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IMPACT OF THE SPECTRAL COUPLING BETWEEN NON-GRAY SKY BOUNDARY CONDITIONS AND A URBAN ATMOSPHERE IN THE CALCULATION OF NET FLUXES IN A STREET CANYON

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ABSTRACT. Most radiative transfer models developed for the analysis of urban configurations consider a transparent urban atmosphere and gray sky conditions. The present work aims at studying these assumptions. For this purpose, reference line-by-line-Monte Carlo calculations are first performed. A more efficient radiative transfer model based on the finite volume method is also developed to treat several street canyon configurations. The aspect ratio of the street canyon, which is a parameter frequently encountered in urban scenarios, is considered for the analysis. It is shown that, in most cases, real urban problems should account for a non-gray participating atmosphere within the streets together with its spectral coupling with the non-gray sky downward radiation, to provide accurate net fluxes on urban surfaces.

1. INTRODUCTION

Solar radiation (shortwave spectral range) and infrared radiation (longwave spectral range) play a significant role in the overall energy balance in urban environments. More specifically, longwave radiation is partly responsible of the cooling of urban surfaces during nighttime and can even become the main factor affecting their heat balance under low wind conditions. During periods of heat stress, an accurate estimate of longwave radiation is of primary importance to suggest relevant heat attenuation strategies for urban areas. The impact of the urban morphology, the fraction of vegetation or the longwave radiative properties of the building materials on the radiative budget of the urban canopy and their role in favorizing urban overheating have been widely studied (see Ref. [1] for an extended review). However, the impact of the interactions between longwave radiation and the participating urban atmosphere have almost never been studied thoroughly. To the best of the authors' knowledge, to date, the radiative models which have been developed for studying heat transfer in urban areas almost systematically consider the urban atmosphere as transparent. Nevertheless, some works have yet emphasized the need to better characterize the effects of radiative longwave absorption in urban contexts since they can be significant [2,3]. For example, longwave simulations in an urban canopy with a mean wall-to-wall distance of 50 m under Mid-Latitude Summer conditions were performed using a discrete-ordinate method coupled with a statistical description of the urban geometry capable of explicitly representing gaseous absorption and emission of the atmosphere within the canopy [3]. When the walls and ground facets are 10 °C hotter than the air, results showed that for a mean building height going from 10 to 50 m, taking the absorption by the urban atmosphere into account results in a decrease in the mean absorbed flux by the vertical walls that ranges from 5.7 to 44.0 W per unit area of the ground facet compared to the case where the urban atmosphere is assumed transparent.

The aim of the present paper is thus to carefully investigate the errors on the thermal fluxes which can be made when considering a transparent atmosphere within the urban canopy. This is achieved by analyzing the influence of the high spectral resolution coupling between the non-gray longwave radiation coming from the sky and the non-gray absorption by the atmosphere. For this purpose, radiative simulations are carried out with a high spatial resolution. Moreover, a simple convection model is used on the canyon surfaces in order to evaluate the impact of these errors on the global heat exchanges between these surfaces and their surrounding environment, impacting their heating or cooling rate.

The paper is structured as follows. In Section 2, a Monte Carlo code is used to achieve high-resolution line-by-line calculations and evaluate the net longwave fluxes in a given street canyon configuration considering a gray or non-gray sky model and a transparent or participating urban atmosphere. Then, in Section 3, an approximate method is proposed to treat similar configurations in a more computationally efficient way. Finally, in Section 4, the numerical method described in Section 3 is applied for a quantitative analysis of the errors associated with the transparent assumption, for various geometries of the buildings, specified here as the H/W ratio between the height H of the buildings and the width W of the canyon.

2. OVERALL IMPACT OF ATMOSPHERIC ABSORPTION/EMISSION ON LONGWAVE RADIATION IN A STREET CANYON

Longwave radiative simulations are carried out in a standard two-dimensional street canyon configuration, as depicted in Figure 1. This street (infinite in the y direction) has a height H of 21 m and a width W of 14 m (*i.e.* an aspect ratio H/W of 1.5). Both the walls and the ground are assumed to be gray with an emissivity of 0.9. The temperatures of wall 1, wall 2, ground and atmosphere within the urban canopy are 25 °C, 35 °C, 25 °C and 20 °C respectively.

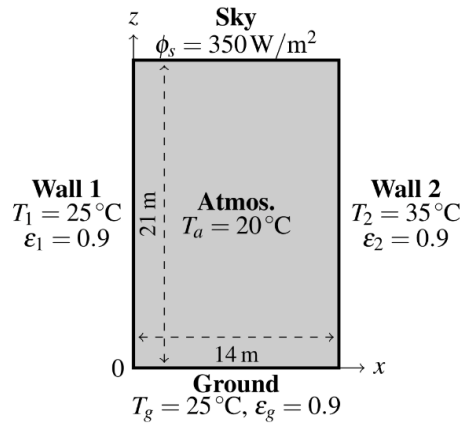


Figure 1. Configuration and size of the street canyon, infinitely long in the y direction. The gray emissivities ε and temperatures T of each wall are specified, along with the temperature of the urban atmosphere and the value of the downward longwave flux.

Two sky boundary condition models are considered. The first one, from now on referred to as “gray sky”, treats the sky as a gray and isotropic surface as usually assumed in radiative transfer models in urban configurations. Its flux density is fixed to $\Phi_s = 350 \text{ W/m}^2$. For the second sky model, from now on referred to as “spectral sky”, a line-by-line (LBL) spectrum has been generated using the HITRAN2020 molecular spectroscopic database [4] to model the downward longwave intensity coming from the sky along the vertical direction, assuming a standard Mid-Latitude Summer (MLS)

atmosphere. The MLS profiles give the temperature, pressure and molar fractions of water vapor, CO₂, O₃, N₂O, CO, CH₄ and O₂ at different altitudes. A sensitivity analysis has shown that - as a first approximation - it is reasonable to consider the sky downward intensity as isotropic (significant errors only appear for directions quasi-parallel to the ground). Scattering phenomena and aerosols have been neglected in the LBL calculations. However, a continuum of 76 W/m² corresponding to a gray emission at a temperature of 20 °C was added to the LBL spectrum, firstly to account for scattering phenomena in an approximate way, and secondly to keep an integrated flux density of 350 W/m², equivalent to the gray sky model. The resulting sky downward intensity spectrum is depicted in Figure 2.a.

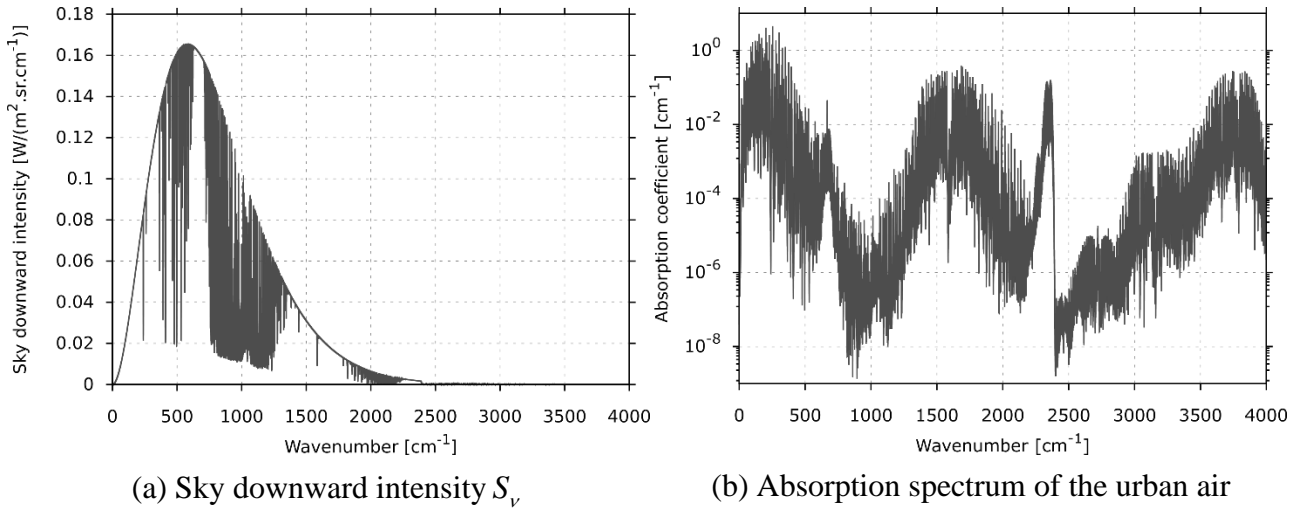


Figure 2. LBL spectra at the surface level generated with the MLS atmospheric profiles.

Similarly, a LBL absorption spectrum was generated to define the participating urban atmosphere at 20 °C located inside the street canyon, called from now on “urban air”. This spectrum is depicted in Figure 2.b. The pressure and species molar fractions of the MLS profile at the ground level were used for the calculation, except for the water vapor molar fraction which was fixed according to a target relative humidity of 60 %. Aerosols and scattering phenomena inside the street canyon are also neglected. Clearly, from Figure 2.b, the urban air is not rigorously transparent.

The radiative transfer equation is solved in the street canyon using a standard backward Monte-Carlo (MC) algorithm. For the spectral integration, wavenumbers are randomly sampled according to the Planck’s distribution at the maximum temperature encountered in our problem, viz. 35 °C. At each location where the net flux (absorbed minus emitted) on surfaces or the divergence of radiative flux (absorbed minus emitted) in the urban air is evaluated, a MC simulation using 10⁸ realizations has been performed. In this section, three different cases, corresponding to different treatments of the spectral attributes of the urban air and the sky downward intensities, are considered: 1/ a transparent urban air combined with the gray sky model, 2/ a non-gray participating urban air combined with the gray sky model, and 3/ a non-gray participating urban air combined with the spectral sky model. Notice that for the first case, using either the gray sky or the spectral sky model with a transparent urban air is strictly equivalent since the integrated sky fluxes are identical and the walls and the ground are gray.

The net fluxes obtained with the LBL-MC solver for each case at several locations on wall 1 and on the ground are depicted in Figure 3. Notice that as each calculation accounts for 10⁸ independent MC samples, standard deviations are negligible and are thus not depicted on the figure. These results show that the combined influence of a spectrally described sky boundary condition together with a

non-gray participating urban air inside the street canyon (case referred to as “Spectral sky – Participating urban air”) leads to significant differences on the net fluxes compared to the transparent case. These differences - averaged over each boundary - are respectively of 15.08 W/m² for wall 1, 8.83 W/m² for wall 2, 13.39 W/m² for the ground and 11.43 W/m² at the top of the street. The impact of such deviations on the thermal balance of these surfaces are not negligible, as will be shown in Section 4.

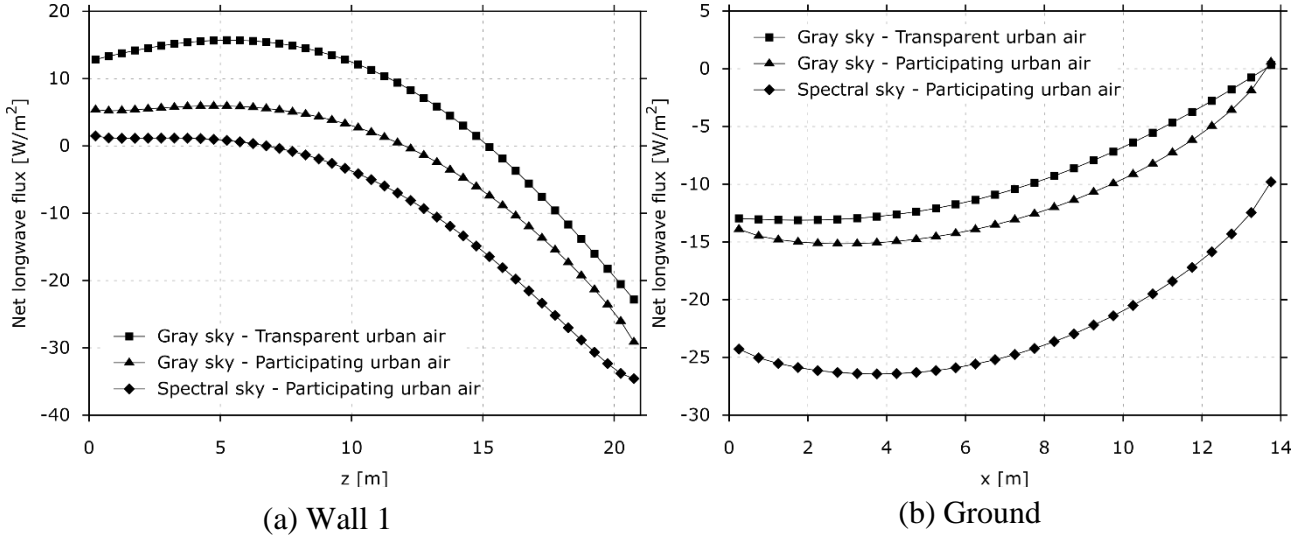


Figure 3. Net longwave fluxes (absorbed – emitted) on the street canyon walls for the three selected spectral treatment cases. The x -axis represents the vertical location for the wall 1 and the horizontal location for the ground, as defined on Figure 1.

In particular, the net fluxes on the ground (that exchanges more with the sky than the vertical walls) show that, even if a non-gray participating medium is considered, the main discrepancies are due to spectral relationships between the high spectral resolution sky downward radiation and the absorption by the urban air. Indeed, if a gray sky is considered with a non-gray participating urban air, the ground fluxes are close to those observed with a transparent urban air, meaning that the urban air is optically thin in this case. This is mainly due to transparency regions of the urban air absorption spectrum that coincide with spectral regions where the sky downward intensity is negligible, *i.e.* in the range 750 – 1250 cm⁻¹ approximately as depicted on Figure 2. On the vertical walls, the choice of the gray sky model has a weaker influence on the net fluxes but it still leads to an underestimation of the impact of the absorbing urban air.

Finally, considering a participating urban air with a spectral sky leads to an average divergence of the radiative flux in the urban air of 2.7 W/m³, with up to 15.0 W/m³ close to the hottest wall and the top surface. These heat sources within the urban air may have significant effects on air convection and temperature. It could therefore be interesting to incorporate this phenomenon in simulations of airflow in street canyons and evaluate its effects.

3. DESCRIPTION OF A FASTER APPROXIMATE RADIATIVE TRANSFER MODEL

The LBL-MC method described in the previous section cannot be recommended for coupled simulations of airflow and longwave absorption by the urban air (by way of the longwave volumetric power impacting the strength of buoyancy forces) due to its high CPU cost. The aim of the present section is thus to develop a faster though accurate model for handling this type of simulations.

As shown in Section 2, the main difficulty to treat radiative transfer in the urban canopy consists of the proper treatment of the relationships, that occur at high spectral resolution, between the non-gray sky downward radiation and the urban air located inside the street canyon. In order to formulate a global absorption method allowing this kind of treatment, let us consider a radiation path that comes from the sky (the corresponding source term is written S_ν . Its integral over the full spectrum is

$S = \int_0^{+\infty} S_\nu d\nu$ - from this definition, we have $\phi_s = \int_{2\pi} S \cos \theta d\Omega$) and travels a distance L inside the urban air where the corresponding absorption coefficient is κ_ν . The amount of radiation absorbed by the urban air can be written in terms of an effective absorptivity α_{eff} defined as:

$$\alpha_{eff} = \frac{1}{S} \cdot \int_0^{+\infty} (1 - e^{-\kappa_\nu L}) S_\nu d\nu \quad (1)$$

Eq. (1) was approximated in the present work by:

1/ firstly, generating a discrete set (gray gases) of values of absorption coefficients in the urban air using the Absorption Line Blackbody Distribution Function (ALBDF) defined at the gas temperature inside the canopy, T_a , together with a Gauss-Legendre quadrature. The corresponding values of urban air absorption coefficients are then k_i^{air} , $i=1, \dots, N$ where N is the order of the Gauss-Legendre quadrature. Supplemental values of absorption coefficients, \tilde{k}_i^{air} , $i=0, \dots, N$, are also generated in the same way as in spectral line weighted-sum-of-gray-gases (SLW) models [5,6].

2/ secondly, using the previous sets of absorption coefficients to approximate Eq. (1) as:

$$\alpha_{eff} = \sum_{i=1}^N (1 - e^{-k_i^{air} L}) \cdot [F(\tilde{k}_i^{air}) - F(\tilde{k}_{i-1}^{air})] \quad (2)$$

where:

$$F(k) = \frac{1}{S} \int_0^{+\infty} H(k - \kappa_\nu) S_\nu d\nu \quad (3)$$

F thus represents the fraction of the source term S_ν averaged over the set of wavenumbers where the absorption coefficient of the urban air takes a value lower than k . F plays the same role as a usual ALBDF, but is defined in terms of the source term S_ν instead of the more usual Planck's distribution $I_{b,\nu}$ at a given temperature. As S_ν is strictly positive, as shown in Figure 2, one can verify easily that Eq. (3) defines a proper distribution function of absorption coefficients [7]. The difference $F(\tilde{k}_i^{air}) - F(\tilde{k}_{i-1}^{air})$ that appears in Eq. (2) thus represents the fraction of the source term S_ν averaged over the set of wavenumbers where the absorption coefficient of the urban air is close to k_i^{air} . $F(\tilde{k}_i^{air}) - F(\tilde{k}_{i-1}^{air})$ allows defining the weights needed to specify the sky boundary conditions. The weights at the walls are defined in terms of the differences $F(\tilde{k}_i^{air}, T_{w=1,2}) - F(\tilde{k}_{i-1}^{air}, T_{w=1,2})$ where

$$F(k, T_{w=1,2}) = \frac{1}{I_b(T_{w=1,2})} \int_0^{+\infty} H(k - \kappa_\nu) I_{b,\nu}(T_{w=1,2}) d\nu \quad (4)$$

are usual ALBDFs at the wall temperatures. This formalism, that also applies to the ground, complies with the method used in SLW modeling [5]. Consequently, this radiative absorption model is from now on referred to as “SLW model”, even if it is formulated in k -form.

A finite volume method (FVM)-based radiative solver [8,9], much faster than the MC method described in Section 2, was developed and associated to the SLW model to perform the radiative transfer calculations. A preliminary sensitivity analysis has been carried out to select suitable spatial and angular meshes for the FVM. Excellent agreement with the MC results has been obtained for a 0.25 m spatial mesh combined with 2112 control angles, based on comparisons of the net wall fluxes and the divergence of the radiative flux in the urban air. This mesh has thus been selected for all the subsequent simulations. Moreover, a sensitivity analysis has shown that using a total of 10 gray gases, including a clear gas, is sufficient for the SLW model to obtain net wall fluxes and divergence of the radiative flux within the urban air closely matching the LBL results. Notice that focusing on the net fluxes on the surfaces only, even a smaller number of gray gases can be used to reach a similar accuracy. Results of the described SLW-FVM solver with 10 gray gases are depicted in Figure 4.

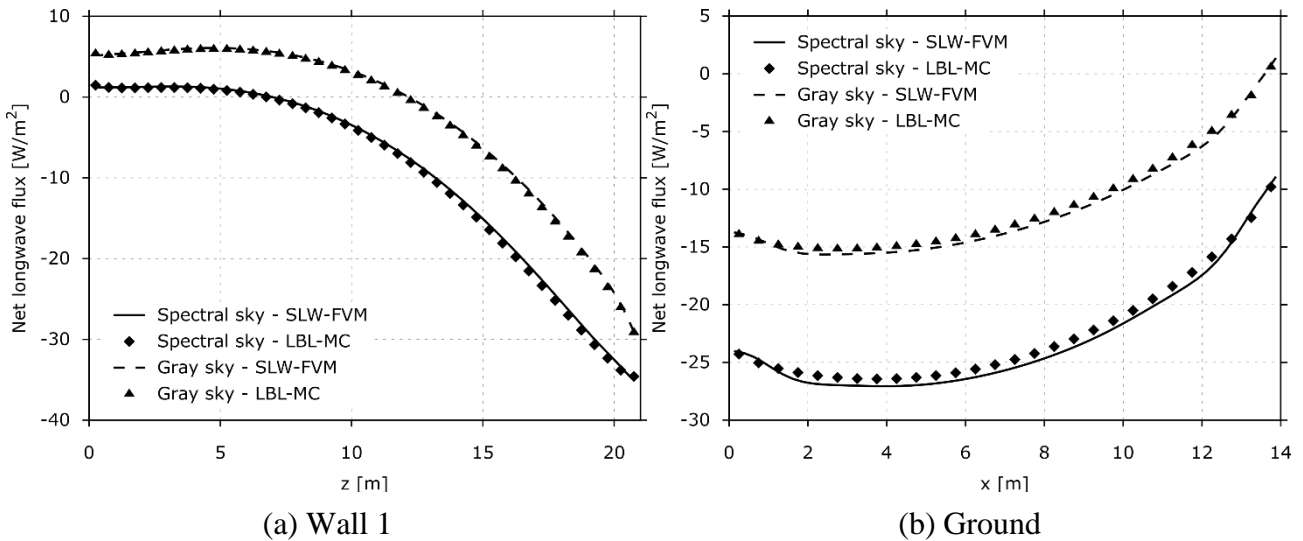


Figure 4. Comparison of the net longwave fluxes (absorbed – emitted) on the street canyon walls calculated by the LBL-MC and SLW-FVM methods for a participating urban air and gray or spectral sky conditions. The x -axis represents the vertical location for the wall 1 and the horizontal location for the ground, as defined on Figure 1

According to Figure 4, the SLW-FVM method with the proposed selection of number of control angles and mesh size is able to simulate accurately the longwave net fluxes on the canyon surfaces along with the divergence of the radiative flux in the urban air (not shown on the figure), whatever the situation treated (gray or spectral sky with non-gray absorbing urban air). Therefore, the sky boundary condition constructed with the help of the ALBDF of Eq. (3) allows representing correctly the spectral coupling between the sky downward radiation and the urban air.

4. ERRORS ON HEAT FLUXES IN A STREET CANYON ASSOCIATED TO THE ASSUMPTION OF A TRANSPARENT URBAN AIR

Using the SLW-FVM model described in Section 3, a range of canyon geometries was studied with the aim of evaluating the errors made on the surface heat fluxes in the street canyon when assuming a transparent urban air.

The parameter linked to the canyon geometry studied is the aspect ratio (H/W) of the canyon. The height H of the building is kept constant while the width W of the street canyon is adjusted to reach a user specified H/W ratio. In this section, differences in longwave fluxes are evaluated by comparing the results obtained in the transparent case to those obtained in the absorbing case. Table 1 summarizes these differences, obtained for H/W ratios of 0.75, 1.5 and 2.4.

Table 1: Differences in the mean net heat fluxes as a function of the H/W ratio.

Surface	H/W	Mean net longwave flux Diff. (W/m^2)	Mean net total flux (longwave + convective)			
			$h_c = 5 W/(m^2.K)$		$h_c = 20 W/(m^2.K)$	
			Value for the absorbing case (W/m^2)	Rel. diff.	Value for the absorbing case (W/m^2)	Rel. diff.
Ground	0.75	+ 15.7	-73.3	21.4 %	-148.3	10.6 %
	1.5	+ 13.4	-48.0	27.9 %	-123.0	10.9 %
	2.4	+ 11.9	-34.6	34.5 %	-109.6	10.9 %
Wall 1	0.75	+ 15.3	-54.6	28.1 %	-129.6	11.8 %
	1.5	+ 15.0	-34.2	44.0 %	-109.2	13.8 %
	2.4	+ 14.3	-21.2	67.5 %	-96.2	14.9 %
Wall 2	0.75	+ 10.5	-173.1	6.1 %	-398.1	2.6 %
	1.5	+ 8.8	-160.9	5.5 %	-385.9	2.3 %
	2.4	+ 7.7	-153.2	5.0 %	-378.2	2.0 %

It appears that when H/W increases, the differences on the mean net longwave fluxes decrease. The flux absorbed on the surfaces is 10.5 to 15.7 W/m^2 higher for $H/W = 0.75$ when the urban air is considered transparent, against 7.7 to 14.3 W/m^2 higher for $H/W = 2.4$. This is due to smaller optical paths in the urban air when the distance between the walls decreases, resulting in a smaller attenuation of longwave radiation by gaseous absorption. Differences are the highest on the coldest faces, *i.e.* the ground and wall 1. These discrepancies may appear small if no information on the other heat exchange phenomena taking place in the street canyon and their order of magnitude is provided. Consequently, in order to have a better picture of the impact that these differences have on the global heat balance of the surfaces, and thus on their cooling potential, a simple though realistic convection model was used. The convective heat flux is modeled as $h_c (T_a - T_s)$ where T_s is the surface temperature and h_c a global value of the convective heat transfer coefficient (CHTC). The mean net total flux on each surface is computed by summing the contributions of the mean net longwave flux and the convective heat flux. Table 1 gathers the relative differences associated with the assumption of a transparent urban air, computed by dividing the differences in longwave flux by the absolute value of the total flux in the absorbing case. For a CHTC equal to 5 $W/(m^2.K)$, corresponding to a weak wind configuration and/or natural convection, the relative difference on the net total heat flux increases with the H/W ratio and can be as high as 67.5 % on wall 1 for $H/W = 2.4$. In other words, neglecting the absorption of longwave radiation by the urban air in this case can lead to an underestimation of 67.5 % of the cooling rate of the coldest vertical wall. Indeed, for such a ratio, the net longwave flux magnitude becomes low so that for a weak convective heat transfer, even a small difference in the net longwave flux can significantly affect the heat balance of the wall. For a CHTC of 20 $W/(m^2.K)$, corresponding to a more intense wind flow, relative differences decrease substantially as the convective heat flux becomes dominant. However, they are still significant, of the order of 10.0 – 15.0 %, on the coldest surfaces.

5. CONCLUSION

The objective of the present work was to study the impact of some assumptions widely used in radiative transfer studies in urban configurations (transparent urban air and gray sky boundary conditions) on the calculation of surface net heat fluxes. For this purpose, several street canyon configurations with various aspect ratios were considered. Radiative transfer calculations were performed using either a Monte Carlo code coupled with high resolution line-by-line data or by a faster though accurate radiative transfer model based on a full spectrum description of urban air absorption and the radiative FVM method. Results of the simulations highlighted that accounting for the strong spectral coupling between the incident sky radiation and the urban air absorption is necessary to evaluate the wall net fluxes accurately. It was shown that the longwave mean net flux on the coldest surfaces can be overestimated by more than 15 W/m^2 in the given configuration when a transparent urban air is considered. This corresponds to a substantial underestimation of up to 68 % of the cooling potential of these surfaces, even when heat convection becomes important. As a perspective, further study should be carried out in order to assess the impact of these assumptions in more realistic configurations, while focusing in details and with care on the considered radiative boundary conditions.

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