

Interactive comment on “Site specific parameterizations of longwave radiation” by G. Formetta et al.

Anonymous Referee #1

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The study evaluates the performance of site-specific parameterizations of longwave radiation. Similar evaluations have already been done by other authors. What's special about this study are two points: 1) The model parameters have been randomly perturbed to analyze their sensitivity. 2) The site-specific model parameters were also estimated with the help of multiple regressions against commonly available local and climatic variables. The results are interesting and definitely worth to be published in HESS after the following comments have been addressed:

The authors thank the reviewer for the prompt revision and the interesting comments and suggestions he made. They definitely improved the quality of the paper. Below we replied one-to-one to each comment.

Q1) *Section 2: Please describe how the last and first hour of daylight was defined.*

A1) We thank the reviewer for the suggestion and we agree with it. We added the following sentence to specify how we computed the first and last hour of daylight.

“The computation of the first and last hour of the day is based on the model proposed in Formetta et al., 20013 that follow the approach proposed in Corripio (2002), equations 4.23-4.25. The sunrise occurs at $t = 12 \cdot \left(1 - \frac{\omega}{\pi}\right)$ and

the sunset will be at $t = 12 \cdot \left(1 + \frac{\omega}{\pi}\right)$ where ω is the hour angle. Those

equations are based on the assumption that sunrise and sunset occur at the time when the z coordinate of the sun vector equals zero”.

Q2) Section 4: There is hardly any discussion of the results. I suggest adding the discussion of the findings in the Result section.

A2) We thank the reviewer for the suggestion. We extended the discussion part as suggested also by reviewer n.2. We added some sentence in the conclusions and some more comments to the results presentation:

“Moreover the Brunt model is able to provide higher performances with the regression model parameters independently of the latitude and longitude classes. For the Idso model the formulation with regression parameter provided lower performances respect to the literature formulation for latitude between [25-30]”.

“Although many studies investigated the influence of snow covered area on longwave energy balance (e.g. Plüss and Ohmura, 1997; Sicart et al., 2006), the SMs do not explicitly take into account of it. As presented in König-Langlo Augstein (1994), the effect of snow could be implicitly taken into account by tuning the emissivity parameter”

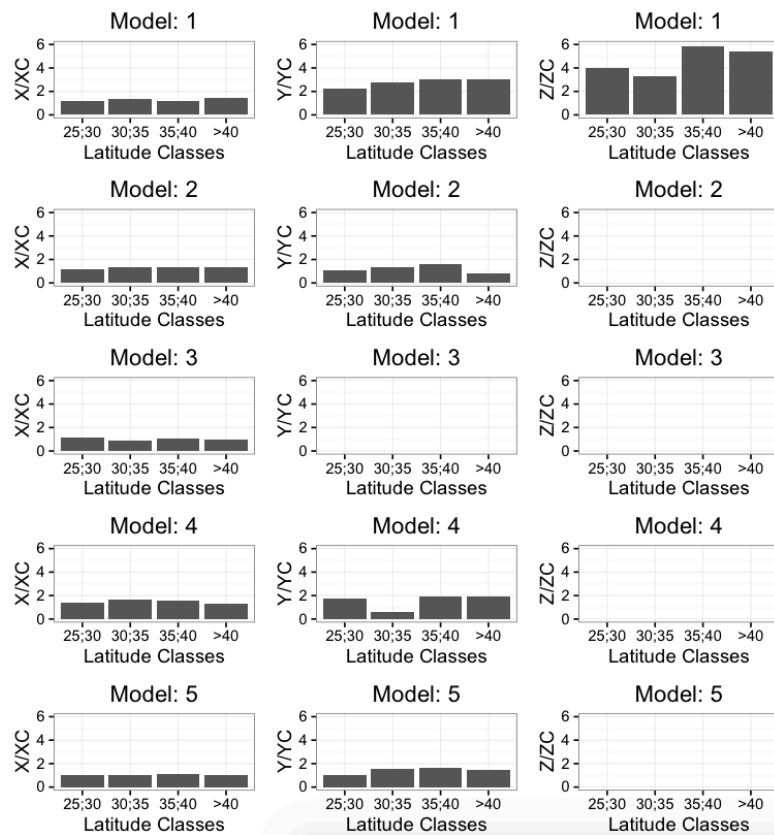
“Finally, the methodology proposed in this paper provides the basis for further developments such as the possibility to: i) investigate the effect different all-sky emissivity formulation, ii) verify the usefulness of the regression models for locations outside the USA; iii) analyze in a systematic way the uncertainty due to the quality of meteorological input data on the longwave radiation balance in scarce instrumented areas.”

Q3) *Section 4.2: I miss a figure or table, which shows the variability of the site-specific model parameters for the different stations analyzed. This information is necessary in order to judge the sensitivity of the parameters on the different climates. Possibly this is reported in the mentioned supplementary material, which I could not find!*

A3) We thank the reviewer for the comment. We attached the missing file of the table containing the parameters value for each model and station few hours after we read the revision. We agree with the reviewer comment and we added below two figures showing the parameters variability for each model and for classes of latitude and longitude.

Figure 1 shows the ratios between the optimal parameter set and the literature parameter set for each model grouped by latitude classes. In general the parameter ratios vary between 0.3 and 2.0 for most of the model and they do not show great variation across latitude classes except model 1, 8, and 9. The same comments are valid for Figure 2 that shows the ratios between the optimal parameter set and the literature parameter set for each model grouped by longitude classes.

For models 1,8, and 9 the ratios reach the maximum value of 6 and for model 1 and 9 they are lower for the latitude classes [25;30] and [30;35] and higher for latitude classes [35;40] and [>40].”



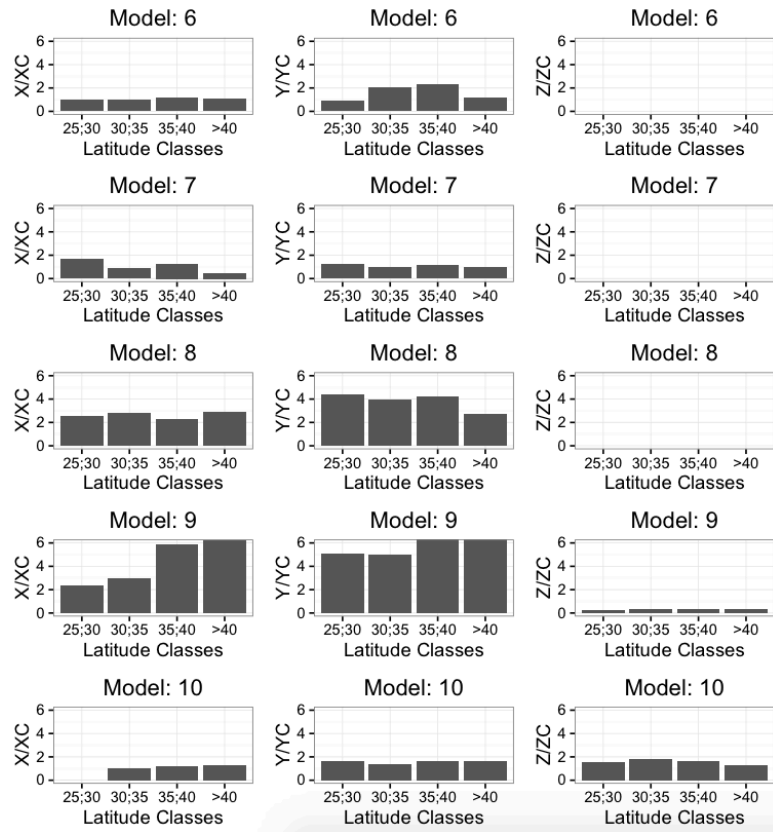
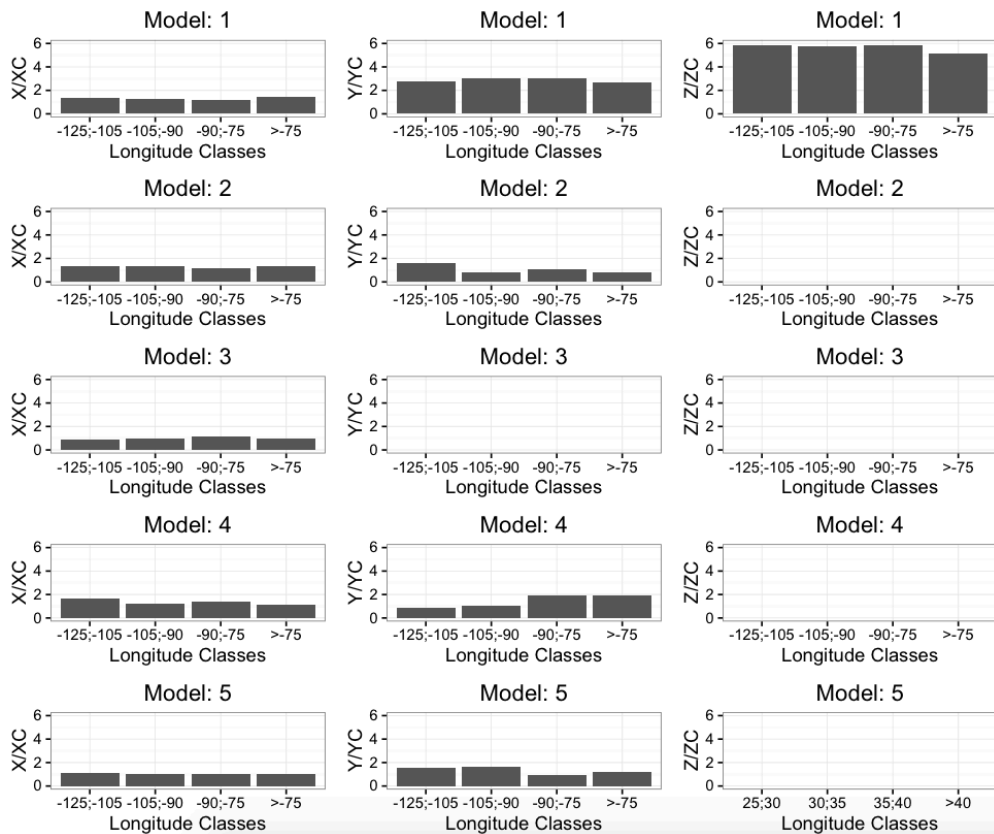


Figure 1: Ratios between optimal and literature parameter set for each model grouped by latitude classes



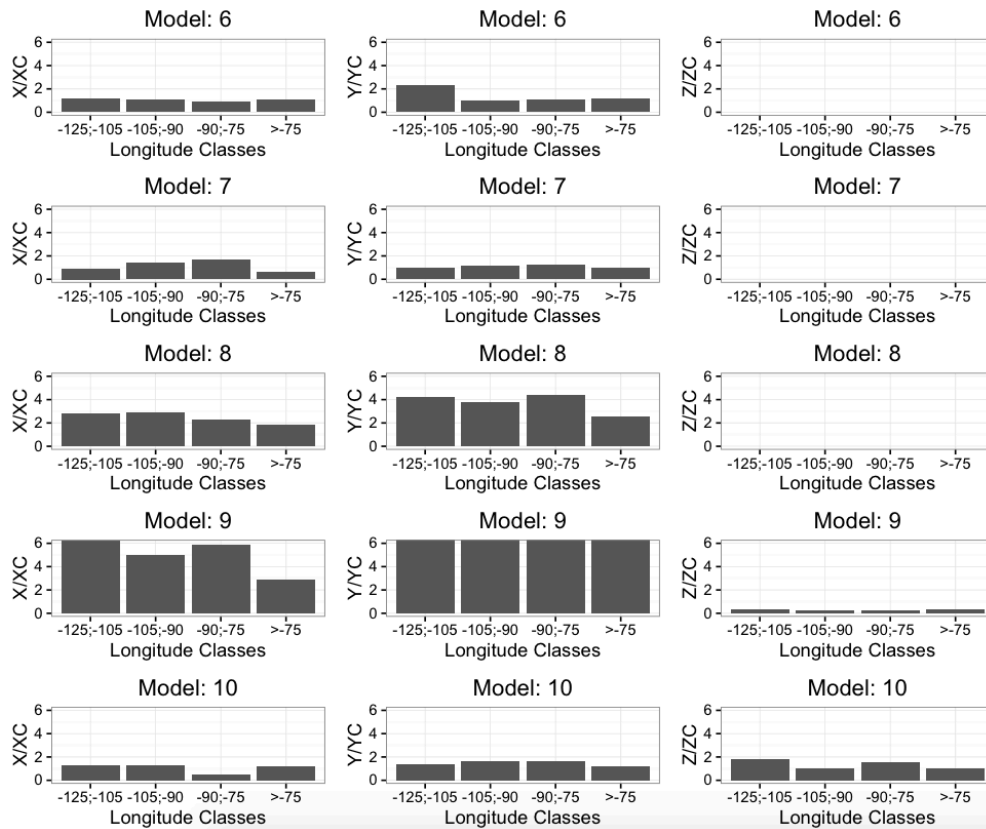


Figure 2: Ratios between optimal and literature parameter set for each model grouped by longitude classes

Q4) Section 4.3: You write “you start with optimal parameter set”. Is done for every station? Moreover, it might be worth mentioning that the all three parameters of model 10 seem to be quite robust.

A4) Yes, we started with the optimal parameter set for each station analysed and for each model. We added the following sentence to clarify better:

Old sentence: “The procedure was repeated for each parameter of each model”

New sentence: “The procedure was repeated for each parameter of each model and for each station of the analyzed dataset.”

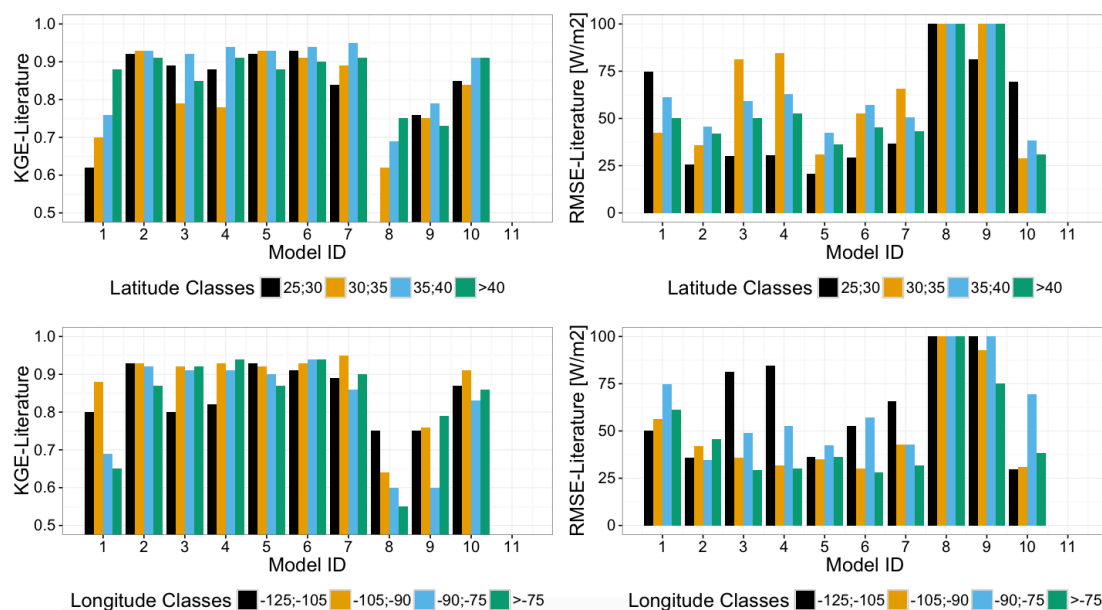
Q5) Section 4.4: This section is really innovative and therefore its potential needs to be explored more. In practice you often don't have stations nearby, which can be used as a training set. I would like to see how a Ameriflux station in northern Alaska (Arctic) and South America (Tropics) performs with your currently used training set. Is there a specific reason you don't show the

RMSE for this section? Which models perform best in this section?

A5) We thank the reviewer for the comment but we did not considered the two station he-her is referring to. The station in Alaska was excluded because has many no-values in the time-series of downwelling solar radiation compared to the 24 station we considered. The station in Brazil was not considered because we focused our attention in the North America.

Q6) As I understand the red bars in Figure 8 represent the same KGE values as the bars in Figure 4. A visual test with model 1 shows a disagreement for latitude class 30;35 and 35;40! Please explain.

A7) We agree with the reviewer comment and we checked again the script to produce Figure 4. We revised the figure and now it is coherent with Figure 8. Here you can find the new figure 4:



Q6) Section 4.5: Did take into account the soil was snow covered for some time at some stations. Please discuss the effect of snow on your approach and how it influences your results?

A6) We thank the reviewer for the question. The model parameterizations do not explicitly take into account of the presence of snow on the soil. We agree with the reviewer suggestion to clarify this aspect and we added the following sentence to state it when we present the models:

“Although many studies investigated the influence of snow covered area on longwave energy balance (e.g. Plüss and Ohmura, 1997; Sicart et al., 2006), the SMs do not explicitly take into account of it. As presented in König-Langlo Augstein (1994), the effect of snow could be implicitly taken into account by tuning the emissivity parameter.”

Q7) Section 5: In the Conclusion section, I miss a focus on the actual results, i.e. the evaluation of the different site-specific parameterizations methods and the performance of the different models. For example, it is not enough to write “A broad assessment of the classic longwave radiation parameterizations clearly shows that the Idso (1981) and Brunt (1932) models are the more robust and reliable for all the test sites, confirming previous results”. First, I don’t “see” this. Please add information based on RMSE or KGE (however this should not be done in the Conclusion section). Second, add the references, which seem to confirm your results.

A7) We added some comments on the results provided by the Idso and Brunt models, moreover we added the citation of the paper in which this results is confirmed and finally we also commented their performances with the model parameters estimated by the regression models. The new sentence is:

“Moreover the Brunt model is able to provide higher performances with the regression model parameters independently of the latitude and longitude classes. For the Idso model the formulation with regression parameter provided lower performances respect to the literature formulation for latitude between [25-30]”

Minor Comments:

Q8): L1: Performance of site specific parameterizations:

A8) We revised according the reviewer suggestion. The new title is: “Performances of site specific parameterizations of longwave radiation”

Q9) L15: for L in SMs

A9) We revised according the reviewer suggestion. The new sentence is:
“to determine by automatic calibration the site-specific parameter sets for L in SMs”

Q10) L29: I guess data also!

A10) We thank the reviewer for the question, but we are not allowed to share data. We provided the website where the ameriflux data are available to download.

Q11) L44: water vapor deficit

A11) We thank the reviewer for the suggestion and we revised the sentence accordingly. The new sentence is:

“To overcome this issue, simplified models (SM), which are based on empirical or physical conceptualizations, have been developed to relate longwave radiation to atmospheric proxy data such as air temperature, water vapor deficit, and shortwave radiation”

Q12) L46: Be consistent - when using L you don't need to add downwelling or upwelling radiation.

A12) We thank the reviewer for the suggestion. In this row we defined hour notation and we indicate the downwelling longwave radiation with the symbol L_{\downarrow} and the upwelling longwave radiation with the symbol L_{\uparrow} . We used this notation consistently in the whole text.

Q13) L49: Instead of old references I suggest to replace it with newer ones, like [doi:10.1007/s00704-012-0675-1](https://doi.org/10.1007/s00704-012-0675-1) and [doi:10.1016/j.coldregions.2013.12.004](https://doi.org/10.1016/j.coldregions.2013.12.004)

A13) We thank the reviewer for the suggestions. We added the newest references as he/she suggested and we preferred to keep the old reference as well.

Q14) L53-54: Why show the results only for this study?

A14) We thank the reviewer for the comment. We show the results of this

study because our results partially confirm them.

Q15) L77: Delete “near surface” or replace with “screen level”.

A15) We thank the reviewer for the suggestion and we revised accordingly, deleting “near surface”.

Q16) Table 1: The Monteith and Unsworth (1990) is missing in the Reference section, but I guess you mean Unsworth and Monteith (1975) anyway.

A16) We thanks the reviewer for the suggestion and we added the missing citation:

“John Lennox Monteith and MH Unsworth. Principles of Environmental Physics . Butterworth-Heinemann,1990.”

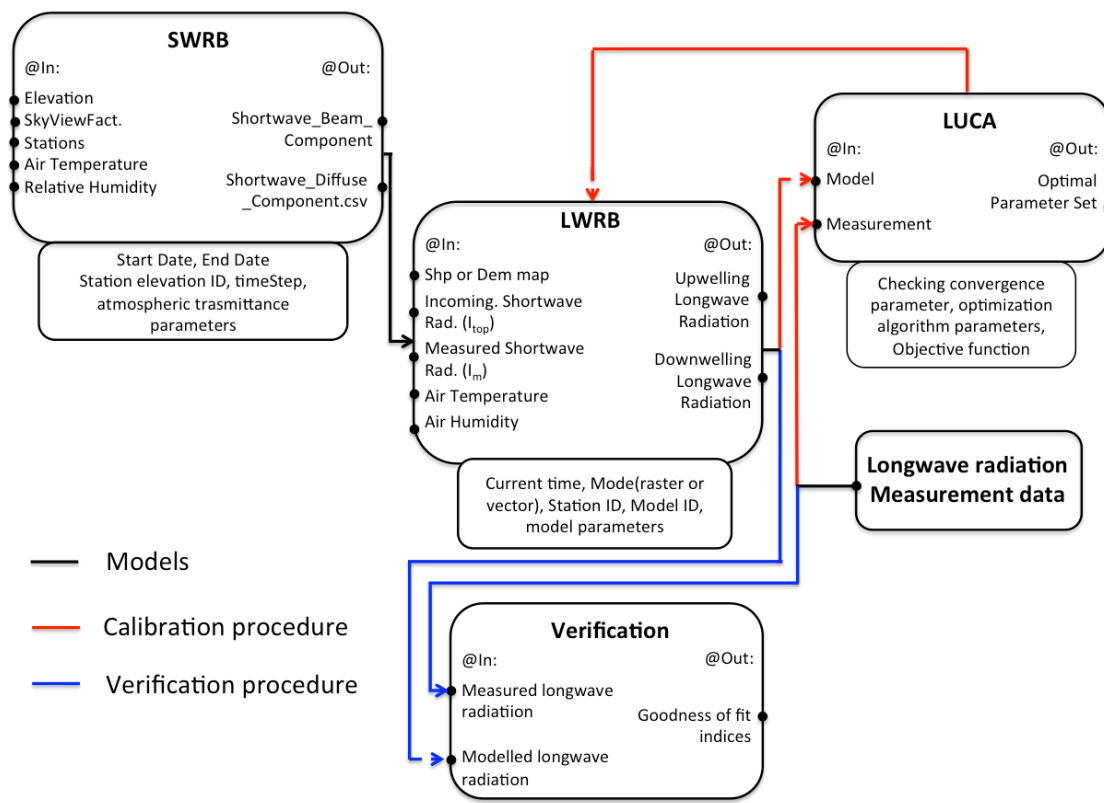
Q17) L103-105: Please reformulate. I suggest to make two sentences.

A17) We thank the reviewer for the suggestion. We splitted the sentence in two and the revised sentence is:

“Is well known that surface soil temperature measurements are only available at a few measurement sites. Under the hypothesis that difference between soil and air temperatures is not too big, it is possible to simulate L_{\uparrow} using the air temperature (Park et al., 2008). ”

Q18) Figure 1: “incoming Radiation” in the LWRB box is confusing. Please replace with “Incoming Shortwave Radation”.

A18) We thank the reviewer for the suggestion and we revised the figure accordingly. The new figure is presented below:



Q19) L134: Why 0.6. Did you also test other thresholds?

A19) We thank the reviewer for the comment. We tested other thresholds and the one we selected offered a good compromise in effectively detecting clear sky day and in obtaining a time series long enough to be used for calibration purpose.

Q20) L164: Could you please add some information about the used longwave instruments its measurement uncertainties.

A20) The longwave radiation is measured with Eppley Pyrgeometer and the uncertainty is $\pm 3 \text{ W/m}^2$ on average. This information is valid for many stations but some of them changed instrument during the time.

Q21) L182-183: The reason is that the Konzelmann model was calibrated for the Greenland ice sheet, which has a totally different climate than you stations.

A21) We thank the reviewer for the comment and we modified the sentence according his/her suggestion:

New sentence: “Model 8 (Konzelmann et al. (1994)) does not perform very well for many of the stations likely because the model parameters were estimated for the Greenland where the ice plays a fundamental role on the energy balance.”

Q22) L225: For better understanding please link this part to the former section by changing the first sentence to: The just performed calibration procedure to estimate: : :

requires: : :

A22) We thank the reviewer for the comment and we modified the sentence according his/her suggestion:

New senetence: “The just performed calibration procedure to estimate the site specific parameters for $L \downarrow$ models requires measured downwelling longwave data.”

Q23) L232: The URL is invalid: I suggest to add this information also to the supplementary material.

A23) We thank the reviewer for the suggestion and we are going to update the link and submit the regression R script in the supplementary material.

Q25) L244: figures (8) and (9)

A25) We thank the reviewer and we revised the typo according his suggestion.

References

König-Langlo, G., & Augstein, E. (1994). Parameterization of the downward long-wave radiation at the Earth's surface in polar regions. *Meteorologische zeitschrift, NF 3, Jg. 1994, H. 6*, 343-347.

Sicart, J. E., Pomeroy, J. W., Essery, R. L. H., & Bewley, D. (2006). Incoming longwave radiation to melting snow: observations, sensitivity

and estimation in northern environments. *Hydrological processes*, 20(17), 3697-3708.

Plüss, C., & Ohmura, A. (1997). Longwave radiation on snow-covered mountainous surfaces. *Journal of Applied Meteorology*, 36(6), 818-824.

Interactive comment on “Site specific parameterizations of longwave radiation” by G. Formetta et al.

Anonymous Referee #2

Received and published: 30 June 2016

General comments:

The study analyses the performance of 10 empirical parameterizations of incoming longwave radiation with original parameters, site-specific fitted parameters and parameters obtained from regression with average climate variables. The calibration and validation data is taken from the AmeriFlux network. Additionally, the study compares the accuracy of outgoing longwave radiation estimates using soil temperature, soil surface temperature and air temperature. In most parts, the study repeats a similar analysis as other papers (Flerchinger et al., 2009; Juszak and Pellicciotti, 2013; Carmona et al., 2014), which is the comparison of parameterizations of incoming longwave radiation with original and fitted parameters.

The novelty of the study arises from the site-specific estimation of the parameters using multivariate linear regression. This part is interesting for future studies that do not have longwave radiation data available. As the multivariate linear regression is the new and relevant part of the study, Section 4.4 should be elaborated more and presented in more detail. If this part is emphasized strongly, the paper may be published in HESS after major revisions.

The authors thank the reviewer for the useful suggestions and corrections he provided in the revision. Below, we answered point by point to each of them.

Q1) *The results section mixes methods, results and discussion. The methods should be moved to the methods section, the discussion should be separate and longer to incorporate (i) Which models are best at all sites and when used with parameter estimates from the regression approach? (ii) Are the regressions likely to work outside the USA? (iii) What are possible sources of uncertainty?*

A1) We thank the reviewer for the suggestion. We modified the structure of the paper according his suggestions. In the revised paper, besides the subsections Calibration (2.1) and Verification (2.2), we added two subsections that describe the model sensitivity analysis (2.3) and the multi-regression model method (2.4). These two subsections previously were located in the results section. We prefer to comment and discuss the results in the subsection where we presented them. This allows us to not completely modify the original structure of the paper. Moreover we added new sentences in the conclusion section containing information in line with the reviewer suggestions. The new sentences are:

“Moreover the Brunt model is able to provide higher performances with the regression model parameters independently of the latitude and longitude classes. For the Idso model the formulation with regression parameter provided lower performances respect to the literature formulation for latitude between [25-30]”.

“Although many studies investigated the influence of snow covered area on longwave energy balance (e.g. Plüss and Ohmura, 1997; Sicart et al., 2006), the SMs do not explicitly take into account of it. As presented in König-Langlo Augstein (1994), the effect of snow could be implicitly taken into account by tuning the emissivity parameter”

“Finally, the methodology proposed in this paper provides the basis for further developments such as the possibility to: i) investigate the effect different all-sky emissivity formulation, ii) verify the usefulness of the regression models for locations outside the USA; iii) analyze in a systematic way the uncertainty due to the quality of meteorological input data on the longwave radiation balance in scarce instrumented areas.”

Q2). *Most formulas have either not been cited correctly (Table 1 of the manuscript), or the given empirical parameters (Table 2 of the manuscript) were derived for different units of the input variables and can thus not be used with other units and without adjustment. This is a serious issue as it affects the results and conclusions. It should be corrected and all graphs need to be updated. Also some of the conclusions like "Model 8 (Konzelmann et al. (1994)) does not perform very well for some reason." (Line 182) and "Regarding the L # simulations, the Brunt (1932) and Idso (1981) SMS, in their literature formulations, provide the best performances in many of the sites." (Abstract) may be wrong.*

A2) We thank the reviewer for the precious suggestion. We double-checked each formula and each unit both in the paper and in the source code. What we found was that only one model was implemented with one imperfection (Model 8). We revised it and we re-executed all the simulations: literature parameters, calibrations, sensitivity, and we re compute the regressions model. The other models were correctly implemented but imperfectly presented in the table 1. We revised the table as well. In the specific comments we answered point by point to each of the reviewer's comment about the models.

Q3) *Some of the cited literature does not appear in the references.*

A3) We double-checked again the cited literature.

Q4) *c is used for the clearness index and the cloud cover fraction. Please rename one of them and write the equation to convert them.*

A4) We clarified the difference between the cloud cover fraction (c) and the clearness index (s) in the revised version of the paper. The modified sentences specify those differences and how the two indices are related each other:

Sentence 1: "where c [-] is the cloud cover fraction and a [-] and b [-] are two calibration coefficients."

Sentence 2: "In this study we use the formulation presented in Campbell (1985) and Flerchinger (2000), where c is related to the clearness index s [-], i.e. the ratio between the measured incoming solar radiation, I_m [Wm^{-2}], and

the theoretical solar radiation computed at the top of the atmosphere, I_{top} [Wm^{-2}], according the following relationship: $c=1-s$, (Crawford and Duchon, 1999).”

Q5) *State in more detail the results of the parameter estimate by regression and provide the formula for the best model including average parameters.*

Q6) We thank the reviewer for the suggestion. We were thinking that, providing the reader or the user, is mostly interested on having a tool that receive in input the average annual rainfall, air temperature, relative humidity and the elevation of the site, and get a parameter set for a selected model. This is the reason why we provided the link to the R-cran source code to perform this operation. Presenting in a table the value of the regression parameters for each model was not our focus but we added it in a supplementary material.

Specific comments:

Q6) *Abstract The study described in the manuscript is largely independent of the hydrological model JGrass-NewAge. The authors do not present any results concerning hydrology. Thus, this model should not be central in the first sentences of the abstract.*

A6) We agree with the reviewer comment on the fact that we do not present anything about hydrology and hydrological simulation with NewAge. Actually the components we implemented in this paper are compatible with the existing NewAge components (such as shortwave radiation model, snow model) and can be connected each other. Moreover in this paper we used some of NewAge capability such as: i) the input output managing (reading the shapefiles, the digital elevation model, the time series), ii) the shortwave radiation model, and iii) the optimization algorithm. For this reason we would like to preserve JGrass-NewAge in the abstract but, in order to satisfy the reviewer suggestion, we removed the sentence “hydrological model JGrass-NewAge” and we used the sentence “JGrass-NewAge modeling system”. The new sentence is:

“In this work ten algorithms for estimating downwelling longwave atmospheric

radiation ($L \downarrow$) and one for upwelling longwave radiation ($L \uparrow$) are integrated into the JGrass-NewAge modeling system.”

Q7) L13–15 *These are really 3 points: (i) original formulation, (ii) site specific calibration, and (iii) parameter estimation based on average site characteristics.*

A7) We agree with the reviewer comments on the fact that they are three points but, the third point “*parameter estimation based on average site characteristics*” is explained after the period: “For locations where calibration is not possible because of a lack of measured data, we perform a multiple regression using on-site variables, such as mean annual air temperature, relative humidity, precipitation, and altitude”. This allows us to better explain the importance of the regression because in most of the case calibration is not possible.

Q8) L16 *Name all variables instead of 'such as'*

A8) We actually named all the variables, for this reason we removed the word “such as” and we used “i.e.”. The new sentence is:

”For locations where calibration is not possible because of a lack of measured data, we perform a multiple regression using on-site variables, i.e. mean annual air temperature, relative humidity, precipitation, and altitude”

Q9). L21–23 This conclusion may change with correct model formulation. The relative performance of the models should be discussed in more detail in a discussion section.

A9) The conclusions did not dramatically changed after the models’ revision. We slightly modified them according the new results. In particular the main change regards only the model 8 in the sense that after the modification the performances using the literature formulation improved respect the results presented in the previous version of the paper. On the other side the optimal parameter values did not change dramatically and remain of the same order of magnitude of the previous version of the paper.

Q10) *L29 Remove this sentence.*

A10) We removed the following sentence according the reviewer suggestion:
“Models and regression parameters are available for any use, as specified in the paper.”

Q11). *L31 3-100 (1 is still shortwave radiation (Oke, 1987))*

A11) We modified the sentence according the reviewer suggestion. The new sentence is:

“Longwave radiation (4-100 μm) is an important component of the radiation balance on earth and it affects many phenomena”

Q12) *L34 Remove 'very expensive', that is relative*

A12) We removed “very expensive” as suggested by the reviewer. The new sentence is:

“Longwave radiation is usually measured with pyrgeometers, but these are not normally available in basic meteorological stations,”

Q13) *L58–59 I do not agree with this major advantage of the current study as compared to the former studies. The empirical formulations of longwave radiation are very simple equations that can be included easily in any model without the need of an open-source tool. Instead, the authors could refer to their parameter estimation approach: 'However, none of the above studies have developed a method to estimate the parameters for any location based on basic site characteristics and ready for practical use by other researchers and practitioners.' More sentences on the added value of this study are needed. What are the research questions?*

A13) We thank the reviewer for the suggestion and we modified the sentence underling the importance of the study in terms of providing a systematic estimate of site-specific model parameters in the location where it is possible and their estimate with a regression model where this is not possible. Finally we really would like to preserve the importance of providing open-source tools ready to be downloaded and eventually used for a reproducible research. The modified sentence we added in the revised paper is:

“However, none of the above studies have: i) developed a method to

systematically compute the site-specific model parameters for location where measurements are available, and ii) provided their estimate for any location based on basic site characteristics. Moreover, differently from other studies, all the tools used in this paper are open-source, well documented, and ready for practical use by other researchers and practitioners.”

Q14) *L68–74 Paragraph not needed*

A14) We deleted the paragraph as suggested by the reviewer

Q15) *L77 the 'k' of 'kg' should be lower-case; it would be more intuitive to provide the unit $\text{Wm}^{-2} \text{K}^{-4}$ as L is given in Wm^{-2}*

A15) We agree with the reviewer comment and we modified the units of the Boltzman constant as he suggested. The new sentence is:

“where $\sigma = 5.670 \cdot 10^{-8} [\text{W m}^{-2} \text{K}^{-4}]$ ”

Q16) *eq. 3 It should be noted that this equation was proposed by Bolz (1949), and that there are other options that potentially work better (Flerchinger et al., 2009; Juszak and Pellicciotti, 2013). The authors should consider using Unsworth and Monteith (1975), which was recommended in both studies.*

A16) We thank the reviewer for the suggestion and we added some more sentence on the possibility to use other formulation respect to equation 3. Testing different formulation of equation 3 was not the object of this study and the flexibility of the system allow the user to add a new formulation for cloudy sky conditions and preserve all the other part of the code we shared as open-source. Unfortunately we preferred to keep equation 3 and we cited a couple of papers where it was used. Moreover, as the reviewer suggested we added the following sentence to clarify the possibility to use other formulations and that those could work better in some cases. The new sentence is:

“The formulation presented in equation 3 was proposed by Bolz (1949) applied in other studies (Carmona et al., 2013, Maykut and Church, 1973, Jacobs, 1978). Evaluating the effectiveness of different formulations respect to equation 3 is still an open question which is not object of the current paper. It has been investigated in several studies (i.e. Flerchinger et al., 2009,

Juszak and Pellicciotti, 2013) and some of them recommended the one proposed by Unsworth and Monteith (1975). ”

Q17) *L81 c is not the clearness index but the cloud cover fraction (as in line 84)*

A17) We revised the sentence according the reviewer suggestions. The new revised sentences are:

Sentence 1: “where c [-] is the cloud cover fraction”

Sentence 2: “The cloud cover fraction, c , can be estimated from solar radiation measurements”

Q18) *L87 Related how? Provide equation!*

A18) We modified the sentence providing the equation as requested by the reviewer. The modified sentence is:

“In this study we use the formulation presented in Campbell (1985) and Flerchinger (2000), where c is related to the clearness index s [-], i.e. the ratio between the measured incoming solar radiation, I_m [Wm^{-2}], and the theoretical solar radiation computed at the top of the atmosphere, I_{top} [Wm^{-2}], according the following relationship: $c=1-s$, (Crawford and Duchon, 1999)”

Q19) Table 1 I have doubts that all formulas in Table 1 are correct and that the parameters in Table 2 have been adjusted to the units of water vapour pressure (and in some cases radiation). I suggest you check Juszak and Pellicciotti (2013) for adjusted parameters. More specifically please consider:

1. Angstrom [1918] does not appear in the reference list. Please provide the correct reference and check the original publication or cite the paper you took the parameters from. Did you adjust the original parameters to match the units in which you computed the radiation and inserted humidity and temperature? I have doubts in the Angstrom case where one original publication computes the radiation in $\text{cal cm}^{-2} \text{min}^{-1}$ (Ångström, 1916). Ångström (1916) also uses e^{Ze} instead of 10^{Ze} .
2. Brunt (1932) uses water vapour pressure in millibar not kPa. Did you adjust the parameter Y ?
3. Swinbank (1963) is clearly used wrongly. The parameters provided in

Table 2 do not refer to the clear sky emissivity but to a formula that computes the radiation directly, and in m W cm^{-2} .

4. Brutsaert (1975) uses water vapour pressure in millibar not kPa. Please adjust the parameters X and Y.
5. Monteith and Unsworth [1990] does not appear in the literature list. Please double-check the formula and parameters and provide the correct citation.
6. Konzelmann et al. (1994) uses water vapour pressure in Pa not kPa. Please adjust the parameters X and Y.
7. Dilley and O'Brien (1998) uses the given formula (Table 1) with the parameters (Table 2) to directly compute the longwave flux, not the emissivity. To get the emissivity, the formula has to be divided by σT^4 . Use round brackets for the reference year as in the rest of the manuscript.

A19) We thank the reviewer for the suggestion. We referred all our formula to the paper Flerchinger et al., 2009 and in particular we follow the table 1 of the paper. In our Table 1 we forgot to specify some of the footnotes presented in the Table 1 of the Flerchinger et al., 2009 paper. For this reason many of the reviewer comments were just related to the fact that the Table 1 in our paper was not completely correct but the code it is. Thanks to the author comments we double-checked all the formulations and we realized that one model was implemented wrong in the sense that in Konzelmann the vapour pressure was in kPa and not in Pa as it should be. We modified the model and re executed the simulation for all the stations (literature formulation, calibration, sensitivity, and regression). We moreover answered point by point to the reviewer comments below:

- 1) We implemented the model in the right way as specified in the Flerchinger et al., 2009 paper but we forgot to specify that the version was the implemented in Niemela et al. [2001]. We added it as footnotes in the Table 1.
- 2) We implemented the model in the right way as specified in the Flerchinger et al., 2009 paper but we forgot to specify that the version was the implemented in Niemela et al. [2001]. We added it as footnotes

in the Table 1.

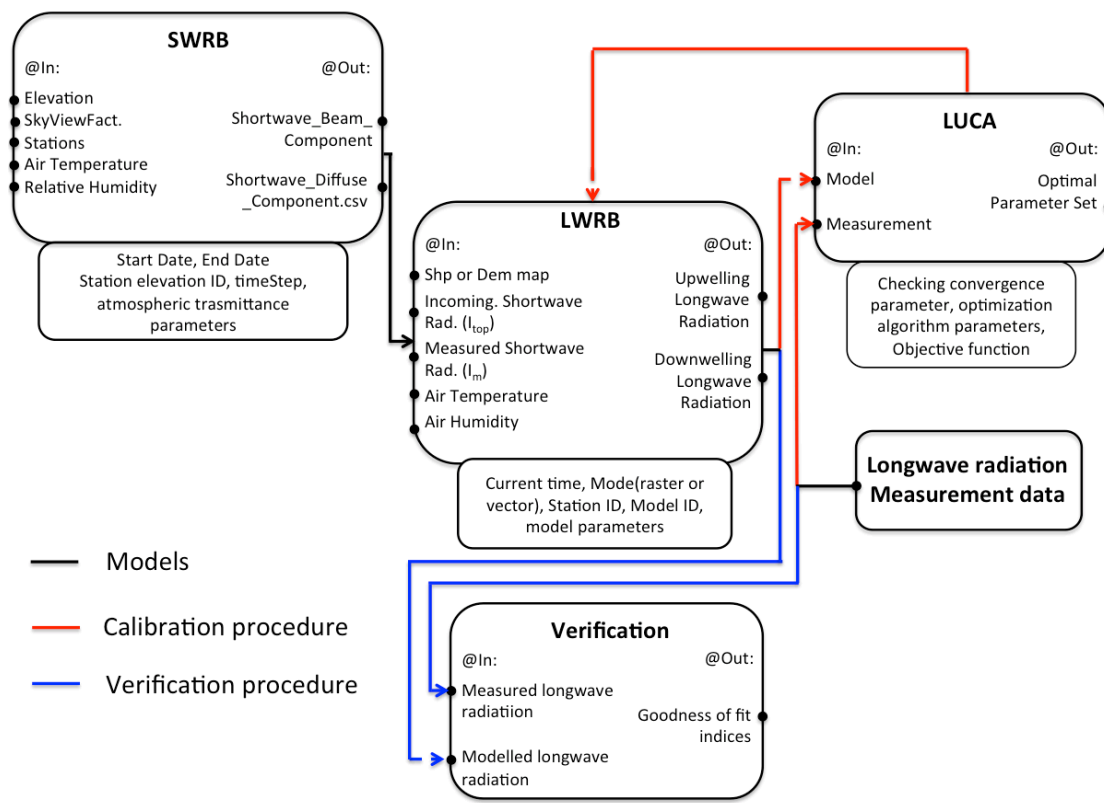
- 3) We implemented the model as specified in Flerchinger et al., 2009, but we forgot to divide by σT^4 to obtain the emissivity. We modified the table accordingly.
- 4) We implemented the model as specified in Flerchinger et al., 2009 and we cite it.
- 5) We double-checked the formula and we added the following correct citation:
“Monteith JL, Unsworth MH (1990) Principles of Environmental Physics Edward Arnold, London”
- 6) We revised the model according the reviewer suggestion and we repeated all the computation for this model. Fortunately there was not a dramatic change in the model results and model parameters. We modified the discussion of the results according the new model output.
- 7) We implemented the model as specified in Flerchinger et al., 2009, but we forgot to divide by σT^4 to obtain the emissivity. We modified the table accordingly.

Q20) *L116 No one-sentence paragraph, this sentence can be removed.*

A20) We removed the sentence as the reviewer suggested.

Q21) *Figure 1 How do I_m and I_{top} fit into this schematic? Only those variables are explained later in the text. The 'Modelled longwave radiation' and 'Measured longwave radiation' items in the Verification box are wrongly connected. Is the SWBR always modelled? Does that affect the optimisation process?*

A21) We revised the figure according the reviewer suggestions i.e. correcting the connections between measured and modeled radiation for the verification box and specifying what is I_{top} and I_m explicitly and the figure and not only in the text. Below you can find the revised figure.



Q22) L134 Did you try different thresholds? 0.6 seems quite low. Did you verify that you do not include cloudy or partly cloudy observations in the clear sky calibration? If you calibrate e_{clear} at $c = 0.6$, e_{all_sky} at that condition will be wrong as you compute it from $e_{all_sky} = e_{clear} (1 + a c^b)$ and $c=0.6$.

A22) The choice of the threshold was due to two main reasons: firstly we considered some values from literature to define clear sky conditions and we find that they vary between 0.6 and 0.7 (Li et al., 2001; Okogbue et al., 2009); secondly we tried different threshold and 0.6 provided a good compromise to get equally long time series of measured downwelling clear radiation for all the stations. This was important for a reliable calibration process. Of course the reviewer comments on the emissivity in all sky condition is correct and we specified it in the revised paper adding the following sentence:

“On one side, a threshold of 0.6 to define the clear-sky conditions helps in the sense that allow to define time-series of measured clear-sky $L \downarrow$ with comparable length in all the stations, and this is useful for a reliable calibration process. On the other side, it introduces an error in computing the emissivity

in all-sky condition using equation 3 which could be compensated by the optimization of the parameters a and b.”

Q23) L143–144 Please provide all variables (not ‘such as’); altitude is not a climatic variable.

A23) We thank the reviewer for the suggestion and we revised the sentence accordingly. The new sentence is:

“As well as parameter calibration, we carry out a model parameter sensitivity analysis and we provide a linear regression model relating a set of site-specific optimal parameters with mean air temperature, relative humidity, precipitation, and altitude.”

Q24) L156 *What is N?*

A24) N is the length of the measured and modeled time-series. We added the following sentence to the revised paper:

“where M and S represents the measured and simulated time-series respectively and N is their length.”

Q25) L161–162 *Sentence not relevant, remove it.*

A25) We thank the reviewer for the suggestion. We agree in part with him: we modified the sentence as he ask, but we would like to keep it in order to give visibility to other works that used the same dataset.

Old sentence: “The dataset is widely known and used for biological and environmental applications. To cite a few, Xiao et al. (2010) used Ameriflux data in a study on gross primary production data, Kelliher et al. (2004) in a study on carbon mineralization, and Barr et al. (2012) in a study on hurricanes.”

New sentence: “The dataset is well-known and used in several applications such as Xiao et al. (2010), Kelliher et al. (2004), and Barr et al. (2012).”

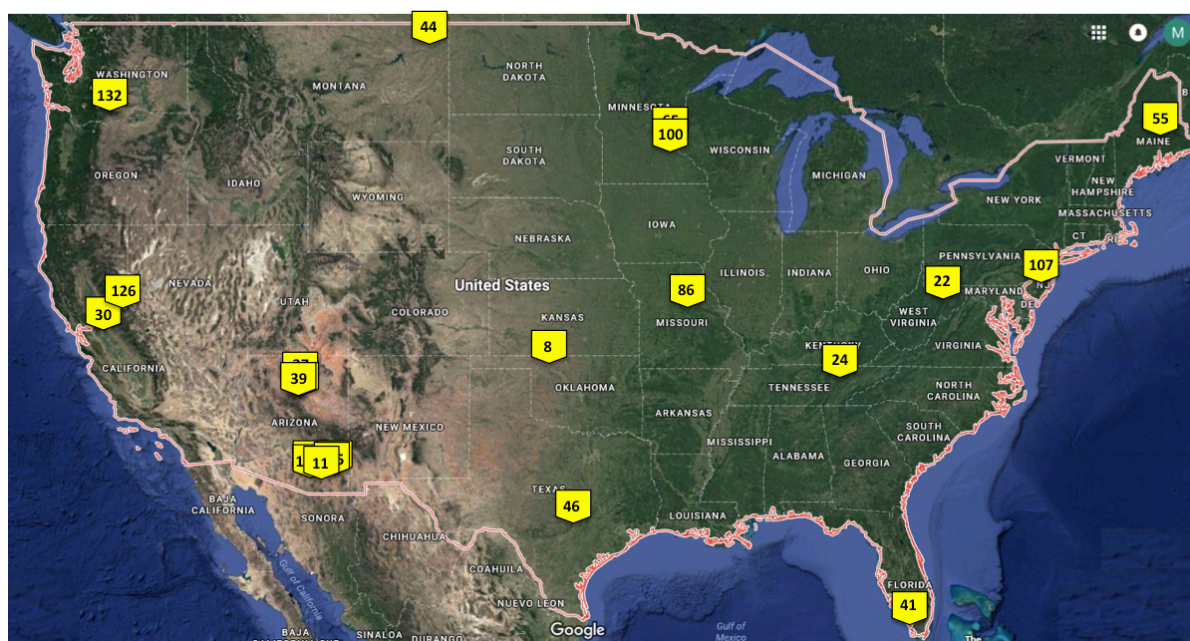
Q26) L166–168 *There is also a gradient towards the colder climate. Why did you choose these 24 stations and not all stations?*

A26) Among the stations where the model input data were available we selected the 24 as a good compromise between the goals of: i) covering

different climates, ii) ensuring a reasonable quality of the data (avoiding long no-value periods in the time-series), and iii) ensuring a reliable computational time for models calibration and verification.

Q27) *Figure 2 Use same index for stations as in Table 4 and make the index bigger so it is readable.*

A27) We thank the reviewer for the suggestion and we modified the figure according his-her suggestion. The new figure is:



Q28) *Table 4 How was the climate defined? 'mild' and 'strongly seasonal' do not match the classic categories.*

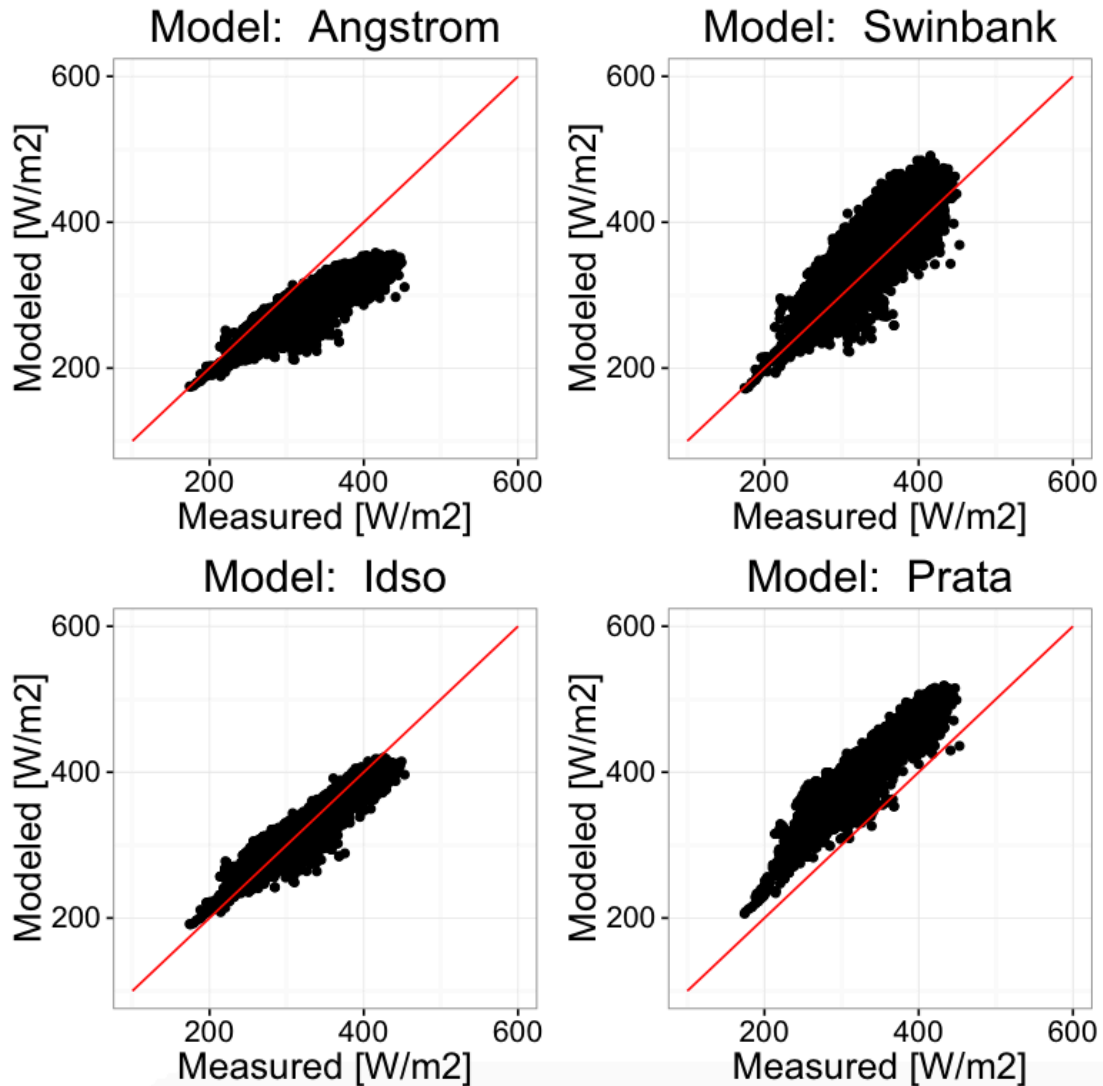
A28) The classification is defined for each station of the AmeriFlux network and it is a standard classification. More information on the classification are available at the web page of each station (<https://fluxnet.ornl.gov/site/833> for the station 833)

Q29) *Section 4.1 Update section with correct model implementation and parameters.*

A29) As above specified, we re-executed the simulations for the model 8 we re-plot the results. All figures have been updated.

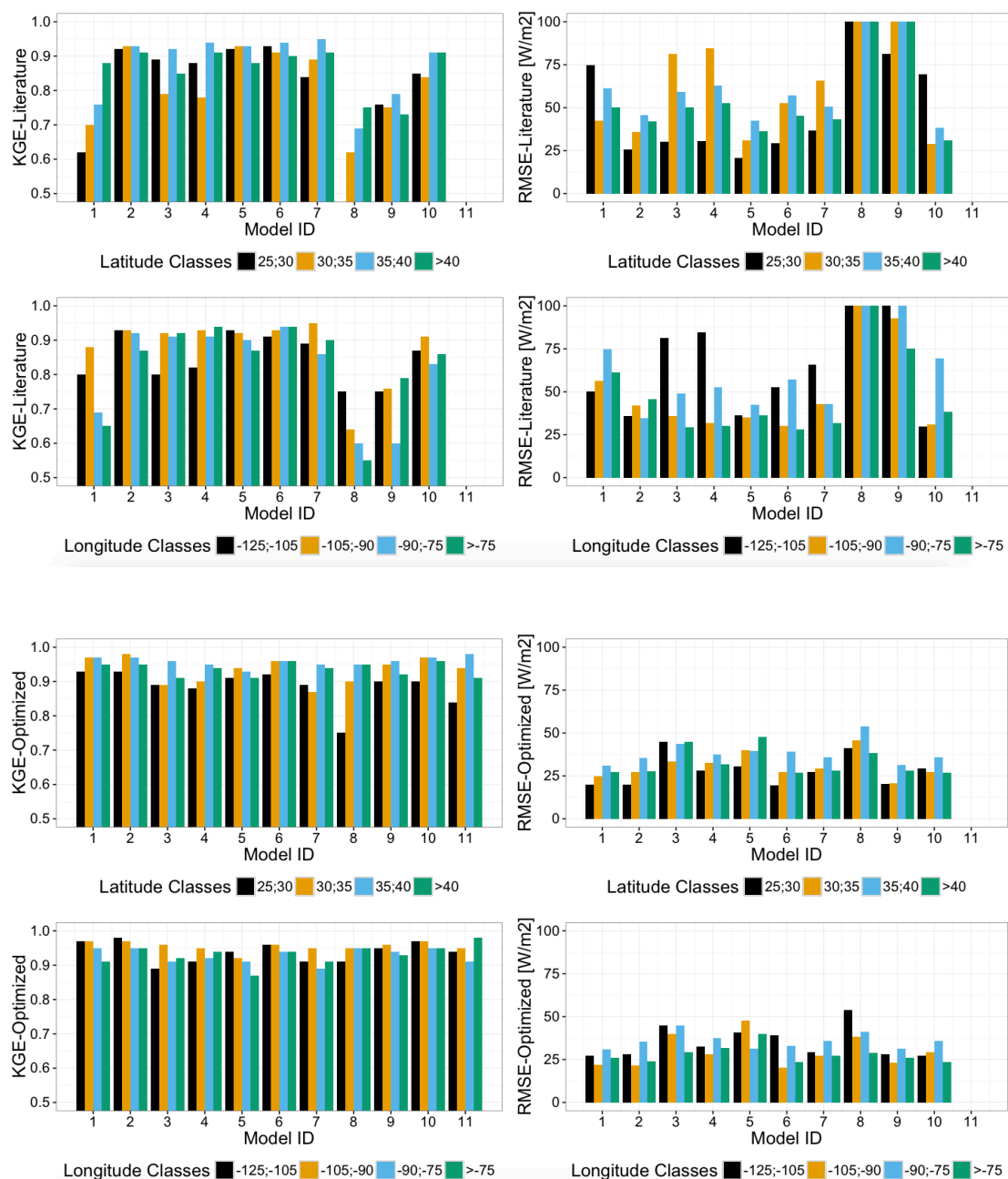
Q30) *Figure 3 Name models in the caption*

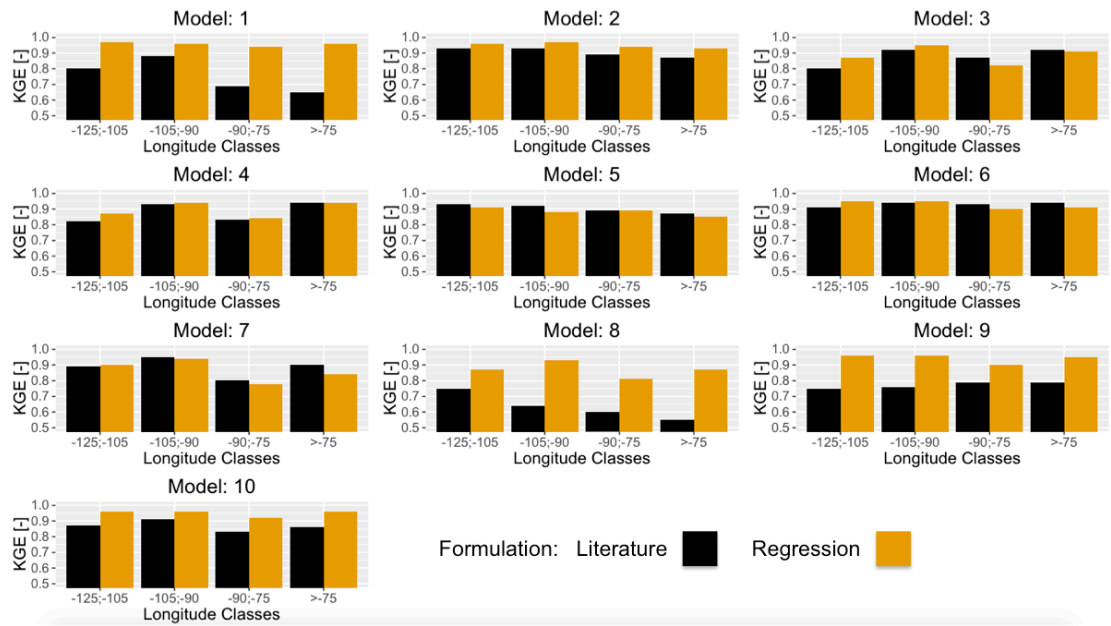
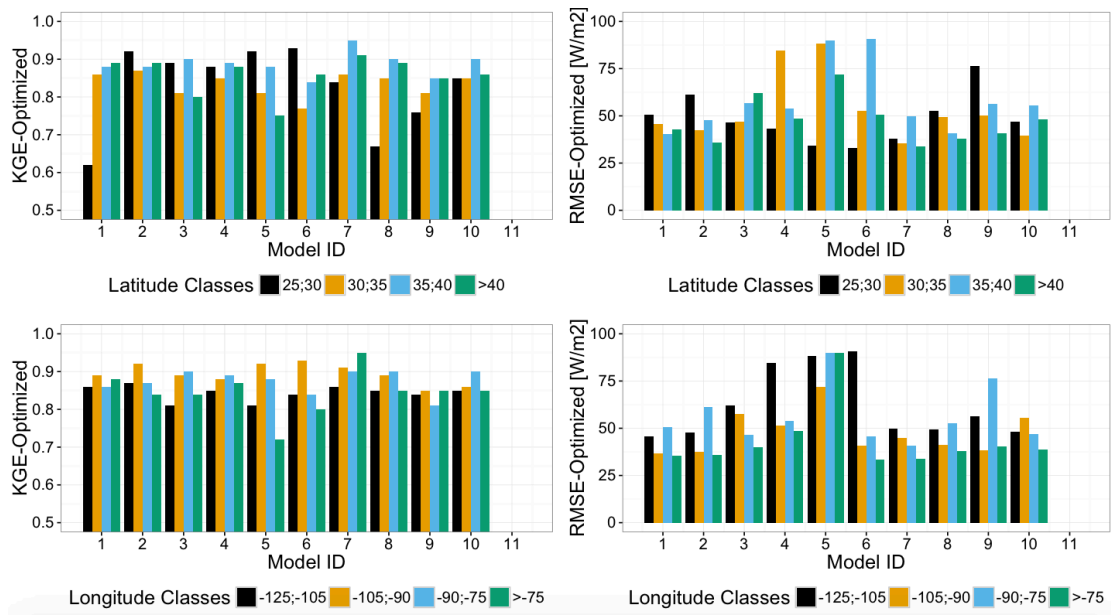
A30) We agree with the reviewer suggestion and we modified the figure accordingly. The new figure is reported below:

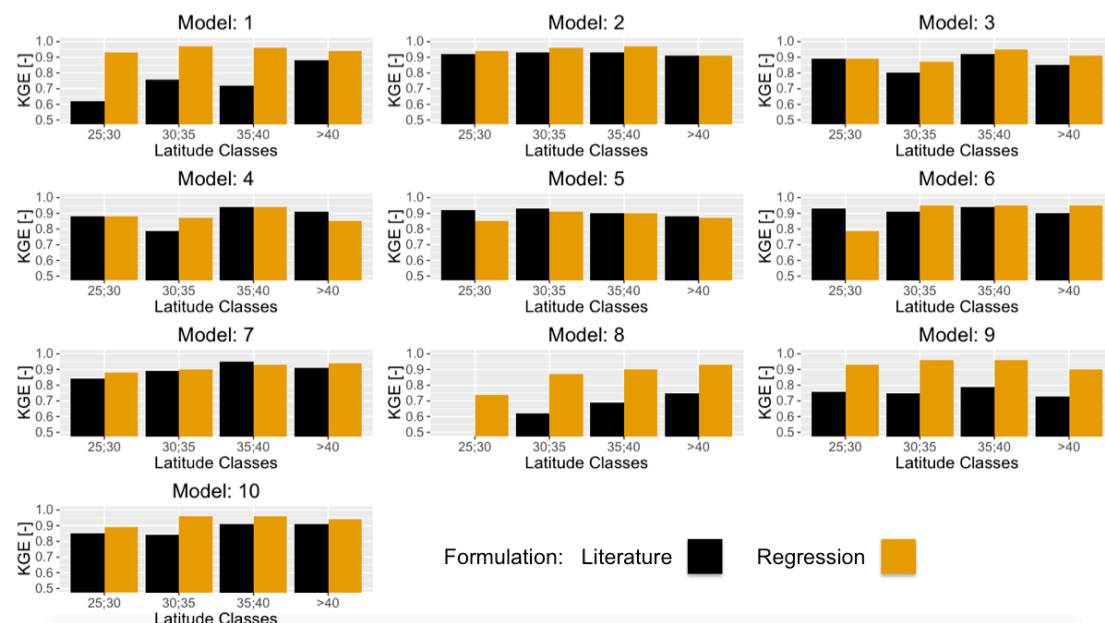


Q31) *Figures 4–6, 8–9 Use boxplots instead of barplots to show the variability within the groups and the range of variation. Reorganise the content to have only two Figures: one for clear sky and one for all sky. In both figures, boxes for results of (i) original parameters, (ii) fitted parameters, and (iii) parameters from regression analysis should be next to each other to enable direct comparison. The figures can be arranged in subplots either one per model, or one per latitude / longitude class. Please choose colours that allow black+white printing and consider color-blind people.*

A31) We thank the reviewer for comment. We agree in part with him: we prefer to keep the plots as we made because it was an original idea of all the coauthors and the meaning of not reducing everything to 2 figures was because we wanted to facilitate the reader and his comprehension of the results. We believe that this configuration was a good compromise between the amount of information for each plot and the possibility of a common reader to easily get the results. We strongly agree with the reviewer to modify the scale color and facilitate color-blind people. We used the r cran package ggthemes and the function `scale_fill_colorblind()` to re plot the results of the figures in discussion. Below you can find the final figures:







Q32) *Section 4.2 Update section with correct model implementation and original parameters.*

A32) As we specified before, all the plots have been updated.

Q33) *L201–202 This should be moved and discussed in more detail in a discussion section.*

A33) We thank the reviewer for the comment. As we explained in the answer A1) we prefer to keep the discussion of the results in the same section in which the results are presented. This is further justified in the answer A1.

Q34) *L213 Time series from which station? Was the analysis done for all stations?*

A34) We thank the reviewer for the suggestion. Yes the procedure was repeated for each station and we specified it in the revised paper:

Old sentence: “The procedure was repeated for each parameter of each model”

New sentence: “The procedure was repeated for each parameter of each model and for each station.”

Q35) *L206–214 This belongs to the methods section.*

A35) We agree with the reviewer suggestion and, as specified in the answer

A1) we moved that part in the methods section as subsection.

Q36) *Figure 7 Given the methods description, why is the peak not always in the middle of the parameter range? Caption: 'of' is missing an 't'; describe the meaning of the boxes and the line!*

A36) We thank the reviewer for the comment. In general the peak is corresponding to the optimal parameter set. Small variations are possibly due to the fact that we subdivided the range of a given parameter into ten equal-sized classes and for each class the corresponding KGE values are presented as a boxplot. This approximation can influence the shape of the final plot. Moreover we agree with the reviewer comment on the figure and we revised the caption accordingly. The new caption is:

“Results of the model parameters sensitivity analysis. It presents as boxplot the variation of the model performances due to a variation of one of the optimal parameter and assuming constant the others. The procedure is repeated for each model and the blue line represents the smooth line passing through the boxplot medians.”

Q37) L225–243 This belongs to the methods section.

A37) We agree with the reviewer suggestion and, as specified in the answer A1) we moved that part in the methods section as subsection.

Q38) *Equation 8 Do not use 'a' as it is used for something else in Equation 4*

A38) We agree with the reviewer suggestion and we used i , that stand for intercept, instead of a .

Q39) L244–250 *Compare also with fitted parameters.*

A39) We thank the reviewer for the comment. We were thinking to plot also the optimal parameters results but at the end we decided to keep only the regression and the literature results, for two reasons: the first is the innovation of this section is to provide a method (the regression) that does better than (or at least equal to) the literature formulation, so regression and literature are fundamental in the plot, the second is that the results with optimal parameter set have been presented in the previous section.

Q40) *Section 4.4 Update section with correct model implementation and original parameters.*

A40) As we specified before, all the plots have been updated.

Q41) *L267–269 This should be moved and discussed in more detail in a discussion section. How about snow cover? How about the different latitudes?*

A41) We thank the reviewer for the comment. As we explained in the answer A1) we prefer to keep the discussion of the results in the same section in which the results are presented. This is further justified in the answer A1. Regarding the snow cover we added the following sentence, as requested also by the reviewer n.1:

“Although many studies investigated the influence of snow covered area on longwave energy balance (e.g. Plüss and Ohmura, 1997; Sicart et al., 2006), the SMs do not explicitly take into account of it. As presented in König-Langlo Augstein (1994), the effect of snow could be implicitly taken into account by tuning the emissivity parameter.”

Q42) *Conclusions Update section with correct model implementation and original parameters.*

A42) We thank the reviewer for the suggestion and we revised the conclusion section accordingly.

Q43) *Supplementary material Please use the same station IDs as in the manuscript. Please include the detailed results of the parameter regression.*

A43) We thank the reviewer for the suggestion and we revised the supplementary material section accordingly. Moreover in the supplementary material we provided the link to the R-cran code to estimate the regression parameters given the input data.

Technical corrections:

Q44) *L12 24 instead of twenty-four*

A44) We used 24 instead of twenty-four in the whole text of the revised paper

Q45) *L36 put references in brackets*

A45) We revised according the reviewer suggestion.

Q46) *L40 put references in brackets*

A46) We revised according the reviewer suggestion.

Q47) *L51 'They' instead of 'It'*

A47) We revised according the reviewer suggestion.

Q48) *L52 remove 'so'*

A48) We revised according the reviewer suggestion.

Q49) *L64 put reference in brackets*

A49) We revised according the reviewer suggestion.

Q50) *Table 1 caption: units not in italics*

A50) We revised according the reviewer suggestion.

Q51) *L101 space missing before reference*

A51) We revised according the reviewer suggestion.

Q52) *L104 put references in brackets*

A52) We revised according the reviewer suggestion.

Q53) *L106 replace ';' with ','*

A53) We revised according the reviewer suggestion.

Q54) *L122 remove brackets from reference*

A54) We revised according the reviewer suggestion.

Q55) *L158 24 instead of twenty-four*

A55) We revised according the reviewer suggestion.

Q56) *L165 24 instead of twenty-four*

A56) We revised according the reviewer suggestion.

Q57) *L178 1:1 instead of 45 degree*

A57) We revised according the reviewer suggestion.

Q58) *L219 'around the' instead of 'about'*

A58) We revised according the reviewer suggestion.

Q59) *L231 'supplementary' instead of 'complementary'*

A59) We revised according the reviewer suggestion.

Q60) *L244 Figure 10 shows something else*

A60) We revised according the reviewer suggestion.

Q61) *L275 24 instead of twenty-four*

A61) We revised according the reviewer suggestion.

Q62) *L284 24 instead of twenty-four*

A62) We revised according the reviewer suggestion.

Q63) *L303 Reformulate 'In order that'*

A63) We modified the sentence as suggested by the reviewer. The new sentence is:

“Researchers interested in replicating or extending our results are invited to download our codes at”

References

Flerchinger, G. N., Xaio, W., Marks, D., Sauer, T. J., & Yu, Q. (2009). Comparison of algorithms for incoming atmospheric long-wave radiation. *Water Resources Research*, 45(3).

Li, Danny HW, and Joseph C. Lam. "An analysis of climatic parameters and sky condition classification." *Building and Environment* 36, no. 4 (2001): 435-445.

Okogbue, E. C., J. A. Adedokun, and B. Holmgren. "Hourly and daily clearness index and diffuse fraction at a tropical station, Ile-Ife, Nigeria." *International Journal of Climatology* 29, no. 8 (2009): 1035-1047.

Performances of site specific parameterizations of longwave radiation

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Abstract

In this work ten algorithms for estimating downwelling longwave atmospheric radiation (L_{\downarrow}) and one for upwelling longwave radiation (L_{\uparrow}) are integrated into the ~~hydrological model~~-JGrass-NewAge [modeling system](#). The algorithms are tested against energy flux measurements available for ~~twenty-four~~ 24 sites in North America to assess their reliability. These new JGrass-NewAge model components are used i) to evaluate the performances of simplified models (SMs) of L_{\downarrow} , as presented in literature formulations, and ii) to determine by automatic calibration the site-specific parameter sets for ~~SMs of~~ L_{\downarrow} [in SMs](#). For locations where calibration is not possible because of a lack of measured data, we perform a multiple regression using on-site variables, ~~such as~~ [i.e.](#) mean annual air temperature, relative humidity, precipitation, and altitude. The regressions are verified through a leave-one-out cross validation, which also gathers information about the possible errors of estimation. Most of the SMs, when executed with parameters derived from the multiple regressions, give enhanced performances compared to the corresponding literature formulation. A sensitivity analysis is carried out for each SM to understand how small variations of a given parameter influence SM performance. Regarding the L_{\downarrow} simulations, the Brunt (1932) and Idso (1981) SMs, in their literature formulations, provide the best performances in many of the sites. The site-specific parameter calibration improves SM performances compared to their literature formulations. Specifically, the root mean square error (RMSE) is almost halved and the Kling Gupta efficiency is improved at all sites.

The L_{\uparrow} SM is tested by using three different temperatures (surface soil temperature, air temperature at 2 m elevation, and soil temperature at 4 cm depth) and model performances are then assessed. Results show that the best performances are achieved using the surface soil temperature and the air temperature.

~~Models and regression parameters are available for any use, as specified in the paper.~~

1 Introduction

Longwave radiation (~~1-100~~ 4-100 μm) is an important component of the radiation balance on earth and it affects many phenomena, such as evapotranspiration, snow melt (Plüss and Ohmura, 1997), glacier evolution (MacDonell et al., 2013), vegetation dynamics (Rotenberg et al., 1998), plant respiration, and primary productivity (Leigh Jr, 1999). Longwave radiation is usually measured with ~~very-expensive~~ pyrgeometers, but these are not normally available in basic meteorological stations, even though an increasing number of projects has been developed to fill the gap ~~Augustine et al. (2000)~~, (Augustine et al., 2000), as seen in Augustine et al. (2005) and Baldocchi et al. (2001). The use of satellite products to estimate longwave solar radiation is increasing (GEWEX, Global Energy and Water cycle Experiment, ISCCP the International Satellite Cloud Climatology Project) but they have too coarse a spatial resolution for many hydrological uses. Therefore, models have been developed to solve energy transfer equations and compute radiation at the surface ~~(e.g. Key and Schweiger (1998), Kneizys et al. (1988))~~. These physically based and fully distributed models provide accurate estimates of the radiation components. However, they require input data and model parameters that are not easily available. To overcome this issue, simplified models (SM), which are based on empirical or physical conceptualizations, have been developed to relate longwave radiation to atmospheric proxy data such as air temperature, ~~deficit-of-vapor-pressure~~ water vapor deficit, and shortwave radiation. They are widely used and provide clear sky (e.g. Ångström (1915); Brunt (1932); Idso and Jackson (1969)) and all-sky estimations of downwelling ~~(L_{\downarrow}) and~~ upwelling (L_{\uparrow}) and upwelling (L_{\uparrow}) longwave radiation (e.g. Brutsaert (1975); Iziomon et al. (2003a)).

SM performances have been assessed in many studies by comparing measured and modeled L_{\downarrow} at hourly and daily time-steps (e.g. Sugita and Brutsaert (1993b); Iziomon et al. (2003b); Juszak and Pellicciotti (2013); MacDonell et al. (2013) ; Schmucki et al. (2014)). Hatfield et al. (1983) was among the first to present a comparison of the most used SMs in an evaluation of their accuracy. ~~It~~ They tested seven clear-sky algorithms using atmospheric data from different stations in the United States. ~~So~~ In order to validate the SMs under different climatic conditions, they performed linear regression analyses on the relationship between simulated and measured L_{\downarrow} for each algorithm. The results of the study show that the best models were Brunt (1932), Brutsaert (1975) and Idso (1981). Flerchinger et al. (2009) made a similar comparison using more formulations (13) and a wider data-set from North America and China, considering all possible sky conditions. Finally, Carmona et al. (2014) evaluated the performance of six SMs, with both literature and site-specific formulations, under clear-sky conditions for the sub-humid Pampean region of Argentina.

However, none of the above studies have ~~provided a comprehensive set of open-source tools that are well documented~~: i) developed a method to systematically compute the site-specific model parameters for location where measurements are available, and ii) provided their estimate for any location based on basic site characteristics. Moreover, differently from other studies, all the tools used in this paper are open-source, well documented, and ready for practical use by other researchers and practitioners.

This paper introduces the LongWave Radiation Balance package (LWRB) of the JGrass-NewAGE modelling system Formetta et al. (2014a). LWRB implements 10 formulations for L_{\downarrow} and one for L_{\uparrow} longwave

radiation. The package was systematically tested against measured L_{\downarrow} and L_{\uparrow} longwave radiation data from 24 stations across the USA, chosen from the 65 stations of the AmeriFlux Network. Unlike all previous works, the LWRB component follows the specifications of the Object Modeling System (OMS) framework [David et al. \(2013\)](#) [\(David et al., 2013\)](#). Therefore, it can use all of the JGrass-NewAge tools for the automatic calibration algorithms, data management and GIS visualization, and it can be seamlessly integrated into various modeling solutions for the estimation of water budget fluxes (Formetta et al., 2014a).

~~The paper is organized into five sections, with Section 1 being this introduction. Section 2 describes methodology, calibration and verification for the L_{\downarrow} and L_{\uparrow} models. Section 3 presents the study sites and the datasets used. Section 4 presents the simulation results for L_{\downarrow} and L_{\uparrow} longwave radiation. It includes model verification and calibration, sensitivity analysis and multiple regressions of the parameters against some explaining variables for L_{\downarrow} . It also presents a verification of the L_{\uparrow} model, which includes an assessment of the model performances in predicting correct upwelling longwave L_{\uparrow} radiation in using different temperatures (soil surface temperature, air temperature, and soil temperature at 4 cm below surface). In Section 5 we present our conclusions.~~

2 Methodology

The SMs for L_{\uparrow} [Wm^{-2}] and L_{\downarrow} [Wm^{-2}] longwave radiation are based on the Stefan-Boltzmann equation:

$$L_{\downarrow} = \epsilon_{all-sky} \cdot \sigma \cdot T_a^4 \quad (1)$$

$$L_{\uparrow} = \epsilon_s \cdot \sigma \cdot T_s^4 \quad (2)$$

where $\sigma = 5.670 \cdot 10^{-8}$ [$\text{Kg s}^{-3} \text{W m}^{-2} \text{K}^{-4}$] is the Stefan-Boltzmann constant, T_a [K] is the ~~near-surface~~ air temperature, $\epsilon_{all-sky}$ [-] is the effective atmospheric emissivity, ϵ_s [-] is the soil emissivity and T_s [K] is the surface soil temperature. To account for the increase of L_{\downarrow} in cloudy conditions, $\epsilon_{all-sky}$ [-] is formulated according to eq. (3):

$$\epsilon_{all-sky} = \epsilon_{clear} \cdot (1 + a \cdot c^b) \quad (3)$$

where c [-] is the ~~clearness index~~ [cloud cover fraction](#) and a [-] and b [-] are two calibration coefficients. Site specific values of a and b are presented in Brutsaert (1975), ($a=0.22$ and $b=1$), Iziomon et al. (2003a) (a ranges between 0.25 and 0.4 and $b=2$) and Keding (1989) ($a=0.183$ and $b=2.18$). In our modeling system a and b are calibrated to fit measurement data under all-sky conditions. The cloud cover fraction, c , can be estimated from solar radiation measurements (Crawford and Duchon, 1999), from visual observations (Alados-Arboledas et al., 1995, Niemelä et al., 2001), and from satellite data (Sugita and Brutsaert, 1993a) or it can be modeled as well. In this study we use the formulation presented in Campbell (1985) and Flerchinger (2000), where c is related to the clearness index ~~s [-]~~ [i.e.](#) the ratio between the measured incoming solar radiation, I_m [Wm^{-2}], and

the theoretical solar radiation computed at the top of the atmosphere, I_{top} [Wm^{-2}], according the following relationship: $c = 1 - s$ (Crawford and Duchon, 1999). This type of formulation needs a shortwave radiation balance model to estimate I_{top} and meteorological stations to measure I_m ; also, it cannot estimate c at night. In our application, the fact that the SMs are fully integrated into the JGrass-NewAge system allows us to use the shortwave radiation balance model (Formetta et al., 2013) to compute I_{top} . Night-time values of c are computed with a linear interpolation between its values at the last hour of daylight and the first hour of daylight on consecutive days. The computation of the first and last hour of the day is based on the model proposed in Formetta et al., 2013 that follow the approach proposed in Corripio (2002), equations 4.23-4.25. The sunrise occurs at $t = 12 \cdot (1 - \omega/\pi)$ and the sunset will be at $t = 12 \cdot (1 + \omega/\pi)$ where ω is the hour angle. Those equations are based on the assumption that sunrise and sunset occur at the time when the z coordinate of the sun vector equals zero.

The formulation presented in equation 3 was proposed by Bolz (1949) applied in other studies (Carmona et al. (2014), Maykut and Church (1973), Jacobs (1978), Niemelä et al. (2001)). Evaluating the effectiveness of different formulations respect to equation 3 is still an open question which is not object of the current paper. It has been investigated in several studies (i.e. Flerchinger et al. (2009), Juszak and Pellicciotti (2013), and citation therein) and some of them recommended the one proposed by Unsworth and Monteith (1975).

Ten SMs from literature have been implemented for the computation of ϵ_{clear} . Table 1 specifies assigned component number, component name, defining equation, and reference to the paper from which it is derived. X, Y and Z are the parameters provided in literature for each model, listed in table 2.

ID	Name	Formulation
1	Angstrom	$\epsilon_{clear} = X - Y \cdot 10^{Z_e}$
2	Brunt's	$\epsilon_{clear} = X + Y \cdot e^{0.5}$
3	Swinbank	$\epsilon_{clear} = X + 10^{-13} \cdot T_a^6$ $\epsilon_{clear} = (X \cdot 10^{-13} \cdot T_a^6) / (\sigma \cdot T_a^4)$
4	Idso and Jackson	$\epsilon_{clear} = 1 - X \cdot \exp(-Y \cdot 10^{-4} \cdot (273 - T_a)^2)$
5	Brutsaert	$\epsilon_{clear} = X \cdot (e/T_a)^{1/Z}$
6	Idso	$\epsilon_{clear} = X + Y \cdot 10^{-4} \cdot e \cdot \exp(1500/T_a)$
7	Monteith and Unsworth	$\epsilon_{clear} = X + Y \cdot \sigma \cdot T_a^4$
8	Konzelmann	$\epsilon_{clear} = X + Y \cdot (e/T_a)^{1/8}$
9	Prata	$\epsilon_{clear} = [1 - (X + w) \cdot \exp(-(Y + Z \cdot w)^{1/2})]$
10	Dilley and O'Brien	$\epsilon_{clear} = X + Y \cdot (T_a/273.16)^6 + Z \cdot (w/25)^{1/2}$ $\epsilon_{clear} = (X + Y \cdot (T_a/273.16)^6 + Z \cdot (w/25)^{1/2}) / (\sigma \cdot T_a^4)$

Table 1: Clear sky emissivity formulations: T_a is the air temperature [K], w [kg/m^2] is precipitable water = $4650 [e_0/T_a] [e_0/T_a]$ and e [kPa] is screen-level water-vapour pressure. The Angstrom and Brunt model was presented as cited by Niemelä et al. (2001). Konzelmann uses water vapour pressure in [Pa] not [kPa].

The models presented in table 1 were proposed with coefficient values (X, Y, Z) strictly related to the location in which the authors applied the model and where measurements of L_{\downarrow} radiation were collected. Coefficients reflect climatic, atmospheric and hydrological conditions of the sites, and are reported in Table 2.

The formulation of the L_{\uparrow} requires the soil emissivity, which usually is a property of the nature of a surface, and the surface soil temperature. Table 3 shows the literature values (Brutsaert, 2005) (Brutsaert, 2005) of the soil emissivity for different surface types: ϵ_s varies from a minimum of 0.95 for bare soils to a maximum of 0.99 for fresh snow.

Since It is well known that surface soil temperature measurements are only available at a few measurement

ID	Name	X	Y	Z
1	Angstrom	0.83	0.18	-0.07
2	Brunt	0.52	0.21	[-]
3	Swinbank	5.31	[-]	[-]
4	Idso and Jackson	0.26	-7.77	[-]
5	Brutsaert	1.72	7	[-]
6	Idso	0.70	5.95	[-]
7	Monteith and Unsworth	-119.00	1.06	[-]
8	Konzelmann et al	0.23	0.48	[-]
9	Prata	1.00	1.20	3.00
10	Dilley and O'brien	59.38	113.70	96.96

Table 2: Model parameter values as presented in their literature formulation.

Nature of surface	Emissivity
Bare soil (mineral)	0.95 – 0.97
Bare soil (organic)	0.97 – 0.98
Grassy vegetation	0.97 – 0.98
Tree vegetation	0.96 – 0.97
Snow (old)	0.97
Snow (fresh)	0.99

Table 3: Soil emissivity for surface types (Brutsaert, 2005).

sites. ~~if the~~. Under the hypothesis that difference between soil and air temperatures is not too big, it is possible to simulate L_{\uparrow} using the air temperature ~~, Park et al. (2008)~~ (Park et al., 2008). In our approach three different types of temperature were used to simulate L_{\uparrow} , specifically: surface soil temperature; ~~air~~ air temperature at 2 m height; ~~and~~ and soil temperature at 4 cm depth.

The LWRB package (see flowchart in figure1) is part of the JGrass-NewAge system and was preliminary tested in Formetta et al. (2014b). Model inputs depend on the specific SM being implemented and the purpose of the run being performed (calibration, verification, simulation). The inputs are meteorological observations such as air temperature, relative humidity, incoming solar radiation, and sky clearness index. The LWRB is also fed by other JGrass-NewAGE components, such as the shortwave radiation balance (SWRB) (Formetta et al., 2013). To test model performances (i.e. verification), the LWRB can be connected to the system's Verification component; to execute the parameter calibration algorithm (Formetta et al., 2014a), it can be connected to the LUCA (Let Us CALibrate) component. In turn, all these components can and/or need to be connected to other ones, as the problem under examination may require.

~~Further information about the SMS used is available in table 1 and in Carmona et al. (2014).~~

Model outputs are L_{\downarrow} and L_{\uparrow} . These can be provided in single points of specified coordinates or over a whole geographic area, represented as a raster map. For the latter case a digital elevation model (DEM) of the study area is necessary in input.

The subsection 2.1 and 2.2 respectively present the calibration and the verification procedure. Moreover a model sensitivity analysis procedure is presented in subsection 2.3 and a multi-regression model to relate optimal parameter set and easy available meteorological data is proposed in subsection 2.4.

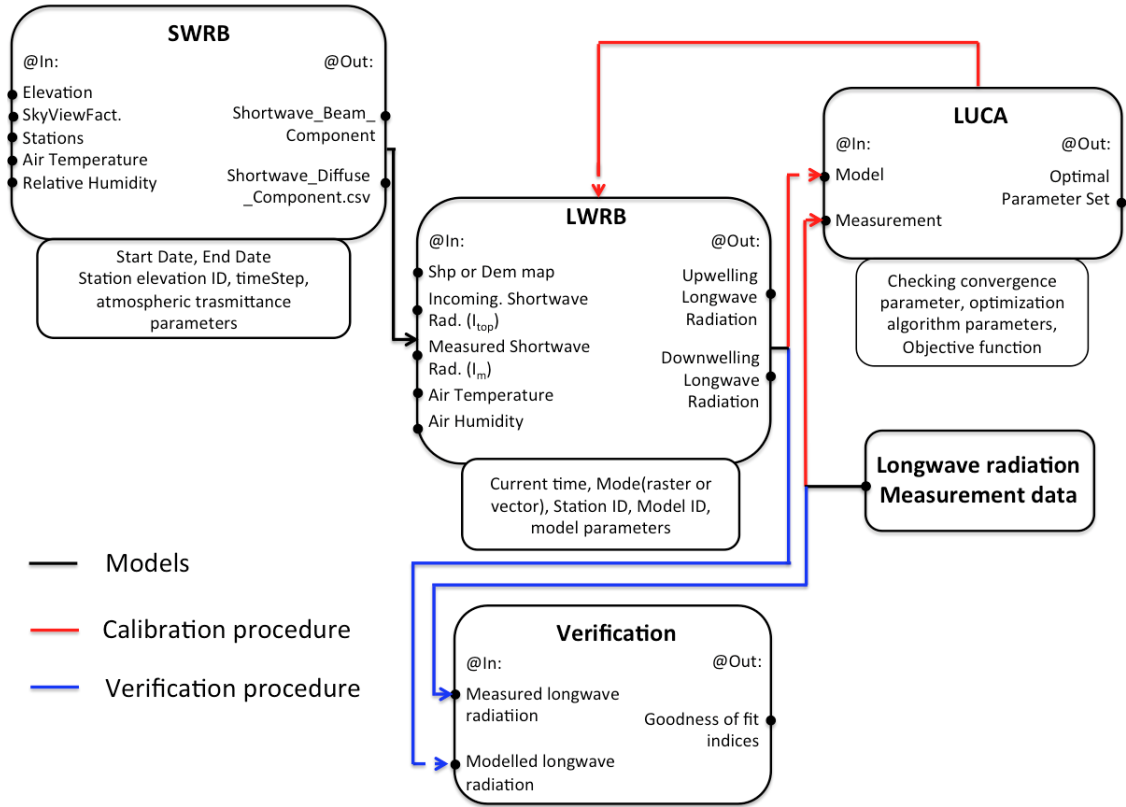


Figure 1: The LWRB component of JGrass-NewAge and the flowchart to model longwave radiation.

2.1 Calibration of L_{\downarrow} longwave radiation models

Model calibration estimates the site-specific parameters of L_{\downarrow} models by tweaking them with a specific algorithm in order to best fit measured data. To this end, we use the LUCA calibration algorithm proposed in (Hay et al., 2006) Hay et al. (2006), which is a part of the OMS core and is able to optimize parameters of any OMS component. LUCA is a multiple-objective, stepwise, and automated procedure. As with any automatic calibration algorithm, it is based on two elements: a global search algorithm; and the objective function(s) to evaluate model performance. In this case, the global search algorithm is the Shuffled Complex Evolution, which has been widely used and described in literature (e.g., Duan et al., 1993). As the objective function we use the Kling-Gupta Efficiency (KGE), which is described below, but LUCA could use other objective functions just as well.

The calibration procedure for L_{\downarrow} follows these steps:

- The theoretical solar radiation at the top of the atmosphere (I_{top}) is computed using the SWRB (see Figure 1);
- The clearness index, c , is calculated as the ratio between the measured incoming solar radiation (I_m) and I_{top} ;
- Clear-sky and cloud-cover hours are detected by a threshold on the clearness index (equal to 0.6), providing two subsets of measured L_{\downarrow} , which are $L_{\downarrow clear}$ and $L_{\downarrow cloud}$. On one side, a threshold of 0.6 to define the clear-sky conditions helps in the sense that allow to define time-series of measured clear-sky L_{\downarrow} with

comparable length in all the stations, and this is useful for a reliable calibration process. On the other side, it introduces a small error in computing the emissivity in all-sky condition using equation 3 which could be compensated by the optimization of the parameters a and b ;

- The parameters X , Y , and Z for the models in table 1 are optimised using the subset $L_{\downarrow clear}$ and setting $a=0$ in eq. 3;
- The parameters a and b for eq. 3 are optimized using the subset $L_{\downarrow cloud}$ and using the X , Y , and Z values computed in the previous step.

The calibration procedure provides the optimal set of parameters at a given location for each of the ten models.

As well as parameter calibration, we carry out a model parameter sensitivity analysis and we provide a linear regression model relating a set of site-specific optimal parameters with easily-available climatic variables, such as mean air temperature, relative humidity, precipitation, and altitude.

2.2 Verification of L_{\downarrow} and L_{\uparrow} longwave radiation models

As presented in previous applications (e.g. Hatfield et al. (1983), Flerchinger et al. (2009)), we use the SMs with the original coefficients from literature (i.e. the parameters of table 2) and compare the performances of the models against available measurements of L_{\downarrow} and L_{\uparrow} for each site. The goodness of fit is evaluated by using two goodness-of-fit estimators: the Kling-Gupta Efficiency (KGE) presented in Gupta et al. (2009); and the root mean square error (RMSE).

The KGE (eq. 4) is able to incorporate into one objective function three different statistical measures of the relation between measured (M) and simulated (S) data: (i) the correlation coefficient, r ; (ii) the variability error, $a = \sigma_S/\sigma_M$; and (iii) the bias error, $b = \mu_S/\mu_M$. In these definitions μ_S and μ_M are the mean values, while σ_S and σ_M are the standard deviations, of measured and simulated time series.

$$KGE = 1 - \sqrt{(r-1)^2 + (a-1)^2 + (b-1)^2} \quad (4)$$

The RMSE, on the other hand, is presented in eq. 5:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - S_i)^2} \quad (5)$$

where M and S represents the measured and simulated data respectively and N is their length.

2.3 Sensitivity analysis of L_{\downarrow} models

For each L_{\downarrow} model we carry out a model parameters sensitivity analysis to investigate the effects and significance of parameters on performance for different model structures (i.e. models with one, two, and three parameters).

The analyses are structured according to the following steps:

- we start with the optimal parameter set, computed by the optimization process for the selected model;
- all parameters are kept constant and equal to the optimal parameter set, except for the parameter under analysis;
- 1000 random values of the analyzed parameter are picked from a uniform distribution centered on the optimal value with width equal to $\pm 30\%$ of the optimal value; in this way 1000 model parameter sets were defined and 1000 model runs were performed;
- 1000 values of KGE are computed by comparing the model outputs with measured time series.

The procedure was repeated for each parameter of each model and for each station of the analyzed dataset.

2.4 Regression model for parameters of L_{\downarrow} models

The calibration procedure previously presented to estimate the site specific parameters for L_{\downarrow} models requires measured downwelling longwave data. Because these measurements are rarely available, we implement a straightforward multivariate linear regression (Chambers et al., 1992; Wilkinson and Rogers, 1973) to relate the site-specific parameters X, Y and Z to a set of easily available site specific climatic variables, used as regressors r_i . To perform the regression we use the open-source R software (<https://cran.r-project.org>) and to select the best regressors we use algorithms known as "best subsets regression", which are available in all common statistical software packages. The regressors we have selected are: mean annual air temperature, relative humidity, precipitation, and altitude. The models that we use for the three parameters are presented in equations (4.4), (4.4), and (4.4):

$$X = i_X + \sum_{k=1}^N \alpha_k \cdot r_k + \epsilon_X \quad (6)$$

$$Y = i_Y + \sum_{k=1}^N \beta_k \cdot r_k + \epsilon_Y \quad (7)$$

$$Z = i_Z + \sum_{k=1}^N \gamma_k \cdot r_k + \epsilon_Z \quad (8)$$

where $N=4$ is the number of regressors (annual mean air temperature, relative humidity, precipitation, and altitude); r_k with $k=1, \dots, 4$ are the regressors; i_X , i_Y , and i_Z are the intercepts; α_k , β_k , and γ_k are the coefficients; and ϵ_X , ϵ_Y , and ϵ_Z are the normally distributed errors. Once the regression parameters are determined, the end-user can estimate site specific X, Y and Z parameter values for any location by simply substituting the values of the regressors in the model formulations.

3 The study area: the AmeriFlux Network

To test and calibrate the LWRB SMs we use ~~twenty-four~~ 24 meteorological stations of the AmeriFlux Network (<http://ameriflux.ornl.gov>). AmeriFlux is a network of sites that measure water, energy, and CO₂ ecosystem fluxes in North and South America. The dataset is ~~widely known and used for biological and environmental applications. To cite a few, Xiao et al. (2010) used Ameriflux data in a study on gross primary production data, Kelliher et al. (2004) in a study on carbon mineralization, and Barr et al. (2012) in a study on hurricanes~~ well-known and used in several applications such as Xiao et al. (2010), Barr et al. (2012), and Kelliher et al. (2004). Data used in this study are the Level 2, 30-minute average data. Complete descriptions and downloads are available at the Web interface located at <http://public.ornl.gov/ameriflux/>.

We have chosen ~~twenty-four~~ 24 sites that are representative of most of the USA and span a wide climatic range: going from the arid climate of Arizona, where the average air temperature is 16 °C and the annual precipitation is 350 mm, to the equatorial climate of Florida, where the average air temperature is 24 °C and the annual precipitation is 950 mm. Some general and climatic characteristics for each site are summarized in table 4, while figure 2 shows their locations. The 30-minute average data have been cumulated to obtain continuous time series of averaged, hourly data for longwave radiation, air and soil temperature, relative humidity, precipitation, and soil water content.

SiteID	State	Latitude	Longitude	Elevation (m)	Climate	T (°C)	Data period
1	AZ	31.908	-110.840	991	semiarid	19	2008 – 2013
2	AZ	31.591	-110.509	1469	temperate, arid	16	2002 – 2011
3	AZ	31.744	-110.052	1372	temperate, semi-arid	17	2007 – 2013
4	AZ	31.737	-109.942	1531	temperate, semi-arid	17	2004 – 2013
5	AZ	31.821	-110.866	116	subtropical	19	2004 – 2014
6	AZ	35.445	-111.772	2270	warm temperate	9	2005 – 2010
7	AZ	35.143	-111.727	2160	warm temperate	9	2005 – 2010
8	AZ	35.089	-111.762	2180	warm temperate	8	2005 – 2010
9	CA	37.677	-121.530	323	mild	16	2010 – 2012
10	CA	38.407	-120.951	129	mediterranean	15	2000 – 2012
11	FL	25.365	-81.078	0	equatorial savannah	24	2004 – 2011
12	ME	45.207	-68.725	61	temperate continental	5	1996 – 2008
13	ME	45.204	-68.740	60	temperate continental	6	1996 – 2009
14	MN	44.995	-93.186	301	continental	6	2005 – 2009
15	MN	44.714	-93.090	260	snowy, humid summer	8	2003 – 2012
16	MO	38.744	-92.200	219	temperate continental	13	2004 – 2013
17	MT	48.308	-105.102	634	continental	5	2000 – 2008
18	NJ	39.914	-74.596	30	temperate	12	2005 – 2012
19	OK	36.427	-99.420	611	cool temperate	15	2009 – 2012
20	TN	35.931	-84.332	286	temperate continental	15	2005 – 2011
21	TN	35.959	-84.287	343	temperate	14	1994 – 2007
22	TX	29.940	-97.990	232	warm temperate	20	2004 – 2012
23	WA	45.821	-121.952	371	strongly seasonal	9	1998 – 2013
24	WV	39.063	-79.421	994	temperate	7	2004 – 2010

Table 4: Some general and climatic characteristics of the sites used for calibration: elevation is the site elevation above sea level, T is the annual average temperature, and data period refers to the period of available measurements.

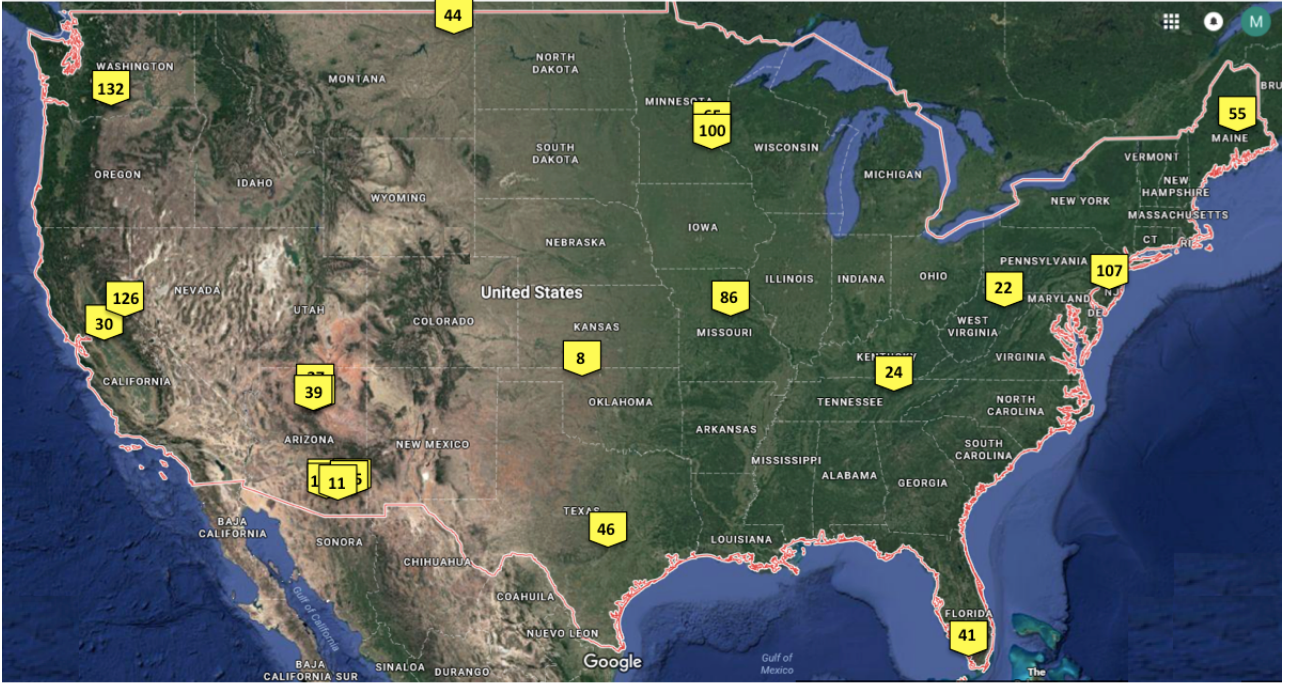


Figure 2: Test site locations in the United State of America.

4 Results

4.1 Verification of L_{\downarrow} models with literature parameters

When implementing the ten L_{\downarrow} SMs using the literature parameters, in many cases, they show a strong bias in reproducing measured data. A selection of representative cases is presented in Figure 3, which shows scatterplots for four SMs in relation to one measurement station. The black points represent the hourly estimates of L_{\downarrow} provided by literature formulations, while the solid red line represents the line of optimal predictions. Model 1 (Ångström (1915)) shows a tendency to lie below the ~~45-degree-1:1~~ line, indicating a negative bias (percent bias of -9.8) and, therefore, an underestimation of L_{\downarrow} . In contrast, model 9 (Prata (1996)) shows an overestimation of L_{\downarrow} with a percent bias value of 26.3.

Figure 4 presents the KGE (first column) and RMSE (second column) obtained for each model under clear-sky conditions, grouped by classes of latitude and longitude. Model 8 (Konzelmann et al. (1994)) does not perform very well for ~~some reason~~ many of the stations likely because the model parameters were estimated for the Greenland where the ice plays a fundamental role on the energy balance. Its KGE values range between 0.16 and 0.41, while its RMSE values are higher than 100 W/m^2 , with a maximum of 200 W/m^2 . Model 6 (Idso (1981)) and model 2 (Brunt (1932)) provide the best results, independently of the latitude and longitude ranges where they are applied. Their KGE values are between 0.75 and 0.94, while the RMSE has a maximum value of 39 W/m^2 .

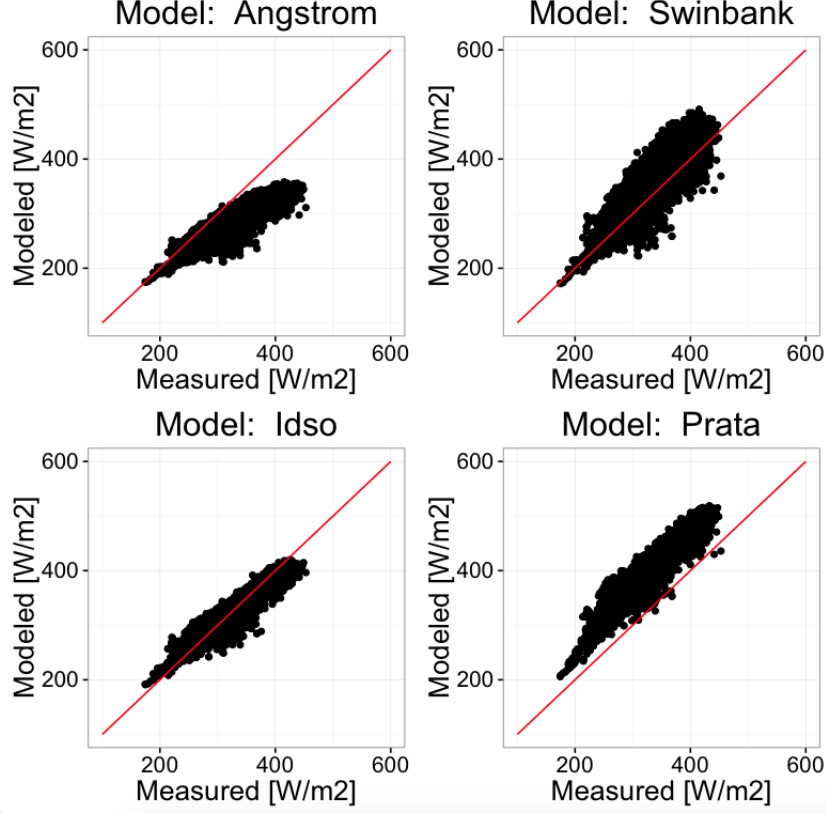


Figure 3: Results of the clear-sky simulation for four literature models using data from Howland Forest (Maine).

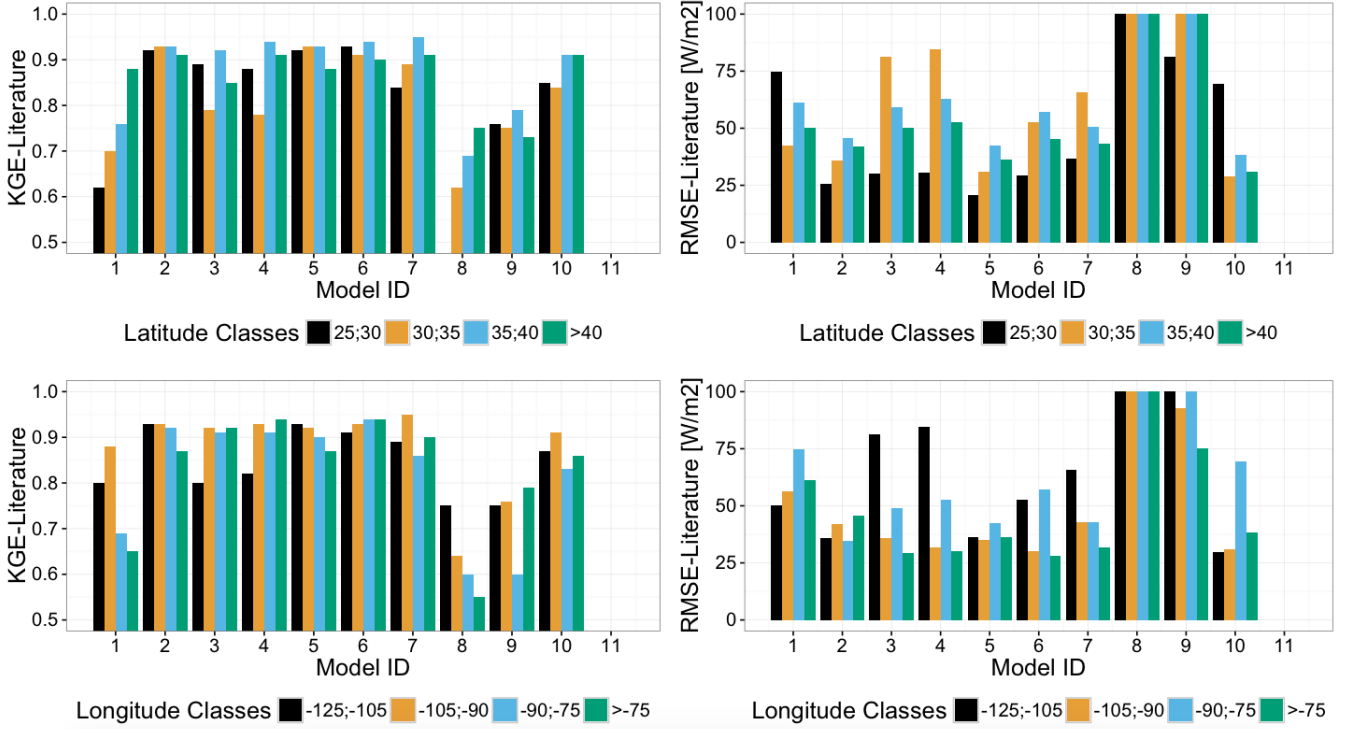


Figure 4: KGE and RMSE values for each clear-sky simulation using literature formulations, grouped by classes of latitude and longitude. The values of the KGE shown are those above 0.5: in this case, model 8 KGE values are not represented as they are between 0.16 and 0.41. The range of RMSE is 0-100 W/m^2 .

4.2 L_{\downarrow} models with site-specific parameters

The calibration procedure greatly improves the performances of all ten SMs. Optimized model parameters for each model are reported in the supplementary material. Figure 5 presents the KGE and RMSE values for clear-sky conditions grouped by classes of latitude and longitude. The percentage of KGE improvement ranges from its maximum value of 80% for model 8 (which is not, however, representative of the mean behavior of the SMs) to less than 10% for model 6, with an average improvement of around 35%. Even though variations in model performances with longitude and latitude classes still exist when using optimized model parameters, the magnitude of these variations is reduced with respect to the use of literature formulations. The calibration procedure reduces the RMSE values for all the models to below 50 W/m^2 , with the exception of model 8, which now has a maximum of 58 W/m^2 .

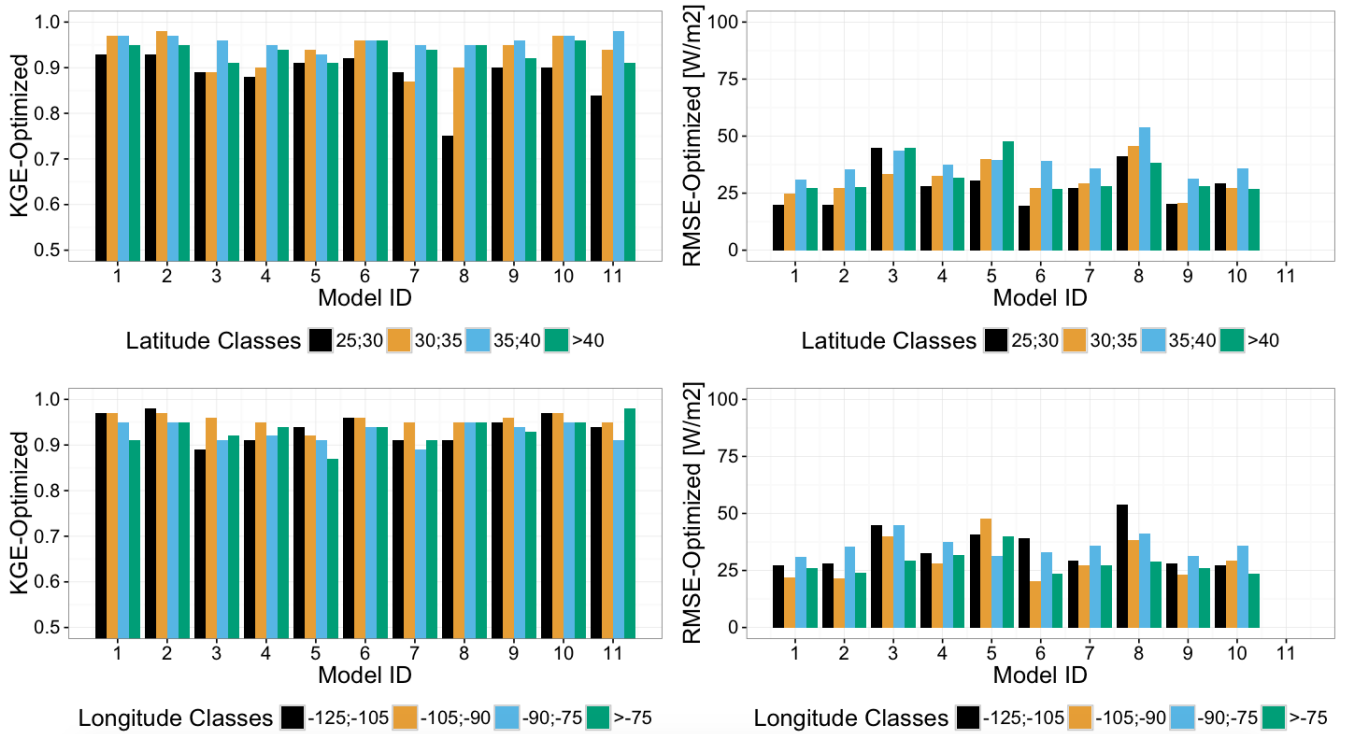


Figure 5: KGE (best is 1) and RMSE (best is 0) values for each optimized formulation in clear-sky conditions, grouped by classes of latitude and longitude. Only values of KGE above 0.5 are shown.

Figure 6 presents KGE and RMSE values for each model under all-sky conditions, grouped by latitude and longitude classes. In general, for all-sky conditions we observe a deterioration of KGE and RMSE values with respect to the clear-sky optimized case, with a decrease in KGE values up to a maximum of 25% for model 10. This may be due to uncertainty incorporated in the formulation of the cloudy-sky correction model (eq. 3): it seems that sometimes the cloud effects are not accounted for appropriately. This, however, is in line with the findings of Carmona et al. (2014).

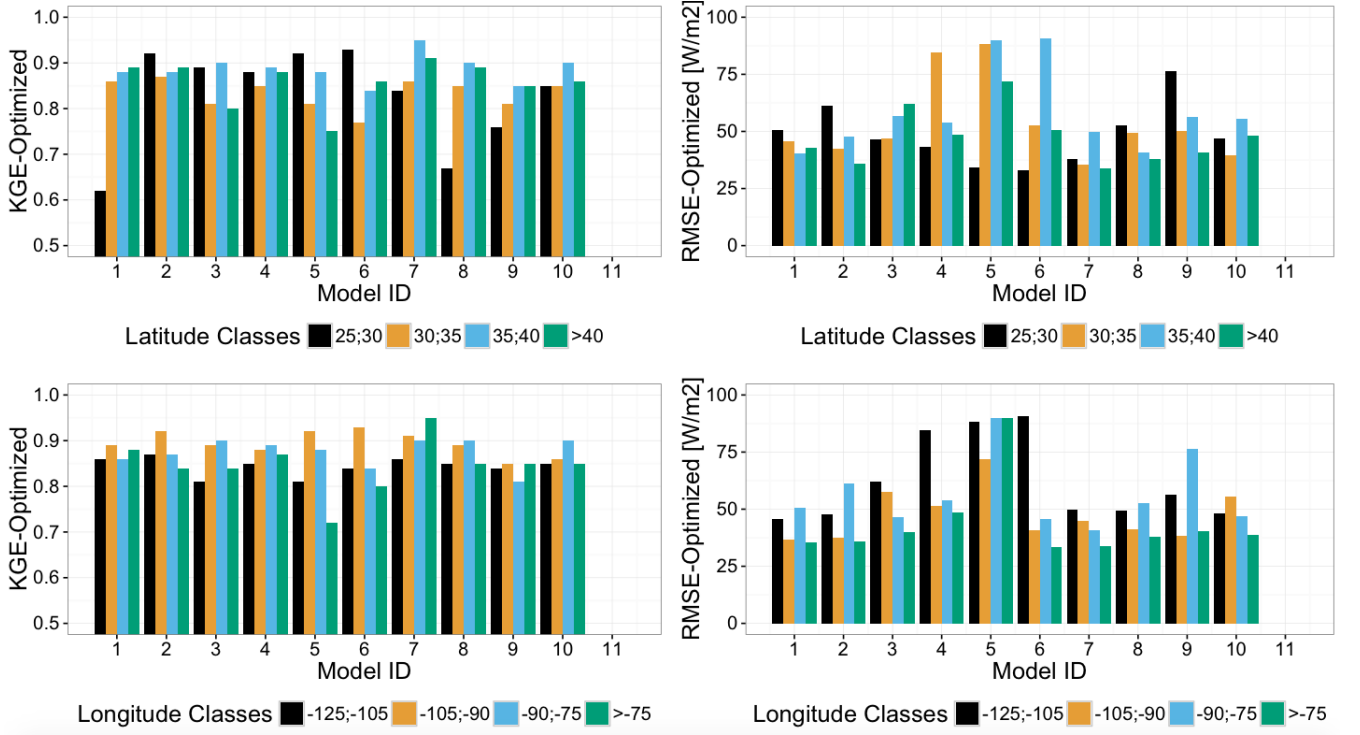


Figure 6: KGE and RMSE values for each model in all-sky conditions, grouped by classes of latitude and longitude. Only values of KGE above 0.5 are shown.

4.3 Sensitivity analysis of L_{\downarrow} models

For each L_{\downarrow} model we carry out a model parameters sensitivity analysis to investigate the effects and significance of parameters on performance for different model structures (i.e. models with one, two, and three parameters). The analyses are structured according to the following steps: we start with the optimal parameter set, computed by the optimization process for the selected model; all parameters are kept constant and equal to the optimal parameter set, except for the parameter under analysis; 1000 random values of the analyzed parameter are picked from a uniform distribution centered on the optimal value with width equal to $\pm 30\%$ of the optimal value; in this way 1000 model parameter sets were defined and 1000 model runs were performed; 1000 values of KGE are computed by comparing the model outputs with measured time series. The procedure was repeated for each parameter of each model. The results of the models sensitivity analysis are summarized in Figures 7-a and 7-b summarize the sensitivity analysis results for models 1 to 5 and models 6 to 10, respectively. Each figure presents three columns, one for each parameter. Considering model 1 and parameter X: the range of X is subdivided into ten equal-sized classes and for each class the corresponding KGE values are presented as a boxplot. A smooth blue line passing through the boxplot medians is added to highlight any possible pattern to parameter sensitivity. A flat line indicates that the model is not sensitive to parameter variation about around optimal value. Results suggest that models with one and two parameters are all sensitive to parameter variation, presenting a peak in KGE in correspondence with their optimal values; this is more evident in models with two parameters. Models with three parameters tend to have at least one insensitive parameter, except for model 1, that could reveal a possible overparameterization of the modeling process.

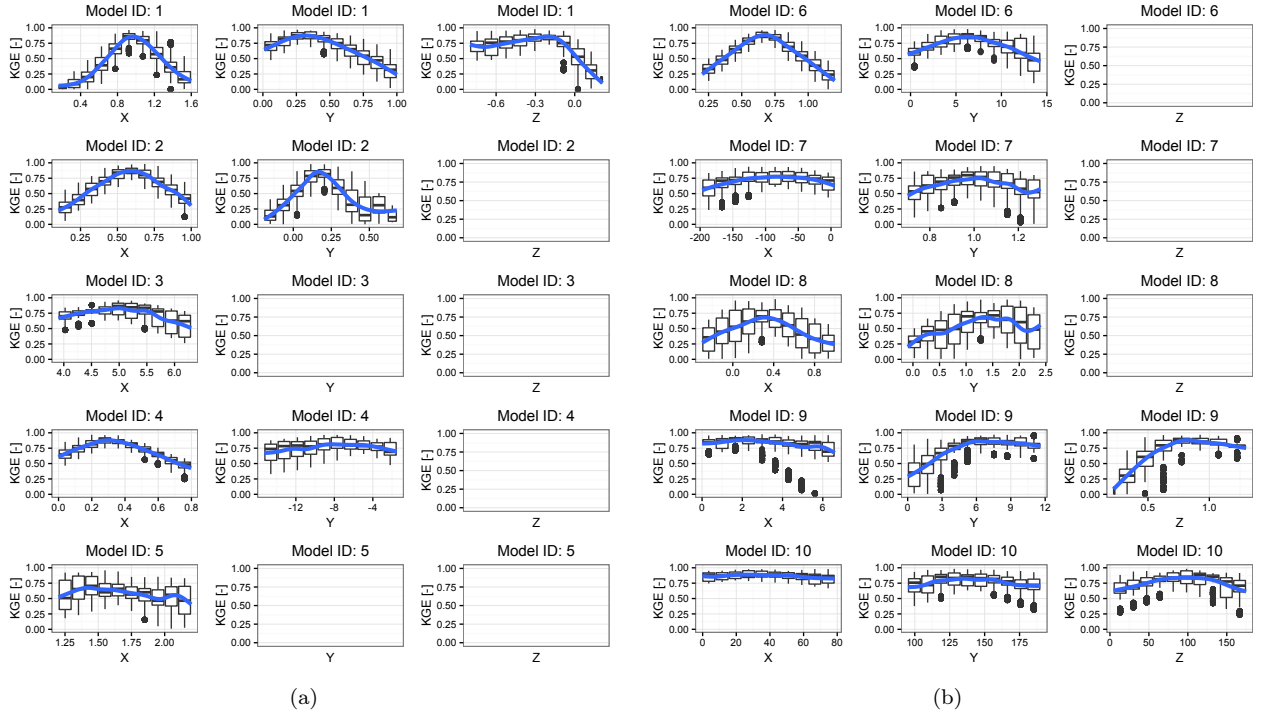


Figure 7: Results of the model parameters sensitivity analysis. It presents as boxplot the variation of the model performances due to a variation of one of the optimal parameter and assuming constant the others. The procedure is repeated for each model and the blue line represents the smooth line passing through the boxplot medians.

4.4 Regression model for parameters of L_{\downarrow} models

The calibration procedure that allows the estimation of site specific parameters for L_{\downarrow} models requires measured downwelling longwave data. Because these measurements are rarely available, we implement a straightforward multivariate linear regression (Chambers et al., 1992; Wilkinson and Rogers, 1973) model was estimated to relate the site-specific parameters X, Y and Z to a set of easily available site specific climatic variables, used as regressors r_i . To perform the regression we use the open-source R software (<https://cran.r-project.org>) and to select the best regressors we use algorithms known as "best subsets regression", which are available in all common statistical software packages mean annual air temperature, relative humidity, precipitation, and altitude. The script containing the regression model is available, with the complementary supplementary material, at the web page of this paper: <http://abouthydrology.blogspot.it/2015/07/site-specific-long-wave-radiation.html>. <https://github.com/geoframecomponents>.

The regressors we have selected are: mean annual air temperature, relative humidity, precipitation, and altitude. The models that we use for the three parameters are presented in equations (4.4), (4.4), and (4.4):

$$X = a_X + \sum_{k=1}^N \alpha_k \cdot r_k + \epsilon_X$$

$$Y = a_Y + \sum_{k=1}^N \beta_k \cdot r_k + \epsilon_Y$$

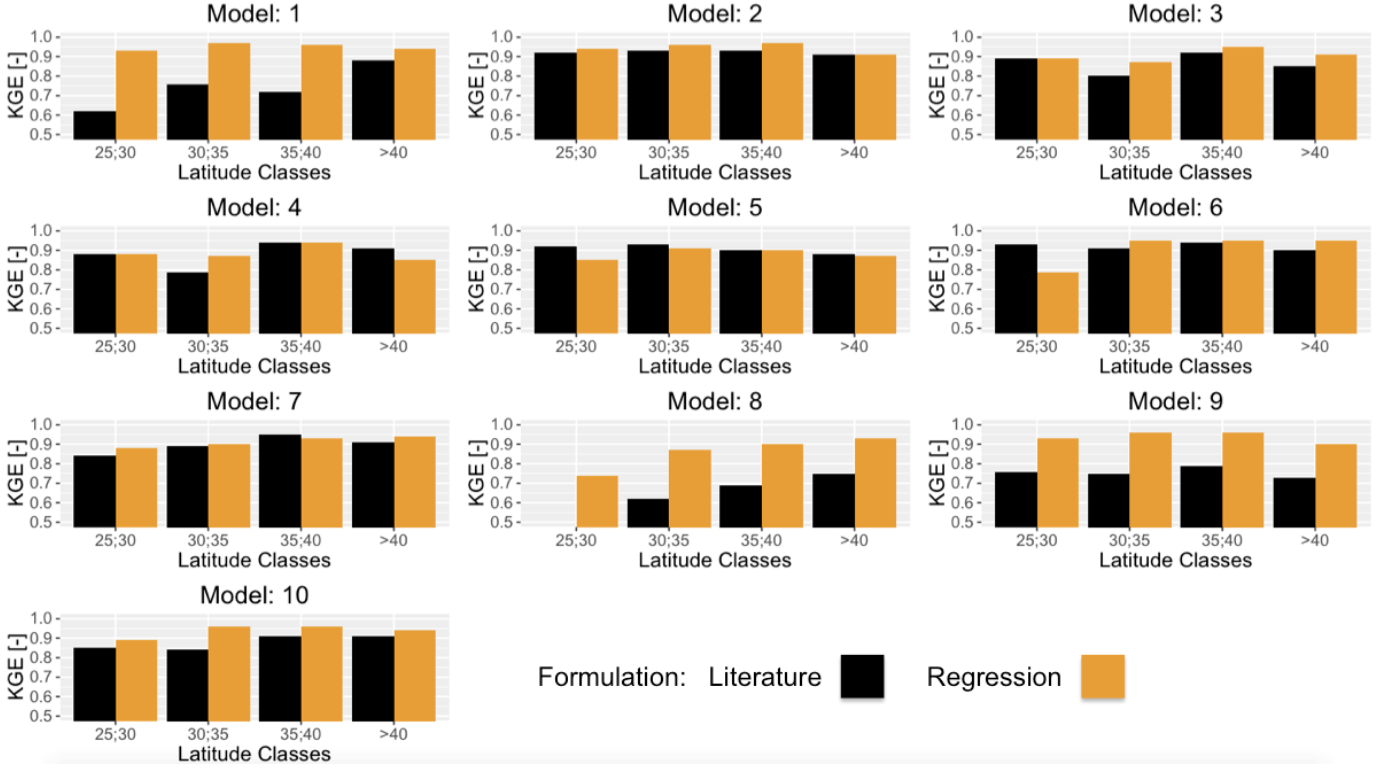


Figure 8: Comparison between model performances obtained with regression and classic parameters: the KGE values shown are those above 0.7 and results are grouped by latitude classes.

$$Z = a_Z + \sum_{k=1}^N \gamma_k \cdot r_k + \epsilon_Z$$

where $N=4$ is the number of regressors (annual mean air temperature, relative humidity, precipitation, and altitude); r_k with $k=1, \dots, 4$ are the regressors; a_X , a_Y , and a_Z are the intercepts; α_k , β_k , and γ_k are the coefficients; and ϵ_X , ϵ_Y , and ϵ_Z are the normally distributed errors. Once the regression parameters are determined, the end-user can estimate site specific X , Y and Z parameter values for any location by simply substituting the values of the regressors in the model formulations.

The performances of the L_{\downarrow} models using parameters assessed by linear regression are evaluated through the leave-one-out cross validation (Efron and Efron, 1982). We use 23 stations as training-sets for equations (4.4), (4.4), and (4.4) and we perform the model verification on the remaining station. The procedure is repeated for each of the 24 stations.

The cross validation results for all L_{\downarrow} models and for all stations are presented in figures (8) and (9), grouped by classes of latitude and longitude, respectively. They report the KGE comparison between the L_{\downarrow} models with their original parameters (in red) and with the regression model parameters (in blue).

In general, the use of parameters estimated with regression model gives a good estimation of L_{\downarrow} , with KGE values of up to 0.97. With respect to the classic formulation, model performance with regression parameters improved for all the models, in particular for model 8 in which the KGE improved from a minimum of 0.16 for the classic formulation to a maximum of 0.97.

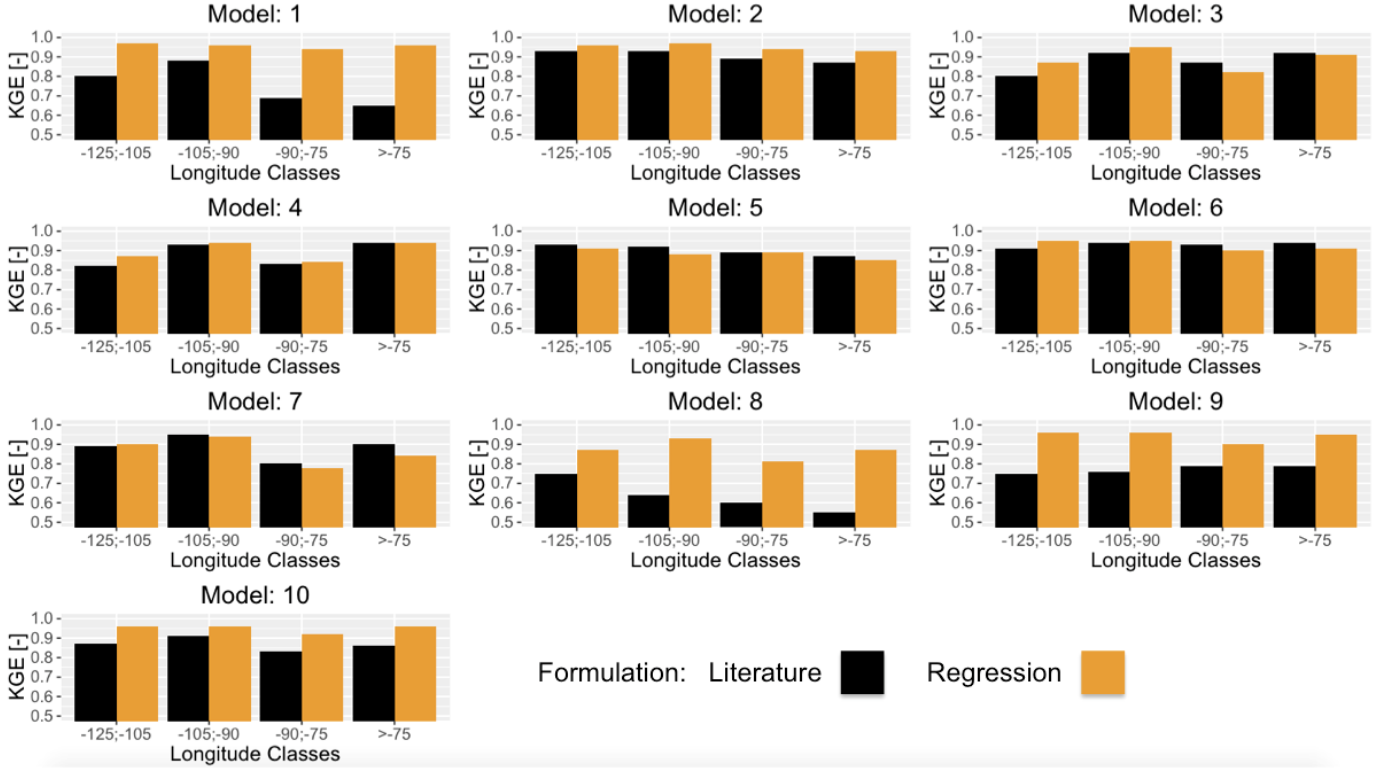


Figure 9: Comparison between model performances obtained with regression and classic parameters: the KGE values shown are those above 0.7 and results are grouped by longitude classes.

4.5 Verification of the L_{\uparrow} model

Figure 9-10 presents the results of the L_{\uparrow} simulations obtained using the three different temperatures available at experimental sites: soil surface temperature (skin temperature), air temperature, and soil temperature (measured at 4 cm below the surface). The figure shows the performances of the L_{\uparrow} model for the three different temperatures used in terms of KGE, grouping all the stations for the whole simulation period according to season. This highlights the different behaviors of the model for periods where the differences in the three temperatures are larger (winter) or negligible (summer). The values of soil emissivity are assigned according the soil surface type, according to Table 4 (Brutsaert, 2005). Although many studies investigated the influence of snow covered area on longwave energy balance (e.g. Plüss and Ohmura (1997) ; Sicart et al. (2006)), the SMs do not explicitly take into account of it. As presented in König-Langlo and Augstein (1994) , the effect of snow could be implicitly taken into account by tuning the emissivity parameter.

The best fit between measured and simulated L_{\uparrow} is obtained with the surface soil temperature, with an all-season average KGE of 0.80. Unfortunately, the soil surface temperature is not an easily available measurement. In fact, it is available only for 8 sites of the 24 in the study area. Very good results are also obtained using the air temperature, where the all-season average KGE is around 0.76. The results using air temperature present much more variance compared to those obtained with the soil surface temperature. However, air temperature (at 2 m height) is readily available measure, in fact it is available for all 24 sites.

The use soil temperature at 4 cm depth provides the least accurate results for our simulations, with an all-season average KGE of 0.46. In particular, the use of soil temperature at 4 cm depth during the winter is

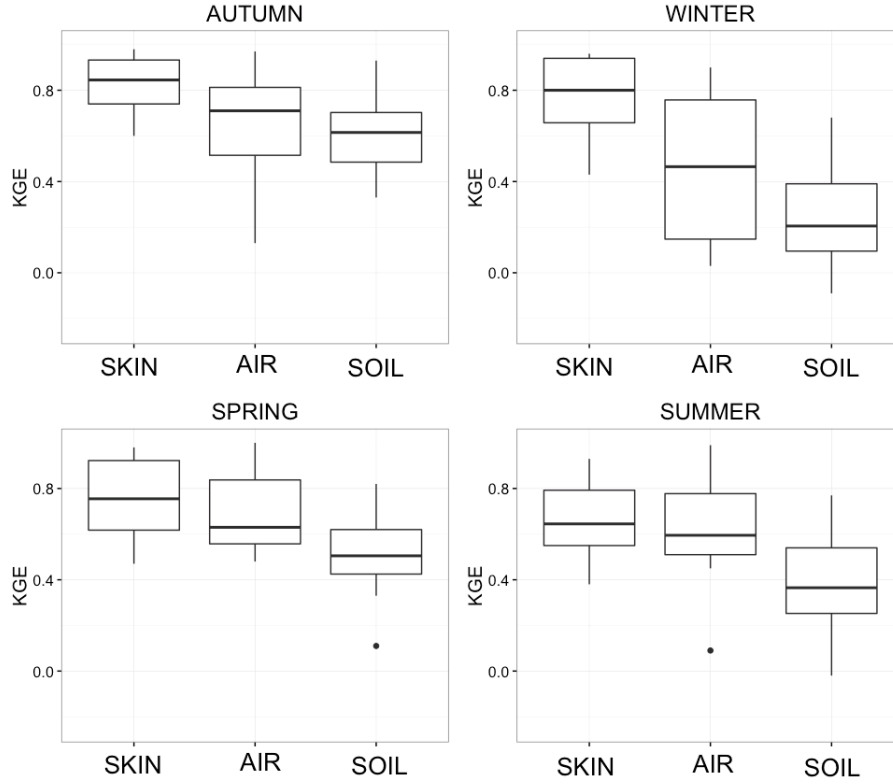


Figure 10: Boxplots of the KGE values obtained by comparing modeled upwelling longwave radiation, computed with different temperatures (soil surface temperature (SKIN), air temperature (AIR), and soil temperature (SOIL)), against measured data. Results are grouped by seasons.

not able to capture the dynamics of L_{\uparrow} . It does, however, show a better fit during the other seasons. This could be because during the winter there is a substantial difference between the soil and skin temperatures, as also suggested in Park et al. (2008).

5 Conclusions

This paper presents the LWRB package, a new modeling component integrated into the JGrass-NewAge system to model upwelling and downwelling longwave radiation. It includes ten parameterizations for the computation of L_{\downarrow} longwave radiation and one for L_{\uparrow} . The package uses all the features offered by the JGrass-NewAge system, such as algorithms to estimate model parameters and tools for managing and visualizing data in GIS.

The LWRB is tested against measured L_{\downarrow} and L_{\uparrow} data from ~~twenty-four~~ 24 AmeriFlux test-sites located all over continental USA. The application for L_{\downarrow} longwave radiation involves model parameter calibration, model performance assessment, and parameters sensitivity analysis. Furthermore, we provide a regression model that estimates optimal parameter sets on the basis of local climatic variables, such as mean annual air temperature, relative humidity, and precipitation. The application for L_{\uparrow} longwave radiation includes the evaluation of model performance using three different temperatures.

The main achievements of this work include: i) a broad assessment of the classic L_{\downarrow} longwave radiation parameterizations, which clearly shows that the Idso (1981) and Brunt (1932) models are the more robust and reliable for all the test sites, confirming previous results (Carmona et al., 2014); ii) a site specific assessment of

the L_{\downarrow} longwave radiation model parameters for ~~twenty-four~~ 24 AmeriFlux sites that improved the performances of all the models; iii) the set up of a regression model that provides an estimate of optimal parameter sets on the basis climatic data; iv) an assessment of L_{\uparrow} model performances for different temperatures (skin temperature, air temperature, and soil temperature at 4 cm below surface), which shows that the skin and the air temperature are better proxy for the L_{\uparrow} longwave radiation. Moreover the Brunt (1932) model is able to provide higher performances with the regression model parameters independently of the latitude and longitude classes. For the Idso (1981) model the formulation with regression parameter provided lower performances respect to the literature formulation for latitude between [25-30].

The integration of the package into JGrass-NewAge will allow users to build complex modeling solutions for various hydrological scopes. In fact, future work will include the link of the LWRB package to the existing components of JGrass-NewAge to investigate L_{\downarrow} and L_{\uparrow} effects on evapotranspiration, snow melting, and glacier evolution. Finally, the methodology proposed in this paper provides the basis for further developments such as the possibility to: i) investigate the effect different all-sky emissivity formulation, ii) verify the usefulness of the regression models for locations outside the USA; iii) analyze in a systematic way the uncertainty due to the quality of meteorological input data on the longwave radiation balance in scarce instrumented areas.

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Replicable Research

~~In order that interested researchers may replicate or extend our results, our codes are made available at~~ Researchers interested in replicating or extending our results are invited to download our codes at:

<https://github.com/geoframecomponents>.

Instructions for using the code can be found at:

<http://geoframe.blogspot.co.uk/2016/04/lwrp-component-latest-documentation.html>.

Regression of parameters were performed in R and are available at

https://github.com/GEOframeOMSProjects/OMS_Project_LWRB/blob/master/docs/Regression.R

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