

ENCIT-2018-0231

IMPROVEMENTS IN SOFTWARE DOMUS ABOUT ATMOSPHERIC RADIATIVE EXCHANGE AND LONG-WAVE BOUNDARY CONDITIONS

Santiago Riquelme

Universidad del Bío-Bío, Department of Mechanical Engineering, Concepción, Chile

Pontifícia Universidade Católica do Paraná, Mechanical Engineering Graduate Program, Curitiba, Brazil

sriquelme@ubiobio.cl

Nathan Mendes**Luís Mauro Moura**

Pontifícia Universidade Católica do Paraná, Mechanical Engineering Graduate Program, Curitiba, Brazil

nathan.mendes@pucpr.br

luis.moura@pucpr.br

Abstract.

External long-wave radiative heat transfer is a typical boundary condition problem in building physics and the solution of the Radiative Transfer Equation (RTE) involve important mathematical skills to apply a simple model and still nowadays the computational cost in algorithms for solving the integral-differential RTE is not explicit implemented in building simulation software. In Building Physics, the empirical approach based in synoptic data to estimate atmospheric long-wave radiation is associated to a fictive sky model with an effective sky emissivity and a representative sky temperature. Some models simplify the phenomenon by assuming the sky temperature as equal to the outdoor air temperature, others present a relationship with different meteorological synoptic data and also more complex models involve to know very clearly the amount of long-wave radiation exchanged with the building external surface. The work aims at proposing a new model for the assessment of long-wave atmospheric radiation in the Building Hygrothermal Simulation Program DOMUS. The proposal will be verified with other available state-of-the-art building simulation programs using statistical analysis for annual series of hourly data.

Keywords: Atmospheric Radiation, Long-wave Radiation, Sky Temperature.

1. INTRODUCTION

Energy efficiency is the smart energy consumption so that its rational use is a permanent need in commercial and residential buildings. Therefore, energy simulation in buildings today is an essential tool worldwide, allowing energy savings and efficient operation of buildings. At the same time, it is a mandatory requirement to achieve an environmental certification, as it is, for example, the certificate LEED given by the U.S. Green Building Council (U.S.GBC, 2018) and the Brazilian Program of Labelling in Buildings (PBE-Edifica, 2018). Some of the objectives of energy simulation are the investigation of new efficient strategies for buildings, evaluation of design options most suitable, check that it complies with legislation and economic analysis that determines the impact of conservation measures. The accuracy of simulation depends on many parameters and one of them is the amount of heat exchanged by long-wave radiation. There are many models in the literature for radiative boundary conditions; however, the results provided by them may vary enormously so that research has to be still carried out in order to improve their accuracy. The aim of this work is focused into the infrared spectrum and this has been extensively studied nowadays because is a source of renewable energy, clearly that is not a very large scale, but it is possible in a near future with projects like harvesting renewable energy from Earth's mid-infrared emissions (Byrnes *et al.*, 2014). The solar energy absorbed by the atmosphere can vary depending on the variable content of water vapor, pollution or aerosol. However, the greatest variation of absorption of the atmosphere is due to cloudiness (Martin, 1995). Buildings are complex structures, because the exterior or facades presents complicated geometry and variable boundary conditions strongly dependent of climatological conditions and on the other hand the internal air conditions are influenced by variations of these outside conditions such as air temperature, solar radiation and level of overcast sky. Focusing on this work: The radiative heat transfer is a typical boundary condition to evaluate the heat transfer in buildings, and the common division is between short-wave and long-wave radiative heat transfer because the intensity of energy involved. The long-wave radiative heat fluxes on wall surfaces can be considered on different levels

of detail. Different approaches exist for the calculation of radiative heat transfer. Some models use Stefan-Boltzmann law while others use linearized radiation equations. Thus, these models differ in the accuracy of their results as well as in computation time. So far, it has not been determined which of these models is best suited for thermal simulation at urban scale (Lauster *et al.*, 2014). In Building Simulation Programs the numerical modeling uses some kind of synoptic model for assessment of atmospheric radiation and the respective sky emissivity or sky temperature using climatic or synoptic data. The synoptic data based models as will be show in this work varies from more complex than others. A revision and analysis of models that are available in literature will be done to continue with a comparison between them to make a brief selection, after that a comparison with other state-of-the-art building simulation programs will be done using statistical indicators for annual data series. Then, it will be proposed a model based on synoptic data to be implemented in DOMUS software for future numerical evaluations.

2. DOMUS: A whole-building hygrothermal simulation program

DOMUS (Mendes *et al.*, 2008) is a software for simulation of multi-zone buildings and analysis of both thermal comfort and energy use. This software has been developed to model coupled heat and moisture transfer in buildings, in order to analyze the performance of typical Brazilian rooms when subjected to any kind of climate conditions.

The calculation of conduction heat transfer through multi-layer walls is done by using the finite difference approach and, for each zone, it was employed a capacitive lumped model to calculate the temperature and relative humidity. DOMUS models predict temperature profiles within multi-layer walls for any time step and the temperature and relative humidity for each zone. Input files containing hourly data provide information on the conditions at the interior and exterior of the building, a library of material properties is also available. The convection coefficients at the exterior of the wall are calculated hourly from wind velocity and direction data (Mendes *et al.*, 2003). Fig. 1 presents an overview of the program.

In DOMUS the estimation of long-wave atmospheric radiation is based in Kasten formulation (Kasten and Czeplak, 1980), this algorithm allows to estimate the solar and atmospheric-terrestrial radiation dependent on the amount and type of cloud. The revision, evaluation and if it is necessary the actualization of certain modules is a normal evolution of a state-of-the-art software. For the above described the aim of this work is the implementation of better accurate formulation for assessment of atmospheric radiation.

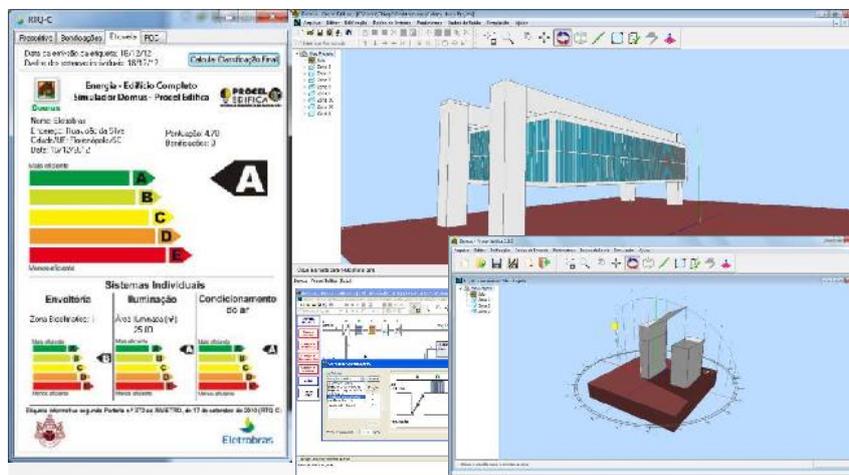


Figure 1. Domus: A whole-building hygrothermal simulation program

3. METHODOLOGY

As indicated before in literature, there are two distinct methods for the determination the atmospheric radiation: Analytical Method and Empirical or Synoptic Data Method. As the aim of this work is the development of a new formulation for atmospheric radiation based in available synoptic data, the application of analytical method for atmospheric modeling will be not develop in this currently paper. As the different available models in literature presents the sky temperature or sky emissivity as results, the first analysis will be done based on this parameter to establish a selection by level of update and possibility of implementation using variables available in the climate file format used in Domus. For the comparison the main synoptic data was obtained from a TMY file of the city of Concepción - Chile (Lat:36°49'41.5" S, Long:73°3'4.93" W), from a weather files database available in the website of the U.S. Department of Energy (D.O.E., 2018). On the other hand the state-of-art programs in Building Simulation as EnergyPlus™ (Crawley *et al.*, 2000), TRN-Sys (Klein, 1975), and WUFI® (Kunzel, 1995), presents the atmospheric radiation as reference, for this reason, the

values for hourly atmospheric radiation are obtained from this programs and will be used to compare the current model and the proposal model for downwelling atmospheric radiation. The numerical models performance will be evaluated using statistical analysis based in performance statistics commonly usage in solar radiation modeling as Mean Bias Deviation (MBD) and Root Mean Square Deviation (RMSD), both in engineering units of W/m^2 . Therefore the procedure is separated into two stages: The first is the evaluation of the models using the sky temperature as a parameter and making the selection of the most appropriate model. The second stage is the comparison of the current model of atmospheric radiation in Domus and the new proposal with other building simulation programs. The results will be presented using the statistical indicators described above. A methodological scheme that graphically shown these two evaluation stages is presented in following Fig.2.

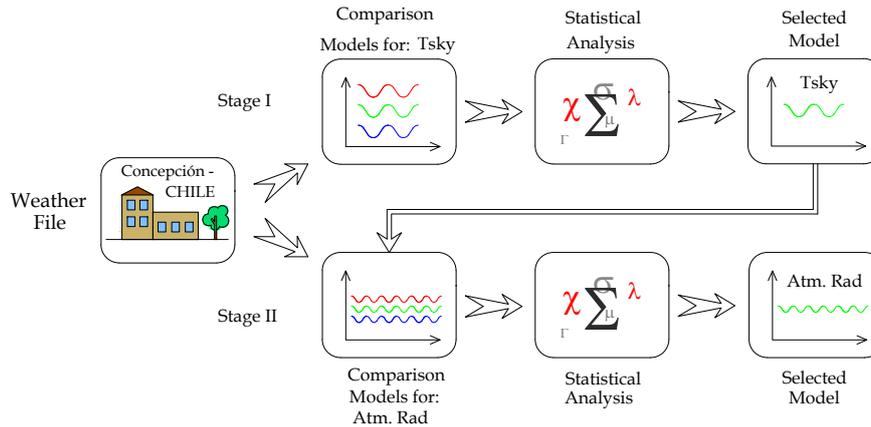


Figure 2. Methodological scheme

Because at this stage of the research work we still do not have direct measured data related to atmospheric radiation. It is not possible to compare the empirical models with measured data, an average value between the selected models in the same time step is established as a criterion for comparison. The performance of the models were evaluated using the root-mean-square deviation (RMSD) and mean bias deviation (MBD) statistics, with the results expressed both in engineering units of Kelvin for Sky Temperature (T_{sky}) and W/m^2 for Atmospheric Radiation (A_R), also as a percent of the mean of the averaged values graphically showed as \bar{x} in Fig.3. The deviation is the average value subtracted from the modelled value. For the MBD, a positive value indicates that the model overestimates on average. Expressions for the calculation of the MBD and the RMSD are provided as Eqs. 1 to 4.

$$MBD = \frac{\sum(y_i - x_i)}{n}, W/m^2, \quad (1)$$

$$MBD = 100 \left[\frac{\sum(y_i - x_i)}{n} \right] \div \left[\frac{\sum(x_i)}{n} \right], \%, \quad (2)$$

$$RMSD = \sqrt{\frac{\sum(y_i - x_i)^2}{n}}, W/m^2, \quad (3)$$

$$RMSD = 100 \left[\sqrt{\frac{\sum(y_i - x_i)^2}{n}} \right] \div \left[\frac{\sum(x_i)}{n} \right], \%, \quad (4)$$

where y_i is the i^{th} modelled value, in W/m^2 or Kelvin; x_i is the i^{th} averaged value, in W/m^2 or Kelvin; and n is the number of averaged or modelled values.

4. ATMOSPHERIC RADIATION BASED IN SYNOPTIC DATA

The estimation of atmospheric radiation based in synoptic data, consist of relating atmospheric radiation with parameters easily obtainable on the earth's surface such as ambient temperature, dew point temperature and water vapour pressure. In order to formulate these empirical equations it is necessary to use instruments to measure the radiation and to correlate this value with the parameters obtained at the level of the terrestrial surface.

For clear sky conditions it has been observed that there is a good correlation between the atmospheric radiation and these parameters. Most of the atmospheric radiation comes from the lower layers and the values of the parameters at the level of the earth's surface differ little from the values of the parameters in the first layers of the atmosphere (Cole,

1979). Some researchers have conflicting views regarding the reliability of various atmospheric radiation assessment methods. Morgan (Morgan *et al.*, 1971), in his work, concludes that both the empirical formulas and the use of radiation charts present good results. Berger (Berger *et al.*, 1984) concludes that there are great differences between different researchers in the determination of atmospheric radiation and that therefore the correlation between atmospheric radiation and other climatic parameters at ground level is not the better; the indicated alternative is the direct measurement through instruments. It can be seen from this that there is no universal method for determining atmospheric radiation. In other hand between the presented models in this paper just Iziomon (Iziomon *et al.*, 2003) parameterization were carried out on highland sites and it is demonstrated the importance of the parametrization based in geographical location. For the following procedure based in Stefan-Boltzmann formulae, it is convenient to consider the atmospheric radiation A_R as the radiation emitted by a gray body at ambient temperature T_a , based on a fictive surface with an effective emissivity denoted in literature as Atmospheric Emissivity or Sky Emissivity, ϵ_{sky} ; therefore,

$$A_R = \epsilon_{sky} \sigma T_a^4 \quad (5)$$

where ϵ_{sky} is the sky emissivity or emissivity of the atmosphere, ie the ratio of the radiation emitted by the atmosphere (A_R) to the radiation emitted by a black body at the atmospheric temperature (σT_a^4).

Moreover, supposing that the radiation emitted by the atmosphere came from a black body, the equivalent temperature of the sky (T_{sky}) is defined as follows (Atwater and Ball, 1978):

$$A_R = \sigma T_{sky}^4 \quad (6)$$

Therefore, atmospheric radiation can be expressed both in terms of the emissivity of the atmosphere (ϵ_{sky}) and in terms of the equivalent temperature of the sky (T_{sky}) however.

4.1 Synoptic models for Clear Sky condition

There are numerous equations that provide correlations for atmospheric emissivity for that selected models are presented in Table 1 as "Clear-Sky Models". The selection was made for the most representative of the traditional models of Swinbank (Swinbank, 1963), and Buchberg-Roulet (H.Buchberg and J.R.Roulet, 1968) and the equations obtained with improved equipment on followed decades, Brutsaert (Brutsaert, 1975), Centeno (Centeno, 1982), Berdahl-Martin (Berdahl and Martin, 1984), Berger (Berger *et al.*, 1984), Prata (Prata, 1996) and Iziomon (Iziomon *et al.*, 2003). Will be keep this correlative year order and codified starting with the capital letter A. In Fig.3 a graphical comparison of the different synoptic models with the local time as reference are shown, the main synoptic hourly data were obtained from a TMY file of the city of Concepción - Chile as was defined before in Methodology Section, the graphical comparison is done for the day September 18th. To have a more visible behaviour of each formulae. To build the graphics each one of the equation presented in Tab.1 and Tab.2 was filled with the respective necessary information and the respective coherence concerning the measurement units have been developed.

Table 1. Clear-Sky Models.

Model	T_{sky}	ϵ_{sky}	Coef.
A 01 Swinbank 1963	$T_{sky} = 0.0552T_a^{1.5}$	—	—
A 02 Buchberg-Roulet 1968	—	$\epsilon_{sky} = T_a(0.55 + 3.85 * 10^{-2} P_w^{0.5})$ $P_w = (RH) P_{w,s}^{0.25}$	—
A 03 Brutsaert 1975	—	$\epsilon_{sky} = a \left(\frac{\epsilon_a}{T_a}\right)^b$	a:1.24;b:0.14
A 04 Centeno 1982	$T_{sky} = T_a(0.56 + 0.08P_v^{0.5})^{0.25}$	$\epsilon_{sky} = 0.56 + 0.08P_v^{0.5}$	—
A 05 Berdhal-Martin I 1984	—	$\epsilon_{sky} = 0.711 + 0.56\left(\frac{T_{dp}}{100}\right)$ $+0.73\left(\frac{T_{dp}}{100}\right)^2$	—
A 06 Berdhal-Martin II 1984	—	$\epsilon_{sky} = 0.711 + 0.0056T_{dp}$ $+0.000073T_{dp}^2 + 0.013\cos(15t)$	—
A 07 Berger 1984	—	$\epsilon_{sky} = 0.77 + 0.0038T_{dp}$ $\epsilon_{sky} = 0.752 + 0.0048T_{dp}$	Day time Night time
A 08 Aubinet 1994	$T_{sky} = 94 + 12.6 \ln(P_v)$ $-13k_0 + 0.341T_a$	—	—
A 09 Prata 1996	—	$\epsilon_a = 1 - (1 - aw)e^{-[(b+cw)^{0.5}]}$ $w = 46.5 \frac{\epsilon_a}{T_a}$	a:0.1;b:1.2 c:0.3
A 10 Izimon 2003	—	$\epsilon_a = 1 - ae^{-\left(\frac{b}{T_a}\right)}$	a:0.35;b:10

T_a :Air temperature; P_v, ϵ_a :Vapour pressure; C_c, c : Cloud cover; RH:Relative humidity; T_{dp} : Dew point temperature; k_0 : Clearness index

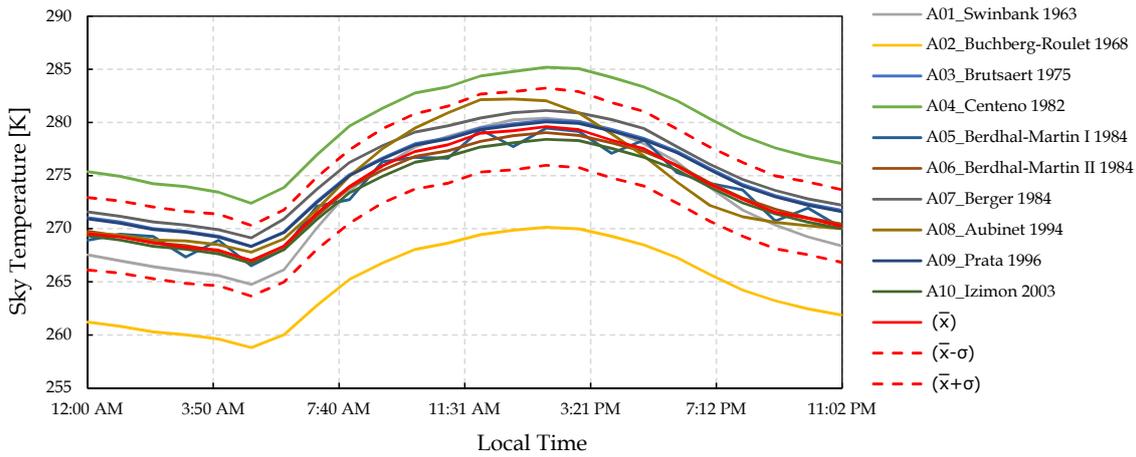


Figure 3. Sky Temperature - Clear Sky Models comparison at September 18th.

4.2 Synoptic models for All Sky condition

The models for atmospheric radiation affected by the presence of clouds are denominated "All-Sky Models" in this paper. The synoptic data based for Sky Temperature according Cole (Cole, 1979), and Dagenet (1985). For Sky Emissivity according Berdahl-Martin (Berdahl and Martin, 1984), Prata (Prata, 1996), and Sridhar (Sridhar and Elliott, 2002) will be presented in Table 2, as above in **Section 4.1 Synoptic models for Clear Sky condition**, will be keep the correlative year order and codified starting with the capital letter B, also is shown a graphical comparison about the models for the selected day September 18th. in Fig. 4.

Table 2. All-Sky Models.

Model	T_{sky}	ϵ_{sky}
B 01 Cole 1979	$T_{sky} = 9.365574 * 10^{-6}(1 - C_c)T_a^6 + T_a^4 C_c \epsilon_{clouds}$	$\epsilon_{sky} = \epsilon_{clouds} = (1 - 0.84C_c) (0.527 + 0.161e^{8.45(1 - \frac{2.73}{T_{air}})}) + 0.84 C_c$
B 02 Berdhal-Martin 1984	—	$\epsilon_{sky} = \epsilon_{clear-sky} + 0.8(1 - \epsilon_{clear-sky})C_c$
B 03 Dagenet 1985	$T_{sky} = (\frac{L}{\sigma})^{0.25}$ $L = L_0(1 + 0.01A) + \frac{BC(8-N)}{8}$ $L_0 = 3.6(T_a - 273) + 231$ $A = 10.1\ln(P_v) - 12.3$ $B = 1.7(T_a - 273) + 107$ $C = -0.22\ln(P_v) + 1.25$	—
B 04 Prata 1996	—	$\epsilon_{sky} = c\epsilon_a + (1 - c)\epsilon_a$
B 05 Sridhar 2002	—	$\epsilon_{sky} = 1.31(10 \frac{\epsilon_d}{T_a})^{1/7}$

T_a : Air Temperature; P_v, ϵ_d : Vapour Pressure; C_c, c, N : Cloud Cover; ϵ_{clouds} : Emissivity of the clouds

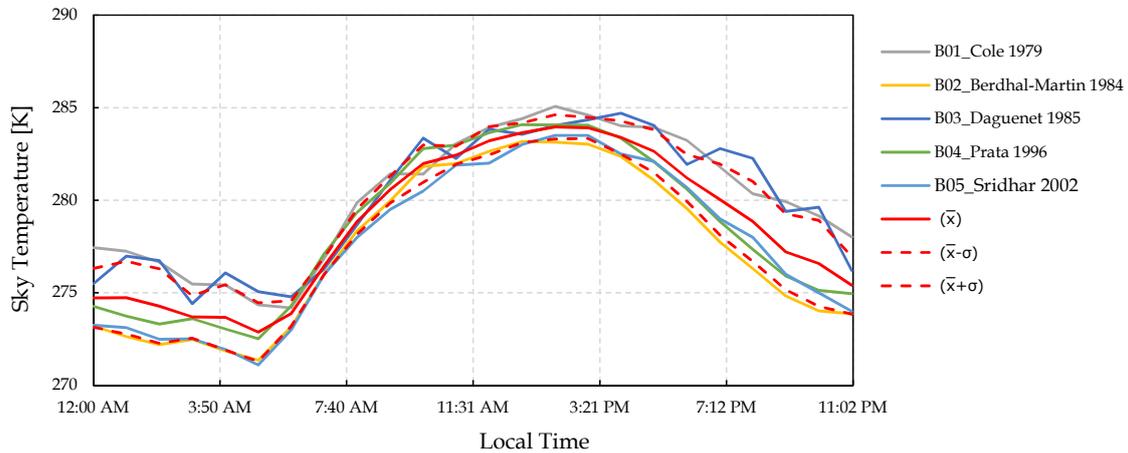


Figure 4. Sky Temperature - All Sky Models comparison at September 18th.

4.3 Results and selection for T_{sky} models analysis

In this section will be presented the results for the comparison of each parametric model for annual hourly synoptic data available in the TMY weather file described above in **Section 3 Methodology**. The data is shown mainly as table format where the models for "Clear sky" condition, they are labelled according to the year of publication and begin with the capital letter A, and for "All sky" models the labelling also it is according the year of publication and begin with the capital letter B. The statistical performance parameters MBD and RMSD for each case, are the main columns presents in the respective table.

Table 3, shows the results for the statistical analysis about the comparison of the empirical models for Clear-Sky atmospheric condition. In this table The A 06 Berdhal-Martin II 1984 model stands out in blue, is the one that presents the best performance in relation to all the available models, because the value of MBD present just a deviation of -0.14 [K] and it is the minimum in comparison with the others, the value for RMSD also present a minimum with the value 0.33 [K]. The percentage MDB of -0.05 and percentage RMSD of 0.12 are correspondent and follow the same general behaviour of the indicated model. The Model A 05 Berdhal-Martin I 1984 is the second in performance and can be affirmed that the "Berdhal-Martin II" modeling is a very good option even today to estimate the effective sky temperature or atmospheric radiation in cloudless sky conditions.

Table 3. Clear-Sky Models: T_{sky} Mean Bias Difference, Root Mean Square Difference.

Model Clear-Sky	n [-]	MBD [K]	MBD [%]	RMSD [K]	RMSD [%]
A 01 Swinbank 1963	8760	-0.72	-0.26	1.45	0.53
A 02 Buchberg-Roulet 1968	8760	-8.74	-3.19	8.76	3.20
A 03 Brutsaert 1975	8760	1.13	0.41	1.18	0.43
A 04 Centeno 1982	8760	5.70	2.08	5.70	2.08
A 05 Berdhal-Martin I 1984	8760	-0.16	-0.06	0.76	0.28
A 06 Berdhal-Martin II 1984	8760	-0.14	-0.05	0.33	0.12
A 07 Berger 1984	8760	1.92	0.70	1.94	0.70
A 08 Aubinet 1994	8760	0.59	0.21	1.55	0.56
A 09 Prata 1996	8760	1.01	0.37	1.08	0.39
A 10 Izimon 2003	8760	-0.59	-0.21	0.70	0.25

In the same way as before, Table 4 shows the results for the statistical analysis about the comparison of the empirical models for All-Sky atmospheric condition. Here the B 04 Prata 1996 model stands out in blue, is the one that presents the best performance in relation to all the available models. The values for MBD (-0.26 [K]) and RMSD (0.74 [K]) keeps at the minimum.

Table 4. All-Sky Models: T_{sky} Mean Bias Difference, Root Mean Square Difference.

Model All-Sky	n [-]	MBD [K]	MBD [%]	RMSD [K]	RMSD [%]
B 01 Cole 1979	8760	1.40	0.50	1.65	0.59
B 02 Berdhal-Martin 1984	8760	-1.31	-0.47	1.50	0.53
B 03 Daguene 1985	8760	1.23	0.44	1.63	0.58
B 04 Prata 1996	8760	-0.26	-0.9	0.74	0.26
B 05 Sridhar 2002	8760	-1.06	-0.38	1.15	0.41

Finally based on the results obtained and presented in Tables 3 and 4. The **A 06 Berdhal-Martin II 1984** model could be selected for Clear-sky condition, but as the aim of the present work is propose a more complete formulation the **B 04 Prata 1996** model for the All-sky condition is selected because it allows a wider range with the possibility of modeling the sky condition with presence of cloudiness.

5. RESULTS AND DISCUSSION

5.1 Atmospheric Radiation Results

In this section, it will be presented a comparison for estimation of Atmospheric Radiation for state-of-the-art programs in Buildings Simulation as EnergyPlus, TRNSys, and WUFI, with the values for hourly atmospheric radiation obtained

from the "Current Model" based in Kasten formulation (Kasten and Czeplak, 1980) and the "Proposed Model" based in Prata (Prata, 1996) modeling for downwelling atmospheric radiation in DOMUS. Fig. 5 shows the annual hour modeling of Atmospheric Radiation for all the available models, as can be observed it is difficult to analyse the global behaviour graphically, even decreasing the interval plotted to a month as shown Fig. 6, the difficulty of a revision is maintained only based on the observation of the curves. Fig. 7 present clearly the behaviour of the models about the atmospheric radiation for three correlatives days (17th to 19th) of September. As was done above in **Section 4 Results and selection for T_{sky} models analysis**, the statistical results for Atmospheric Radiation (A_R) using the root-mean-square deviation (RMSD) and mean bias deviation (MBD) in W/m^2 are presented in Table 5. In the table is possible to observe that the model labelled as "Proposal Domus" presents a value of 1.27 [W/m^2] as MBD that is less than 1% of percentage of bias respect to the defined average (0.91 [%]). This value represent a great improvement when is compared with the value of $MBD = -17.11 [W/m^2]$ that represent a 8.36 [%] of bias percentage for the Current Atmospheric Model in Domus.

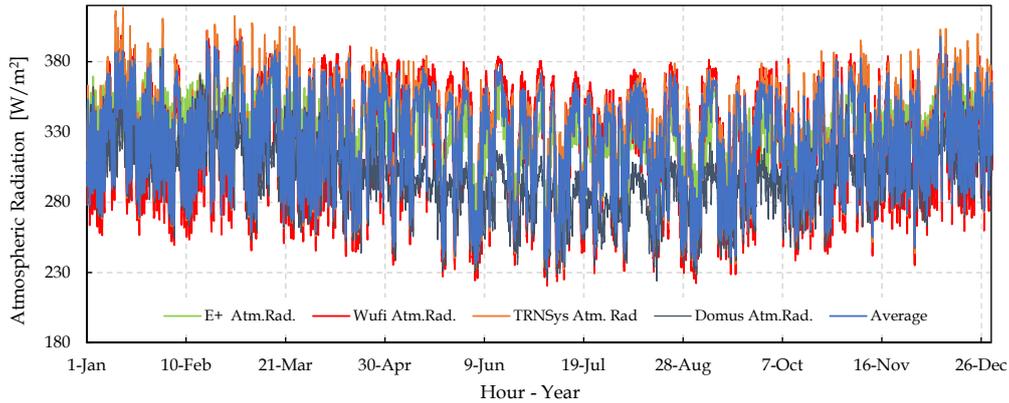


Figure 5. Atmospheric Radiation - Annual models comparison.

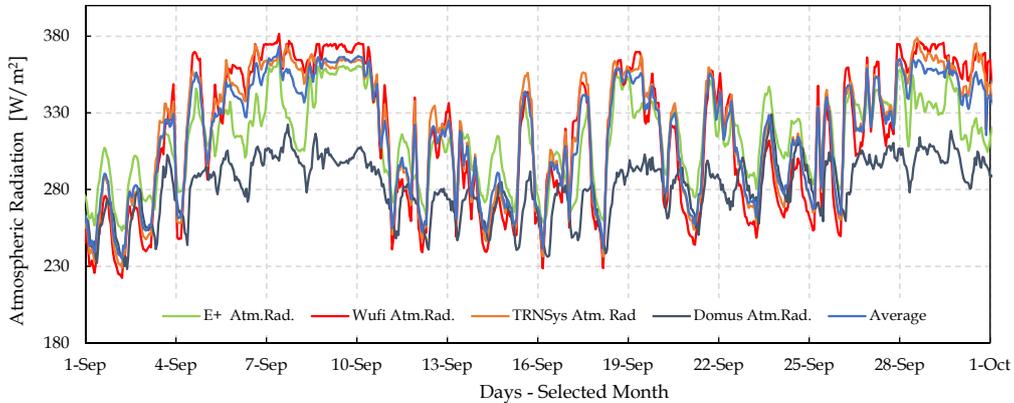


Figure 6. Atmospheric Radiation - September month models comparison.

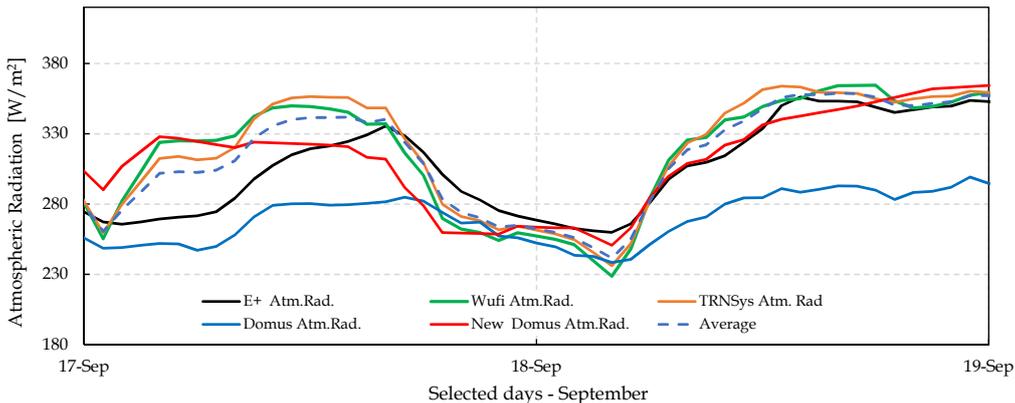


Figure 7. Atmospheric Radiation - Selected September Days.

Table 5. Atmospheric Radiation: Mean Bias Difference and Root Mean Square Difference.

B.Sim. Program	n [-]	MBD [W/m ²]	MBD [%]	RMSD [W/m ²]	RMSD [%]
Current DOMUS	8760	-17.11	-8.36	696	191.61
Wufi	8760	-2.98	-0.92	149	46.22
E+	8760	-0.22	-0.06	207	64.13
TRNSys	8760	3.21	0.99	40	12.63
Proposed DOMUS	8760	1.27	0.91	33	8.91

6. CONCLUSIONS

The difference among all authors of the available models to estimate the atmospheric radiation using synoptic data is interesting, because for zones where is not available measured information just the use of this formulations help to obtain an estimate of heat exchange between buildings and the atmosphere. Is important to notice that the major of this formulation are strongly dependent of the geographical location, and some authors clearly indicates that some models are only valid for the region where the parameterization was done. Due that is not easy to define a universal formulation but is possible to find formulations that fit better in reference at the local condition. A geographical analysis could be a good future work and the effect of clouds and stratification on atmospheric emissivity is also highly dependent on regional factors, which may lead to the need for development of local expressions. A conclusion can be notice as the importance of the correct estimation of atmospheric radiation because in building simulation is very common the use of a software for estimating energy consume and thermal comfort at any geographical location in world and the formulation for atmospheric radiation it is not explicitly demonstrated or sometimes probably ignored. As it was previously described, it is very difficult to define a universal modeling, for this reason it is still necessary to investigate the behavior of this type of parameterization based on experimental data. Today instrumentation for determining atmospheric radiation such as pyrgeometers is much easier to access, so obtaining correlations for different geographical locations, climatic zones and altitudes should be more recurrent.

In reference to the work presented in this paper, the results show a clear improvement due to the implementation of a new modeling for the evaluation of atmospheric radiation, based on three climatic parameters such as air temperature, vapour pressure and the cloudiness index. The cloudiness index or cloud information is not a typical data in climate files such as TRY or IWEC. For climatic archives that contain cloudiness information such as the TMY format, cloudiness is presented in oktas whereas in the EPW format the cloudiness is reported in tens. Due to this it can be observed that an imprecise treatment of this parameter implies a strong dependence in the evaluation of long-wave atmospheric radiation. As a main conclusion, a new modeling was presented to estimation of atmospheric radiation, the following step is the implementation in Domus for energetic simulation in buildings.

This work is part of the continuous improving in Domus's algorithms for more accurate assessment of buildings energy performance and hygro-thermal comfort. Keeping in mind a future evaluation of exterior radiative balance between the atmosphere, nearest buildings, and the neighbourhood around.

7. ACKNOWLEDGMENTS

All the authors acknowledge the Brazilian agencies CAPES, of the Ministry of Education, and CNPq (Grant 459149/20-14-8), of the Ministry of Science, Technology, and Innovation, for the financial support given to the Thermal Systems Laboratory at PUCPR. The author S. Riquelme also acknowledge the Universidad del Bío-Bío by the support in doctoral studies.

8. REFERENCES

- Atwater, M.A. and Ball, J.T., 1978. "Computation of ir sky temperature and comparison with surface temperature". *Solar Energy*, Vol. 21, No. 3, pp. 211–216. ISSN 0038-092X. doi:[https://doi.org/10.1016/0038-092X\(78\)90023-3](https://doi.org/10.1016/0038-092X(78)90023-3).
- Berdahl, P. and Martin, M., 1984. "Emissivity of clear skies". *Solar Energy*, Vol. 32, No. 5, pp. 663–664. doi:[https://doi.org/10.1016/0038-092X\(84\)90144-0](https://doi.org/10.1016/0038-092X(84)90144-0).
- Berger, X., D.Buriot and F.Garnier, 1984. "About the equivalent radiative temperature for clear skies". *Solar Energy*, Vol. 32, No. 6, pp. 725–733. doi:[https://doi.org/10.1016/0038-092X\(84\)90247-0](https://doi.org/10.1016/0038-092X(84)90247-0).
- Brutsaert, W., 1975. "On a derivable formula for longwave radiation from clear skies". *Water Resource Research*, Vol. 11, No. 5, pp. 742–744. doi:<https://doi.org/10.1029/WR011i005p00742>.
- Byrnes, S.J., Blanchard, R. and Capasso, F., 2014. "Harvesting renewable energy from earth's mid-infrared emissions". *Proceedings of the National Academy of Sciences*, Vol. 111, No. 11, pp. 3927–3932. ISSN 0027-8424. doi:<https://doi.org/10.1073/pnas.1402036111>.

- Centeno, M., 1982. “New formulae for the equivalent night sky emissivity”. *Solar Energy*, Vol. 28, No. 6, pp. 489–498. doi:[https://doi.org/10.1016/0038-092X\(82\)90320-6](https://doi.org/10.1016/0038-092X(82)90320-6).
- Cole, R., 1979. “The longwave radiation incident upon inclined surfaces”. *Solar Energy*, Vol. 22, No. 5, pp. 459–462. ISSN 0038-092X. doi:[https://doi.org/10.1016/0038-092X\(79\)90177-4](https://doi.org/10.1016/0038-092X(79)90177-4).
- Crawley, D.B., Pedersen, C.O., Lawrie, L.K. and Winkelmann, F.C., 2000. “Energyplus: Energy simulation program”. *ASHRAE Journal*, Vol. 42, pp. 49–56.
- D.O.E., 2018. “U.S. Department of Energy”. 23 Mar. 2018 <https://www.energy.gov/>.
- H.Buchberg and J.R.Roulet, 1968. “Simulation and optimization of solar collection and storage for house heating”. *Solar Energy*, Vol. 12, No. 1, pp. 31–50. doi:[https://doi.org/10.1016/0038-092X\(68\)90023-6](https://doi.org/10.1016/0038-092X(68)90023-6).
- Iziomon, M., Mayer, H. and Matzarakis, A., 2003. “Downward atmospheric longwave irradiance under clear and cloudy skies: Measurement and parameterization”. *Journal of Atmospheric and Solar Terrestrial Physics*, Vol. 122, No. 533, pp. 1107–1116. doi:<https://doi.org/10.1016/j.jastp.2003.07.007>.
- Kasten, F. and Czeplak, G., 1980. “Solar and terrestrial radiation dependent on the amount and type of cloud”. *Solar Energy*, Vol. 24, No. 2, pp. 177 – 189. ISSN 0038-092X. doi:[https://doi.org/10.1016/0038-092X\(80\)90391-6](https://doi.org/10.1016/0038-092X(80)90391-6).
- Klein, S., 1975. *TRNSYS, a Transient Simulation Program*. University of Wisconsin-Madison. Solar Energy Laboratory. The Laboratory.
- Kunzel, H., 1995. *Simultaneous Heat and Moisture Transport in Building Components: One- and Two-dimensional Calculation Using Simple Parameters*. IRB-Verlag. ISBN 9783816741039.
- Lauster, M., Remmen, P., Fuchs, M., Teichmann, J., Streblov, R. and Muller, D., 2014. “Modelling long-wave radiation heat exchange for thermal network building simulations at urban scale using modelica”. In *Proceedings of the 10th International Modelica Conference; March 10-12; 2014; Lund; Sweden*. Linköping University Electronic Press; Linköpings universitet, 96, pp. 125–133. ISSN 1650-3740.
- Martin, M., 1995. *Comportamiento termico de cerramientos soleados : un modelo de simulacion por diferencias finitas*. Ph.D. thesis, Escuela Tecnica Superior de Arquitectura, Madrid.
- Mendes, N., R.Oliveira and Santos, G., 2003. “Domus 2.0: a whole-building hygrothermal simulation program”. In *Eighth International IBPSA Conference*. Eindhoven, Netherlands.
- Mendes, N., Barbosa, R.M., Freire, R.Z. and Oliveira, R.C.L.F., 2008. “A simulation environment for performance analysis of hvac systems”. *Building Simulation*, Vol. 1, No. 2, pp. 129–143. ISSN 1996-8744. doi:<https://doi.org/10.1007/s12273-008-8216-7>.
- Morgan, D.L., Pruitt, W.O. and Lourence, F.J., 1971. “Estimation of atmospheric radiation”. *Journal of Applied Meteorology*, Vol. 10, No. 3, pp. 463–468. doi:[https://doi.org/10.1175/1520-0450\(1971\)010](https://doi.org/10.1175/1520-0450(1971)010).
- PBE-Edifica, 2018. “Programa Brasileiro de Etiquetagem de Edificações – PBE Edifica”. 04 Apr. 2018 <http://www.pbeedifica.com.br/>.
- Prata, A.J., 1996. “A new long-wave formula for estimating downward clear-sky radiation at the surface”. *Quarterly Journal of the Royal Meteorological Society*, Vol. 122, No. 533, pp. 1127–1151. doi:<https://doi.org/10.1002/qj.49712253306>.
- Sridhar, V. and Elliott, R., 2002. “On the development of a simple downwelling longwave radiation scheme”. *Journal of Atmospheric and Solar Terrestrial Physics*, Vol. 112, No. 1, pp. 237–243. doi:[https://doi.org/10.1016/S0168-1923\(02\)00129-6](https://doi.org/10.1016/S0168-1923(02)00129-6).
- Swinbank, W., 1963. “Longwave radiation from clear skies”. *Quarterly Journal of the Royal Meteorological Society*, Vol. 89, No. 1, pp. 339–348. doi:<https://doi.org/10.1002/qj.49708938105>.
- U.S.GBC, 2018. “U.S. Green Building Council”. 17 May. 2018 <https://new.usgbc.org/leed>.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.