern and eastern low lands show lower ET0 values than the southern basins and valleys. This feature might result from larger differences between Tmin and Tmax indicating more days with clear sky conditions. Bigger diurnal temperature ranges also increase ET0 in the HM, since it as a proxy for radiation.~~

Figure 10b shows exemplary the ET0 field of August 8$^{th}$ 2013. For the first time ~~On~~ on that particular day, temperatures reached ~~for the first time in the instrumental period~~ above 40 °C in Austria at some stations in the East and South. Values of ET0 are particularly high, reaching up to 7 mm day$^{-1}$ in some areas in the Southeast. That day was also characterized by an approaching cold front, bringing rain, dropping temperatures and overcast conditions from the West. This is featured as well in the ET0 field, showing a considerable gradient from West to East, with nearly zero ET0 at the headwaters of the Inn River in the far Southwest of the domain. Furthermore, the implications of overcast conditions in the West with lower altitudinal gradients of ET0 compared to the East with sunny conditions and distinct gradients along elevation are visible.

July, the month with the highest absolute values of ET0 shows considerable variations in the last 53 years. As an example, the mean anomaly of ET0 in July of 1983 with respect to the July mean of 1961-2013 is displayed in Figure 11a. This month was characterized by a considerable heat wave and mean temperature anomalies of +3.5 °C which also affected ET0. The absolute anomaly of ET0 reaches above 1 mm day$^{-1}$ with respect to the climatological mean in some areas. The relative anomaly is in a range between 10 to 30 % (Figure 11c). On the other hand, July of 1979 was rather cool with temperatures 1.5 °C below the climatological mean and accompanied by a strong negative anomaly in sunshine duration, particularly in the areas north of the main Alpine crest. These ~~features~~ characteristics implicated a distinctly negative anomaly of ET0 in this particular month (Figure 11b). The absolute anomaly stretches between 0 and more than -1 mm day$^{-1}$, equivalent to a relative anomaly of 0 to -30 % (Figure 11d). The negative signal is stronger in the areas north of the Alpine crest, zero anomalies are found in the some areas south of the main Alpine crest.

In Figure 12 the overall benefits of the re-calibration of the HM are revealed. It shows the mean ET0 in ~~August 2003~~July 2012, a month accompanied by a considerable heat wave ~~and drought occurring widespread over Central Europe~~at the beginning and an overall temperature anomaly of around +2 °C.~~,~~ In Figure 12b the ET0 field ~~by means~~ of the original HM formulation without calibration is shown, and Figure 12a ~~(12b) and with~~ displays the results with re-calibration as described in this study ~~(12a)~~. Overall, the gradient along elevation of ET0 is larger in the non-calibrated field. Particularly in this time of the year with large absolute values, the re-calibration has a considerable impact, although $C_{adj}$ in ~~August~~ July is relatively small compared to winter. As shown before (cf. Figure 4), the ET0 estimation using the original C is good for July in the lowlands, since biases tend to be rather small. However, going to higher elevations, the overestimation of the original HM is rather pronounced. Mean biases reach +1 mm day$^{-1}$ or +30 %. This signal switches to negative biases of -0.5 mm day$^{-1}$ (-25 %) above 1500 m.a.s.l. ~~However, ET0_h.c is clearly higher above 1500 m.a.s.l. The bias shows a distinct spatial pattern with altitude as the driving mechanism. In the Alpine areas the underestimation of ET0_h is up to 1 mm day$^{-1}$ or 30 %. On the other hand, ET0_h shows an overestimation in the lowlands, but the bias in these areas is smaller, around 0.5 mm/d or 15%.~~

## 5 Discussion

By comparing the characteristics of ET0 based on HM and PM on a daily time step it came clear that a re-calibration of C within the formulation of Hargreaves follows distinct patterns. The values of $C_{adj}$ show markedly variations in space and time (over the course of the year). It turned out, that a monthly re-calibration of C reveals an annual cycle of $C_{adj}$, with $C_{adj}$ being close to the original value of 0.0023 in the warm season (April-October) and low elevations. Going to higher elevations, ~~unfolded decreasing $C_{adj}$ in the warm season until roughly 1000 m.a.s.l.~~ $C_{adj}$ decreases until roughly 1000 m.a.s.l. Reaching altitudes above 1700 m.a.s.l., $C_{adj}$ is generally above the original 0.0023, particularly in the cold season (November-March). This altitude dependency of the calibration parameter in HM is mentioned in Samani (2000), ~~but was relativized by this relationship being affected by latitude~~but the authors also claimed that this relationship may be affected by different latitudes. Aguila and Polo (2011) also found that the original HM using a C of 0.0023 underestimates ET0 at higher elevations and defined a value of 0.0038 at an elevation of 2500 m.a.s.l. However, this altitude dependency of C turned out to be more complex, as we are able to display, showing a distinct variation throughout the year along with elevation. So this relationship is used to derive $C_{adj}$ values for every day of year and every grid point of the forcing fields.

To reveal the sources of this altitude dependence of C we accomplished some additional analysis. In general, the HM utilizes the Diurnal Temperature Range (DTR, $T_{max}$ minus $T_{min}$) to mimic the amount of global radiation at the land surface. Clear sky conditions are usually associated with higher DTR. There will be more heating during daytime due to large proportions of direct solar radiation, whereas at night time temperatures are dropping further down since the outgoing long-wave radiation is not reflected by clouds. The connection between DTR and radiation is shown in numerous studies (Pan et al., 2013; Makowski et al., 2009; Bindi and Miglietta, 1991; Bristow and Campbell, 1984). All these investigations showed considerable correlations, for example Makowski et al. 2009 reported a correlation coefficient of 0.87 of the annual means of DTR and solar radiation averaged over 31 stations across Europe.

Figure 13 shows the correlation of DTR and global radiation on a daily time scale at the 42 stations used in this study. The coefficients show a distinct altitudinal dependency, particularly in winter. In January the correlations are above 0.90 at some stations and

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generally high at altitudes between 400 and 1000 m.a.s.l. At higher elevations the correlations are dropping considerably, getting negative between 1500 and 2000 m.a.s.l. In July the correlations are generally higher. Apart from two stations the correlations lie between 0.45 and 0.98, but again accompanied by a decline with altitude, which is also seen in the year round correlations. Interestingly, the patterns of the correlations along altitude are rather similar to the $C_{adj}$ patterns as can be seen in Figure 8. Therefore we think that the DTR-global radiation nexus is the crucial point in the altitude dependence of $C_{adj}$.

The reasons for the correlation patterns in Figure 13 seem to be rooted in the lower atmospheric mixing ratios at the lowest stations, some of them located in, or nearby cities, which might dampen the DTR, although clear sky conditions are apparent. At moderate altitudes between 400 and 1500 m.a.s.l. the daily temperature amplitude is more dominantly driven by surface energy balance processes which reflects the higher correlations. Going further up, the proportion of the DTR which is determined by large scale air mass changes rises, as the station locations reach up above the planetary boundary layer into the free atmosphere, causing considerably low correlations at higher elevations, particularly in winter.

Although these circumstances seem to be a drawback of the methodology, the overall effect is only minor. Figure 14 shows the HM ET0 in dependence of the DTR and the daily mean temperature. At low daily mean temperatures, between -10 and +10 °C, the contour lines determining the value of ET0 are rather steep. This implies that a change in DTR has only minor effects on the ET0 outcome, whereas a change in daily mean temperature is more important.

However, ~~this~~ the procedure of ~~alternating~~ altering C has also implications on the variability of ET0 on a daily time scale. As was visible in Figure 2a the variability of ET0 based on HM is lower than~~e~~ ~~conducting~~ using PM. The presented re-calibration has only little effect on the enhancement of variability. By scaling C, variability is slightly enhanced in those areas and time of the year where $C_{adj}$ is higher than 0.0023. This is the case for most of the time and widespread areas, but there are regions or altitudinal levels where the opposite is taking place. As is visible in Figure 8 areas up to 1500 m.a.s.l. show lower than original values of $C_{adj}$ in the summer months. There are particular areas in June between altitudes of 500 to 1000 m.a.s.l. that show the largest deviation from the original value. In these areas variability is lower in the re-calibrated version. On the other hand the benefit of an ET0 formulation being unbiased compared to the reference of PM may overcome these shortcomings.

The overall performance of the final gridded dataset compared to the PM estimates is displayed in Figure 15. 15a shows the monthly bias of the original HM ET0 and the calibrated ET0 of the nearest grid point. The bias is clearly reduced in nearly all months. However, in April, as the only exception, the bias of the calibrated grid point values is larger than the bias of the original estimation. The biases concerning different levels of altitude are reduced as well, as can be seen in Figure 15b which shows the biases in July and Figure 15c displaying the biases in January.

## 6 Conclusion

In this paper a gridded dataset of ET0 for the Austrian domain from 1961-2013 on daily time step is presented. The forcing fields for estimating ET0 are daily minimum and maximum temperatures from the SPARTACUS dataset (Hiebl and Frei 2015). These fields are used to calculate ET0 by the formulation of Hargreaves et al. (1985). The HM is calibrated to the Penman-Monteith equation, which is the recommended method by the FAO (Allen et al. 1998), at a set of 42 meteorological stations from 2004-2013, which have full data availability for calculating ET0 by PM. The adjusted monthly calibration parameters $C_{adj}$ are interpolated in time (resulting in daily $C_{adj}$ for a standard year) and space (resulting in $C_{adj}$ for every grid point of SPARTACUS and day of year). With these gridded $C_{adj}$ the daily fields of reference evapotranspiration are calculated for the time period from 1961-2013.

This dataset may be highly valuable for users in the field of hydrology, agriculture, ecology etc. as it aims to provide ET0 in a high spatial resolution and a long time period~~, which is rather important for impact studies dealing with the effects of observed climate change on the water cycle~~. Data for calculating ET0 by recommended PM is usually not available for such long time spans and/or with this spatial and temporal resolution. However, the method presented in this study tries to combine both strengths of long time series, high spatial and temporal resolution provided by the temperature based HM and the physical more realistic radiation based PM by adjusting HM.

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1 Table 1. Location, altitude and setting of the 42 meteorological stations used for calibration.

| | Station | Lon (°) | Lat (°) | Alt (m) | Setting |
|---|---|---|---|---|---|
| 1 | Aflenz | 15.24 | 47.55 | 783 | Mountainous |
| 2 | Alberschwende | 9.85 | 47.46 | 715 | Mountainous |
| 3 | Arriach | 13.85 | 46.73 | 870 | Mountainous |
| 4 | Bregenz | 9.75 | 47.50 | 424 | Lakeside |
| 5 | Dornbirn | 9.73 | 47.43 | 407 | Valley |
| 6 | Feldkirchen | 14.10 | 46.72 | 546 | Valley |
| 7 | Feuerkogel | 13.72 | 47.82 | 1618 | Summit |
| 8 | Fischbach | 15.64 | 47.44 | 1034 | Mountainous |
| 9 | Galzig | 10.23 | 47.13 | 2084 | Alpine |
| 10 | Graz_Universitaet | 15.45 | 47.08 | 366 | City |
| 11 | Grossenzersdorf | 16.56 | 48.20 | 154 | Lowland |
| 12 | Gumpoldskirchen | 16.28 | 48.04 | 219 | Lowland |
| 13 | Irdning_Gumpenstein | 14.10 | 47.50 | 702 | Valley |
| 14 | Ischgl_Idalpe | 10.32 | 46.98 | 2323 | Alpine |
| 15 | Jenbach | 11.76 | 47.39 | 530 | Valley |
| 16 | Kanzelhoehe | 13.90 | 46.68 | 1520 | Summit |
| 17 | Krems | 15.62 | 48.42 | 203 | Lowland |
| 18 | Kremsmünster | 14.13 | 48.06 | 382 | Lowland |
| 19 | Langenlois | 15.70 | 48.47 | 207 | Lowland |
| 20 | Lilienfeld_Tarschberg | 15.59 | 48.03 | 696 | Mountainous |
| 21 | Lofereralm | 12.65 | 47.60 | 1624 | Alpine |
| 22 | Lunz_am_See | 15.07 | 47.85 | 612 | Valley |
| 23 | Lutzmannsburg | 16.65 | 47.47 | 201 | Lowland |

| | | | | | |
|---|---|---|---|---|---|
| 24 | Mariapfar | 13.75 | 47.15 | 1153 | Mountainous |
| 25 | Mariazell | 15.30 | 47.79 | 864 | Mountainous |
| 26 | Neumarkt | 14.42 | 47.07 | 869 | Mountainous |
| 27 | Patscherkofel | 11.46 | 47.21 | 2247 | Summit |
| 28 | Poertschach | 14.17 | 46.63 | 450 | Lakeside |
| 29 | Retz | 15.94 | 48.76 | 320 | Lowland |
| 30 | Reutte | 10.72 | 47.49 | 842 | Valley |
| 31 | Rudolfshuette-Alpinzentrum | 12.63 | 47.13 | 2304 | Alpine |
| 32 | Schaerding | 13.43 | 48.46 | 307 | Lowland |
| 33 | Schmittenhoehe | 12.74 | 47.33 | 1973 | Alpine |
| 34 | Sonnblick | 15.96 | 47.05 | 3109 | Summit |
| 35 | Spittal_Drau | 13.49 | 46.79 | 542 | Valley |
| 36 | Villacheralpe | 13.68 | 46.60 | 2156 | Summit |
| 37 | Virgen | 12.46 | 47.00 | 1212 | Valley |
| 38 | Weissensee_Gatschach | 13.29 | 46.72 | 945 | Lakeside |
| 39 | Wien_Donaufeld | 16.43 | 48.26 | 161 | City |
| 40 | Wien_Hohewarte | 16.36 | 48.25 | 198 | City |
| 41 | Wien_Unterlaa | 16.42 | 48.12 | 201 | City |
| 42 | Wolfsegg | 13.67 | 48.11 | 638 | Lowland |

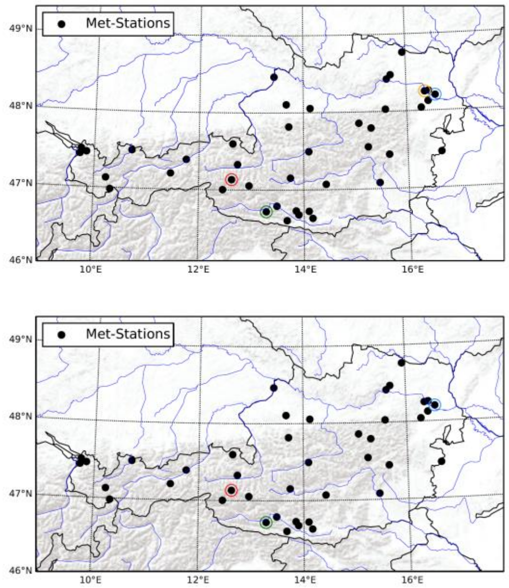



Figure 1. Location of the meteorological stations used for calibration; coloured circles around points indicate stations that are exemplary displayed in other plots: Grossenzersdorf (blue), Weissensee_Gatschach (green)~~,~~ and Rudolfshuette-Alpinzentrum (red)~~ and Wien_Hohewarte (orange)~~.

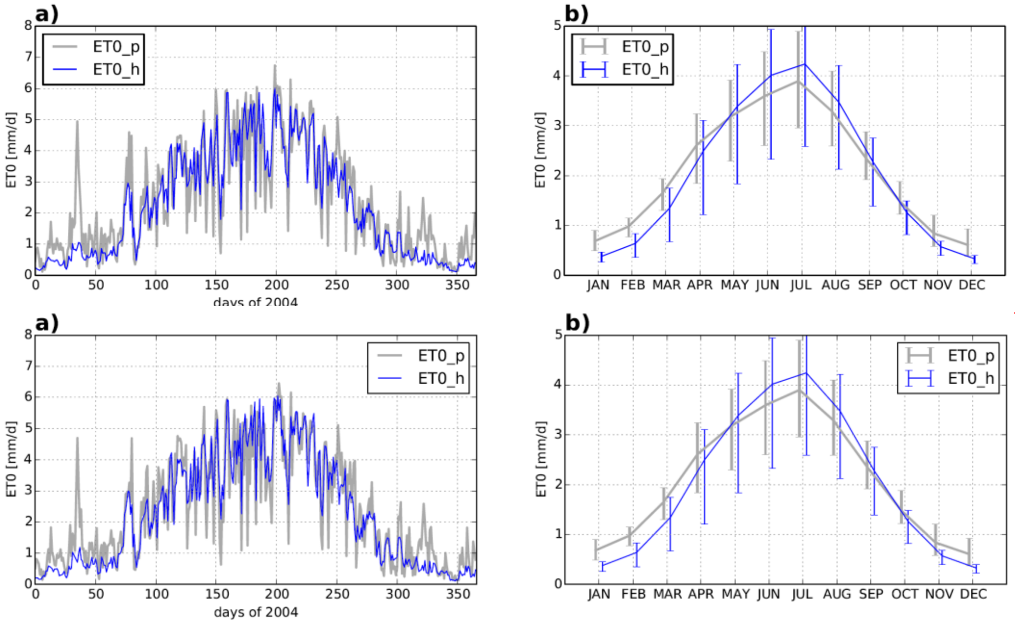



Figure 2. Daily time series of ET0 in 2004 for ET0 based on PM (ET0_p) and HM (ET0_h) at the station ~~Wien_Hohewarte~~Grossenzersdorf (a); Monthly mean ET0 from 2004 to 2013 averaged over all station, error bars denote for the spread among all stations (b).

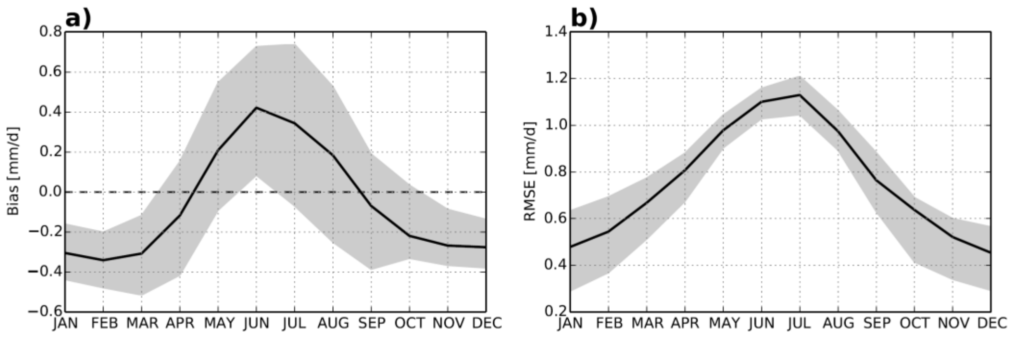



Figure 3. Monthly Bias (a) and monthly Root Mean Square Error (b) between daily ET0_p and ET0_h for all stations; the grey shading indicates the spread among the different stations.

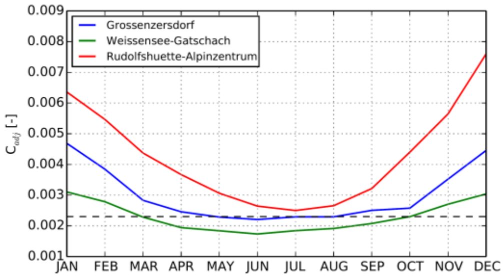



Figure 4. Monthly values of $C_{adj}$ at three different stations, the dashed black lines indicates the original C value of 0.0023 from Hargreaves et al. (1985).

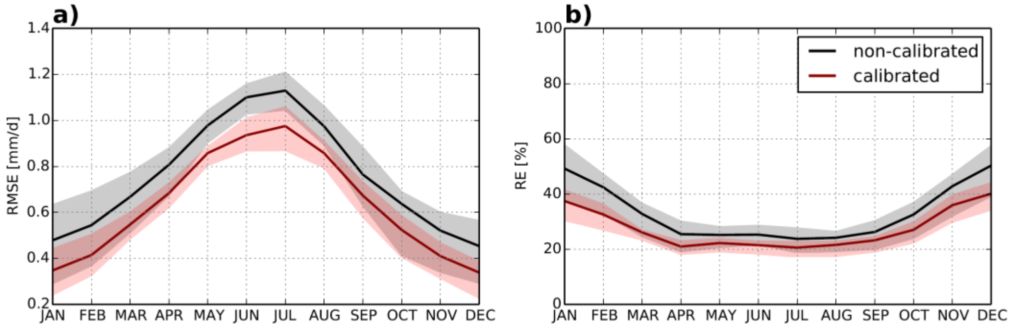



Figure 5. Monthly Root Mean Square Error (a) and monthly Relative Error (b) between daily ET0_p and ET0_h (black) and ET0_p and ET0_h.c (red).

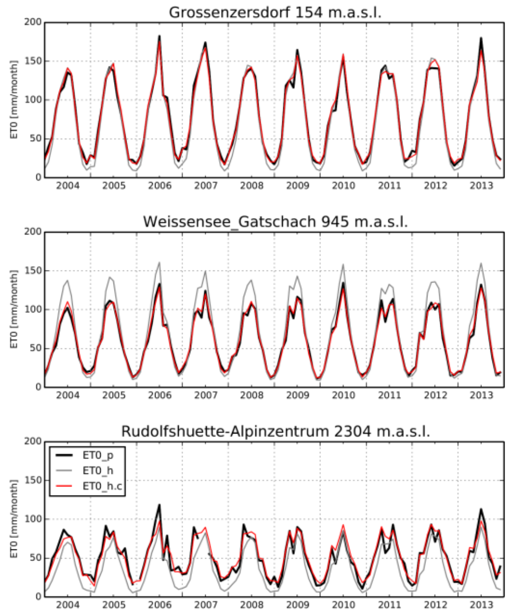



Figure 6. Monthly ET0 sums derived from ET0_p, ET0_h and ET0_h.c for three stations located at different altitudes.

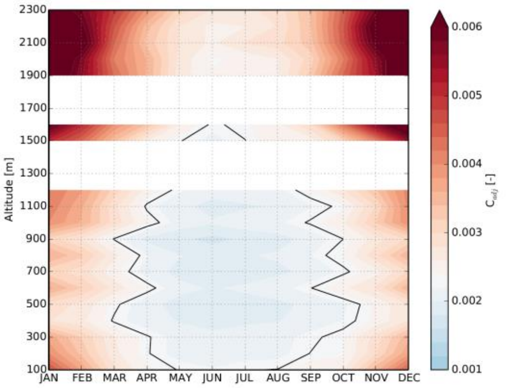



Figure 7. Monthly variations of $C_{adj}$ with respect to altitude; the black contour line defines the original Hargreaves Calibration Parameter C value of 0.0023; stations are binned to classes of altitude from 100 to 2300 m every 100 m; white areas denote classes of altitude with no station available.

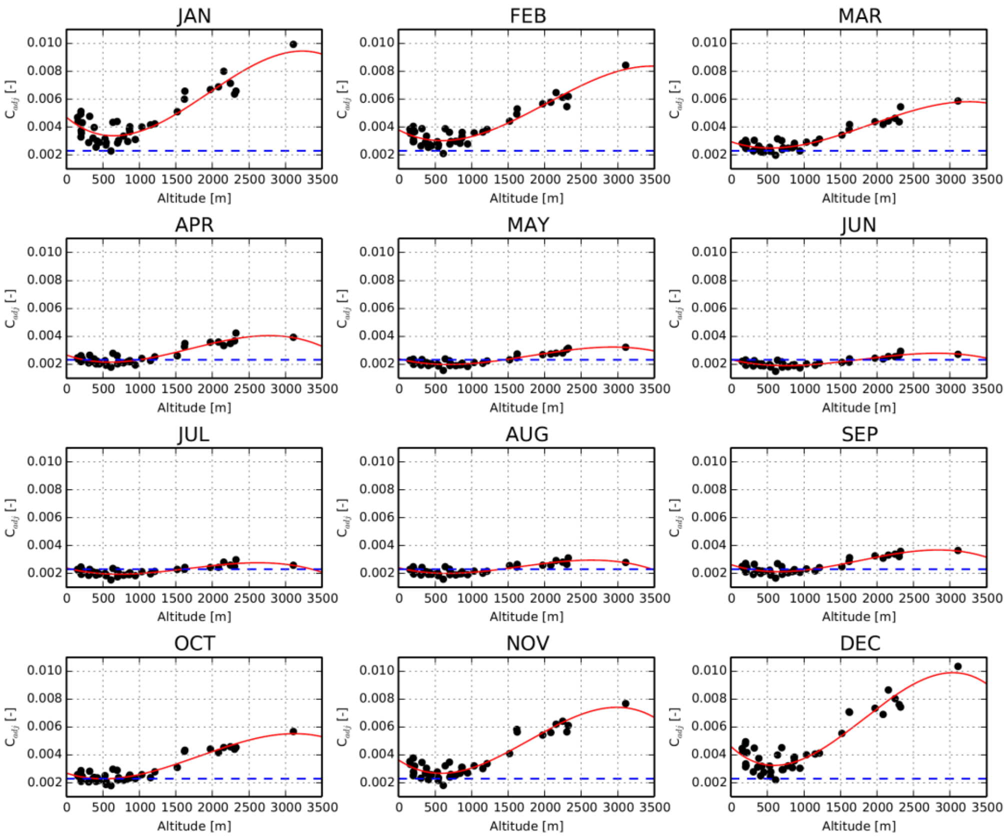



Figure 8. Station-wise monthly third-order polynomial fit of the Hargreaves Calibration Parameter $C_{adj}$ against altitude; the blue dotted line indicates the original C value of 0.0023.

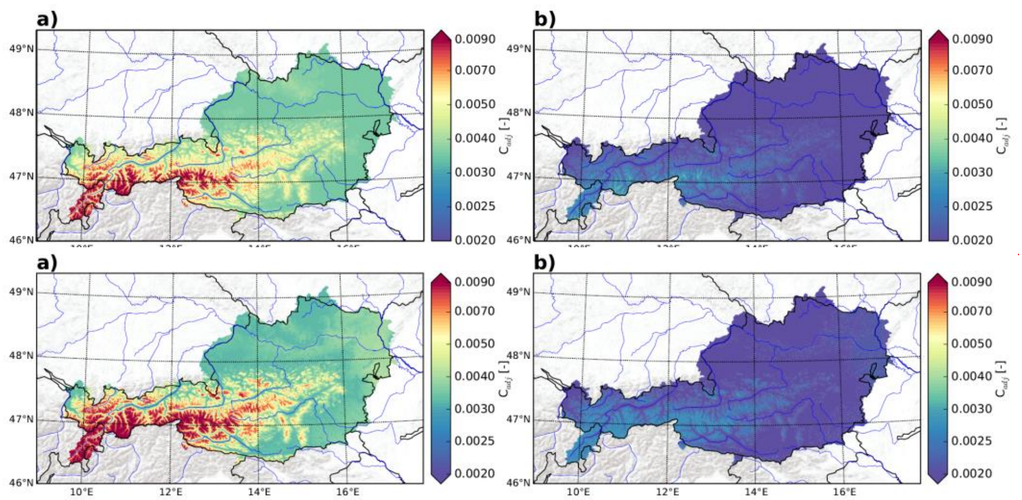



Figure 9. Spatially interpolated $C_{adj}$ values for January 1st (a) and July 1st (b).

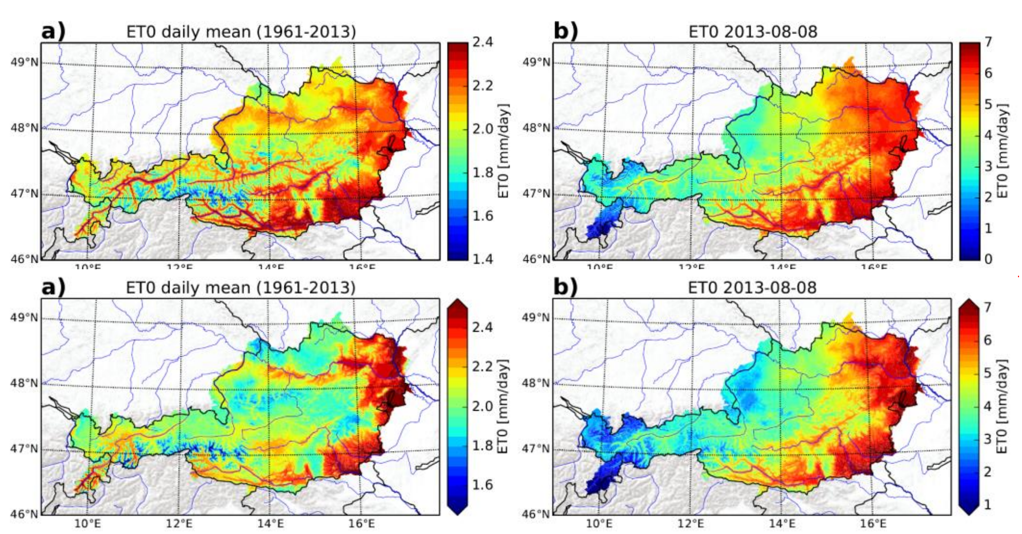
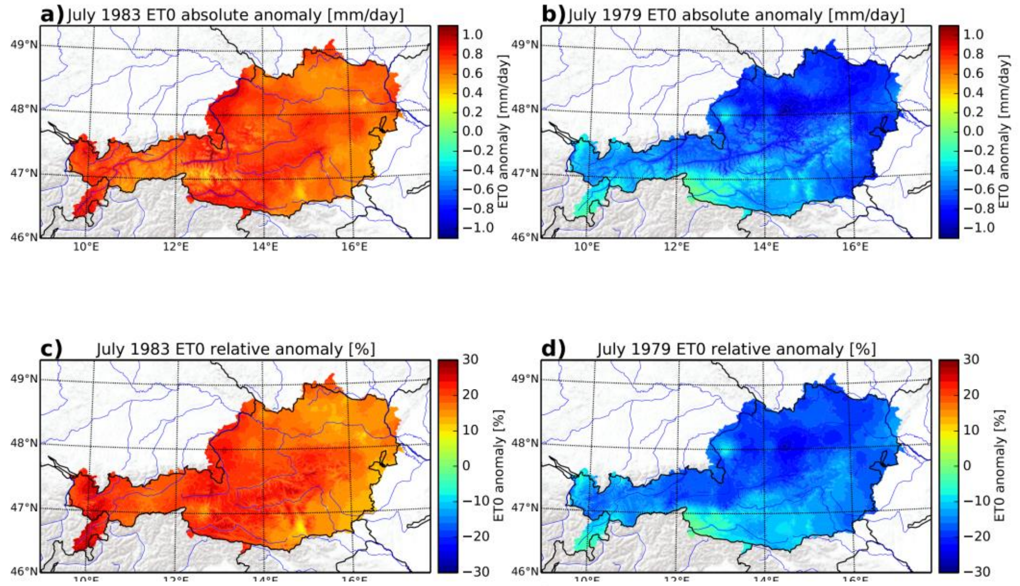



Figure 10. Climatological ~~mean annual sum of~~daily mean ET0 from 1961-2013 (a); example of a daily field of ET0 on August $8^{th}$ 2013 (b).



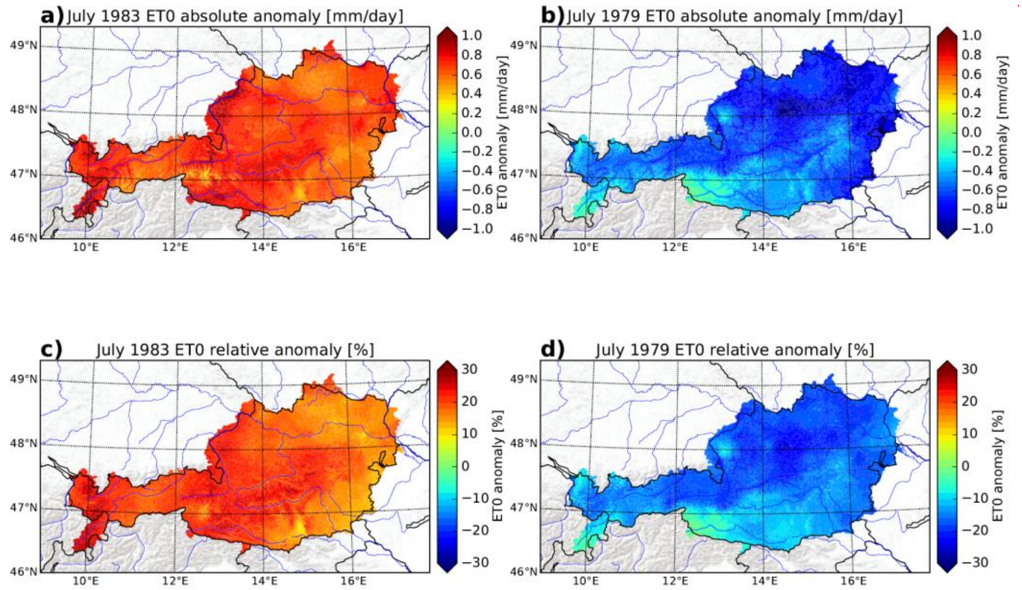
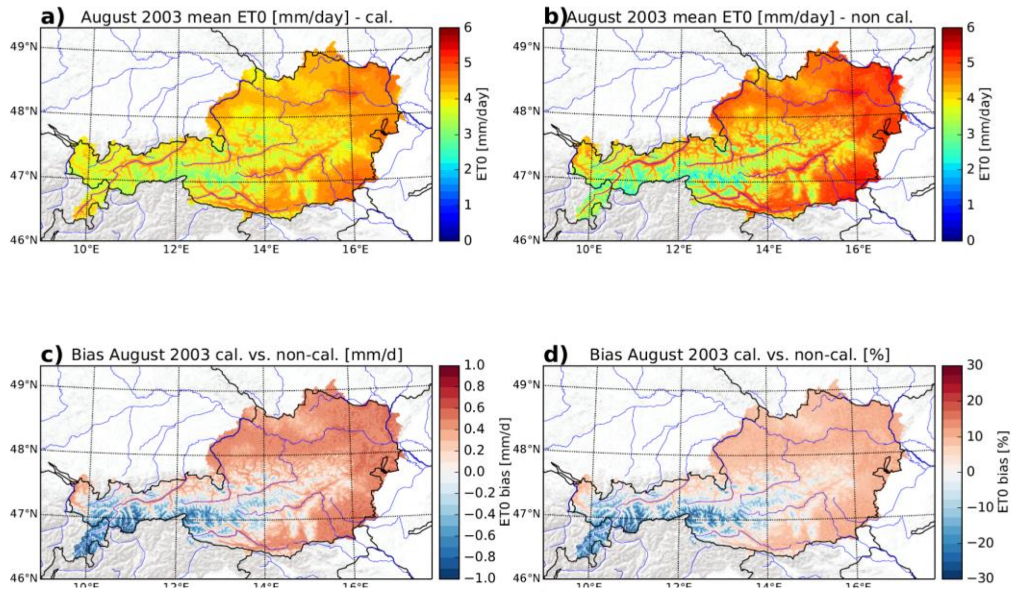




Figure 11. Upper panel: absolute anomalies of ET0 sum in July 1983 (a) and July 1979 (b) with respect to the climatological mean in July from 1961-2013; lower panel: corresponding relative anomaly (c, d).



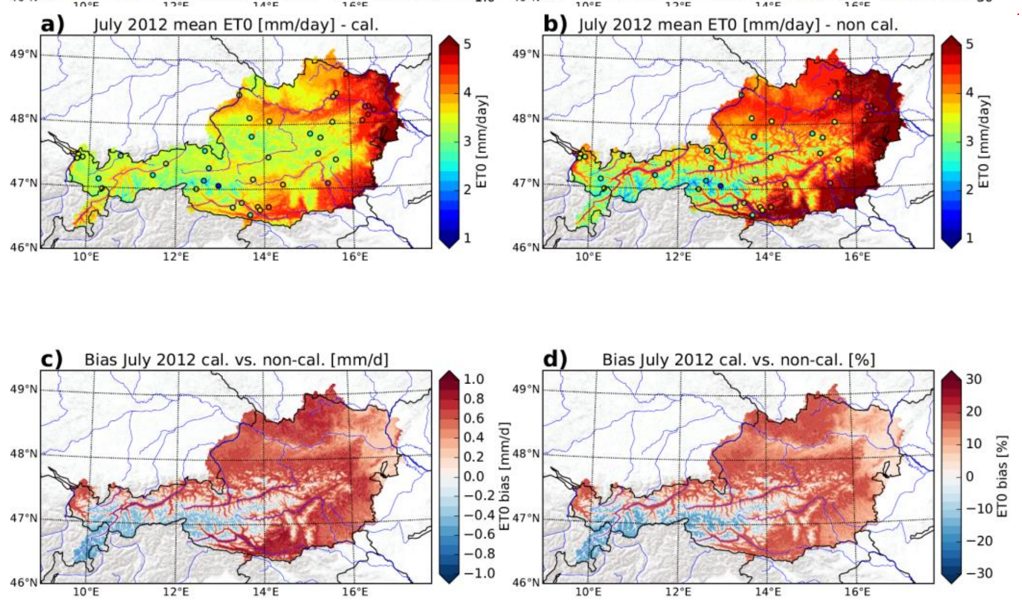




Figure 12. ~~August 2003~~July 2012 monthly mean ET0 based on $C_{adj}$ values – ET0_h.c (a), using the original C of 0.0023 for the whole grid ET0_h (b) and the corresponding absolute (c) and relative bias (d); the dots in (a) and (b) denote for the PM ET0 at the stations.~~.~~

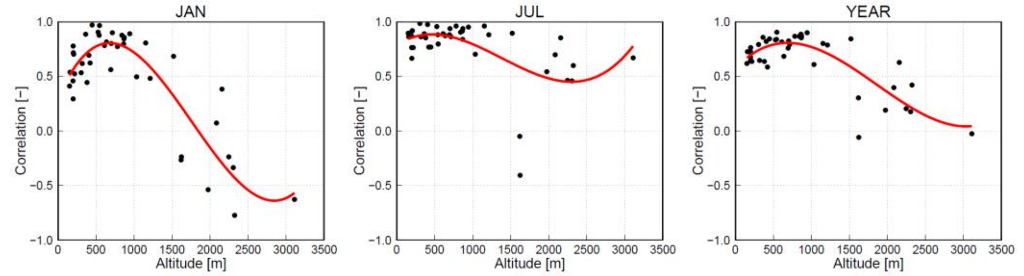



Figure 13. Station-wise Correlation of Global Radiation and Diurnal Temperature Range ($T_{max}$-$T_{min}$) against altitude represented by black dots in January (left), July (middle) and all-year (right); the red line represents a third-order polynomial fit.

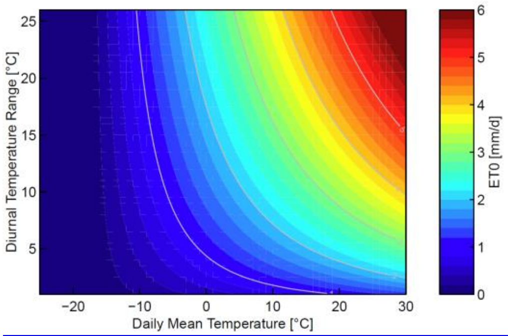



Figure 14. ET0 response to varying Daily Mean Temperature and Diurnal Temperature Range; ET0 values are calculated with 1st of April Top of the Atmosphere Radiation and the original C value of 0.0023.

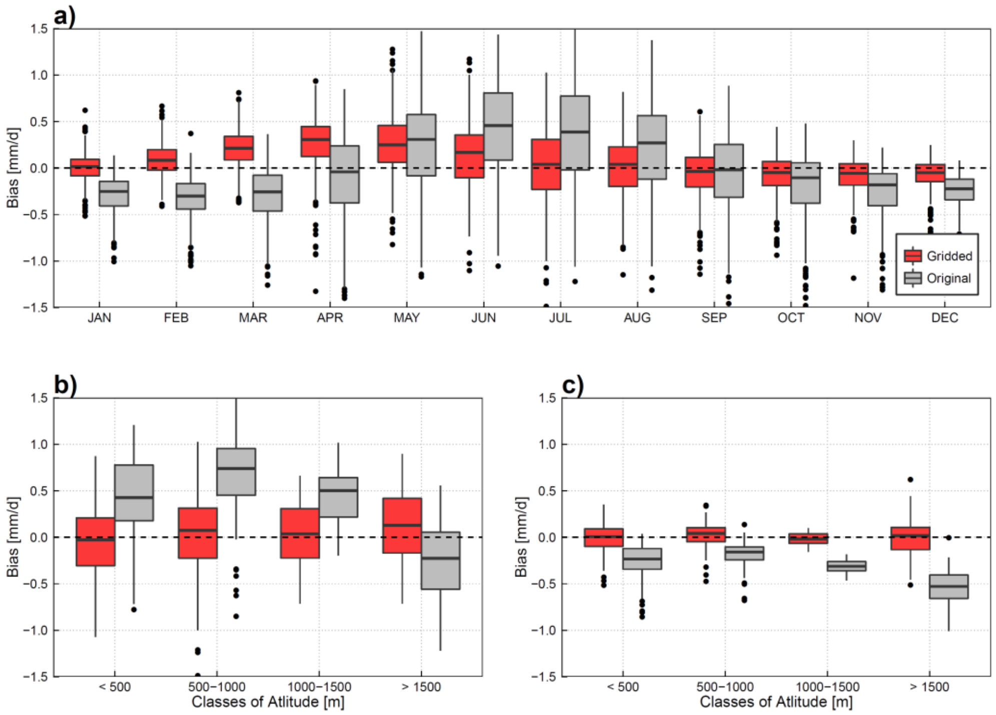



Figure 15. Boxplots of monthly mean bias of the station-wise original Hargreaves ET0 (grey) and the final gridded, re-calibrated ET0 (red) against Penman-Monteith ET0 (a); stratified by different classes of altitude in July (b) and January (c);