The shape and magnitude of Porto's heat island as a sustainability indicator

1. Introduction

One of the most often used arguments to promote low carbon cities has been the need to adapt urban areas to global warming. This is, in our opinion, a precarious and unsteady option because drives us into a complex and endless controversy about the real value of human actions on climate behaviour at a global scale and push us away from the needed solutions to solve the real problems that affects the quality of the air we breathe and the climate of the place where we live.

While the importance of human activities in the global climate system is still unknown for sure because climate has a chaotic performance and an imprecise time lag response, the local relationships between human activities and the microclimate are easy to demonstrate and understand looking, for instance, to the impacts in the atmospheric chemistry and energy budget.

Therefore, the appeal to create low carbon cities excessively anchored in the global warming threats can be severe weakened and even fail because people – citizens and decision makers – will, with some legitimacy, expect to see the effects of their new attitudes and actions on climate answers, and, they may not come as they expect.

So, if we want to improve our urban ecosystems' sustainability and at the same time discourage the inputs of large amounts of greenhouse gases in the atmosphere to avoid some potential undesirable answers from the climate system, we must try to downscale this issue using local and regional cause-effect relationships. At this scale level, the climate behaviour' mechanics is much more clear and easier to verify.

The *urban heat island* might be a good option to motivate the implementation of low carbon cities because it is a steady evidence of human interference in climate system. The identification of causes – gaseous and liquid emissions, waste, new geometries, new materials, decrease of green areas, large and very inefficient energy consumption, etc. – and consequences - thermal positive anomalies, rainfall changes, wind modification, atmospheric pollution, etc. – is easy to do at the local and regional level.

The shape and magnitude of urban thermal anomalies due to urban lifestyle and planning options are indeed excellent indicators of some of the major cities' pathologies, namely the huge increase of CO emissions.

Since Luke Howard's studies of London urban climate, published in 1818, there have been an extraordinary number of works done in urban areas that express clearly how the urban metabolism matters to local climate. One of the main key issues tackled, in some of these studies, is precisely the air quality degradation generated by several human activities and by the way atmospheric circulation is changed because of the new artificial geometries or even by the decrease of CO sink capacity (less water surfaces, green areas, etc.).

At Porto, we have already data of thermal and humidity measurements inside the metropolitan area since 1990, and the achieved results might help to explain better how we need, as individuals and as society, to implement a fast shifting towards a low carbon way of life.

One of the most obvious examples of new imbalances created by man during the urbanization process may be seen in our city looking to the way how it assisted at the same time to a carbon emissions increase due to the diversification and increase of human activities and, simultaneously, to a considerable contraction of CO sinking capacity because of the green areas removal. This double and cumulative stress upon atmosphere is a decision makers' and urban planners' responsibility because they ignored nature complexity and failed to have holistic and systemic approach to the urban ecosystem.

2. Porto case study

2.1. The spread of urban life style

All population's projections show that human beings, despite everything, will continue to prefer living in urban areas than in rural ones. This will be particularly evident in less developed countries which may mean an enormous imbalance increase between the size and location of the available space, resources and people needs (Fig. 1). Since 2003 till 2030 the urban population in the world is expected to rise from 3 billion to 5 billion while the rural population is expected to decrease, in the same lag of time, from 3.3 billion to 3.2 billion (Fig. 1).

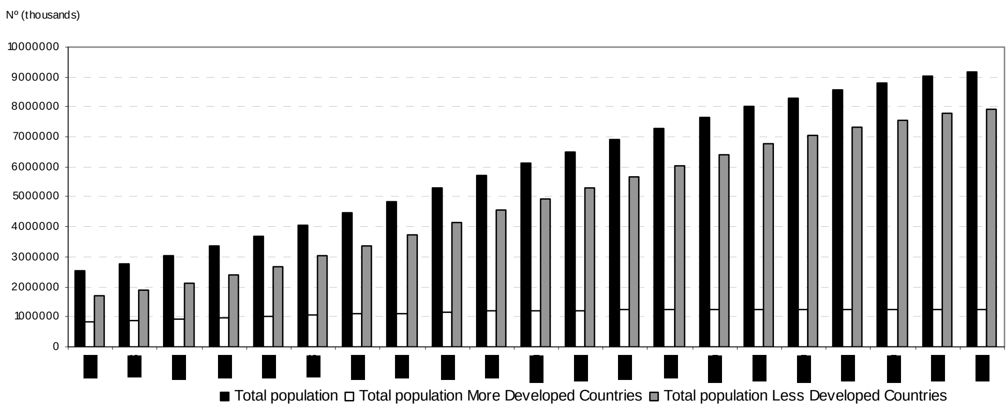

Fig. 1 – UNPD Population projection (2007).

Since 2007, the world has, for the first time in history, more urban than rural inhabitants and according to UNPD projections the annual rate will raise 1.8% what means an expected doubling in a 40 years period.

For the time being one of the major apprehensions comes precisely from the way this lifestyle have spread at an extremely high rate in developing countries where the growth of urbanization started in 1970 with a population increase rate that was the double of the rural. In Africa, for instance, the rate overpasses the 4.5% per year - a doubling in an interval of 15 years.

This urban growth process changed completely the social, economic and man-environment relationships. The complexity and intensity of the territorial and social multidimensional sculpture created by this new lifestyle generated an imbalance between people needs and available natural resources that carried entirely new faces on earth.

2.2. Porto's urbanization process

Portugal follows the EU urban growth rate trend with considerably higher values (Fig. 2). However, Lisbon and Porto, the two major Portuguese cities show, as in all EU, a decrease in urban growth rate after the 80's (Fig.3).

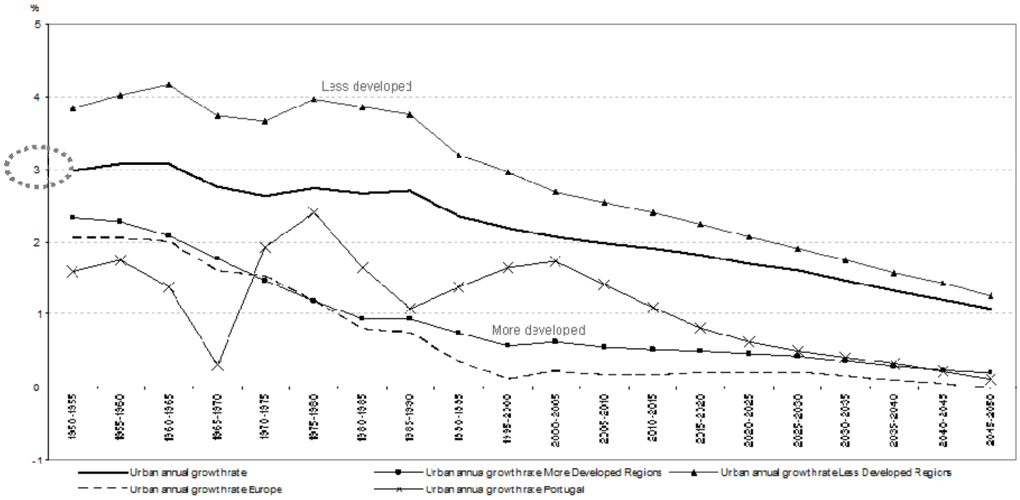

Fig.2 – UNDP urban growth rate projections (2007).

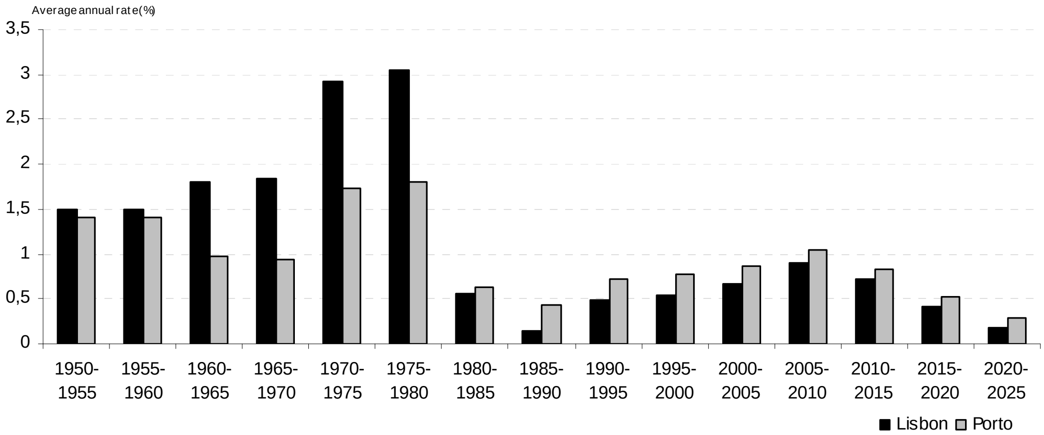

Fig.3 – UNDP urban growth rate projections to Lisbon and Porto (2007).

Porto is the second most important town in Portugal and is situated inside a metropolitan area (GAMP - Porto Metropolitan Area) with 1 281 424 inhabitants, located in the NW coast of Iberian Peninsula (Fig. 4 and 5).

In 2005, Porto had 233 465 inhabitants. It is a city with a daily flux of more than 500 000 persons. It concentrates mainly services – administrative, educational and cultural – and offers more than 218 000 jobs. About 50% of the employees come from nearby municipalities using public and private transports.

Porto had an enormous economic growth during the three last decades. Especially after becoming membership of the EU, in 1986, Portugal has constantly benefited from significant amounts of EU funds in order to create and/or renew its productive tissue, infrastructures and human resources qualifications. During this period we assist, in Porto, at a considerable change in industrial and commercial location patterns and in accessibility networks. This was closely followed by great changes in behaviour and mentalities. These new economic period of hope and prosperity, translated by an increase in the family incomes, carried also a great temptation to survive in a wild competition inside an enlarged and more appellative market, which unfortunately led also some negligent attitudes towards all the environmental components (eg. air, water, soil, etc.).

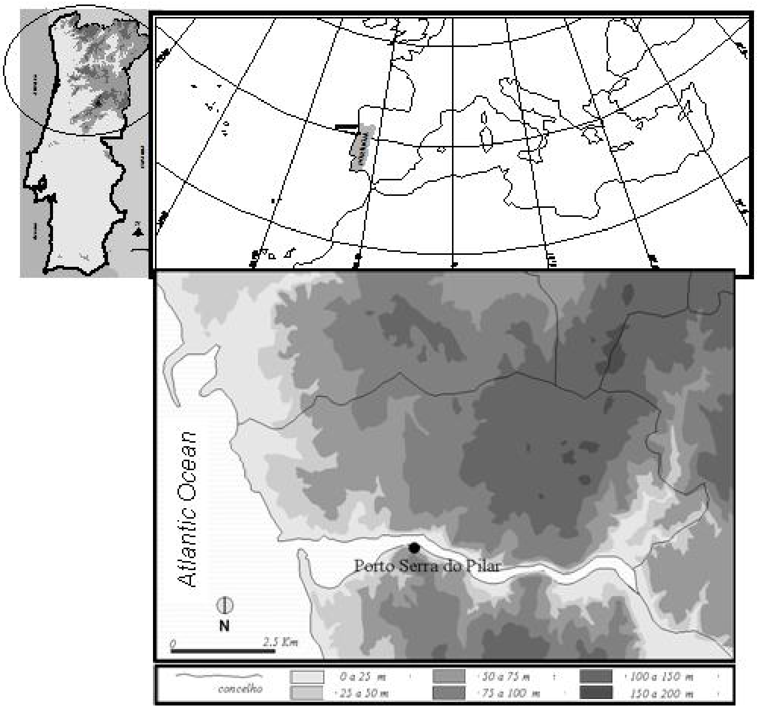

Fig. 4 – Site and geographical position of Porto.

Fig. 5 - Porto Metropolitan Area (GAMP).

If to all this we add the fact that these last three decades has been a time of tremendous progress in the scientific and technological innovation, it is explained the belief that it was possible to replicate any urban model regardless each geographical specificity. The conviction was that everything could be solved with creativity, science, technology and extra inputs of energy. Porto has several urban planning evidences of this way of urban planning at that time.

Porto's population evolution was, until the 80's, very similar to the rhythm of its metropolitan area (GAMP). After this decade, while Porto's population decreases, its metropolitan area experienced a population increment (Fig. 6 to 9). The demographic regression of Porto along the last decade of the 20th century happened mainly because of the huge housing decentralization, as well as to an enormous fall on the birth rates.

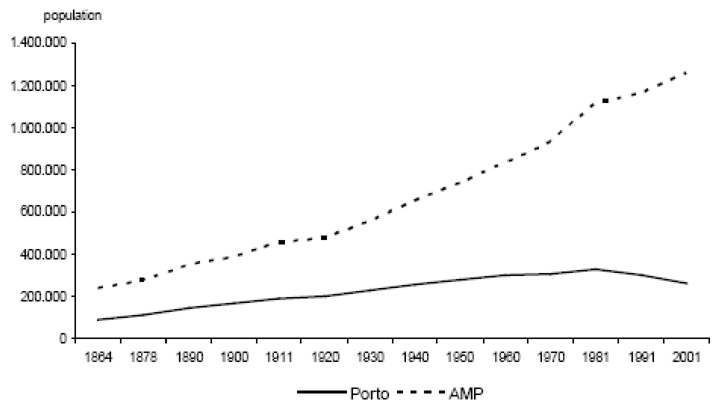

Fig. 6 – Porto's inhabitants (INE, 1884-2001).

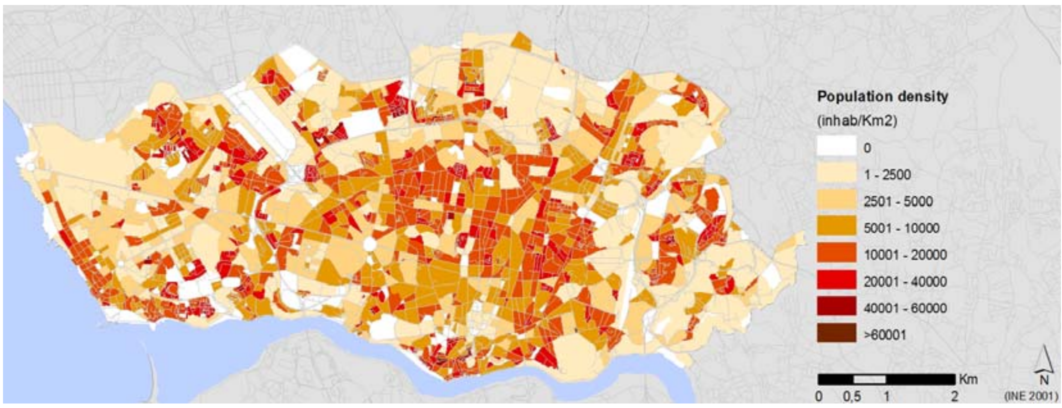

Fig. 7 – Porto population density (INE, 2001).

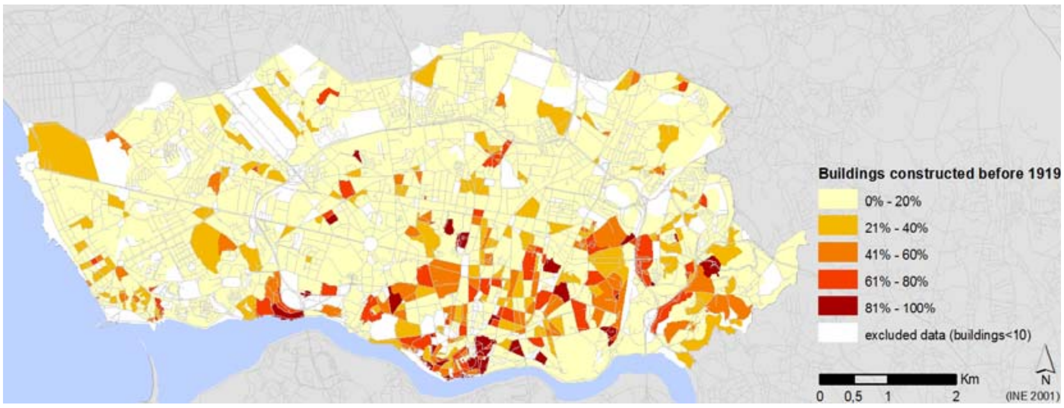

Fig. 8 – Buildings constructed before 1919 (INE, 2001)

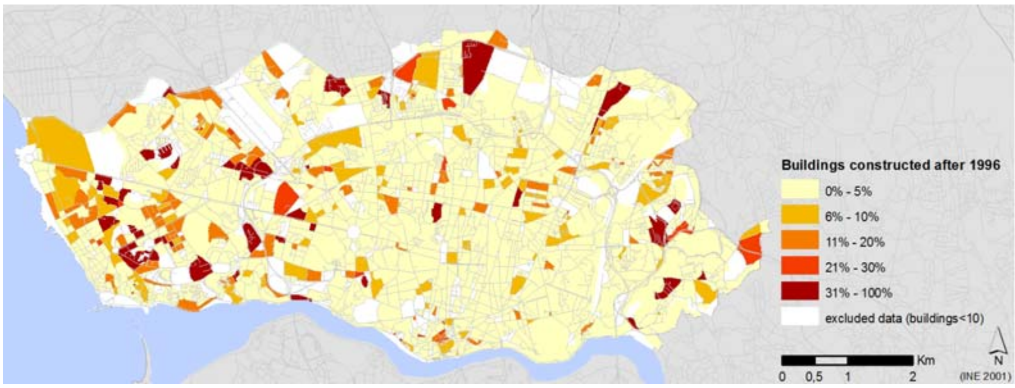

Fig. 9 – Buildings constructed after 1996 (INE, 2001).

Porto's population drainage process, mostly towards the GAMP's nearby municipalities, and the births drop was accompanied by structural changes in family type and in the age pyramid distribution. The average family size diminished and the number of single parent families augmented as well as the number of lonely elderly people increased.

The CMP's mobility report (2007) confirm the high expression of individual movements in the city of Oporto daily traffic - a total of 93 thousand travels by car registered between 7:30 a.m. and 9:30 a.m (Fig. 10 to 12).

30 thousand of the totals 42 thousand motor vehicles circulating inside the city go to the central urban area, especially to the old town – *Baixa* – Boavista roundabout and Asprela (CMP, 2007).

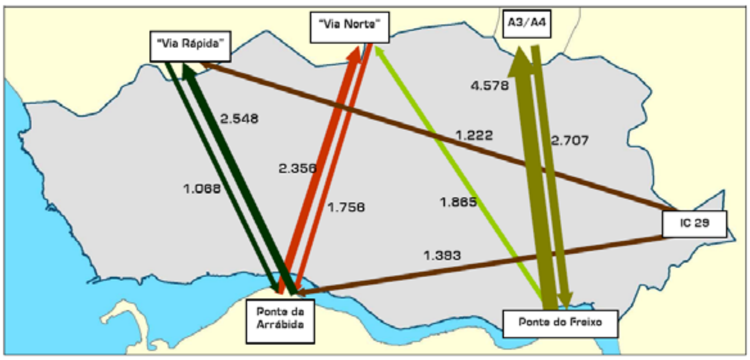

Fig. 10 – Cross-city traffic between 7.30-9.30 am (CMP, 2007, pg.7).

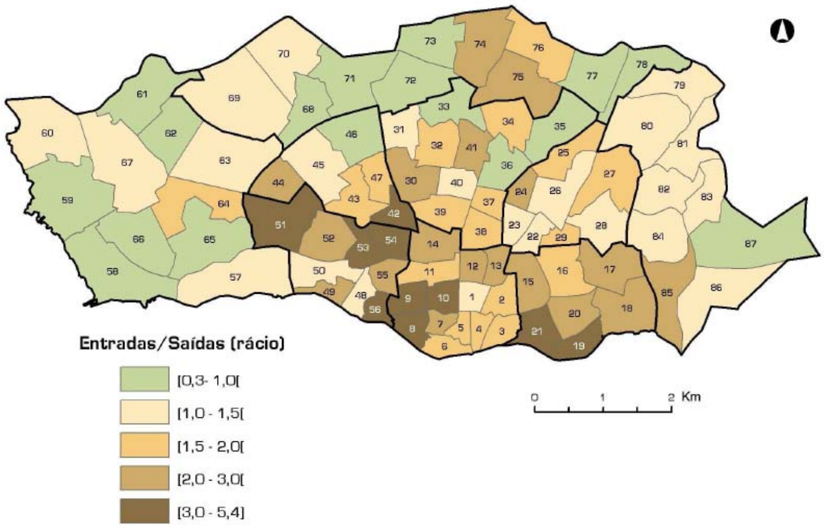

Fig. 11 – Ratio in-out traffic between 7.30-9.30 am (CMP, 2007, pg.17).

As Madureira (2001) showed in her research, the comparison of green surface shape and area between 1890 and 2001, clearly expresses the sustainability of the development and urban planning options (Fig. 12).

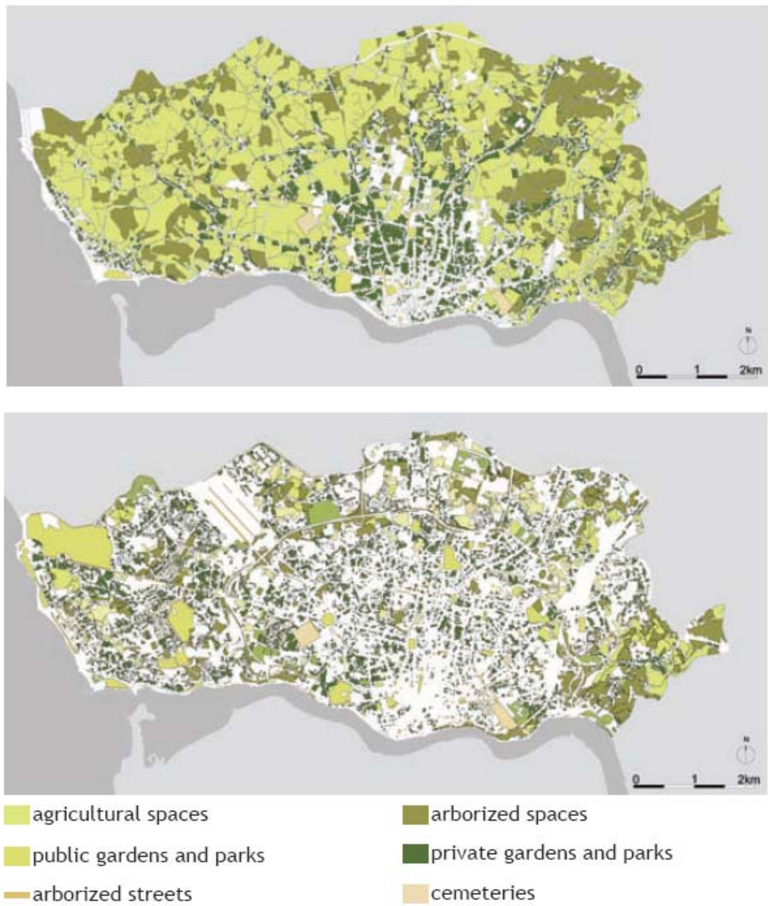

Fig. 12 - Porto's green areas in 1890 and 2000 (Madureira, 2001).

3. The urban heat island in Porto (1990-2005) versus carbon emission and sink capacity estimations

3.1. Methodology to define the urban heat island

To evaluate the thermal anomalies inside Porto we have done itinerant measurements in a validated transect whose star shape allow several points of data validation (Fig.13).

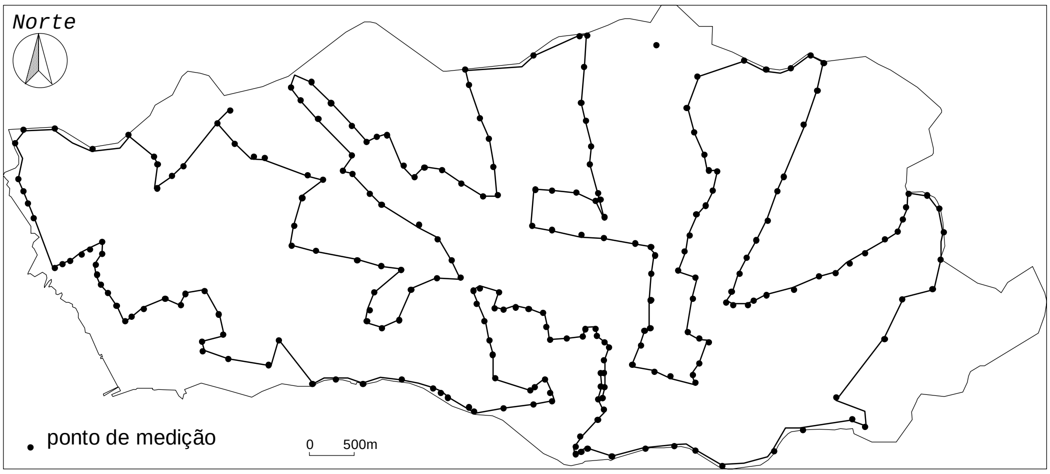

Fig.13 – Porto's itinerant measurements routing (1990-2005).

The chosen route reflects a wide range of urban *facies* – topography, morphology and metabolism. It includes most of the higher altitudes and lower areas, it comprises places far away from the sea and the closest ones. Tries to cross districts are of great built compactness and the more recent residential blocks with high and spaced housing areas at the same time that goes through areas of great promiscuity of use. The route has also samples of different urban functions - industrial, commercial and residential.

The data acquisition was made with a Delta OHM-HD 8501 digital thermohigrometer installed on the right side of the car roof of passengers' vehicle at the height of about 1.5 m.

The time lag between the beginning and end of the route – 70-80 minutes - prevented us from using, directly, the temperature values recorded. We standardized the obtained data series calculating the difference between each record and the simultaneously recorded value at the climatological reference station of Porto Serra do Pilar.

This route was repeatedly done under different weather conditions, weekdays and seasons. There were also done some measurements using the same data acquisition procedures inside specific areas inside Porto – Asprela, Cordoaria, Sé – and in the nearby municipalities – Matosinhos, Srª Hora, Espinho, S.João da Madeira – that confirm the results obtained in these route (Gois, Balkestbal,)

3.1. Methodology to define carbon emission and sink capacity

To estimate the CO_2 emissions we used the data compiled by the *Carbon Dioxide Information Analysis Center*, witch indicates the annual CO_2 emissions from fossil per country. The Porto CO_2 emissions from fossil-fuel were calculated proportionally to its population at each census date.

To estimate the city sink capacity we used de *CityGree*n method, developed by the *US Forest Service*, which calculates the amount of carbon stored in the trees represented on the land cover map and calculates the annual carbon removal by the trees. *CITYgreen* defines three distribution categories based on the diameter of the tree, witch are associated with a certain multiplier:
Carbon Storage Capacity = Study area in acres x Percent tree cover x Carbon Storage Multiplier
Carbon Sequestration Annual Rate = Study area in acres x Percent tree cover x Carbon Sequestration Multiplier

In the absence of precise data on tree age distribution, we used an average multiplier

3.2. Results

3.2.1.Shape and magnitude of the Porto's urban heat island

Before any further comment about the average nocturnal urban heat island found in Porto (Fig. 14), we must remember that the city is divided into two distinct areas, the western part, lower and plan, and the east, with higher altitudes and more rugged. We must also keep in mind that the Douro riverside slopes are steep and that it is to this area of the city that converge most of the streets, with a NNE-SSW orientation, that go to the oldest and historic city centre. These old town road networks have been drawn between great granite and tall buildings blocks that make very difficult the entrance of sunlight till the lower floors of buildings whatever the exposure.

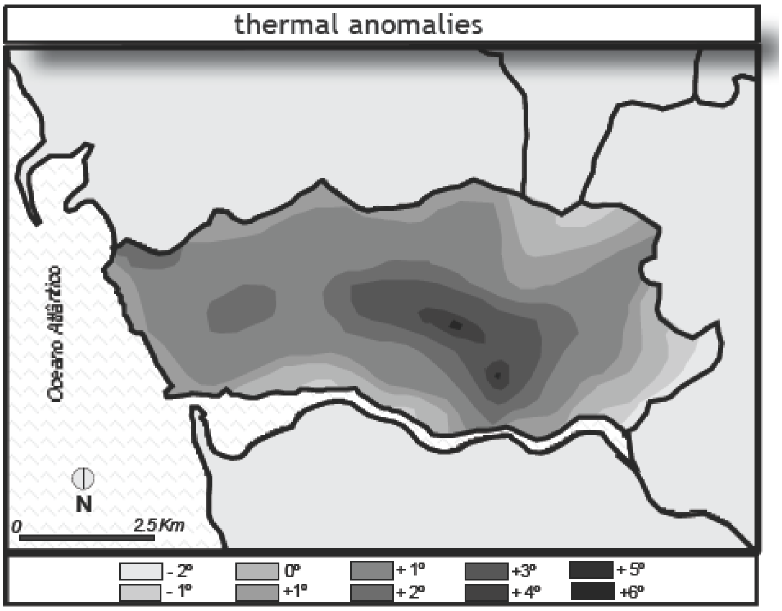

Fig. 14 – Average nocturnal urban heat island at Porto (Monteiro, 1993).

The east area of the city corresponded to the rural ring at the beginning of the 20th century and, since then, suffered an enormous increase in the occupation density. The buildings are usually lower, but in the interior, the space is completely filled by "ilhas" – an answer to the lack of housing for the lower socio-economic classes who immigrated to the city in the middle of the 20th century.

The western area was occupied most recently and has a large number of new neighbourhoods, where individual houses and / or large blocks of flats have been emerging over wide avenues.

As far as our fieldwork shows, neither the topographic differences between the eastern and western parts of the region, nor the two water surfaces close to the city (the Atlantic ocean and Douro river), nor even the spatial occupation miscellany throughout more than eight centuries of history, which brought unique and original features to Porto, have diminish Porto's urban metabolic impacts, specially in its energy budget.

The altitude differences, the effect of the sea breezes, the proximity of the Douro River, the distribution of green areas and the different types of urban space occupation, altered the form of the "heat-island", but very seldom annulled its effects. However, the weather type, at a given moment and some hours before, is of a great importance to the definition of either the shape and the magnitude of the positive thermal anomalies.

We can recall, as an example of this cause-effect relationship between the type of *modus vivendi* inside Porto and the temperature's behaviour, to an episode that happened in the city centre from 22nd to 24th December 1990. During this episode we had a half hourly temperature record located at the city centre (Av. da Liberdade) and we saw how the temperature showed an uninterruptedly raise (Fig. 15)

This behaviour in terms of temperature is only understandable – without night and day fluctuation –because during those three days the weather stability allowed us to see the importance of increase in downtown urban vitality due to the prolonging of the Christmas's shopping activity till midnight.

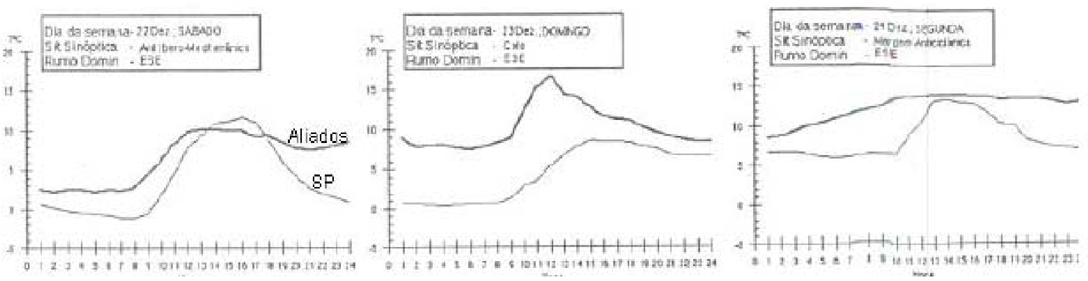

Fig. 15 – Half hourly temperature records at Av. Aliados and at Porto Serra do Pilar (22nd to 24th December 1990).

The fieldwork, under the most diverse weather conditions, in different seasons and days of week, showed the frequent presence of two axis inside the city - Av. Aliados, Pç. República, R. Boavista and Marquês, Constituição, S. Roque – with higher positive anomalies than other points disseminated throughout the city (Fig. 14). These two "heat-islands" coincide with the administrative and functional city centre. The first "heat-island" set the limits of the coalescence of the main CBD, located at Av. da Liberdade, with the secondary CBD around the R. Boavista. The second "heat island" includes the areas of the city most used by the transport network, those with the best accessibility to the city centre, which serves the east area of the city, apart from being an area where the residential function coexists with a large number of small and medium industries.

The "heat-islands" were especially evident on days of great stability, weak barometric gradient, weak wind and frequent periods of calm. Conditions normally associated with the presence of anticyclone weather types, but which, as we saw, can arise also under the influence of depression weather types, when the ascendant movement of the air is conditioned by the presence, in altitude, of a "cold drop", or when caused by a strong base heating.

It is also significant that there was no particular intensification in the "heat-island" during the coldest time of the year. In our opinion, this did not occur because, on the one hand, the annual thermal amplitudes were quite weak and, on the other, because the state of Portugal's economic development is not compatible with the generalised use of the incredibly varied range of equipment which can be used to create a more comfortable ambience in the interior of buildings.

We have detected that, according to the functional vitality of each of the different Porto's subareas, there were changes in the intensity of the positive thermal anomalies recorded and that these frequent positive thermal anomalies were definitely associated with a greater density in the use of space, heavier traffic areas but also to the areas where there are higher human activities' heat sources, etc.

The shape and magnitude of the urban "heat islands" revealed the importance of the human impacts, among other factors, on the lower atmosphere chemistry. The increase of CO_x sources at Porto

3.2.2. The CO emissions and sinkage estimations in Porto

When we address the need of planning low carbon cities to promote steady and sustainable development strategies, we must clarify that we are dealing with an atmospheric component that can result from natural or artificial sources and that can exist alone or in a variety of compounds of several families (carbon and hydrogen, carbon and oxygen, carbon and sulphur, carbon and nitrogen, etc.).

The carbon atoms have an enormous ability to join together with other atoms and there are about two million of known carbon compounds resulting either from natural or artificial combinations.

The hydrocarbons and the carbon dioxide are of great importance to the climate system because they can direct and indirectly increase the atmosphere greenhouse effect. However, it is important to notice that as CO_2 is not responsive in the lower atmosphere it is subject to great distance transportation and distribution within the atmosphere. Therefore, it is very difficult to reach a cause-effect relationship at a local or regional level. Once emitted, the CO_2 can spread around and circulate within the atmosphere too far away from the source.

So, with such a profile it is possible to estimate the emissions and evaluate the sink capacity of a certain place but it is impossible to relate those characteristics to the climate behaviour at that place. The CO_2 concentration of a certain area doesn't reveal the emissions at that place.

Anyhow, evaluating the emission and sink capacity of an urban area is a useful exercise to show the importance of urban way of life to change the atmosphere chemistry.

Having all this in mind we estimate that Porto's CO_2 emissions from fossil fuels, overpasses, in 2001, the 400000 of metric ton per year (Fig. 16), which is less than 1.5% of the total world emissions.

It is very important to notice that the Porto's carbon dioxide emissions from fossil fuels increased rapidly over the last century in Porto, and in the last thirty years it was a five-fold increase (Fig. 16).

Simultaneously, due to the decrease in green areas (Fig. 10), the carbon storage capacity and the carbon sequestration rate have decrease between 1890 and 2000 (Fig. 17 to 19).

Having in mind that a century ago the green occupied more than 75% of the Porto surface (3.044 ha) and actually occupies less than 30% (1.164 ha), we may presume the great reduction of city carbon storage.

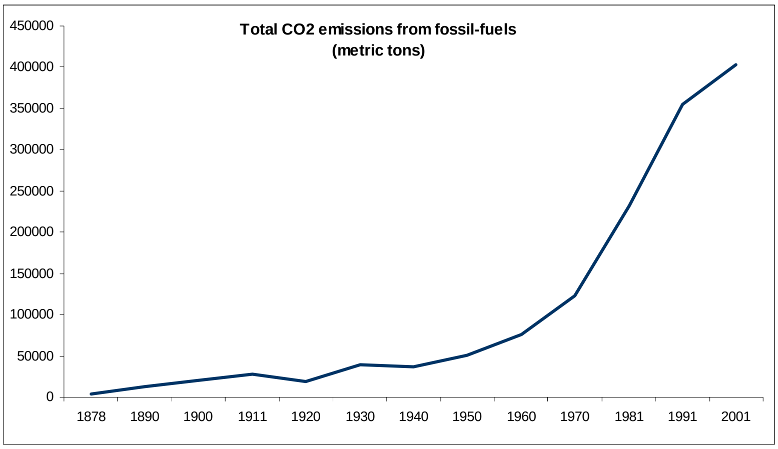

Fig. 16 – Total CO_2 emissions at Porto

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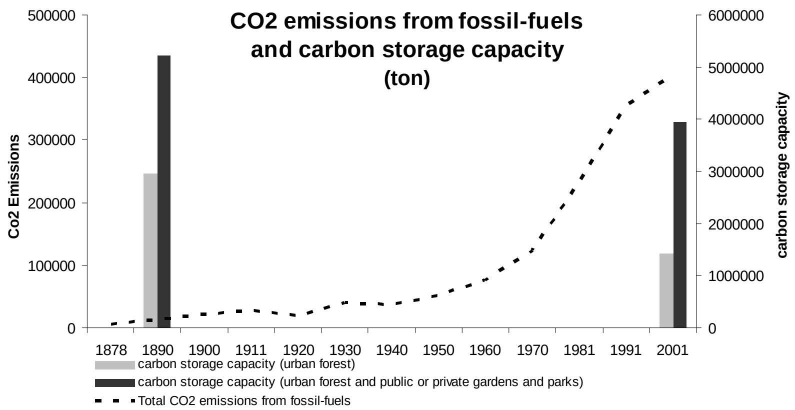

Fig. 17 – CO_2 emissions and storage capacity at Porto (1878-2001).

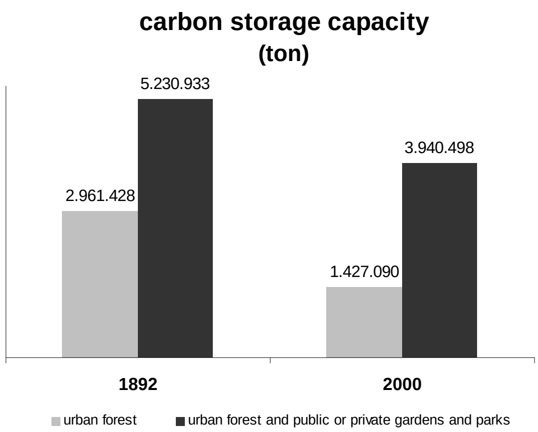

Fig. 18 - CO_2 storage capacity at Porto (1892-2001).

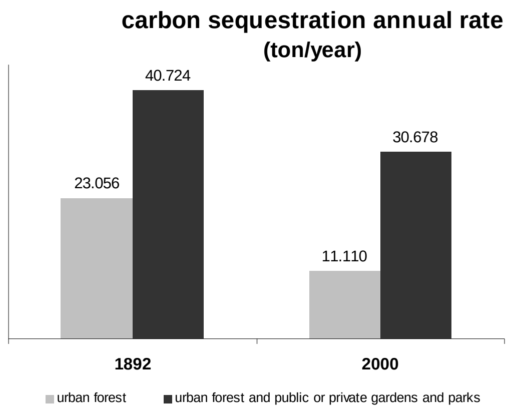

Fig. 19 - CO_2 sink capacity annual rate at Porto (1892-2001).

Considering only the urban forest carbon storage capacity the rate dropped, from 1892 to 2001, about 50%. However, if we consider the urban forest and also the public and private gardens or parks, the decrease was about 25%.

Therefore, in 1890 the annual carbon sequestration rate was higher than the CO2 emissions from fossil-fuels. In 2000 is above thirty-fold smaller.

If we compare these estimations with the 20th century with the minimum and maximum temperatures recorded at Porto, we cannot easily confirm the coincidence among those variables (Fig. 20). The inherent variability of temperature, along the century, does not allow us to have an accurate perception of the effects of warming due to the increase of CO2 emissions.

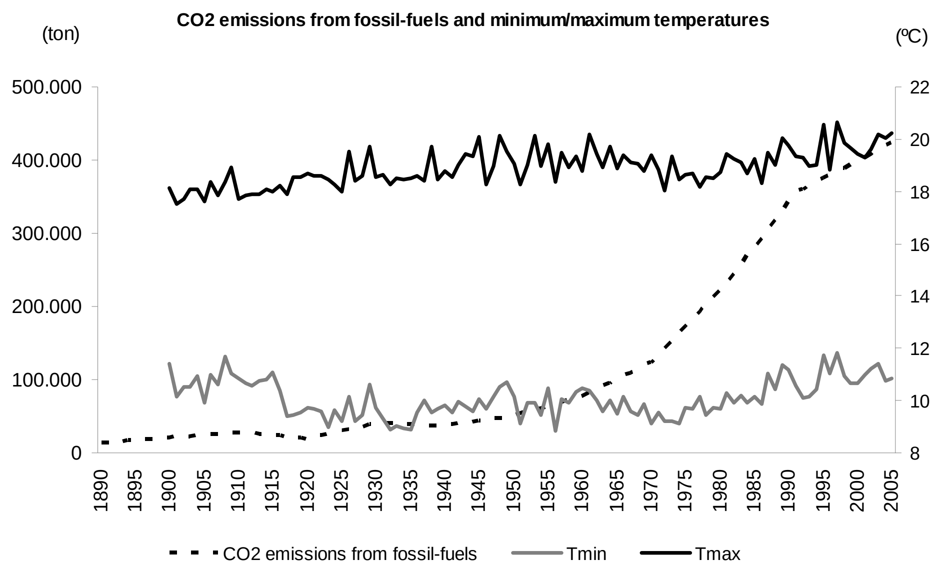

Fig. 20– Maximum and minimum temperature and CO_2 emissions, at Porto, (1880-2005).

Nevertheless, if we look only to the 2nd half of the 20th century and in more detail to the last three decades, it seems that it might exist some relationship between a slightly minimum temperature increase and the fact of, at the same time, the city emissions having had a great increase (Fig. 20).

But, as we know that, during this period, the Porto's storage capacity had diminished substantially, we would expect to see a much better parallelism between CO_2 emissions increase, CO2 storage capacity decrease and temperature.

4. Conclusions

The results achieved, namely the relationship between the rise of local CO_2 emissions and temperature and, on the other hand, the diminution of CO_2 sink capacity, may help us to call the attention of decision makers and urban planners for the importance of green areas to promote a better air quality but is not *de per si* a consistent argument to justify the need of the implementation of Global Warming mitigation measures at the urban level.

In contrast, the urban heat island evaluation and monitoring can straightforwardly led decision makers, urban planners and citizens to demand a more sustainable approach.

This bottom-up strategy to achieve an urban sustainable development implies, itself, a continuous awareness to each different planning option like: buildings' density, materials albedo, colours, people and activities' compaction/dispersion, sky view factor, accessibility, road traffic, urban functions' distribution, hydrological cycle interferences, green areas coherence, etc. The narrow relationship between the local climate and the way where and how people live, helps to change attitudes and motivates a holistic vision of cities that will drive, among others, to lower carbon emissions.

5. References

Akbari, H., Konopacki, S. (2005). "Calculating energy-saving potentials of heat-island reduction strategies", *Energy Policy,* 33, 721–756

American Forests (2002). *CITYgreen: Calculating the Value of Nature. Version 5.0 User's Manual*. American Forests, Washington D.C.

Balkeståhl, L. (2005). *Os efeitos da intensificação dos processos de urbanização no balanço energético local: Estudo de caso no pólo da Asprela*, tese de mestrado, FLUP, Porto.

Barton H, Grant M. (2006). "The Determinants of Health and Well-being in our Neighbourhoods". *The Health Impacts of the Built Environment*, Institute of Public Health in Ireland.

Díaz J. . García-Herrera R. et al (2006). "The impact of the summer 2003 heat wave in Iberia: how should we measure it?", *J Biometeorol* (2006) 50: 159–166.

GÓIS, J. (2002). *Contribuição dos Modelos Estocásticos para o Estudo da Climatologia Urbana*. PhD, Faculdade de Engenharia da Universidade do Porto.

Madureira, H. (2001). *Processos de transformação da estrutura verde do Porto*. Dissertação de Mestrado, FAUP/FEUP, Porto

Marland, G., Boden T.A. and Andres R.J. (2008). "Global, Regional, and National CO2 Emissions", *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge.

Monteiro, A. (1997) *O Clima Urbano do Porto – Contribuição para a definição das estratégias de Planeamento e ordenamento do território*, FCG/JNICT, Lisboa.

Monteiro, A., Matos, F., Madureira, H. (2009) *Historical and geographical contexto of Porto's housing*, Cost Action TU0701 - Improving the Quality of Suburban Building Stocks, Porto.

Organisation of Economic Co-operation and Development (1997). *Better Understanding Our Cities, The Role of Urban Indicators*, OCDE, Paris.

Rosenzweig, C. et al (2002). *Mitigating New York city's heat island with urban forestry, living roofs and light surfaces*, Columbia University, New York, NY, Hunter College, New York, NY

Sassen, S. (2001). *The Global City: New York, London and Tokyo*. Princeton, NJ: Princeton University Press.

Smith, D.A. (1996). *Third World Cities in Global Perspective*. Boulder, CO, Westview Press, USA.

United Nations. (1996). *An Urbanizing World: Global Report on Human Settlements*, Oxford University Press, New York.

United Nations. (2000). *World Development Report*, Oxford University Press, New York.

United Nations Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2007). *World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision*, http://esa.un.org/unup, Friday, April 24, 2009; 7:47:48

Wolman, M. Gordon (1993). "Population, Land Use, and Environment: A Long History," *Population and Land Use in Developing Countries*, ed. Carole L. Jolly and Barbara Boyle Torrey, Committee on Population, Commission on Behavioural and Social Sciences and Education, National Research Council, Washington, DC, USA.

Svensson, M. K., Eliasson, I. (2002). "Diurnal air temperatures in built-up areas in relation to urban planning", *Landscape and Urban Planning* 61, 37–54.