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SEASONAL IMPACT OF BUILDING DENSITIES AND URBAN TREE CONFIGURATIONS ON THE THERMAL CONDITIONS IN URBAN CANYONS. THE CASE OF MENDOZA METROPOLITAN AREA IN ARGENTINA

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Abstract

The characterization of urban radiant fields is fundamental information to assess energy consumption's increase and environmental pollution associated to urbanization phenomenon. Starting from this analysis and diagnosis, it is possible to develop a strategic planning of the city's growth.
In this study, the reference case is Mendoza Metropolitan Area (MMA) located in a seismic and semiarid zone. The urban model presents wide road channels and different tree species along the streets in opposition to the compact city model.
This paper evaluates the impact on the (SVF) that is produced by the combination of different buildings densities (high, medium and low) and diverse magnitudes of the forest species (first, second and third); and their impact on thermal conditions in different seasons (summer and winter) of the year. A computational tool has been developed to obtain the value of the (SVF) from digital hemispherical photo image processing.
The results show that if the building density remains constant, the use of first magnitude tree species restricts the possibilities of upgrading the thermal conditions of urban canyons, during both summer and winter; showing the most favourable configuration differences in temperatures that do not exceed 2 ºC in relation to the worst condition.

Key words: Sky View Factor (SVF), urban canyon, building density, urban forest, seasonally thermal behaviour.

1. Introduction

Cities settled in arid regions usually follow an urban development model based on compact morphologies. They feature a continuous network of narrow streets and buildings with interwoven small courtyards, aiming at casting shadows to reduce solar exposure in the hot season and, consequently, storage of heat in the hard surfaces of the environment.
The city of Mendoza, Argentina, also located in a semiarid region, presents a development model different from the one described above. Its urban conception is defined by wide streets and buildings laid out in a gridiron pattern, lined with tall trees constituting green tunnels. That is, the shading strategy is accomplished by a vegetal network that minimizes the solar exposure of the whole city
However, the intense afforestation of the urban viaducts reduces the available vision of the sky dome and increases the terrain roughness of the metropolitan area, which, in addition to its climatic features, (low frequency and intensity of winds and predominance of clear sky), diminishes the passive cooling possibilities of the city by convection and radiation. Consequently the urban heat island effect reaches values up to 10ºC, producing a 20% increase of the cooling need [1].
Several authors have studied correlations of the passive cooling potential with the Sky-View-Factor (SVF). Oke [2] proposed an equation that described the urban heat island magnitude as a linear function of SVF. However, in the case of Mendoza, the correlation between both variables does not present such a defined pattern[3], since the urban geometry is defined by a mixed material structure (massive and green) whose radiant and thermal properties differ from each other and consequently, their energy behaviours are different.
For this reason, in the case of MMA, this paper evaluates the impact on the (SVF) that is produced by the combination of different buildings densities (high, medium and low) and diverse magnitudes of tree-species (first, second and third); and their impact on thermal conditions in the extreme seasons of the year.
The results will allow, in future stages, to elaborate design proposals for the open space within the framework of sustainable urban

planning; that is, aiming at avoiding, on a micro scale, the transformation of the city into a thermal storage mass that degrades the oasis' thermal conditions and, on a macro scale contributing to reduce the urban heat island effect.

2. Methodology

Air temperature and comfort conditions in an urban canyon are affected by a great number of variables; it is therefore necessary to determine the interrelationship between these variables and each variable weight, with the purpose of obtaining their optimal combination to get thermal comfort in outdoors spaces, and to minimize energy consumption and its consequent pollution emissions.

On the other hand, SVF is a parameter that expresses the relationship between the visible sky area and the portion of sky hemisphere masked by the different components of the environment. The parameterization of canyon geometry in terms of SVF is a common practice when studying thermal behaviour of outdoor spaces because it modifies nocturnal cooling rates as well as solar access.

It is interesting to analize in depth the effect of the different tree species and their configurations on the thermal balance of urban canyons; particularly, in cities, located in seismic desert zones, that display wide road channels and that in addition show an oasis urban configuration like Mendoza Metropolitan Area in opposition to the compact city model.

2.1- Selection of the study cases

In this paper the impact on the SVF on the city climate is comprehensively evaluated, including: the combination of different building densities (high, TOF[1] more than 6 m^3/m^2; medium TOF around 4.25 m^3/m^2- and low, TOF less than 2.75 m^3/m^2-) ; and different width of circulation channels (30, 20 and 16 meters) and diverse magnitudes of the tree species (first, more than 15mts in height; second; 10 to 15 m, and third less than 10 m); and their impact on thermal conditions in different seasons (summer and winter) of the year.

2.2 Sky view factor calculation from hemispherical digital images

In the present conditions within MMA, it is impossible to assess the SVF, departing from geometrical models, so in order to obtain a SVF parametric value of SVF that better adjusts to reality, the use of processing hemispherical digital images was proposed.

For this reason, a simple and accurate digital approach to calculate the SVF was developed from hemispherical digital images in clear sky conditions, intense urban forest and cities with high reflectivity typical of semiarid regions as in the study case. This tool labelled PIXEL DE CIELO (Sky's Pixel) was developed [4], using DELPHI 5.0 and can be run entirely in a Windows environment. This software obtains the SVF value for a determined urban environment from digital fish-eye images, JPG format which is captured using a Nikon CoolPix digital camera equipped with a Nikon fish-eye lens and correctly oriented for suntracking calculations by means of a global positioning system.

2.3 Thermal behaviour of different urban canyon configurations.

Six cases were selected for presentation in this paper (See Fig. 1). They illustrate the combinations between two building densities (high and low), three width of road channel's (30, 20 y 16mt) and first magnitude trees (*Platanus acerifolia*). The reason for this selection is that previous studies [5] showed that this species has a critical thermal behaviour in comparison with the other tree-species (second and third magnitude). The Plane-tree is the first magnitude species most representative in the studied area-21.52%-. The London Plane-trees are adult tree species over 18m high, shaping dense and continuous tunnels, building a green vault over causeway and sidewalks.

With the purpose of monitoring the thermal behaviour of different urban canyon configurations, fixed stations were installed in six urban canyons. The stations are of H08-003-02, two channel logger with internal temperature and RH sensors type. The sensors have been placed at a height of 2.5m above street level [6], within perforated PVC white boxes, in order to avoid irradiation and assure adequate air circulation.

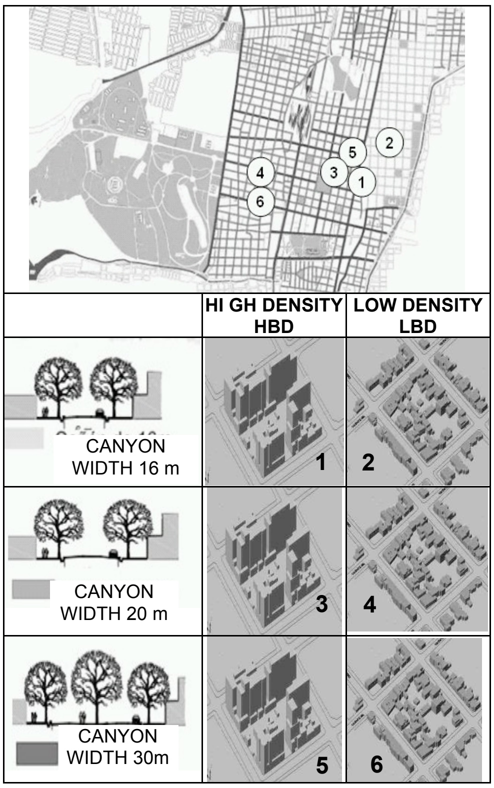


Fig 1 Locations of measurement points and evaluated cases within MMA

[1] TOF: Total Occupation Factor (total built-up area to total buildable area of ground level)

3. Results

3.1 Impact of the configuration's urban canyons over the sky vision

The results obtained show that, taking into account the city building configuration and its network, in the absence of the arboreal component, the masking of the sky vault in high building densities varies between 28 and 36%; which represents a SVF between 74 and 82%, available for thermal transferences. For mean building densities, the masking varies from 10 to 17% and for low-densities from 2 to 8.5% (which means a SVF of 83 to 98%).

The road channel width impact on the SVF does not meet the expected behavior (the lesser the width of the viaduct, the lesser the percentage of sky vision), instead, it presents a random behavior and, in some cases, even the opposite is seen, for instance, the combination of first tree species magnitude and high building density.

This behavior can be explained by the city soil-use patterns, due to the high densities concentrated at the city-centre that layer along the most important road channels, which generally feature 30m wide avenues and a more homogeneous height of building facades (less number of voids). Thus, despite having wider road channels, the more compact building component has a greater impact.

The presence of first magnitude tree species in high densities reduces sky vision between 70 and 80% in summer and 40 and 60% in winter, depending on the space geometrical composition and its intersection with the tree crowns. An important factor is the interval between trees: at lesser distances, greater lateral crossing of crowns; in this case the smaller width of the road channel combined with first magnitude species conditions,mainly in summer, the configuation of a tunnel. On the other extreme, the first tree species magnitude combined with low building density, reduces the vision of the vault between 70 and 80% in summer and 35 to 40% in winter.

The blockage proportions of the first magnitude, in high and low building densities, are similar in summer, while its winter impact is smaller for the low density, given the fact that the summer foliage covers all the voids of the building masses, independently from its density; while in winter, the low density combined with the bare branches allows greater permeability.

The second tree species magnitude offers a special behavior in low densities and 16m wide road channels, corresponding to the most unfavorable situation: blocking 85% in summer and 30% in winter. This situation becomes worse in the case of minimum spacing between tree-species and conformation of tunnel over causeway .

As far as the third magnitude tree species, only consolidated situations of low-building density are registered, showing minimal impact, in winter and in summer as well (10% of the blockage in summer and 5% in winter). The values obtained for the case of 20 m road width, high and low building densities are presented in Figure 2.

Fig 2 SVF value for the case of 20 m road width, high and low building densities

Finally, a high impact of the first and second arboreal magnitudes on the SVF available for the different networks of high building density can be observed. For the low density case, the disadvantage of using first magnitude species as far as sky vault vision availability is clearly observed; while for cases of second and third magnitude the impacts are almost negligible (Fig. 3).

A larger reduction of the SVF is only observed when the second tree species magnitude is combined with 16m wide road channels in summer. The evaluations for the mean building density do not contradict the above-mentioned behavior presenting a high impact of the first magnitude and much lesser ones of the second and third magnitudes.

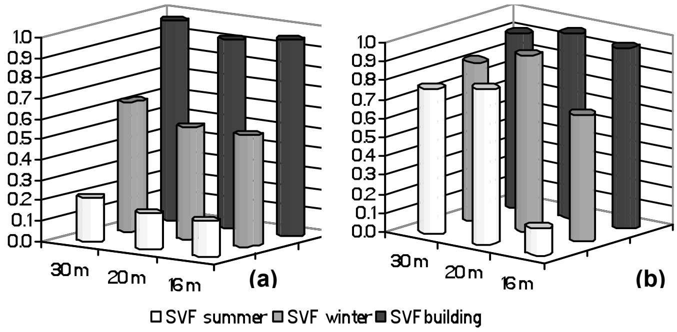


Fig 3 SVF value for the case of low building density combined with (a) first and (b) second tree magnitudes

3.2 Thermal behavior

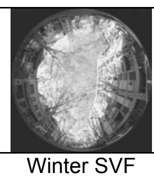
During the months of January and May-June 2008, in 30-day periods, continuous readings of the air temperature and humidity conditions for the analyzed cases were taken (Fig. 1). They all feature E-W orientation, which offers the best sun -lightning conditions for the urban network

For a better assessment of the incidence of the space morphology on its thermal behavior, statistical analysis was performed during two periods of the day: warming and cooling for both extreme seasons.

The resulting frequency distribution of air temperature of the different configurations, are presented in Tables 1 and 2.

Table 1: Frequency distribution of temperature differences between spaces forested with first magnitude, keeping constant building density and varying the urban net work width.

		SUMMER	
		Cooling Period 20.00 PM-6.00 AM	**Heating Period** 6.15 AM-19.45 PM
HBD	16 vs.30	72% of registered cases Δ ºT>1-2ºC	52% of registered cases Δ ºT<1ºC
	16 vs.20	75% of registered cases ΔºT>1-2ºC	60% of registered cases Δ ºT>1-2ºC
	30 vs.20	67% of registered cases Δ ºT<1ºC	53% of registered cases Δ ºT>1-2ºC

	High density 20 m canyon width	
Summer SVF	Building SVF	Winter SVF
		

LBD	30 vs.16	74% of registered cases Δ ºT>1-2ºC	80% of registered cases Δ ºT>1-2ºC
	16 vs.20	68% of registered cases Δ ºT>1-2ºC	64 % of registered cases Δ ºT>1-2ºC
	30 vs.20	66% of registered cases Δ ºT<1ºC	81% of registered cases Δ ºT>1-2ºC

		WINTER	
		Cooling Period 18.45 PM-8.15 AM	**Heating Period** 8.30 AM-18.30 PM
HBD	16 vs.30	88% of registered cases Δ ºT>1-2ºC	52% of registered cases Δ ºT>1-2ºC
	16 vs.20	89% of registered cases Δ ºT>1-2ºC	84% of registered cases Δ ºT>1-2ºC
	30 vs.20	78% of registered cases Δ ºT<1ºC	69 % of registered cases Δ ºT>1-2ºC
LBD	16 vs.30	93% of registered cases Δ ºT>1-2ºC	60% of registered cases Δ ºT<1ºC
	16 vs.20	95% of registered cases Δ ºT>1-2ºC	67% of registered cases Δ ºT<1ºC
	30 vs.20	98% of registered cases Δ ºT>1-2ºC	67% of registered cases Δ ºT<1ºC

Table 2: Frequency distribution of temperature differences between spaces forested with first magnitude trees, keeping the road channel width constant and varying the building density.

		SUMMER	
		Cooling Period 20.00 PM-6.00 AM	**Heating Period** 6.15 AM-19.45 PM
16m	**HBD vs. LBD**	83% of registered cases Δ ºT>1-2ºC	70% of registered cases Δ ºT>1-2ºC
20m	**HBD vs. LBD**	76% of registered cases Δ ºT>1-2ºC	75% of registered cases Δ ºT>1-2ºC
30m	**HBD vs. LBD**	86% of registered cases Δ ºT<1ºC	83% of registered cases Δ ºT<1ºC

		WINTER	
		Cooling Period 18.45 PM-8.15 AM	**Heating Period** 8.30 AM-18.30 PM
16m	**HBD vs. LBD**	92% of registered cases Δ ºT>1-2ºC	59 % of registered cases Δ ºT>1-2ºC
20m	**HBD vs. LBD**	98% of registered cases Δ ºT>1-2ºC	57% of registered cases Δ ºT<1ºC
30m	**HBD vs. LBD**	98% of registered cases Δ ºT>1-2ºC	52 of registered cases Δ ºT>1-2ºC

3.2.1 Thermal behavior in summer

Summer presents itself as a critical season, given the increase of solar irradiance which, in our city reaches mean values of 22-25 MJ/m2; for this reason the inhabitability of urban canyons during noon and afternoon hours is conditioned by the availability of shade. In this sense, first magnitude arboreal species display a significant development of crowns, providing good shading conditions. However, urban terrain roughness increase**s** and the SVF is reduced, limiting the possibilities for convective and nocturnal radiant cooling.

• ***Spaces forested with first magnitude tree species, keeping constant building density and varying the urban network width.***

In the case of high building density, the thermal behavior in the warming period (6.15 AM to 7.45 PM) shows that the thermal confinement produced by the combination of high building density and narrow road channel (16m) produces a low SVF, less solar access but also, a reduced access to the wind for ventilation and passive cooling. For this reason, with first magnitude tree species (greater roughness and masking of the sky vault) the situation becomes more intense, resulting in an increase of the air temperature for this configuration type during the period that reaches differences of 2ºC (75% of registered values) in relations to the same situation for 20m wide channels. However the same building and tree species morphology for the 30m wide channels does not present significant differences in air temperature (lower than 1ºC, for the 52% of the evaluated registers). This behavior can be explained by the fact that first magnitude tree species do not build tunnels on 30m wide avenues, thus increasing solar and wind access and consequently, a balance between radiant gain and convective loss and the thermal behavior nearing that of the 16m wide channels. However, 30m wide channels have shown to be 2 ºC warmer than the 20m wide ones, where good shading condition is maintained while cooling condition in the 16m wide cases.is better (See Table 1)

During the cooling period (8 PM to 6 AM) the evaluated cases show that the configuration corresponding to 16m wide channels present the most disadvantageous situation, maintaining the air temperature 2ºC higher than the corresponding to 20m and 30m wide channels (75% of the observed cases), among which no significant differences are registered during the cooling period (Table 1).

In the case of low building density, the thermal behavior during the warming period (6.15 AM to 7.45 PM) shows that air temperature in the 16m wide channel is always 2ºC above that of the 20m wide one (64% of registered cases) pointing out that, under similar solar gain conditions, better ventilation of the 20m wide channel upgrades space thermal behavior.(See fig.4). However, when comparing the 30m wide channel (greater solar gain and better ventilation) it can be observed that its temperature is 2ºC above the temperature of 16 and 20m wide channels. This behavior can not be explained solely by the results of the space geometrical configuration on the solar gain and ventilation variables.

In this case, the particular soil use, corresponding to a recreational area harboring restaurants and bars, produces a significant contribution of additional anthropogenic heat, increasing air temperature in the space, as it is shown in Fig 5.

During the cooling period (8 PM to 6 AM) the 16 wide channel shows the expected behavior:, greater confinement results in higher temperature, (< SVF), when it is compared to the 20m wide channel, however, this situation doesn't maintain itself when it is compared to the 30m wide channel, which is explained by the soil use of the channel as mentioned above, however, the behavior of the 30m wide channel, returns to its geometric features after 2.00 AM, time when the anthropogenic heat contribution decreases Fig 5.

- **Forested spaces with first magnitude species, constant road channel width and variable building density**

If the road width is kept constant and the impact of the building density, which adds mass for thermal accumulation, decreases the space sky view, and its potential ventilation, is compared during the warming and cooling periods as well, the thermal behavior is the expected one: greater building density results in higher air temperature during daytime and night time as well (Table 2). The exception is that of the 30m wide channel due to the contribution of anthropogenic heat associated to soil use at low density.

3.2.2. Thermal behavior in winter

For the case of high building density, thermal behavior corresponding to the warming period (8.30 AM.- 6.30 PM.), shows an advantageous confinement situation, in similar solar access conditions; since the air temperature in the 16 m wide channel is maintained 2ºC above that of the 20 m channel (84% of registered cases), and of 30 m (52% of registered cases). Nevertheless, facing the possibility of less solar access and similar cooling condition, a likely situation, in the 30 and 20 m channels , the situation is reversed and in 69% of the observed cases the temperature in the 30m road channel is 2ºC higher than the one in the 20m channel.

During the cooling period (6.45 PM- 8.15 AM), the evaluated cases show that the configuration of the 16m wide channels presents the most advantageous situation maintaining air temperature at a difference of 2ºC above the corresponding values in 20 and 30m wide channels (88% of the observed cases). No significant differences between 20 and 30m wide channels are registered, as it happens in summer .(Table 1)

For the case of low building density, the behavior during the warming period (8.30 AM-6.30 PM), shows no significant temperature variations among the possible configurations, which would mean that the forestation in low density with first magnitude would annul any possibility of thermal conditioning related to the handling of the space geometry.

During the cooling period (6.45 PM-8.15AM) the evaluated cases show a behavior that iscoherent with its geometry: given greater confinement and less SVF, higher temperature.

- **Spaces forested with first magnitude trees, keeping the road channel width constant and varying the building density.**

In this case, the behavior is similar to the corresponding summer condition including the one of the 30m wide channel.

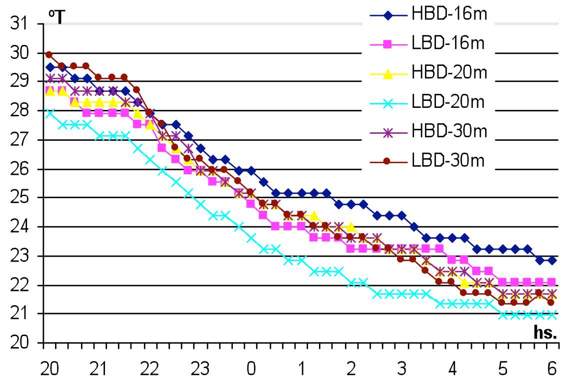


Fig 4 Temperature air distribution during cooling period in summer for all evaluated cases.

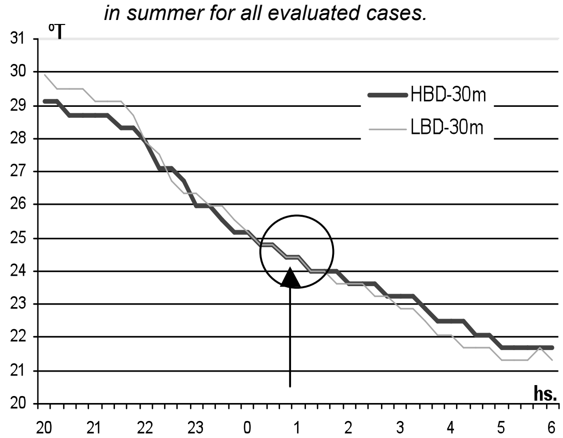


Fig 5 Temperature air distribution during cooling period in summer for 30m width road channel.

4. Conclusion

Incidence of different tree species magnitudes and their relationship to the urban-building variables:

The negative impact of using first magnitude tree species in low density areas is observed, being of great advantage to use second and third magnitude species in this case.

In high density, specially during the summer (more compromised thermal condition) there is no significant difference on the sky-view between first and second magnitude tree species, therefore, the choice of either species should be based on other favorable features (longevity, management, hydric adaptation, etc.). As a proposal it would be interesting to verify the third magnitude tree species behaviors in this building density.

The significance of the forestation impact on the sky-view increases or decreases according to the combinations between road channel width and the planting intervals between trees.

The choice of the different magnitudes must be related to the tree species profile searched for, in response to the thermal and light needs of the space being considered; that is to say, the configuration can be: continuous tunnel over causeway and sidewalks, interrupted tunnel above causeway and homogeneous screen over

sidewalks, or else, the individual development of each tree without overlapping crowns.
The first configuration suggested offers the advantages of shade and the reduction of solar gain over horizontal and vertical buildings envelopes, but it minimizes the possibilities of radiant and convective cooling. The second alternative increases solar gain but preserves the shading on the pedestrian walkways of the road channel and improves the conditions for nocturnal cooling. The third option offers the best conditions for cooling and the most unfavorable for thermal gain. In this sense, a careful study of the thermal behavior of these configurations, considering the features of each particular city, is needed.
It is worth noticing that urban sustainability must not only be supported by the optimiziation of space thermal conditions, but also by the sustainable use of all resources. In this sense, it is necessary to remember that tree species magnitude is directly related to their longevity, that is to say, the first magnitude includes the species with the longest useful life. This point should be highly taken into account, since the selection of tree species of lesser longevity, as third magnitude species, implies that the renovation time of the trees will be shorter than in the cases of first and second magnitude. It is, therefore, necessary to corroborate whether the advantages of energy optimizing of the spaces exceed the consumption of resources associated to reforestation.

Incidence of the combination of first magnitude tree species to the different urban-building variables and their effect on the thermal behavior of urban canyons:
The results show that if building density remains constant, the use of first magnitude tree species limits the possibilities of upgrading the thermal conditions of urban canyons, during both summer and winter; showing more favourable configuration differences in temperatures in as much they do not exceed 2 ° C in relation to the worst possible condition.
The use of first magnitude trees in urban canyons of low building' density; annuls any possibility of thermal improvement associated with the handling of the space geometry during the warming period in winter.
In the presence of first magnitude trees, at equal width of urban canyons; the thermal mass related to the building density controls the heat transfer, determining the air temperature, in both extreme seasons of the year.
The only possibility of improving the solar access, regardless of building density, in the presence of first magnitude forest is working with channels of 30 m.
During the summer for both heating and cooling periods, the best thermal conditions are associated with 20 m wide road channels.

6. References

1. Correa, E. N., De Rosa, C. and Lesino G. (2006). Impact of the urban design strategies on the urban climate in arid regions. The case of Mendoza Metropolitan Area, in Argentina. International Conference "Living in hot Deserts: Is a sustainable urban design still possible in arid regions", Algeria, December 4-7.
2. Oke, T. R., Johnson, G. T., and Steyn, D. G. (1991). Simulation of surface urban heat islands under 'ideal' conditions at night. Part 2: Diagnosis of causation. Boundary - Layer Meteorology 56: p. 339-358.
3. Correa, E. (2006). Isla de calor urbana. El caso del AMM. Tesis Doctoral. Universidad Nacional de Salta. Argentina.
4.Correa, E. et al. (2005). Evaluación del factor de visión de cielo a partir del procesamiento digital de imágenes hemiesféricas. Influencia de la configuración del cañón urbano en la disponibilidad del recurso solar. AVERMA. Vol.9 N°1: p. 11.43-11.48. ISSN 0329-5184. INENCO, Salta - Argentina.
5. Correa, E. et al. (2007). Evaluación del impacto sobre la visión de cielo de las distintas densidades edilicias forestadas a partir de imágenes hemiesféricas. Caso del Área Metropolitana de Mendoza**.** IX Brazilian Meeting on Comfort and Energy Efficiency in the Built-Up Environment. Brazil, December 8-10.
6. Oke, T.R (2004). "Initial Guidance To Obtain Representative Meteorological Observations At Urban Sites". Iom Report, Td In Press, World Meteorological Organization, Geneva.