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Testing site-specific parameterizations of longwave radiation integrated in a GIS-based hydrological model

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Abstract: Incoming (Rli) and outgoing (Rlo) longwave atmospheric radiation are very important components of the global radiation balance. They influence many hydrological processes such as evapotranspiration, soil-surface temperature, energy balance, and snowmelt. Field measures of Rli and Rlo are extremely rare except for a few sites and experimental watersheds. Many parameterization schemes were proposed in order to model Rli and Rlo by using easily available meteorological observations such as air temperature, relative humidity, incoming solar radiation and cloud cover.

In this work 10 methods of parameterizing clear sky radiation for the estimation of Rli and Rlo were integrated in the GIS based hydrological system NewAge-JGrass and tested against field measurement data at hourly and daily timesteps. Two applications were performed. In the first application the 11 algorithms were applied by using the model parameters as proposed in literature. In the second application we preserved the analytical formulation of the models but site-specific parameters were estimated by using the automatic calibration algorithms available in the NewAge-JGrass system. Model verification was performed computing classical goodness of fit indices such as root mean square error, mean absolute error, percentage bias and Kling-Gupta efficiency. The use of site specific model parameters improves simulation results providing an improvement of all the indices of goodness of fit for all the parameterizations tested in the paper.

Keywords: Solar radiation balance, Longwave radiation modelling, Object Modelling System.

1.   INTRODUCTION

Radiation balance is crucial for land surface, atmospheric and oceanic processes which develop on the Earth. Longwave radiation (1-100 μm) is an important component of the radiation balance and for this reason affects many phenomena such as evapotranspiration, snow melt (Plüss et al., 1997), surface radiation budget, vegetation dynamics (Rotenberg et al., 1998), plant respiration and primary productivity (Leigh, 1999), glaciers' evolution (e.g. MacDonell et al., 2013 and reference therein).
Ground-based measure of longwave solar radiation are lacking even if an increasing number of projects (e.g. the Surface Radiation Budget Network, and the FLUXNET) have been developed to fill the gap (respectively reported in Augustine et al., 2000 and Augustine et al., 2005 and Baldocchi et al., 2001)). Pyrogeometers, the instrument for measuring longwave radiation, are very expensive and sensitive compared to instruments for measure shortwave radiation, and for this reason they are not available in basic meteorological stations. Use of satellite's products for estimating longwave solar radiation is increasing (GEWEX, Global Energy and Water cycle Experiment, ISCCP the International Satellite Cloud Climatology Project) but they have spatial and temporal scale constraint.

To fill the gap left by measures, models have been developed in order to solve energy transfer equations and compute radiation at the surface (Key and Schweiger, 1998; Kneizys et al., 1998, Rigon et al., 2006). These physically based and distributed models provides accurate estimate of the radiation components but at the same time they requires an amount of input data and model parameters that often are not easily available.

Simplified models (SM) based on empirical or physical relationship relate longwave radiation to atmospheric data such as air temperature, deficit of vapor pressure, shortwave radiation measurement providing clear sky (Angstrom, 1918; Brunt, 1932, Idso, S.B. and Jackson, R.D., 1969) and all-sky parameterization (Brutsaert, 1982, Iziomon et al., 2003a).

SM's performances were assessed by comparing measured and modelled incoming longwave radiation at hourly and daily time-step (Iziomon et al., 2003b, Juszak, and Pellicciotti, 2013). In particular Flerchinger et al., 2009 optimizes original SMs parameters in order to fit incoming longwave radiation at multiple sites.

In this paper a component containing various SMs is implemented in the NewAge-JGrass modelling system (Formetta et al., 2014) according the Object Modeling System framework (David et al., 2013). OMS is a Java based, object-oriented modelling framework that treats models as plain objects with metadata provided by means of annotations. In OMS there are no interfaces to implement, no classes to extend and polymorphic methods to overwrite; no framework-specific data types need to replace common native language data types. There is only the use of annotations to specify and describe "points of interest" for existing data fields and methods for the framework. Each component is a self-contained unit implemented with a standard, well-defined purpose and interface in mind. Finally, simulations (model applications with data) can be executed individually from the graphical interface.

Three are the innovations of the work with respect to existing literature: i) the integration of an open source-package for modelling longwave radiation based on different formulation, ii) the possibility to link these models with any NewAge components, for instance that estimating the shortwave radiation budget (Formetta et al., 2013a), evapotranspiration components, snow melting component (Formetta et al., 2013b); iii) the possibility to connect the package with any OMS components such as those containing automatic calibration algorithms to make the model parameters site-specific.

Section 2 describes the SMs formulation and their input–output system, Section 3 presents the calibration procedure and Section 4 presents a test-site application: models' calibration and evaluation.

2. METHODOLOGY

SM's formulation for Rlo $\left[W \cdot m^{-2} \right]$ and Rli $\left[W \cdot m^{-2} \right]$ are based on the Stefan-Boltzmann equation:

$$Rli = \varepsilon_{all-sky} \cdot \sigma \cdot T_a^4 \quad (1)$$

$$Rlo = \varepsilon_s \cdot \sigma \cdot T_s^4 \quad (2)$$

where $\sigma = 5.670 \cdot 10^{-8} \left[W \cdot m^{-2} \cdot K^{-4} \right]$ is the Stefan-Boltzmann constant, $T_a \left[K \right]$ is the near-surface air temperature, $\varepsilon_{all-sky} \left[- \right]$ is the atmosphere effective emissivity, $\varepsilon_s \left[- \right]$ is the soil emissivity and $T_s \left[K \right]$ is the surface soil temperature.

In order to account for the increase of Rli in cloud cover conditions $\varepsilon_{all-sky}$ is formulated according to eq. (3):

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

where c [-] is the cloud cover fraction and a and b are two calibration coefficients. Site specific values of a and b are presented in Brutsaert, 1982 (a=0.22 and b=1), Iziomon et al., 2003 (a ranges between 0.25 and 0.4 and b=2) and Keding, 1989 (a=0.183 and b=2.18). In our modelling system a and b will be calibrated in order to fit measurement data in all-sky conditions.

Parameter c can be assessed by using satellite data or otherwise, it can be modelled as well. We used the formulation presented in Campbell, 1985 and Flerchinger, 2000 where c was related to the clearness index, ratio between the measured incoming solar radiation (I_m) and the theoretical solar radiation computed at the top atmosphere (I_{top}). These formulations need of the shortwave radiation balance component to estimate I_{top} and meteorological stations to measure I_m and therefore they are not able to estimate c during night-time. In our formulation, for the fact that SMs are components of the NewAge-JGrass system, the shortwave radiation balance component (Formetta et. al., 2013) is used to compute I_{top}. Moreover, during night-time c is modelled by using a linear interpolation of c_a, last cloud cover computed in afternoon and c_m first cloud cover compute in early morning of the day after. If during the night rainfall is observed, c assume a default value of 0.9.

Ten classical formulations were implemented for the computation of $\varepsilon_{all-sky}$.

The complete list of parameterizations used is contained in Table (1) that presents each component name, the equation that defines it, and the reference to the paper from which it is derived. X, Y and Z are parameters provided in literature for each model, Table (2).

Because the formulation of the Rlo requires soil temperature, the user can choose between three options: i) to use measured values, ii) to model soil temperature by simple relationship with air temperature (Parton and Logan, 1981), iii) to use air temperature (Brutsaert, 2005).

Table 1. Clear sky emissivity formulations: Ta is the air temperature [K], w [kg/m2] is precipitable water = 4650 [e0/Ta] and e [kPa] screen-level water-vapour pressure.

Component Name	Formulation	Reference
Angstrom	$\varepsilon_{clear} = X - Y \cdot 10^{-0.067 \cdot e}$	Angstrom [1918]
Brunt's	$\varepsilon_{clear} = X + Y \cdot e^{0.5}$	Brunt's [1932]
Swinbank	$\varepsilon_{clear} = X \cdot 10^{-13} \cdot T_a^6$	Swinbank [1963]
Idso and Jackson	$\varepsilon_{clear} = 1 - X \cdot \exp(-Y \cdot 10^{-4}(273 - T_a)^2)$	Idso and Jackson [1969]
Brutsaert	$\varepsilon_{clear} = X \cdot (\frac{e}{T_a})^{1/7}$	Brutsaert [1975]
Idso	$\varepsilon_{clear} = X + Y \cdot 10^{-4} \cdot e \cdot \exp(\frac{1500}{T_a})$	Idso [1981]
Monteith and Unsworth	$\varepsilon_{clear} = (X + Y \cdot \sigma \cdot T_a^4)$	Monteith and Unsworth [1990]
Konzelmann	$\varepsilon_{clear} = X + Y \cdot (\frac{e}{T_a})^{1/8}$	Konzelmann et al [1994]
Prata	$\varepsilon_{clear} = [1 - (X + w) \cdot \exp(-(Y + Z \cdot w)^{1/2})]$	Prata [1996]
Dilley and O'brien	$\varepsilon_{clear} = X + Y \cdot (\frac{T_a}{273.16})^6 + Z \cdot (w/25)^{0.5}$	Dilley and O'brien [1998]

Table 2. Models' parameters values as presented in their classical formulation and as computed for the site-specific application. X, Y and Z are the parameters' values of the parameterization presented in table 1.

	Classical Formulation			Site-Specific Formulation		
Component Name	X	Y	Z	X	Y	Z
Angstrom	0.83	0.18	[-]	1.54	0.80	[-]
Brunt's	0.52	0.21	[-]	0.65	0.09	[-]
Swinbank	5.31	[-]	[-]	4.75	[-]	[-]
Idso and Jackson	0.26	7.77	[-]	0.25	-1.00	[-]
Brutsaert	1.72	[-]	[-]	1.71	[-]	[-]
Idso	0.70	5.95	[-]	0.71	3.23	[-]
Monteith - Unsworth	-119.00	1.06	[-]	-138.38	0.67	[-]
Konzelmann et al	0.23	0.48	[-]	0.33	1.14	[-]
Prata	1.00	1.20	3.00	0.56	2.96	0.94
Dilley and O'Brien	59.38	113.70	96.96	72.75	122.53	77.19

3   MODEL CALIBRATION

The models presented in Table 1 were proposed with coefficient' values (X, Y, Z) strictly related to the location in which authors applied the model. Coefficients reflect climatology, atmospheric and hydrological conditions of the sites used. In order to obtain site-specific coefficients we optimized them to fit Rli measurements data by using the particle swarm calibration algorithm (PSO, Kennedy and Eberhart R., 1995). PSO is part of the OMS core and it is therefore able to optimize any OMS component. The calibration procedure follows these steps:

- Clear and cloud-cover hours are detected by a threshold on c providing two subset of measured Rli: CL and CC respectively.
- Parameters X, Y, and Z of the models in Table (1) were optimized using the subset CL and setting a=0 in eq.(3).
- Parameters a and b of eq. (3) were optimized by using the subset CC and setting X, Y, and Z equal to the optimal values computed in the previous step.

4   APPLICATION

The system was tested in the Rocky Ford river basin (Colorado, USA). In the basin a complete meteorological station (Fig. 1) measures shortwave and longwave outgoing and incoming radiations, precipitation, air temperature and relative humidity. Three months of data, from 25/08/2010 to 25/11/2010 with hourly time step were available.

Figure 1. Meteorological monitoring station in Rocky ford river basin.

Two applications were performed with the objective to reproduce the temporal variation of the longwave radiation.

In the first, models were applied with parameters equal to the value presented in their classical formulation. In the second application models' parameters were calibrated following the procedure presented in the previous section. Table 2 presents models parameters taken from literature and calibrated as the site-specific values. Figure 2 presents scatter plot of measured and simulated Rli for four models for the subset CL. Points in black represent the result provided by the calibration of parameters X, Y and Z and points in blue represent the result provided by classical models formulation. Figure 3 presents the scatter plot of measured and modelled Rli for all sky condition where both X, Y and Z and a and b were optimized.
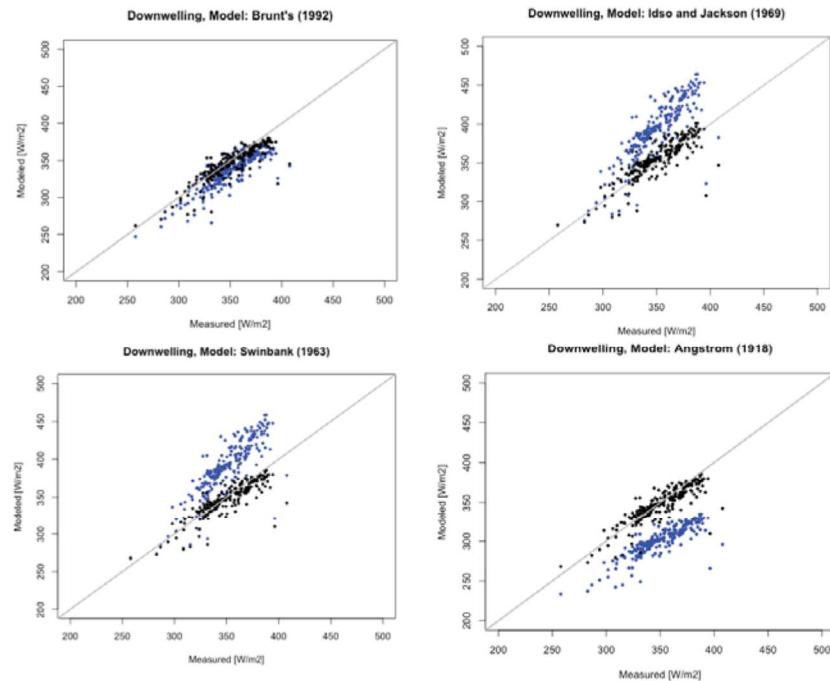
Figure 2. Scatter plot of modelled and measured Rli for CL subset. Comparison between classical model formulations (in blue) and site specific models' parameters optimisation (in black) for Brunts, Idso, Swinbank and Angstrom component.
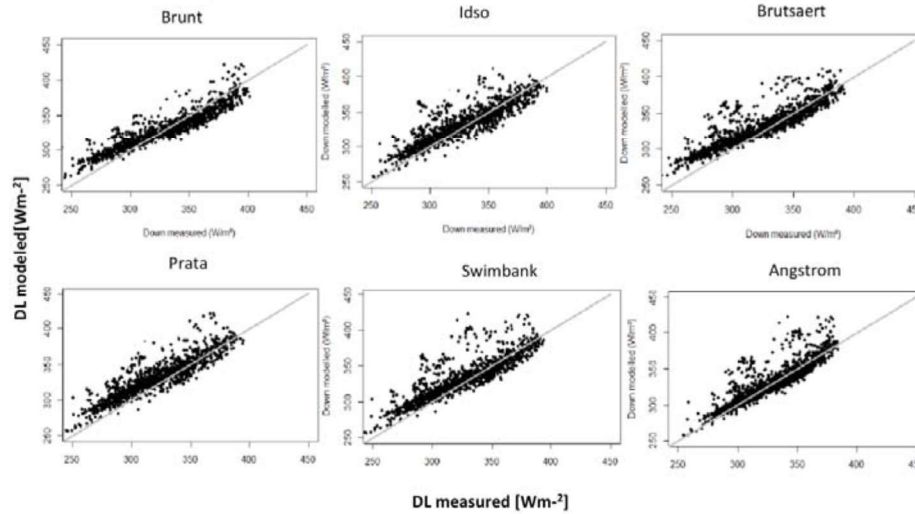
Figure 3. Scatter plot of modelled and measured Rli for CC subset and for six models with site-specific calibration: Brunt, Idso, Vrutsaert, Prata, Swinbank and Angstrom.

Finally results in term of quantitative performance metrics were presented in table (4). Root mean square error, mean absolute error, percentage bias and Kling-Gupta were computed for classical and site-specific formulations.

The use of SMs with classical formulation could overestimate (Swimbank model in Fig.2) or underestimate (Angstrom model in Fig. 2) Rli under clear-sky conditions. Even in the case in which classical formulations provides satisfactory results (Brunt's model in Fig. 2), the use of site-specific calibrated parameters improves model Rli estimate. In all-sky application, the models' parameters optimization definitively improves the simulation of Rli and the results are confirmed both from a qualitative point of view (Figures 2 and 3) and from a quantitative point of view (Table 3) showing better values of root mean square error (RMSE), percentage bias (PBIAS), and Kling Gupta efficiency (KGE). The best model for the application was Brunt with RMSE of 13.1, PBIAS of -1.4, and KGE of 0.85

Table 3. Model's goodness indices of fit for Rli in CL dataset. Root mean square error (RMSE), Percentage Bias (PBIAS), and Kling Gupta Efficiency (KGE) were computed for classical and site specific formulations.

Model	Classical Formulation			Site specific formulation		
	RMSE	PBIAS	KGE	RMSE	PBIAS	KGE
Angstrom	51.13	-14.1	0.71	13.21	-1	0.83
Brunt's	19.95	-4.3	0.84	13.16	-1.4	0.85
Swinbank	44.81	11.3	0.42	18.37	-0.5	0.58
Idso e Jackson	48.92	12.5	0.38	14.48	1.1	0.83
Brutsaert	13.61	0.6	0.84	13.42	-0.2	0.84
Idso	19.14	4.1	0.82	11.95	-0.1	0.82
Monteith and Unsworth	25.84	5.5	0.64	13.38	-0.9	0.77
Konzelmann et al	162.94	-46.3	0.31	13.03	-1.4	0.84
Prata	103.55	29.2	0.61	17.95	0	0.72
Dilley and O'brien	20.9	-4.8	0.77	11.98	0.1	0.81

5   CONCLUSIONS

A component of models for the estimation of the longwave radiation budget was integrated in the JGrass-NewAge system. The package uses all the system facilities offered by components to fit models' parameters, to visualize data, and the connection to the uDig GIS for the management of input-output. Different formulations for Rli are tested in order to reproduce measured Rli data in Colorado, (US). Models were executed according their classical formulation and estimating site-specific values of their parameters. The second application provides the best results in reproduction of Rli with in some cases substantial improvements.

The integration of the package in JGrass-NewAge will help to buils more complex modelling solutions for various hydrological scopes. In fact, linking the package to existing components of JGrass-NewAge (Formetta et al., 2011, Formetta et al., 2013a, Formetta et al., 2013b, Formetta et al., 2014) allows to investigate Rli and Rlo effects on evapotranspiration, snow melting, and glacier evolution.

One simple foreseen further application that the system offers is the possibility to perform comparisons between modeled longwave radiation, and remote sensing products. Using the system's components, the differences in pattern reproduction can, in fact, be easily assessed.

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