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Impact of the anisotropy of the sky vault emissivity on the building envelope radiative budget

R. Nahon[1], O. Blanpain[1], and B. Beckers[2]

[1] Université de Lille 1
Cité Scientifique 59655 Villeneuve d'Ascq, France
raphael.nahon@ed.univ-lille1.fr, olivier.blanpain@univ-lille1.fr

[2] Université de Technologie de Compiègne (UTC), Sorbonne Universités
Rue du Dr Schweitzer, 60200 Compiègne, France
benoit.beckers@utc.fr

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Abstract. *Atmospheric radiation is commonly taken into account as isotropic when modelling the thermal behaviour of a building's envelope. In this article, we study the distribution of the sky temperature along the year under different climates. We show the strong variation between the zenith and the horizon, especially under a dry climate, and point out the interest of taking it into account in the estimation of the walls surface temperatures for the characterization of the thermal comfort and the building's energy needs.*

1 Introduction

According to the United Nations, the Earth's population will reach 9.3 billion in 2050. The demographic growth is combined to the urban one; each year, a crop area equivalent to Italy is taken over by cities [Beckers, 2013]. In 1800, only 2% of the world population was living in urban areas, against more than 50% nowadays. According to the United Nations, this portion will reach 75% in 2050, 20% of which living in megalopolis counting more than 4 millions of habitants. In this context, it is today necessary to build cities of high densities ensuring the comfort of its inhabitants.

[Dollfus, 1954] shows that, until the end of the ninetieth century, building typologies were mainly guided by the local climate and the search of thermal comfort. The advent of new construction processes, such as reinforced concrete, air conditioning or elevators, combined to the boom of automobile and the cheap energy led to the *globalisation of architecture* : the same processes are used under different climates and the use of energetic systems insure the comfort of the population. The global energy crises following the oil shocks of 1971 and 1978 led to a first questioning of this way of doing and to the search of an urban layout optimal regarding energy efficiency and thermal comfort.

A building's energy efficiency is mainly characterized by its warming and cooling needs. The analysis of both aspects implies the modelling of the heat transfers between the building and its environment. The *mean radiant temperature*, the mean temperature of a fictitious enclosure, is a key parameter of the thermal comfort [Huang 2014]. Therefore, it seems necessary to use physical models which permit the analysis of surfaces temperatures and heat flows in order to guide the urban planners when defining the urban geometry.

The analysis of the thermal behaviour of buildings' envelopes at the urban scale can be achieved through different methods, mostly through the use of simplified models [Kampf 2007]. The latter ensure the dynamic modelling of the air temperature inside the buildings with low data requirement and calculation costs. The geometry is summarily taken into account; the vertical walls, roof and ceiling of each building are represented as a unique branch and it is not possible to estimate directly the surfaces temperatures.

The atmospheric radiation, the long wave radiation (above 4 μm) from the sky, plays a significant part in the cooling of buildings. [Givoni 2011] shows for instance that the use of a passive radiant roof may maintain the interior temperature below 21°C for an exterior temperature of 34°C. The sky vault is usually considered as isotropic; its *radiance* is constant in every direction. However, [Kruczek 2015] shows through sky thermography the anisotropy of clear skies; he observes *sky temperatures* of 10°C at the horizon and -50°C at the zenith. [Bliss 1961] proposes a simplified model to take into account this phenomenon. On the basis of this work, [Awanou 1998] establishes the expression of the directional emissivity for clear skies.

This article analyses the distribution of temperature on the sky vault at different periods and under different climates in order to initiate a discussion on a thermal model for the modelling of heat flows and surfaces temperatures at the urban scale.

2 The atmospheric radiation

The sun can be assimilated to a blackbody at a temperature of 5780K. It emits energy as electromagnetic waves with short wavelengths (inferior to 4 µm); nearly 50% of which in the visible spectrum (380 to 780 nm), with a maximum at 500 nm (wavelength of the yellow), 50 % in the near infrared (780 to 4000 nm) and 1% in the ultraviolet (inferior to 380 nm). Part of the radiation reaching the atmosphere is absorbed and reflected by the clouds (23% and 23%), and by the Earth (47% and 7%). The absorbed energy is returned essentially in the far infrared (wavelengths superior to 4 µm) [Beckers 2012].

As the sun, the sky vault can be assimilated to a black body at a varying temperature; the term *sky temperature* (T_{sky} [K]) is used. It can as well be assimilated to a grey body at the air temperature T_a [K]; we use the term *sky emissivity* (ε_{sky}), to denote its capacity to absorb and return radiative energy. The sky vault emits energy to the Earth as electromagnetic waves with long wavelength (LW); the *atmospheric radiation* (φ_{sky}) [W/m²] is mainly due to the atmosphere water content, which is a function of the air temperature, relative humidity and altitude.

$$\varphi_{sky} = \sigma\, {T_{sky}}^4 \tag{1}$$

$$\varphi_{sky} = \varepsilon_{sky}\, \sigma\, {T_a}^4 \tag{2}$$

$$T_{sky} = \varepsilon_{sky}^{1/4}\, T_a \tag{3}$$

[Angström 1915] proposes a first model for the estimation of the atmospheric radiation on an horizontal plane as a function of: the air temperature T_a, the water vapour pressure V_p [hPa] and the degree of cloudiness N [oktas].

$$\varphi_{sky} = \left(0.82 - 0.25\, 10^{-0.0945 \times V_p}\right) \left(1 + 0.21 \left(\frac{N}{8}\right)^{2.5}\right) \sigma\, {T_a}^4 \tag{4}$$

Since the presentation of this formula, various models have been proposed for the estimation of atmospheric radiation. Meanwhile, [Tang 2004] indicates that their correlation with observed sky temperatures is poor and that each of them can only be applied under specific weather conditions.

The measurement of sky temperature can be done directly using a pyrgeometer or indirectly using a pyrradiometer. However, [Tang 2004] indicates that these instruments are expensive and need frequent calibrations; meteorological observatories are not always equipped with those instruments. In the next parts of this article, we use the weather data available at https://energyplus.net/weather. Each data is associated to a source and an uncertainty class. For the files used in this article, the source of the infrared radiation on an horizontal plane is unknown (class "?") and associated to an uncertainty range from 35 to 50%. T_a, V_p and N and are associated to classes A to C, corresponding to a measured data, with an uncertainty consistent with the instrument used for its acquisition.

We compare the atmospheric radiation calculated with the Angström formula and the one extracted from the weather database of Paris-Orly observatory (cf. Figure 1). We choose a range of fifteen days with clear and overcast skies, from the 10th to the 25th of January. The parameter V_p is calculated using the expression proposed by [Buck 1981], with R_h [%] the air relative humidity and T_a(expressed here in [°C]) the air temperature :

$$V_p = \frac{R_h}{100}\, 6.1121 \exp\left(\left(18.678 - \frac{T_a}{234.4}\right)\left(\frac{T_a}{257.14+T_a}\right)\right) \tag{5}$$

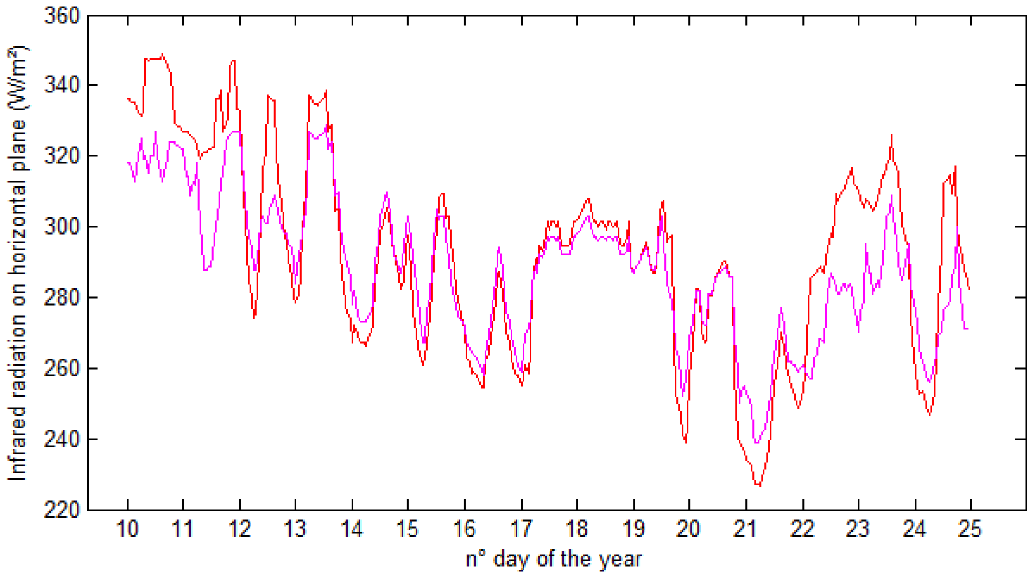


Figure 1: Comparison of modelled (*red*) and measured (*magenta*) infrared radiation

The correlation between these curves tends to indicate that the atmospheric radiation extracted from the weather file is calculated through a similar model. This is why in this article, we choose to use the Angström formula in order to analyse the respective impact of T_a, V_p and N on the atmospheric radiation.

We study the evolution of the sky temperature along the year for the city of Paris. We obtain values from -29 to 25°C for an air temperature from -6 and 30°C. We illustrate in Figure 2 the respective impacts of the air temperature and cloud cover on the sky temperature. We note that ε_{sky} tends to 1 for an overcast sky, and so T_{sky} tends to T_{air}. The observed differences for a cloud cover of 100% come from the water vapour pressure V_p (cf. equation 4). The latter fluctuates between 2.5 and 23.5 hPa for the city of Paris; that is to say a minimal and maximal difference between the air and sky temperatures of 2 and 14°C for an air temperature of 15°C. The sky temperature strongly decreases for clear skies; the minimal and maximal values of ε_{sky} are 67 and 82%, that is to say a minimal and maximal difference between the air and sky temperatures of 14 and 27°C for an air temperature of 15°C.

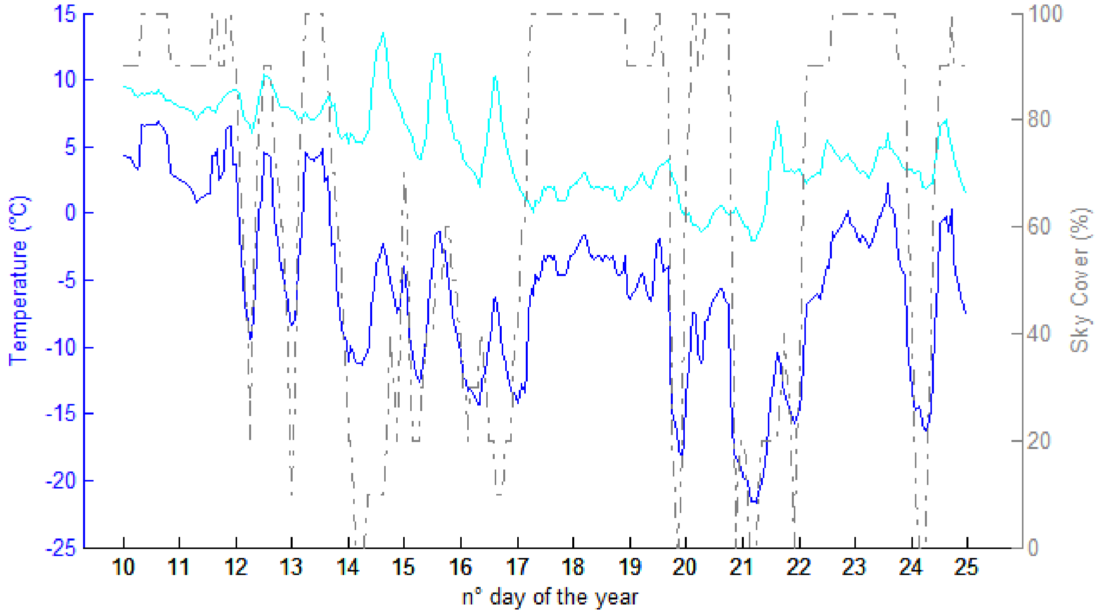


Figure 2: Evolution of the sky temperature (*blue*), air temperature (*cyan*) and cloud cover (*grey*)

We note that the sky temperature cannot be greater than the air temperature; the long wave radiative budget of a surface at the air temperature is always negative. The buildings' walls are cooled by the atmospheric radiation throughout the whole year ; we speak of *passive radiative cooling*. The inhabitants of the Persian desert benefited from this phenomenon to produce ice for an exterior temperature of up to 9°C [Tang 2004].

3 Anisotropy of the sky vault emissivity

The sky temperature is commonly considered isotropic for the modelling of the thermal behaviour of the buildings' envelope, and more generally for the calculation of the energy budget of a surface at the ground level. [Bliss 1961] shows that the sky emissivity depends on the zenith angle. He makes the hypothesis that, in the absence of clouds, the atmosphere is made of parallel layers at uniform temperature, pressure and composition; on this basis, he establishes a first link between the emissivity of a fragment of the sky vault and its zenith angle. [Kruczek 2015] illustrates this phenomenon through the thermography of the sky vault for a clear and an overcast sky (cf. Figure 3).

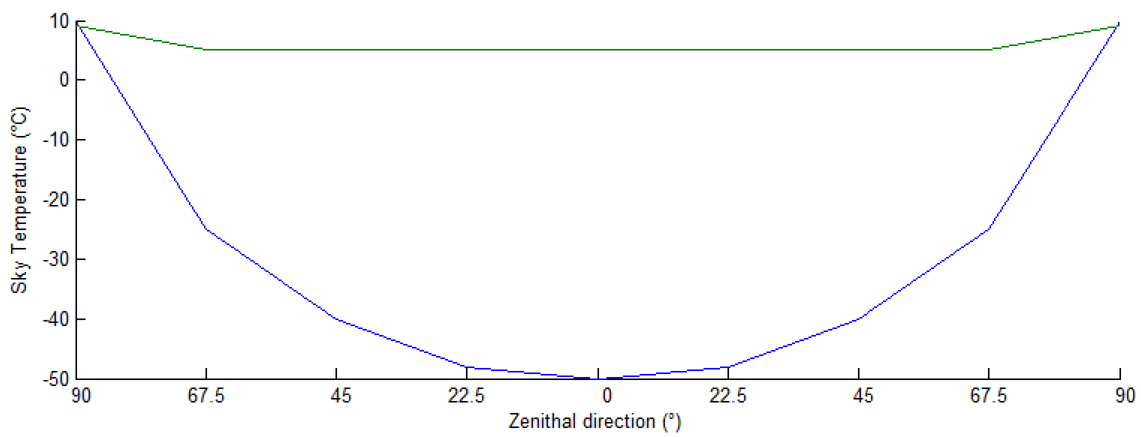


Figure 3 : Sky temperatures observed by Kruczek for a clear (*blue*) and an overcast (*green*) sky

Since Bliss, many authors, such as [Berdhal 1982] and [Berger 2003] studied the anisotropy of the sky emissivity. [Awanou 1998] proposes the following expression of ε_θ, the sky emissivity for the zenith angle θ, as a function of the mean emissivity of the sky vault ε_{sky} :

$$\varepsilon_\theta = 1 - \left(1 - \varepsilon_{sky}\right)^{\frac{\cos(56.25)}{\cos(\theta)}} \qquad (6)$$

He identifies a frontier for a zenith angle of 56.25°: above this value, the directional emissivity is inferior to the mean sky emissivity and vice versa. He shows a convergence between theoretical results obtained following this model and the observations of the sky radiance made by [Berdhal 1982] for zenith angles of 0, 60, 75, 90° in six cities of the United States.

We note that ε_{sky} tends to 1 for a sky cover of 8 oktas (okta is the fraction equal to one eighth of the celestial dome, used in the coding of cloud amount) and a high relative humidity, and so does ε_θ; the model seems then valid for extreme cases. We study the sky temperature in Paris in winter for a clear and an overcast sky (cf. Figure 4). The sky vault is divided in 1000 of tiles following the partition proposed by [Beckers 2014]. We consider each tile at a uniform temperature, equal to that of its centre.

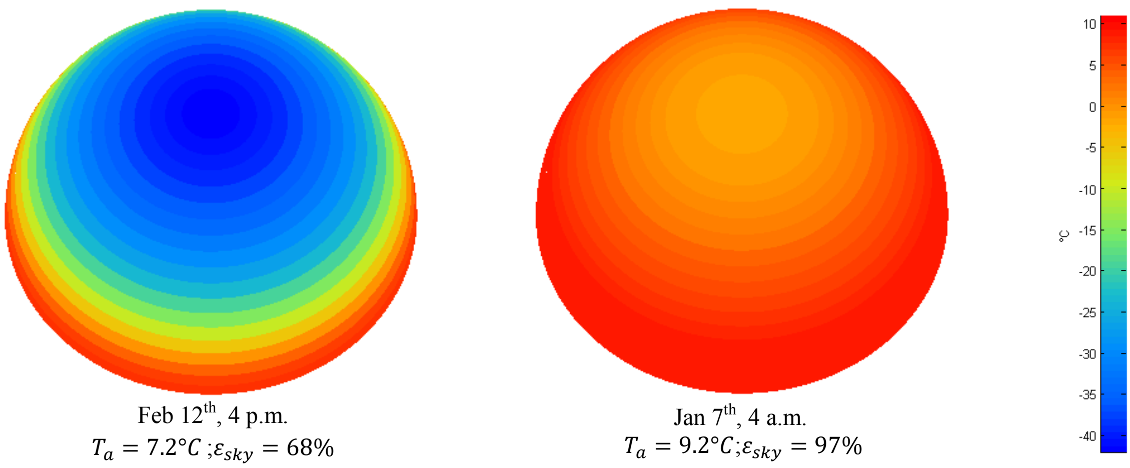


Figure 4 : Sky temperatures for a clear (*left*) and an overcast (*right*) sky in winter in Paris

For a clear sky, we obtain sky temperatures of -42°C at the zenith against 7°C at the horizon for an air temperature of 7.2°C; for an overcast sky, we obtain a relatively uniform sky temperature, close to that of the air. We obtain for these extreme cases ($\varepsilon_{sky} = 68\%$ and 97%) the behaviour observed by Kruczek.

The taken into account of cloud cover on the repartition is difficult because of the multiple types and heights of clouds. We have seen that ε_{sky} can be of 82% both for:

- a cloud cover of 8 oktas when V_p is low;
- a cloud cover of 0 oktas when V_p is high.

If we apply the formula proposed by [Awanou 1998], we obtain in this case a similar temperature gradient for a clear and an overcast sky (cf. Figure 5).

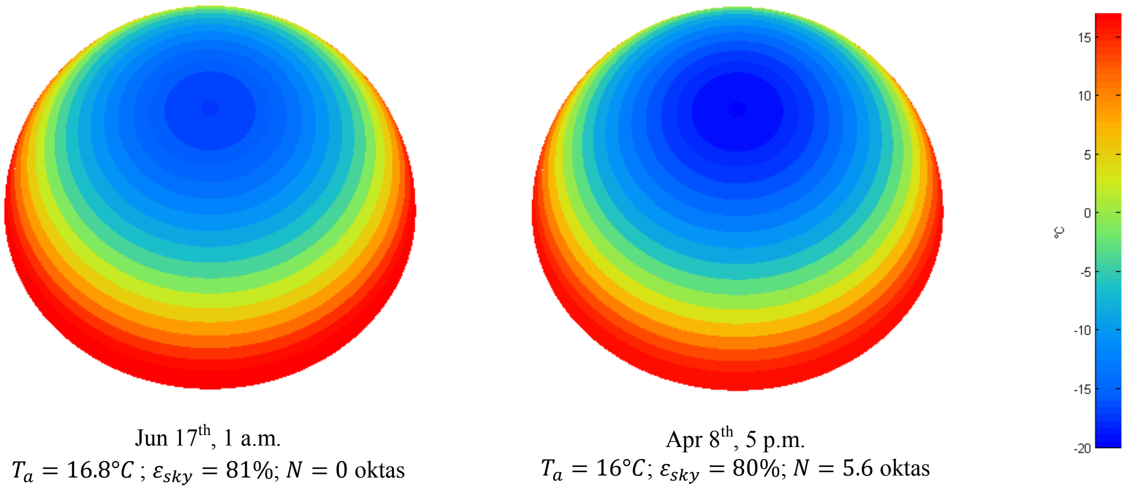


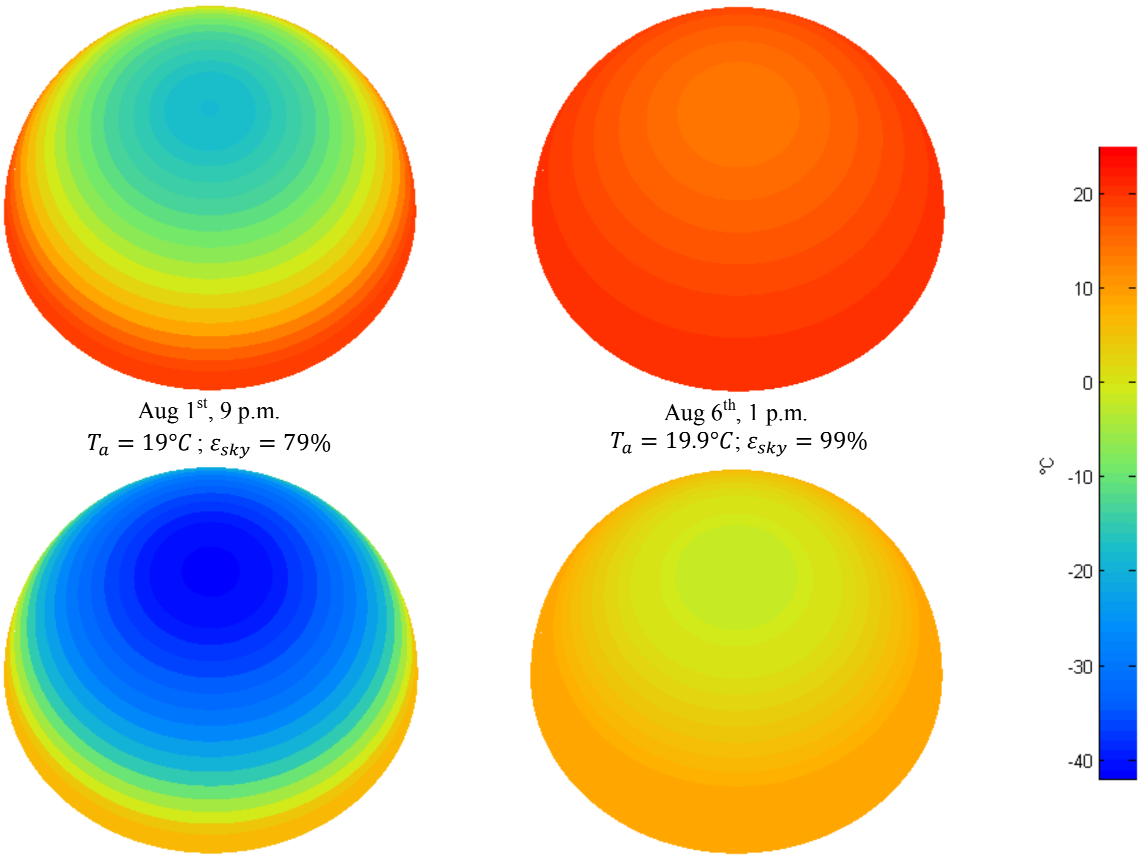
Figure 5 : Sky temperatures for a clear (*left*) and an overcast (*right*) sky in Paris

To date, there is no model for the correct estimation of the sky temperature of an overcast sky. The lack of data makes this last result difficult to analyse. Meanwhile, the differences of temperature between the zenith and the horizon for a clear sky are so important that it seems necessary to take this variation into account when calculating the energy budget of the buildings' envelope. The model proposed by [Awanou 1998] permits a good estimation of the sky temperature both for clear and strongly overcast skies; it appears reasonable to prefer this to an isotropic one, even though the one obtained for partially overcast sky may be wrong.

4 Climate influence

[Clark 1981] and [Argiriou 1992] illustrate the impact of the local climate on the atmospheric radiation; they show that the passive radiative cooling of buildings has a strong potential in most of the cities of the southwest of Europe but not in the southeast of United States.

The city of Paris is characterized by a relatively cold and wet winter, with a mean air temperature of 5°C and a relative humidity of 80%, and a relatively hot and dry summer, with a mean temperature of 20°C and relative humidity of 70%. We compare the sky temperature in winter and in summer for a clear and an overcast sky (cf. Figure 6). The minimal value of ε_{sky} is of 78% in summer against 67% in winter; the sky temperature is generally colder and the difference between the zenith and the horizon is more important in winter than in summer.



Aug 1st, 9 p.m.
$T_a = 19°C$; $\varepsilon_{sky} = 79\%$

Aug 6th, 1 p.m.
$T_a = 19.9°C$; $\varepsilon_{sky} = 99\%$

Feb 12th, 4 p.m.
$T_a = 7.2°C$; $\varepsilon_{sky} = 68\%$

Jan 7th, 4 a.m.
$T_a = 9.2°C$; $\varepsilon_{sky} = 97\%$

Figure 6 : Sky temperature in summer (*up*) and in winter (*down*), for a clear (*left*) and overcast (*right*) sky

We compare the evolution of the cloud cover during the course of a year for the cities of Paris, Montreal and Quito (cf. Figure 7). In order to do so, we compare the theoretical values of the incoming shortwave radiation from the sun for a clear sky, calculated following the model proposed by [Liu 1962], and the ones from the weather database.

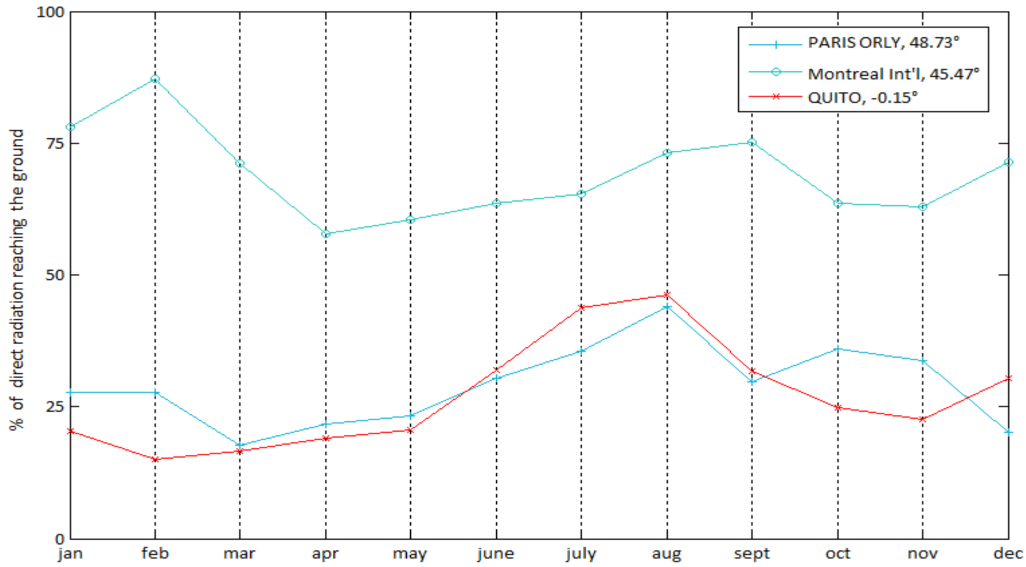


Figure 7 : Evolution of the cloud cover (monthly average)

We note a similar profile in the cities of Paris and Quito, with respectively 70 and 73% of the sun direct radiation intercepted by the clouds over a year, a minimum of 56 and 54% in August and a maximum of 82 and 85% in March and February. In Montreal, only 32% of the sun direct radiation is intercepted by clouds over a year, with a minimum of 13% in February and a maximum of 42% in April.

We compare for these three cities the sky mean temperature from the 1st of January to the 21st of March and from the 21st of June to the 21st of September (cf. Figure 8). The mean air temperature and relative humidity are displayed on the figure.

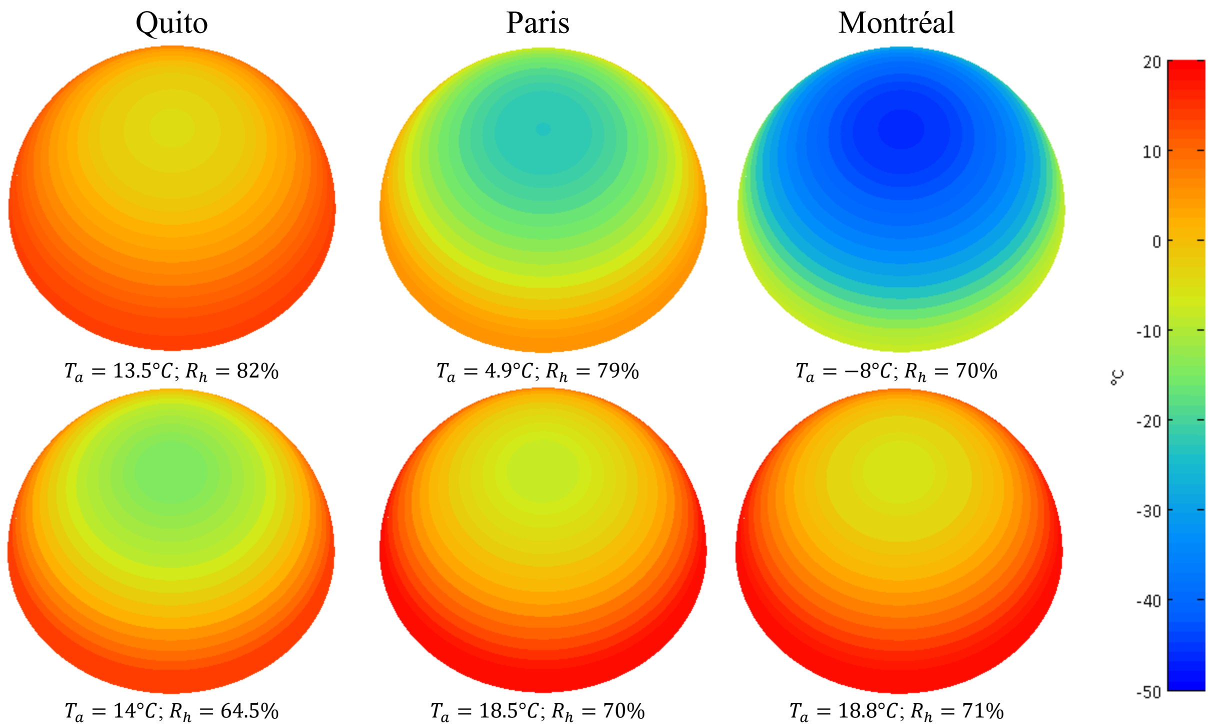


Figure 8 : Mean sky temperatures from the 1st of January to the 21st of March (*up*) and from the 21st of June to the 21st of September (*down*)

We note a similar mean sky temperature in Paris and Montreal in summer, with respective temperatures of -8 and -5°C at the zenith and 18.5°C at the horizon. On the same period, the sky temperature is of -14°C at the zenith and 14°C at the horizon in Quito. In winter, the temperature are clearly inferior in Montreal, with -46°C at the zenith, against respectively -23 and -4°C in Paris and Quito, and -8°C at the horizon, against 5 and 13.5°C.

In Figure 8, the potential for passive radiative cooling of buildings appears limited in Montreal and Paris. Meanwhile, the cooling of the buildings' wall exposed to the zenith and its potential impact on the heating needs appears important.

[Nahon 2016] studies the distribution of light on the sky vault and identifies the most useful areas regarding the access to daylight in an interior; he shows that it is possible to define a *useful* sky factor regarding daylight access. Given those results, it seems possible to identify for a given climate the sky vault areas that favour thermal comfort and limit the energy needs for heating and cooling of buildings.

5 Conclusion

In this article, we illustrate the strong variation of the sky vault emissivity along the year and under different climates. We point out the interest of taking it into account for the estimation of external surfaces temperatures and the calculation of a building's energy budget. The long wave radiative balance of the building's envelope in the modelling of its thermal behaviour is usually done through the estimation of a mean exterior surface temperature, considering an isotropic atmospheric radiation. The authors will present during the conference a comparison of the exterior surfaces temperatures and energy budget obtained following that method and considering differentiated surfaces temperatures and an anisotropic sky.

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References

[Argiriou 1992] Athanassios A. Argiriou, Mat Santamouris, Constantinos Balaras, Sheldon Jeter, Potential of radiative cooling in southern Europe, *International Journal of Solar Energy*, vol. 13, Pages 189-203, January 1992.

[Awanou 1998] Cossi Norbert Awanou, Clear sky emissivity as a function of the zenith direction, *Renewable Energy*, vol. 13 n°2, Pages 227-248, February 1998.

[Beckers 2012] Benoit Beckers, *Solar Energy at Urban Scale,* Wiley-ISTE, 384 pages, May 2012.

[Beckers 2014] Benoit Beckers, Pierre Beckers, Sky vault partition for computing daylight availability and shortwave energy budget on an urban scale, *Lighting Research and Technology,* vol. 46 n°. 6, Pages 716-728, December, 2014

[Berdhal 1982] Paul Berdhal, Richard Fromberg, The thermal radiance of clear skies, *Solar Energy*, vol. 29 n°4, Pages 299-314, 1982.

[Berger 2003] Xavier Berger, Bathiebo, J., Directional spectral emissivities of clear skies, *Renewable Energy*, vol. 28, Pages 1925–1933, 2003.

[Bliss 1961] Raymond W. Bliss Jr., Atmospheric radiation near the surface of the ground, *Solar Energy*, vol.5 n°.3, Pages 103-120, September 1961.

[Buck 1981] Buck, Arden L., New equations for computing vapor pressure and enhancement factor, *Journal of Applied Meteorology*, vol. 20, Pages 1527–1532, 1981

[Clark 1981] Clark G., *Passive/hybrid comfort cooling by thermal radiation*, Proceedings of the international passive and hybrid cooling conference, Miami Beach, Pages 682–714, 1981.

[Dollfus 1954] Jean Dollfus, Les aspects de l'architecture Populaire dans le monde, Albert Morancé, 30 pages, 1954.

[Givoni 2011] Baruch Givoni, Indoor temperature reduction by passive cooling systems, *Solar Energy*, vol. 85 Pages 1692–1726, 2011.

[Kämpf 2007] Jérôme-Henri Kämpf, Darren Robinson, A simplified thermal model to support analysis of urban resource flows, *Energy and Buildings*, vol. 39 n°4, Pages 445-453, April 2007.

[Kruczek 2015] Tadeusz Kruczek, Use of infrared camera in energy diagnostics of the objects placed in open air space in particular at non-isothermal sky, *Energy*, vol. 91, Pages 35–47, November 2015.

[Liu 1960] Benjamin Y.H. Liu, Richard C. Jordan, The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Solar Energy*, vol. 4, Pages 1–19, 1960.

[Tang 2004] Runsheng Tang, Y. Etzion, I.A. Meir, Estimates of clear night sky emissivity in the Negev Highlands, Israel, *Energy Conversion and Management*, vol. 45 n°11-12, Pages 1831–1843, July 2004.