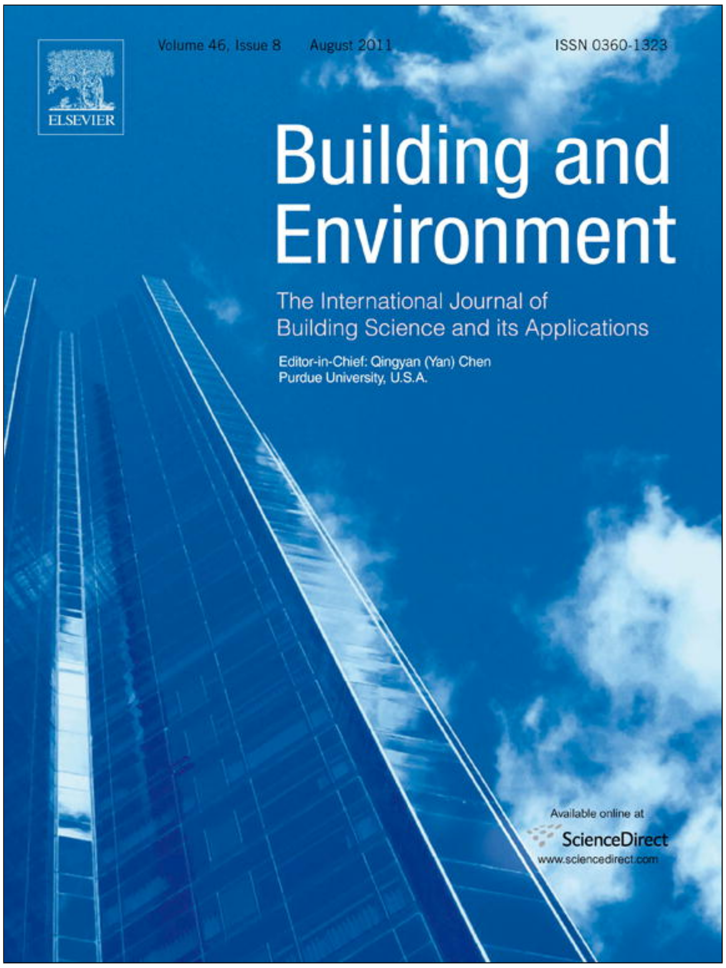

Volume 46, Issue 8
August 2011
ISSN 0360-1323
ELSEVIER
Building and Environment
The International Journal of Building Science and its Applications
Editor-in-Chief: Qingyan (Yan) Chen
Purdue University, U.S.A.
Available online at
ScienceDirect
www.sciencedirect.com

Building and Environment 46 (2011) 1545–1557

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Simulation of the urban climate variations in connection with the transformations of the city of Nantes since the 17th century

Mohamed Benzerzour [a,1], Valéry Masson [b,*], Dominique Groleau [a,2], Aude Lemonsu [b]

[a] CERMA, UMR1563, Ecole Nationale Supérieure d'Architecture de Nantes, Nantes, 6 quai F. Mitterrand, BP16202, 44262 Nantes, France
[b] CNRM/GAME, Météo-France/CNRS, 42 av Coriolis, 31057 Toulouse Cedex, France

ARTICLE INFO

Article history:
Received 19 August 2010
Received in revised form
7 January 2011
Accepted 12 January 2011

Keywords:
Urban planning
Historical analysis
City transformation
Urban microclimate
Numerical modelling

ABSTRACT

The paper seeks to quantify the effect of urban politics on the microclimate of the city of Nantes (France), in particular those initiated by the sanitarians in the mid-19th century to find a remedy for the insalubrity that had been developing with urban densification since the late 17th century. Intensive historical research was first carried out in order to define and date the major transformations undergone by the city, its structure (densification, then widening of the streets, filling of water courses), the lifestyle habits (heating) or the building practices (appearance of stone and paving, higher buildings, insulation). This led to the definition of 5 characteristic states of the city, in 1680, 1756, 1835, 1880 and 1945.

A numerical modelling approach is then used to simulate the urban microclimate of Nantes for these 5 states. The historical information (plans, illustrations) is incorporated into a Geographic Information System in order to determine the general characteristics of the city at the different dates. These are then used to initialize the TEB model which simulates urban energy behaviour and microclimate. While air temperature increases regularly and evaporation decreases (as expected) with greater amount of mineral surfaces, the evolution of humidity is more surprising. Air humidity first increases until the 1850s due to narrower streets. Then it decreases further with the sanitarian transformations which allow the streets to become ventilated and dry. This study gives a good indication of how town-planning actions can, in the long term, influence the urban climate.

1. Introduction

The present context of climate change ([1] IPCC, 2007) combined with the growth of the world's urban population is leading us to take various environmental dimensions into consideration in the design or improvement of cities in order to attenuate global warming (by reducing greenhouse gas emissions) and adapt to the warming to come (thus limiting the possible health and economic consequences). The new “eco-cities” are an example of town planning intended to respond to environmental challenges, e.g. by the use of renewable energies, improvement of transport systems to reduce emissions. However, these eco-cities are home to a very small proportion of the population. The main challenge is to succeed in carrying out town-planning improvements on a large scale in existing cities. For instance, in the study for the “Grand Pari de l'agglomération parisienne” (http://www.legrandparis.culture.gouv.fr/), an urban planning strategy for Paris and its suburbs showed that large-scale modifications, if well targeted (30% increase in forests in a radius of 50 km around Paris, lightening of surfaces in periurban areas), could reduce the urban heat island in the centre of Paris by 2–3 °C during heatwaves ([2] Lion et al., 2009). Such urban transformations may take a very long time; structural changes in cities tend to spread over long periods ([3] Goldstein and Moses, 1973). In Europe, it took centuries to reach the structure of present-day cities ([4] Grazi and van den Bergh, 2008) and a building has a lifetime varying from 50 to over 100 years ([5] Balaras et al., 2007).

Historical studies have shown that these environmental and climate concerns were present in town planning of the past ([6] Péneau, 1998, [7] Guillerme, 1990, [8] Etlin, 1977). As we shall see, priorities in terms of the urban environment were not the same as they are today, as even people's perception of the quality of the urban microclimate was different ([9] Corbin, 1986), but they came close sometimes, such as during the sanitarian planning of the 19th century.

At that time, the city of Nantes, like most French towns, possessed very unhealthy urban spaces and dwellings inherited from its past development. In 1852, the members of the unhealthy dwellings commission ([10] Cherot et al., 1852) declared 24% of the homes in

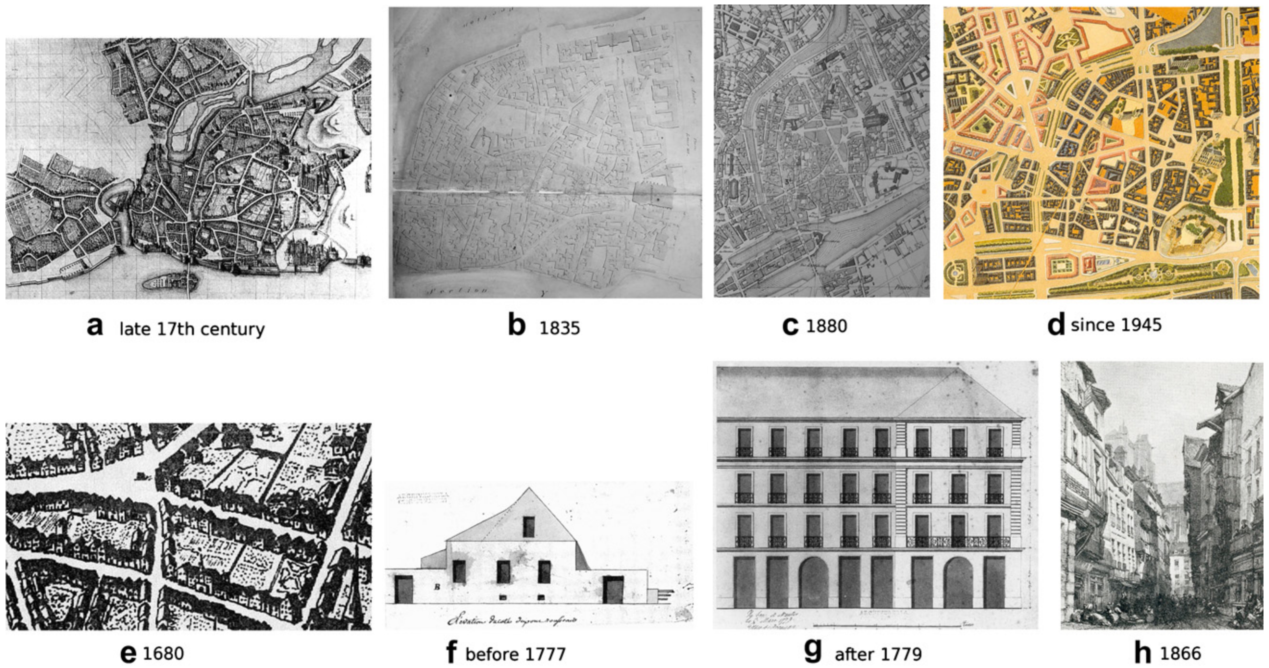
---

[*] Corresponding author. Tel.: +33 5 61 07 94 64; fax: +33 5 61 07 96 26.
E-mail addresses: mohamed.benzerzour@franck-boutte.com (M. Benzerzour), valery.masson@meteo.fr (V. Masson), d.groleau@free.fr (D. Groleau), aude.lemonsu@meteo.fr (A. Lemonsu).

[1] Present address: Agence Franck Boutté Consultants, 43 BIS, rue d'Hautpoul 75019 Paris, France.

[2] Retired.

0360-1323/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2011.01.014



a late 17th century **b** 1835 **c** 1880 **d** since 1945

e 1680 **f** before 1777 **g** after 1779 **h** 1866

Fig. 1. Plans of the city (top) and drawings (bottom) of Nantes from the 17th century to 1945.

the suburbs and the old centre uninhabitable for reasons of insalubrity. This insalubrity was mainly due to outdoor conditions. “ *The insalubrity of the dwellings stems not only from the conditions of existence specific to each one but […] , very often, also from external, permanent causes. The commission has come to recognise that the serious nature of the inside causes of insalubrity are almost always connected with that of the outside causes. It is in the badly ventilated, damp and dirty quarters that hygiene is most neglected in the dwellings. Similarly, this is also where the partial implementation of water systems would be the least effective*” (the original citations in old French are listed in Appendix A1). Given these causes, directly related to the morphology of the urban spaces, individual interventions on dwellings were thus deemed ineffective. Priority should therefore be given to transforming the spaces and structure of the city: *“Openings must be made in the quarters, streets must be widened, houses opened up, paving restored in the streets and the sewers drained”* ([10] Cherot et al., 1852; Appendix A2).

The aim of this study is to explore the impact of long-term town-planning policies on the urban microclimate and to present the interest of numerical approaches for this. It will focus on the example of the city of Nantes (France) for a period of 300 years. The major changes in the city from the 17th century to the present day are analysed using several historical sources presented in Section 2. Five periods corresponding to one or more major changes in terms of urbanization or systems (heating, sewers, etc.) are then identified (late 17th century, 1756, 1835, 1880 and 1945, cf. Section 3) and numerically simulated in order to estimate the potential impact of all these transformations on the urban climate (Section 4). Our conclusions are given in Section 5.

2. Historical analysis of the transformations to the city of Nantes

In this section, we present all the urban transformations that, according to the current understanding of urban climatology, could have led to changes in the urban microclimate. Some of them were set out explicitly to make the air cleaner in urban areas, while others were put forward in response to technical and safety priorities.

2.1. *Nantes in the 17th century: the pre-sanitarian city*

From the end of the Middle Ages, Nantes drew back within its ramparts (see the 1680 plan of the city in Fig. 1a) for security reasons. This way of life generated unhealthy conditions for population by favoring the stagnation of warm and damp air masses. Such conditions were however compatible with the economic activities, still based on advances in organic chemistry. They were even sought ([11] Olivier de Serres, 1600) because damp air and organic waste stored within the city itself were required for the fabrication of numerous products such as saltpetre (necessary for making gunpowder), textiles, leather and paper.

The southern part of the river Erdre in Nantes was bordered by streets, most of which were the filthiest of the city ([12] Wismes and Gaëtan, 1907, [13] Edouard, 1906). A veritable “open sewer”, the river Erdre had a microclimate that set it apart from the rest of the city. This is confirmed by a police order of 30th January 1572 (Nantes Municipal Archives). Dirty activities were concentrated around the Erdre, religious functions taking place in the North-East of the city, in a higher location and a good distance from the unhealthy air of the river ([14] Dubuisson, 1663, [15] Favre, 1977).

These variations in the microclimate were also measured sometimes. In 1852, a great difference in humidity, measured with a hair hygrometer,[3] was observed between the streets and courtyards of the Fosse district (densely built up with cramped urban spaces near the river Loire) and the Delorme district (a fairly wide boulevard). It reached 5–10% ([10] Chérot et al., 1852).

The change from the “stinking city” to the “polluted city” of the industrial era took place slowly, as people became aware of a whole series of questions: “*political and cultural, symbolic and everyday, scientific and technical, economic and environmental*” ([7] Guillerme, 1990). The change in military priorities meant that it was no longer

---

[3] The length of a human hair increases by 2 to 2.5% when the humidity of the air goes from 0 to 100%. The hair hygrometer was developed into an instrument (a sort of compass) that gave a direct reading of the relative humidity of the air quite simply.

necessary to take refuge in the morbid atmosphere of the inner cities. The appearance of inorganic chemistry led to a change in production techniques that no longer required a damp and unmoving atmosphere. The acceptance of this evolution toward a healthier city with an atmosphere characterized by its fast flow was only motivated by these new production techniques.

The change of context induced an evolution from a "passive attitude", where the only alternative was to adapt to the spatial variations of the urban microclimate, to an "interventionist position", which was expressed by the transformation of elements of the shape of the city.

2.2. *Increasing density of the urban centre*

Very few plans of the city before the 18th century, all archived in Nantes' Municipal Archives (NMA), are available today. The oldest is one drawn up by Nicolas Tassin and published in 1632 ([16] Bienvenu, 1989). Two other plans were then drawn, in 1716 (by Defer) and in 1722 (by Joualnoulx). The first geometrical plan of Nantes, established on site by "*a professional surveyor and topographer*", was drawn up by François Cacault in 1757. It is the first plan to very accurately plot the layout of the city as it was at the time. By cross-referencing information coming from plans of the city with those from illustrations of the buildings (Fig. 1), it was possible to form an idea of the growth of Nantes and the considerable increase in its density between 1650 and 1850, which were mainly due to:

- gardens between the houses being replaced by courtyards and, later, by buildings; and
- an increase in the number of storeys.

These changes, dictated by economic necessity and the need for safety (the city centre was surrounded by ramparts), thus led to a very dense urban fabric with very high buildings and narrow roads, which posed problems for public health.

The Police regulation of March 1696 thus points out: "*through the little regularity that was observed in past times in the Architecture and construction of the houses, most of the streets are extremely narrow, their entrances are so small that it is not possible to turn coaches or barrows into them*". (Appendix A3). In 1781, a ruling by the King's Council of State reveals that the narrowness of the streets (Fig. 2) results from the high prices of land:*"[…] The houses are very high there, the streets narrow, and the public squares small; and what will cause more surprise is that in all the Commerce quarter, which is the quarter where wealth is to be found, houses rented as dearly as in Paris […] There are only narrow alleys, almost impassable and even dangerous, being only three, four and five feet wide"* (NMA, DD. 225) (Appendix A4).

2.3. *Alignment and widening of streets*

The streets of Nantes, as in other towns of France, were aligned and widened, which simultaneously cleared and aired them and improved their accessibility ([17] Harouel, 1977).

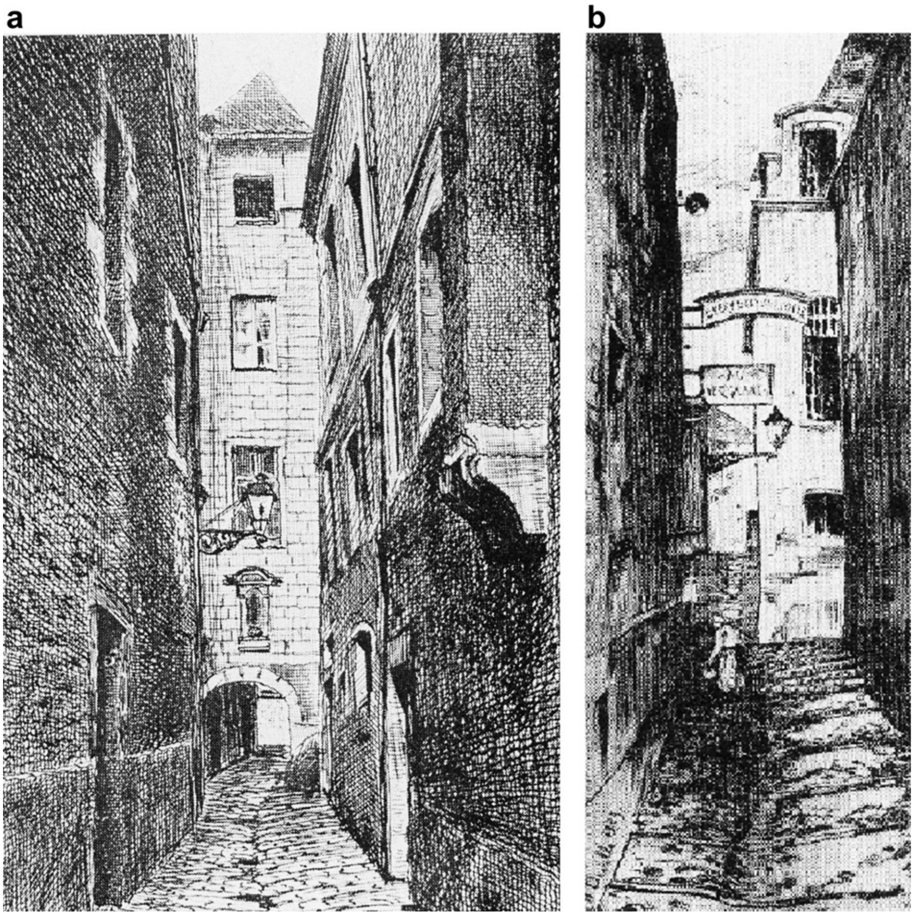


Fig. 2. Drawings of Nantes before the opening of streets in the late 19th century (from [18] Cosneau, 1978). (a) Narrow street; and (b) draining of water in the middle of the street.

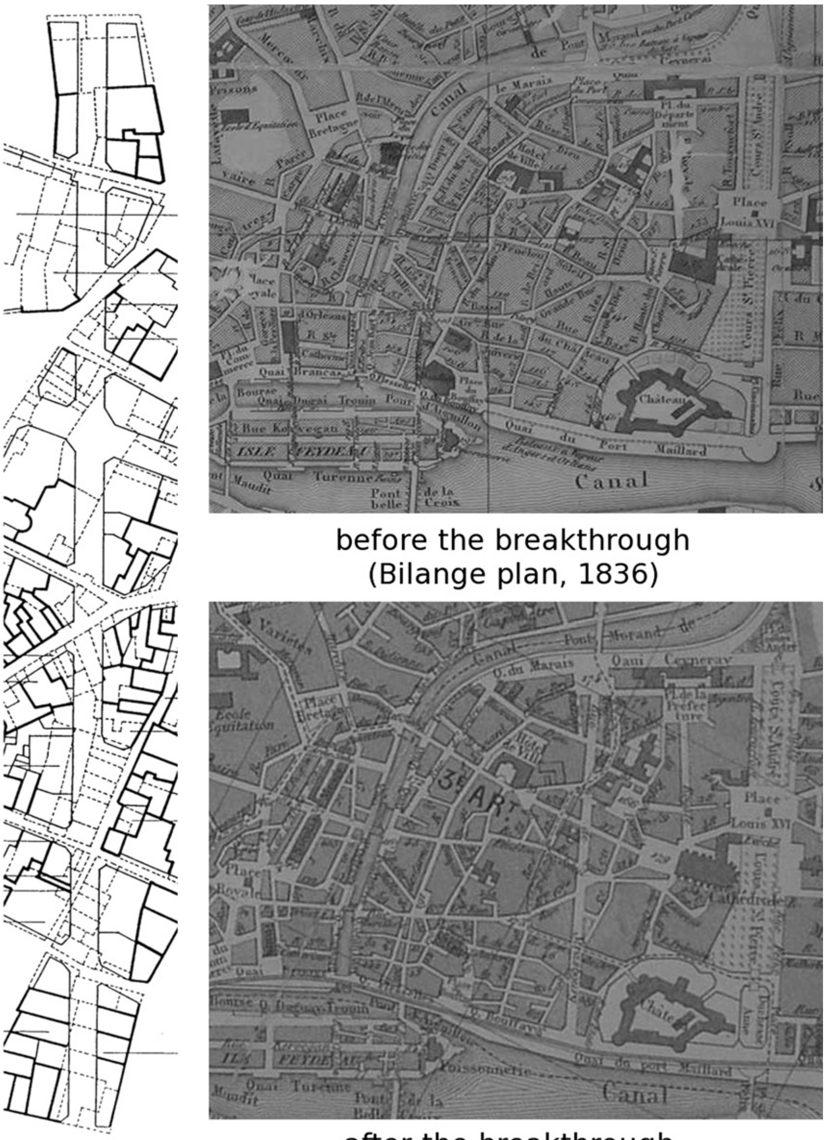
Mellier, the mayor of Nantes in 1720, had already written a “treatise on the rights of road management” as early as 1709 where his urban ideal is stated: “ *A town with straight, aligned streets appearing to be bordered by a single house”*. However, his projects were only to take shape in the suburbs and it was only in the next century, under the impetus of [10] Cherot (1852), that health necessities led to the widening of the streets in the city centre and the opening up of broad avenues (Fig. 3). These interventions caused the density of buildings to be reduced in the centre ([19] Darin, 1987).

2.4. *Creation of underground drainage networks*

En 1743 (NMA, DD 301) it was ordered that the streets of Nantes should be cleared of the gutters that stuck out too far from the walls. The slope of the ground of the paved streets was also stated. It was defined by a drop of six inches for a width of two toises (about 13 feet) from the facade of the houses so that water flowed properly into the central stream (Fig. 2b). Until 1870, water coming out of the houses was discharged directly on to the surface of the streets before eventually flowing into the few pipes that existed here and there ([20] Demoget, 1883). It was only after the police regulation of 10th June of that year that the laying of a complete network of underground drains was explicitly envisaged.

2.5. *Filling of ditches and rivers*

The sections of the two rivers crossing Nantes were gradually filled in within the city ([21] Bloyet, 1999). The Erdre (Fig. 4), a river that flowed very slowly because of its width, could not easily carry away all the matter that was thrown into it at the time. The ruling of the Council of State of 10th May 1723 for the cleaning of the river Erdre states: *“Full of refuse, by the actions of workers of the lowly trades, who bring waste matter resulting from their work and throw it in daily […] and that the butchers on one side of the said river also*



before the breakthrough
(Bilange plan, 1836)

after the breakthrough
(Jouanne plan, 1892)

Fig. 3. Breakthrough of the rue de Strasbourg in the old city centre.

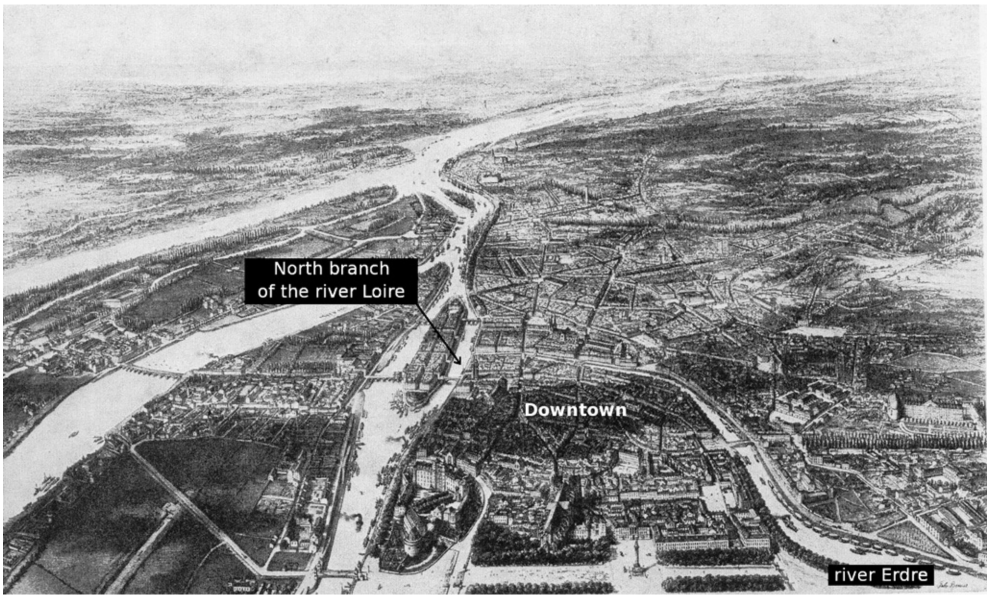


Fig. 4. Aerial view of the city of Nantes from a balloon in 1846 (from [18] Cosneau, 1978). The northern and southern branches of the Loire and also the Erdre have been filled in within the city today.

throw in the remains of their kills so that they cause this refuse to block the water course and prevent the mills from turning"[4] (Appendix A5).

Filling the East and West ditches around the old centre of Nantes and canalizing the Erdre were first envisaged by Ceineray (the city architect) in 1766 in his plan "*for the convenience and embellishment of the city of Nantes*" ([22] Lelièvre, 1988). Apart from these occasional operations canalizing parts of the Erdre and the Loire that concerned the city centre, the filling of water courses remained partial. It was not completed until the first half of the 20th century (Fig. 5).

2.6. Paving of the streets

On the need to pave the streets of Nantes, the oldest texts available in the city archives date back to the last quarter of the 15th century. A text from 1475 stipulates the requirement to:*"properly clean and scrape out, and pave so that water and infection do not stay there, and do this at both ends of this street so that it is not possible to carry or place any rubbish or infection there (…) Nantes, by the Duke, on the 14th day of April of the year 1475*" (Appendix A6). However, it was not until the first quarter of the 18th century that decrees imposed the obligation to pave all the streets of the city and stated precise regulations for the extent, layout and cost of the paving. Precautions were to be taking during the construction to ensure the resistance of the pavement to wear by coach and barrow traffic, which was on the increase at this time.

Finally, the highway regulations of 1899 stipulated that the inside courtyards should also be paved. Before these regulations came in, the main concern was that paving should make it easier to travel on and clean the streets but now it was the "waterproofing" of the paved areas that came to the forefront in judging their effectiveness: *"The ground covering in courtyards shall be waterproof and shall form slopes so that rain water can run off "* (Appendix A7).

2.7. Changes in building materials

The Nantes police regulation of March 1696, concerning *"the construction of houses"*, mentions, for the first time in a general regulation, the necessity to build in stone. In spite of the fact that the authorities of the time deemed this material to be more economical and more robust, it remained little used by builders, who preferred building with wooden sections (Fig. 6). But the main motive mentioned for replacing wood with stone was to combat fire. In 1725 a ruling of the King's Council of State (NMA, DD 329) explicitly forbid the construction of wood-frame buildings with anything other than non-inflammable materials: *"it is forbidden to all people in future to build new, repair or rebuild houses of the city of Nantes, and notably those of the Fosse quarter, otherwise than with cold stone masonry, brick or other materials not capable of catching fire, because the use of constructions in wood is the source of two ills, one the ease with which fires progress, that often consume several quarters of a town, as has unfortunately been seen in recent years in the city of Rennes; and the other the keeping the price of wood for framework higher than it should be"* (Appendix A8).

3. Definition of 5 major changes to the city from the 17th century to 1945

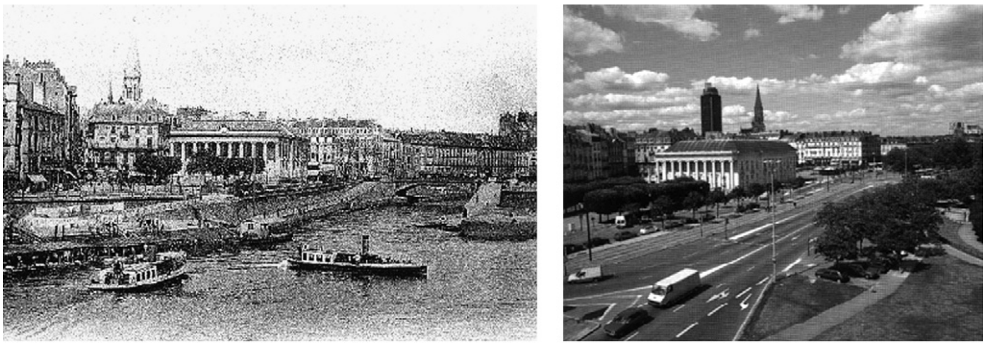
3.1. Method

To quantify the effects of urban changes on the local microclimate, we tried to define the evolution of the urban form of the old centre of Nantes by investigating the archives of the city. We encountered several difficulties linked with the availability and nature of the historical sources at our disposal (presented in Section 2 and in [23] Benzerzour, 2004):

○ Absence of sources over long periods.
○ Difficulty in superimposing sources because of the different graphical scales of plans and illustrations.

---

[4] In the same article, it is projected not only to clean the river Erdre but also to widen it by 12 feet and deepen it by 2 feet. [NMA, DD 167].



a Northern branch of the Loire before and after it was filled

b Filling in the Erdre (1940)

Fig. 5. Filling in the Loire and the Erdre (a) Northern branch of the Loire before and after it was filled. (b) Filling in the Erdre (1940).

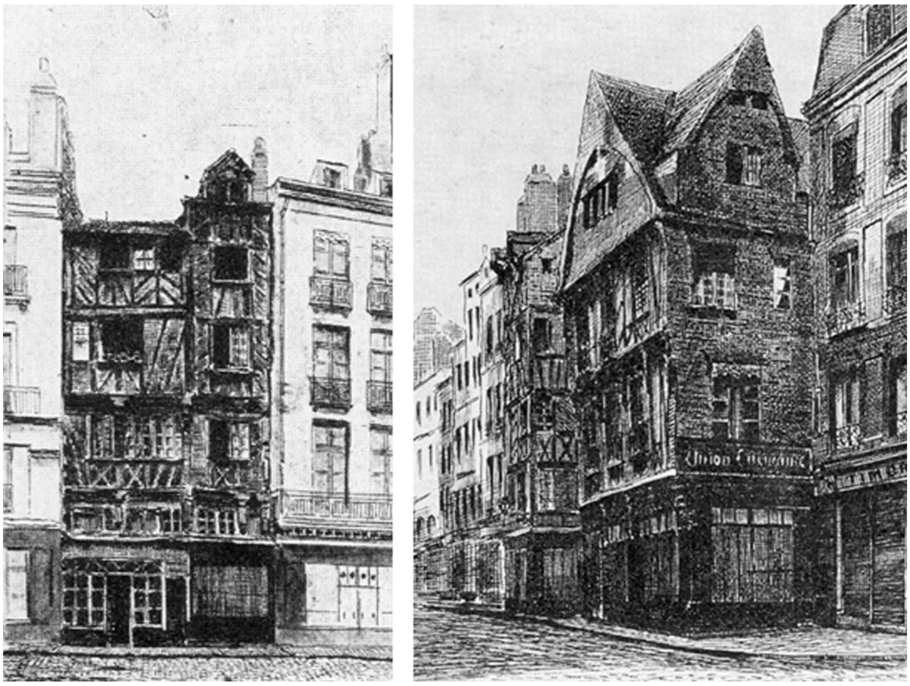


Fig. 6. Wood-frame houses (15th century).

○ Poor knowledge of the periods when transformations really took place at the scale of the city centre as a whole. The information is generally local and fragmentary.

Consequently, rather than an exhaustive description that is impossible here, we have chosen to define 5 states representative of changes to the city (Fig. 7), corresponding to approximately the end of the 17th century, 1756, 1835, 1880 and 1945. Having no precise information on the dates when urban transformations were carried out as they often occurred in parallel and over fairly long periods, we referred to the plans of the city, on which changes made to the shape of the city could be read. Finally, the last representative state of Nantes used here is that of 1945, before periurban districts began to grow, in order to consider the climatic effects connected with changes to the old city centre only, without the impact of geographical expansion on the urban heat island (UHI).

Apart from density of the built up areas and the building-height to street-width ratio, which changed at each state (except the last), the other transformations in the 5 states were:

State 1. Late 17th century: This represents the initial state of the old city centre before any intervention (see illustration in Fig. 1a and e). It is characterized by unpaved streets, low buildings of wood frame, and very low building density. To reconstruct the plan of the streets, we relied on the Cacault plan (1756).

State 2. 18th century (1756): This state highlights three main transformations: paved streets, the replacement of wood-frame buildings by stone ones, and buildings having been made higher.

State 3. Early 19th century (1835): Streets are starting to be aligned and widened, the ditches surrounding the centre have been filled and building is denser within each block. At the time of these sanitarian changes, the blocks of the old city centre simultaneously became more densely built up, more particularly by removing the gardens.

State 4. Late 19th century (1880): Following the instructions of the Cherot commission (1852), the street alignment and widening were conducted throughout the old centre, as well as the opening up of new sections of streets. During the same period, the inside courtyards were paved. We also assume that the network of water drained from the surface was buried under ground, even if this was not completely achieved for all the streets.

State 5. Post-World War Two: This last state representative of the changes made to the old city centre results from the filling in of the Erdre and the Northern branch of the Loire. Buildings were insulated.

3.2. Numerical reconstruction of the old plans of the city

The reconstruction of the old states of the centre of Nantes was performed by starting from its present state. The current plan of the city provided an "exact" representation of the city, on which "former" states could be superimposed. Once the 5 states had been reconstructed in a Geographic Information System (Fig. 8), the various morphological parameters (geometry, widths of streets, ground occupation by buildings/gardens, etc.) were computed locally for each street or block, and then averaged over the scale of Nantes city centre. Only these averaged parameters are then used in the microclimate simulations, in which a single area is representative of the whole city.

3.3. Urban parameters for the 5 states of the city of Nantes

The parameters concerning the urban (and rural) surfaces necessary for the simulations were defined for the 5 states and are summarized in Table 1. The details of the thermal characteristics taken for the building and road materials are given in Table 2. A few changes are particularly noteworthy:

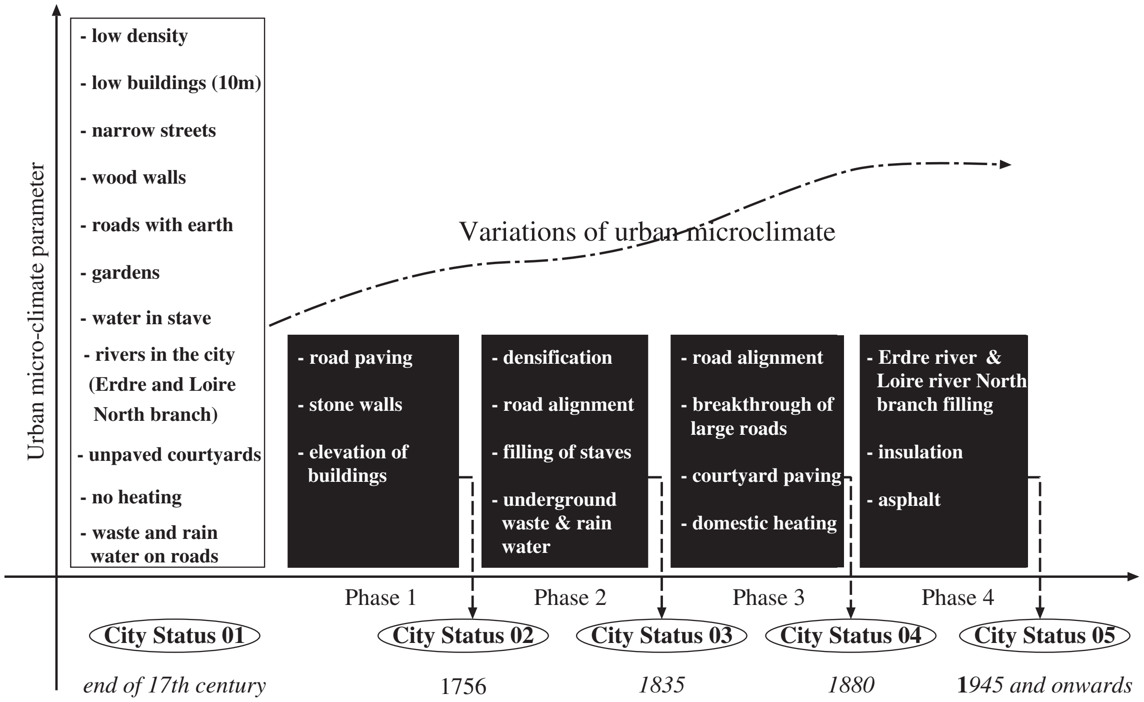


Fig. 7. Schematic overview of the 5 states representative of the city and the evolution from one to another.

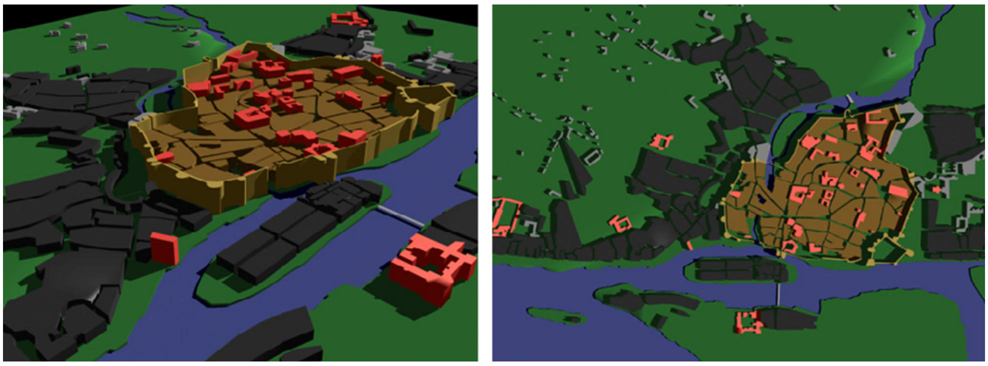


Fig. 8. Numerical reconstruction of the city of Nantes for 1756 (3D view and plan).

1. The surface areas of gardens and free water bodies decreased continuously over time.
2. Waste and rain water flowed on the street surfaces in states 1, 2 and 3 (1680, 1756 and 1835).
3. The surface areas occupied by buildings increased strongly up to 1835 (state 3, by increasing the density of building per block), then decreased slightly because of the opening of new streets.
4. Along with the area built up, the height of buildings increased, from 10 m (1680) to 21 m at state 3, to stabilize at a slightly lower value thereafter.
5. Through the combination of the two latter effects, the aspect ratio of the streets was maximum in state 3 (3.08) clearly indicating very narrow streets, and then fell to 2.22.

As far as gardens were concerned, the vegetation parameters were typical of those found in an oceanic climate. Vegetation was predominantly meadows with a leaf area index of between 0.5 and 2 depending on the season ([24] Lemonsu et al., 2007).

4. Simulation of evolution of the urban climate

4.1. Choice of the numerical model

Observational (in-situ measurement, thermal remote sensing, physical modelling) and numerical (urban canopy models, CFD at building- or city-scale) approaches each have limitations to study the UHI ([25] Mirzaei and Haghighat, 2010). Here, the lack of measurements over the studied period (3 centuries) has motivated the numerical approach. CFD models that are quite CPU expensive are not adapted to study the climate of the city over a long period of time ([25] Mirzaei and Haghighat, 2010). In addition, building-scale CFD has the drawback to discard atmospheric phenomena (as cloud and rain, often radiation). Furthermore, creating a database of

Table 1
Parameters for the simulations for all five city status.

Parameter	Unit	1680	1756	1835	1880	1945
Cover type relative fraction						
Urbanized surface	–	0.15	0.23	0.45	0.55	0.94
Vegetated courtyards	–	0.30	0.31	0.21	0.16	0.02
Other vegetation	–	0.34	0.25	0.18	0.13	0.02
Water bodies	–	0.21	0.21	0.16	0.16	0.02
Geometrical parameters						
Building height	m	10	15	21	19	19
Road width	m	5.7	5.7	6.8	8.5	8.5
Road aspect ratio	–	1.75	2.62	3.08	2.22	2.22
Building width	m	8	10	15	16	16
Building aspect ratio	–	1.25	1.50	1.41	1.19	1.19
TEB geometrical parameters						
Building fraction (relative to urbanized surface)	–	0.32	0.48	0.71	0.67	0.64
Roughness length	m	1.0	1.5	2.1	1.9	1.9
Wall surface / horizontal surface	–	0.8	1.44	2.	1.59	1.52
Radiative parameters						
Roof albedo	–	0.10	0.10	0.10	0.10	0.10
Wall albedo	–	0.20	0.25	0.25	0.25	0.25
Road albedo	–	0.15	0.11	0.11	0.11	0.08
Roof emissivity	–	0.92	0.92	0.92	0.92	0.92
Wall emissivity	–	0.88	0.85	0.85	0.85	0.85
Road emissivity	–	0.92	0.95	0.95	0.95	0.95
Construction materials						
Roof		Slate	Slate	Slate	Slate	Slate + insulation
Wall		Wood	Stone	Stone	Stone	Stone + insulation
Road		Unpaved	Paved	Paved	Paved	Asphalt
Anthropogenic parameters						
Minimum internal temperature	°C	10	10	10	19	19
Minimum water fraction on road (waste and rain water)	–	0.25	0.25	0.25	0	0

Table 2
Thermal parameters for the simulations for all five city status; d is thickness (m), C is heat capacity (MJ m^{-3} K^{-1}) and λ is thermal conductivity (W m^{-1} K^{-1}).

Layer	1680			1756			1835			1880			1945		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Roof	Slate	Wood	Wood	Dito			Dito			Dito			Slate	Wood	Insulation
d	0.01	0.05	0.05										0.01	0.10	0.15
C	2.00	0.52	0.52										2.00	0.52	0.04
λ	2.10	0.19	0.19										2.10	0.19	0.03
Walls	Wood frame	Wood frame	Wood frame	Stone	Stone	Stone	Dito			Dito			Stone	Stone	Insulation
d	0.10	0.10	0.10	0.02	0.15	0.33							0.02	0.48	0.10
C	1.47	1.47	1.47	1.54	1.54	1.54							1.54	1.54	0.04
λ	0.68	0.68	0.68	0.88	0.88	0.88							0.88	0.88	0.03
Road	Compressed soil	Compressed soil	Natural soil	Stone pavement	Stone pavement	Natural soil	Dito			Dito			Asphalt	Concrete	Natural soil
d	0.05	0.10	1.00	0.05	0.10	1.00							0.05	0.10	1.00
C	1.30	1.30	1.40	2.00	2.00	1.40							1.74	2.00	1.40
λ	1.00	1.00	0.40	2.10	2.10	0.40							0.82	2.10	0.40

buildings for the whole city for the past, as explained above, contained a lot of uncertainties.

We thus used an Urban Canopy Model (UCM). It is well suited because of its fast computing time, and some of its inherent limitations are not problematic for the present study. While the assumed shape of wind velocity usually present in such schemes may be a strong assumption, the fact that they are valid only for steady state solution (typically every hour), is not a problem here, as this is what is needed for long-term climate studies. Some atmospheric effects are neglected, but one can take into account radiation and rainfall. The assumption of a city with homogeneous arrays of buildings would have raised also because of the lack of completeness in the historical sources.

The UCM model chosen is TEB ([26] Masson, 2000). It takes into account all physical processes necessary to energy but also water exchanges with the atmosphere. The ISBA scheme ([27] Noilhan and Planton, 1989) simulates the exchanges between the plants and the atmosphere, and thus allows the role of gardens to be modelled here. Finally, the temperature of the Loire and the Erdre, which typically varies from 7 °C to 20 °C between winter and summer, is simulated using the Flake numerical scheme ([28] Mironov, 2008).

No meteorological data were available to validate the model against observations for the old centre of Nantes, even for recent times, but the TEB-ISBA models have been intensively validated elsewhere for contemporary urban environments ([26] Masson, 2000, [29] Masson et al., 2002, [30] Lemonsu et al., 2004, [31] Hamdi and Masson, 2008, [32] Leroyer et al., 2010, [33] Lemonsu et al., 2010). Typical error of the model ranges between 5 and 20 W m^{-2} on the radiative, turbulent and storage energy fluxes (around 5% of relative error when compared to available energy). Furthermore [24] Lemonsu et al., 2007 validated TEB on a suburban catchment in Nantes, using the same 6 years of data as will be used here. All this gives confidence to the evaporation / sensible heat / storage partition.

The latest developments of TEB ([34] Masson and Seity, 2009, [31] Hamdi and Masson, 2008) explicitly simulate temperature, moisture, wind and turbulence vertical profiles in the streets and above, using a 1D vertical turbulence scheme. Using observations of BUBBLE experiment ([35] Rotach et al., 2005), errors on mean wind are less than 0.2 m/s (relative error of 20% near the road and less than 15% upper in the canyon and above) and error on temperature 3 m above road is 0.35 K ([31] Hamdi and Masson, 2008). Only simulated microclimate variations larger than these model errors will be discussed hereafter. The removal of the velocity assumed shape in the canopy layer makes this model particularly suitable for the study of urban microclimates.

4.2. Setup of simulations

The objective here was to quantify the contribution made by urban policies to the microclimate, in particular changes initiated in the mid-19th century by the sanitarians to cure the unhealthy environment that had been developing since the late 17th century following the increasing density of urban building. Therefore, the urban microclimate of Nantes was first simulated for 5 states of the city under the same climate. The meteorological conditions are based on the mean climate of the 19th century (see Appendix B), chosen as being an intermediate time slice to the 5 periods studied (from 1680 to 1945).

However, since climate also changed during the 3 centuries of focus, an additional set of simulations was performed, taking into account the mean monthly temperature anomalies of each decade corresponding to the 5 states of the city (Appendix B). Comparing the two sets of simulations allowed to quantify the relative effects of urban changes and climate change.

5. Results

5.1. Impact on energy fluxes between city and atmosphere

Cities create their own microclimate, mainly by modifying the energy exchanges with the atmosphere above. For this reason, we will consider these energy exchanges first. In the countryside, there is generally one source of energy: the sun, completed by infrared radiative losses governed by the temperatures of the air and the surface. This available energy is called the “net radiation” and is noted Q^*. In cities, an additional source of energy, Q_F, comes directly from human activities (heating or air-conditioning and, to a lesser extent, road traffic). All this energy ($Q^* + Q_F$) is released in three forms[5] ([36] Oke, 1982):

$$Q^* + Q_F = Q_H + Q_E + Q_S$$

One part, Q_H, is released into the atmosphere in the form of heat and serves to increase the temperature of the air (or limit the cooling caused by the rural environment, which explains the night-time heat island). Another part, the evaporative flux, Q_E, serves to evaporate the water on (or in) the ground. This increases the humidity of the air and limits its warming (since there is less energy for Q_H). Finally, any energy left serves to heat the surfaces

---

[5] Because the entire city is simulated, the lateral advective effects can be neglected [36].

themselves. During the night, this term becomes negative and the surfaces cool down, returning a part of the energy stored in the day back to the atmosphere. This energy storage/release term is larger for areas without vegetation, and particularly for buildings and roads, as stone and asphalt can store a considerable amount of heat.

The TEB and ISBA (for gardens) models are capable of simulating how this energy is distributed. The evolution of the various terms between 1680 and 1945 is thus estimated by the model.

The net radiation, Q^*, changes little from one simulation to another, mainly because the meteorological conditions (sunlight, clouds) are the same for all 5 simulations. We thus pay attention to the daytime partitioning between Q_H, Q_E and Q_S (Fig. 9):

- The heat flux Q_H significantly increases (compared to model uncertainty of 5% on normalized fluxes) regularly from the mid 18th to the 20th century. The evaporation energy flux strongly decreases continuously.
- The greatest variation of Q_E (decrease) and Q_S (rise) occurs in the last period, because of the drastic decrease in vegetation and river areas, replaced by stone or asphalt. Evaporation also lessened considerably when the sewer networks were buried underground.
- The heat flux Q_H increases the most between 1835 and 1880. Note that only part of this increase is compensated by a decrease in evaporation. This indicates that a new source of energy has appeared: domestic heating was installed in most of the city of Nantes during this period. Heating is used most in winter, leading to stronger warming, but it is notable in all seasons (the air temperature is 19 °C on average in summer in this oceanic climate). In addition, the fact that the walls were not insulated in 1880 and were heated from the inside meant that wall heating from the outside could be less strong (lowering of Q_S in autumn and winter).
- There is no other seasonal dependency.
- For the period 1680 to 1945, the impact of climate change relative to urban changes on energy fluxes is negligible: it is smaller than 2% for all fluxes, except for Q_S during the cold winters of the decade around 1680, which reaches 5% (not shown). This can be explained by the fact that the energy balance is mainly driven by the incoming solar radiation.

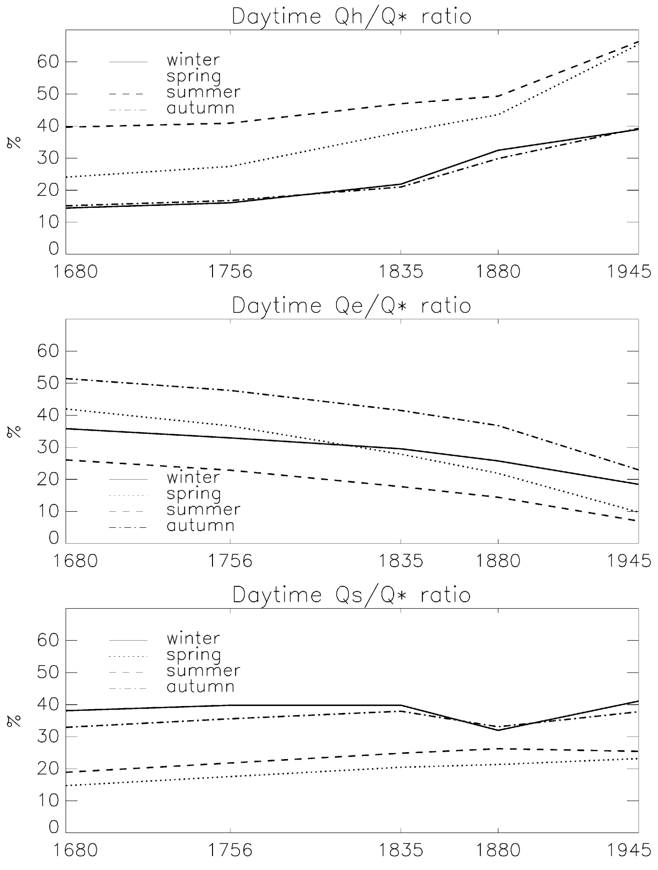


Fig. 9. Variation of Q_H/Q^*, Q_E/Q^* and Q_S/Q^* for each season according to the state of the city of Nantes.

5.2. Impact on the microclimate

In order to evaluate the impact of sanitarian action on the urban microclimate, the mean variation of the standard meteorological parameters (temperature, humidity, wind) was calculated for each time period, both at the scale of an urban canyon and at the scale of the city, taking account of gardens and rivers.

The mean annual air temperature (Fig. 10) simulated for the whole old city centre of Nantes is similar to that of the countryside in the 17th century (the fraction of built-up land being very small). Unexpectedly, while the city density increases, it remains stable until 1835 (usually denser cities show higher UHI, see the review by [37] Souch and Grimmond, 2006, and vegetated spaces are cooler, [38] Bowler et al., 2010). This is in part due to the presence of wastewater on roads, and to the extreme narrowness of the streets at that time: it prevents sunlight from penetrating into them. This leads to a temperature drop inside the street. The temperature then

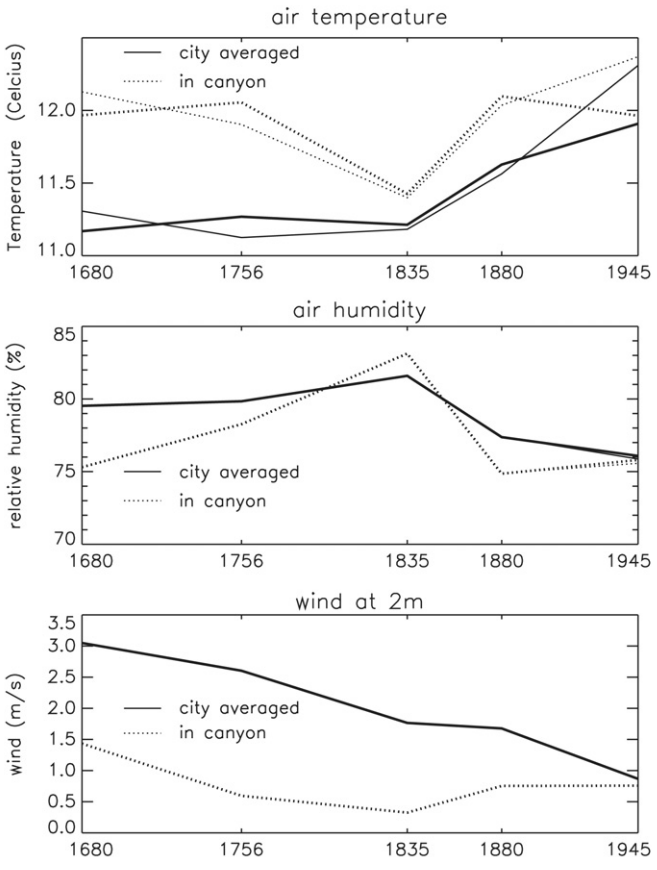


Fig. 10. Urban climate of the city of Nantes (top: temperature; middle: humidity; bottom: wind). Dotted line: air in the streets; and solid line: average air in the city. Bold lines are for simulations describing only urban impacts. Thin lines are for simulations with both urban and climate variation impacts.

rises again, to reach a total increase of almost 0.8 degree. A phase of stronger warming seems to appear. This rapid warming phase (about 0.1 degree per decade) occurs in the middle of the 19th century, when domestic heating becomes common throughout Nantes city centre. This strongly reinforces the heat flux (Fig. 9) and the air temperature in the canyon. Finally, the simulated temperature rises until 1945 but more slowly because of the spread of building insulation.

Relative humidity is smaller in cities ([39] Liu et al., 2009, [40] Unkasevic et al., 2001). By day there is less evaporation ([41] Deosthali, 2000, [42] Kopec, 1973). By night the larger urban temperature maintains lower relative humidity, even if water loss by dewfall is limited ([43] Mayer et al., 2003, [44] Richards, 2005). [45] Kim et al., 2009 showed that the restoration of the inner river in Seoul indeed decreased temperature and increased humidity. Then, given the tendencies on evaporation and temperature due to Nantes densification, we could expect a continuously decreasing humidity over centuries. The variation of the simulated humidity over the centuries is somewhat different (Fig. 10).

The 17th century is relatively humid as the area of vegetation and gardens is large. The paving of the streets would have tended to reduce the humidity slightly between 1680 and 1756 but this trend is masked by the narrowing of the streets, which reduces their ventilation and thus prevents the humidity from escaping. The continuous rise in the density of the city centre and the increase in the number of storeys (and thus in the building-height to street-width ratio) tend to make the air more humid until 1835. The 3% difference in humidity between the air in the unhealthy streets and the average for the city leads to a difference of about 7% (the built-up fraction being about 0.45 at the time) with the driest areas of the city. These, well ventilated, areas are gardens or no doubt – but this is not simulated explicitly – the rich quarters on the high ground. This value of 7% is consistent with the only measurement available, that of [10] Cherot in 1852, indicating differences of between 5% and 10%. It is only when the sewers were buried under ground in the mid-19th century that the humidity in the streets falls drastically (by about 9% for the annual average). The city then becomes dryer than the surrounding countryside. Finally, the humidity decreases until 1945 through the disappearance of the last areas not previously converted for human use.

The mean wind in the streets decreases as the city becomes denser, up the 1850s when the sanitarians undertook the widening and opening up of streets. The model then reproduces greater ventilation of the streets, which had been foreseen by the town planners of the time in order to purify the air.

The past climate variations do not show a significant influence on the microclimate. Before the 20th century, the air temperature variations due to climate variations (thin lines on Fig. 10) are less than 0.15 °C, and the effects of urban modifications dominate. It is only for 1945 that the climate impacts the temperature significantly: it increases the air temperature in the street by 0.4 °C, adding its effect to the air warming caused by the urban densification.

6. Discussion and conclusions

A numerical approach based on the TEB model was used to simulate the energy behaviour and the urban microclimate of Nantes for 5 states from 1680 to 1945. The historical information (plans, illustrations, statutory documents) was incorporated in a Geographic Information System so that the general characteristics of the city could be determined at the different dates and used to initialize TEB.

The effects on energy exchanges between the city and the atmosphere were the conventional ones: an increase in the heat fluxes and in heat storage and decrease of evaporation as the amount of mineral mater in the city gradually increased. A strong increase was noted in the heat flux, notably in winter, when domestic heating became generalized.

The evolution in terms of urban microclimate was, however, more surprising. Although it could have been expected that the temperature would rise (and the humidity fall) continuously as the overall mineral cover of the city increased, this was not what the simulations showed nor what was observed by the Cherot commission of 1852.

Firstly, between the late 17th century and the 1850s, the increasing density of the city led to weak ventilation of the streets. The temperature of the air in the streets, at the pedestrians' level, became coolest in 1835. As the streets became very narrow sunlight hardly reached the paved surface, which thus remained cool, like the air immediately above it. Because of the lack of ventilation and of the continuing presence of rain- and wastewater on the pavement, the humidity of the air, already high, increased more and more. We recall that this was necessary for the city's economy, partly based on organic chemistry. At this time, higher density went hand in hand with higher humidity of the air.

The simulations then show how the sanitarian changes undertaken helped to ventilate and dry the streets (the wind doubled on average because of street widening). The temperature rose in the city because, on the one hand, of the wider streets that let in the sunshine as the sanitarian town planners wanted and, on the other hand, of the general spread of domestic heating. From this time on, denser building meant warming and drying of the air.

This study gives a good indication of how town-planning actions can, in the long term, influence the urban climate. In particular, the fact that the study concerned a real city that already existed and a sufficiently long past period of over three centuries demonstrates that it is possible to implement consistent town-planning policies with what, today, would be called environment protection objectives. This policy, launched by the sanitarians, is here based both on targeted actions (like filling in the rivers or building boulevards) and on regulations (defining building-height to street-width ratio, construction techniques and materials, underground sewer systems).

Such studies could also be useful, no longer for looking at the past but for forecasting the future and quantifying the contributions to the urban microclimate (and the associated well-being of the population) of various town-planning projects at the scales of towns or wider urban areas (ancient or modern). For each town, this would help to set up a very long-term view of town-planning actions depending on the challenges, some of them environmental, to be faced.

Appendix A. Original citations in old French

A1: *" L'insalubrité des logements tient non-seulement à des conditions d'être particulières à chacun d'eux, mais, […] , très souvent aussi à des causes extérieures et permanentes. La commission a été conduite à reconnaître que la gravité des causes intérieures d'insalubrité était presque toujours en rapport avec celle des causes extérieures. C'est dans les quartiers mal aérés humides et sales que l'hygiène des logements est la plus négligée. C'est là encore que les mesures partielles d'assainissement auront le moins d'efficacité ".*

A2: *"Il faut effectuer des percements dans les quartiers, élargir les rues, ouvrir les habitations, rétablir le pavage des rues et assainir les égouts "*

A3: *"par le peu de régularité qui a été observé anciennement dans l'Architecture et construction des maisons, la plupart des rues sont extrêmement resserrées, l'entrée de celles ci étroite, qu'il n'est pas possible d'y tourner les carrosses et les charrettes".*

Table B1
Monthly temperature anomalies in Paris and the North of France for the periods studied (baseline: 19th century climate), after [46] Rousseau 2009.

Temperature anomaly (°C)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	annual mean
1676–1685	−0.77	−1.07	0.29	0.48	1.49	0.78	0.43	0.07	0.3	0.72	−0.67	−0.4	+0.14
1750–1759	0.24	−0.33	0.37	−0.27	−0.24	0.41	0.45	−0.23	0.11	−0.43	−0.74	0.11	−0.05
1830–1839	−0.95	0.13	0.11	−1.04	0.19	0.69	0.45	0.12	−0.5	0.52	0.32	−0.28	−0.02
1875–1884	0.13	0.74	0.64	−0.16	−0.05	−0.25	−0.21	0.32	−0.28	−0.59	−0.16	−0.69	−0.05
1940–1949	−0.51	−0.53	1.19	1.29	0.27	−0.06	0.62	0.46	0.81	0.12	0.16	−0.06	+0.31
1990–1999	2.39	1.16	2.18	0.29	1.07	−0.11	1.31	2.1	0.52	0.55	0.88	0.15	+1.04

A4: "*[…] Les maisons y sont très élevées, les rues étroites, les places publiques petites ; et, ce qui causera encore plus d'étonnement, c'est que dans tout le quartier du commerce, qui est celui de la richesse, des maisons louées aussi chèrement qu'à Paris […] Ce ne sont que des ruelles étroites, presque impraticables et même dangereuses, n'ayant que trois, quatre et cinq pieds de large*"

A5: "*Remplie d'immondices, par le fait des ouvriers des basses œuvres, qui auraient porté les matières qu'ils en tirent et les jetaient journellement […] et que les bouchers d'un côté de la dites rivière y jettent pareillement les débris des tueries qu'ils font en sorte que ces immondices empêchent le cours de l'eau et le virement des moulins* "

A6: "*bien nectoyer et curer, faire baulcer et paver en manière que les eaux et infections n'y demeurent, et faire es deux boutz d'icelle rue et faczon que l'on ny puisse porter ne mectre aucuns bourriers ne infections (…) A Nantes, par le duc, le 14e jour d'avril, l'an 1475* ".

A7: "*Le revêtement de sol des cours et courettes sera imperméable et formera des pentes pour l'évacuation des eaux pluviales* ".

A8: "*défenses à toutes personnes de bâtir à neuf, réparer ou réédifier à l'avenir les maisons de la ville de Nantes, et notamment celles du quartier de la Fosse, autrement qu'avec des maçonneries de pierre froide, de briques et autres matières non sujettes à s'enflammer, parce que l'usage des constructions en bois opère deux maux, l'un la facilité des progrez des incendies qui consument fort souvent plusieurs quartiers d'une ville, comme on l'a vu malheureusement arriver les années dernières à la ville de Rennes ; et l'autre à maintenir le prix des bois de charpente plus haut qu'il ne devrait estre* ".

Appendix B. Reconstruction of the meteorological forcing for the past centuries

Continuous records of temperature are not available before the mid-19th century when the first meteorological observatories started (such as London or Paris). For Nantes, the meteorological conditions over the past centuries are rebuilt by combining recent meteorological data, available at a high temporal frequency and with high accuracy, with climate anomalies measured or estimated for our study period (from 1680).

The present data forcing period come from observations collected from 1993 to 1998 at Nantes airport meteorological station (temperature, humidity, wind, pressure and solar radiation, every hour). Rainfall was measured every 5 min over the same 6-year period by the Laboratoire Central des Ponts et Chaussées.

Climatic anomalies are derived from the works of [46] Rousseau (2009). He combined several time series of manual and automated measurements done in Paris from 1676 to 2008 in order to estimate mean monthly temperature anomalies. The data homogenization was performed using the dates of harvest in Burgundy vineyards. By comparing these data with measurements done in England and Netherlands, [46] Rousseau (2009) showed that mean monthly anomalies are homogeneous over an area of 500 km around Paris. So we can apply them for Nantes (see Table B1).

The air temperature forcing used in our urban sensitivity simulations (without considering climate changes between the 5 periods studied) corresponds to the 19th century mean climate, obtained by removing from the 1993–1998 time series the monthly anomalies calculated over the 1990–1999 decade. The additional effect of past climate is studied by adding to the mean forcing of the 19th century baseline the monthly temperature anomalies calculated for the decades of the 5 periods studied. For the first 4 periods, temperature variations are very small (+0.14 °C, −0.05 °C, −0.02 °C, −0.05 °C, on average over each decade respectively). The last decade 1940–1949 is a little warmer (+0.31 °C on average).

As only temperature records were available for the past centuries, climate changes rely only on temperature and temperature dependent parameters. In terms of incident infrared radiation, it is estimated as a function of temperature following [47] Prata (1996). Absolute humidity is calculated by keeping relative humidity unchanged. Wind and precipitation are not modified. Solar radiation variations due to sun activity and volcanic eruptions are lower than 0.4 Wm^{-2} ([48] Swingedouw et al., 2010), which has a negligible impact at the urban scale.

References

[1] IPCC. Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007. 996 pp.
[2] Lion Y, et al. Ce qui serait extraordinaire serait d'améliorer l'ordinaire. Paris: Ateliers Lion; 2009. 300pp, in French.
[3] Goldstein GS, Moses LN. A survey of urban economics. J Econom Liter 1973; 11(2):471–515.
[4] Grazi F, van den Bergh JCJM. Spatial organization, urban transport and climate policy: comparing instruments of spatial planning and policy. Ecol Econ 2008;67(4):630–9. doi:10.1016/j.ecolecon.2008.01.014.
[5] Balaras CA, Grossman G, Henning HM, Infante Ferreira CA, Podesser E, Wang L, Wiemken E. Solar air conditioning in Europe – an overview. Renew Sustain Energy Rev 2007;11:299–314.
[6] Péneau JP. Quelques éléments sur l'aérisme et l'ajustement climatique de la ville au siècle des lumières. PhD thesis, University of Nantes, Faculty of sciences et des techniques, Nantes; 1998, 432 p. [in French].
[7] Guillerme A. Les temps de l'eau: la cité, l'eau et les techniques. coll. Milieux Macon: Champ vallon; 1990. 263 p.
[8] Etlin R. L'air dans l'urbanisme des lumières. revue Dix-huitième siècle 1977;n° 9:123–34. le sain et le malsain, Garnier, Paris.
[9] Corbin A. Le miasme et la Joncquille, l'odorat et l'imaginaire social XVIIIème XIXème siècles. Champs Flammarion; 1986. 336 p.
[10] Cherot A, et al. Travaux de la commission pour l'assainissement des logements insalubres. Imp. Mangin. Nantes: Bibliothèque municipale de Nantes; 1852. 92 p.
[11] De Serres O. Le théâtre d'agriculture, Paris; 1600.
[12] Wismes, Gaëtan. Commentaire étymologique des notices sur les rues, ruelles, cours, impasses, quais, ponts, boulevards, places et promenades de la ville de Nantes, Lafolye Vannes; 1907.
[13] Edouard P. Notices sur les rues, ruelles, cours, impasses, quais, ponts, boulevards, places et promenades de la ville de Nantes. Fonds local Bibliothèque Municipale de Nantes; 1906.
[14] Dubuisson A. Itinéraires de Bretagne. Nantes Municipal Archives; 1636.
[15] Favre R. Du "médico-topographique" à Lyon en 1783. revue Dix-huitième siècle 1977;n°9:151–60. le sain et le malsain, Garnier Paris.
[16] Bienvenu G. Architecture de la ville et réglementation urbaine, V1: les textes réglementaires à Nantes aux XVIIIème, XIXème et XXème siècles. Nantes: School of Architecture; 1989.
[17] Harouel JL. Les fonctions de l'alignement dans l'organisme urbain. revue Dix-huitième siècle 1977;n° 9:135–50. le sain et le malsain, Garnier Paris.
[18] Cosneau C. Iconographies de Nantes. Exhibition catalogue. Nantes: Musée Dobrée; 1978.

[19] Darin M. Alignement des rues (Nantes). , Nantes: B.R.A, School of architecture, CERMA; 1987. 99 p.
[20] Demoget. Rapport de l'architecte en chef de la ville: De l'alimentation de la ville de Nantes au moyen des eaux de la Loire, du nettoiement de la voie publique, de l'assainissement des habitations et de l'entretien des chaussées, Nantes; 1883, 51 p.
[21] Bloyet D. Erdre et Loire les travaux de Comblement. coll. Nantes les dossiers de la mémoire, édit. Angers: CMD; 1999. 36 p.
[22] Lelievre P. Nantes au XVIIIe siècle urbanisme et architecture. Picard; 1988. 295 p.
[23] Benzerzour, M., 2004. Transformations urbaines et variation du micro-climat: application au centre ancien de Nantes et proposition d'un indicateur morpho-climatique. Ph.D. thesis, School of architecture, Nantes, 300 pp.
[24] Lemonsu A, Masson V, Berthier E. Improvement of the hydrological component of an urban SVAT model. Hydrol Proces 2007;21:2100–11.
[25] Mirzaei PA, Haghighat F. Approaches to study urban heat island – abilities and limitations. Build Environ 2010;45:2192–201.
[26] Masson V. A physically-based scheme for the urban energy budget in atmospheric models. Bound Layer Meteorol 2000;94:357–97.
[27] Noilhan J, Planton S. A simple parameterization of land surface processes for meteorological models. Mon Weather Rev 1989;117:536–49.
[28] Mironov DV. Parameterization of lakes in numerical weather prediction. Description of a lake model. COSMO technical report, No. 11. Offenbach am Main, Germany: Deutscher Wetterdienst; 2008. 41 pp.
[29] Masson V, Grimmond CSB, Oke TR. Evaluation of the town energy balance (TEB) scheme with direct measurements from dry districts in two cities. J Appl Meteorol 2002;41:1011–26.
[30] Lemonsu A, Grimmond CSB, Masson V. Modelling the surface Energy Balance of an old Mediterranean city core. J Appl Meteorol 2004;43:312–27.
[31] Hamdi R, Masson V. Inclusion of a drag approach in the town energy balance (TEB) scheme: offline 1-D validation in a street canyon. J Appl Meteorol Climatol 2008;47:2627–44.
[32] Leroyer S, Mailhot J, Bélair S, Lemonsu A, Strachan I. Modeling the surface energy budget during the thawing period of the 2006 montreal urban snow experiment. J Appl Meteorol Climatol 2010;49(1):68–84.
[33] Lemonsu A, Bélair S, Mailhot J, Leroyer S. Evaluation of the town energy balance model in cold and snowy conditions during the montreal urban snow experiment 2005. J Appl Meteorol Climatol 2010;49(3):346–62.
[34] Masson V, Seity Y. Including atmospheric layers in vegetation and urban offline surface schemes. J Appl Meteorol Climatol 2009;48(7):1377–97.
[35] Rotach M, Coauthors. BUBBLE – an urban boundary layer meteorology project. Theor Appl Climatol 2005;81:231–61.
[36] Oke TR. The energetic basis of the urban heat island. Quart J Roy Meteorol Soc 1982;108:1–24.
[37] Souch C, Grimmond CSB. Applied climatology: urban climate. Prog Phys Geogr 2006;30(2):270–9.
[38] Bowler DE, Buyung-Ali L, Knight TM, Pullin AS. Urban greening to cool towns and cities: a systematic review of the empirical evidenc, Landsc Urban Plan 2010;97(3):147–55.
[39] Liu W, You H, Dou J. Urban–rural humidity and temperature differences in the Beijing area. Theor Appl Climatol 2009;96(3–4):201–7.
[40] Unkasevic M, Jovanovic O, Popovic T. Urban–suburban/rural vapour pressure and relative humidity differences at fixed hours over the area of Belgrade city. Theor Appl Climatol 2001;68:67–73.
[41] Deosthali V. Impact of rapid urban growth on heat and moisture islands in Pune City, India. Atmos Environ 2000;34:2745–54.
[42] Kopec RJ. Daily spatial and secular variations of atmospheric Humidity in a small city. J Appl Meteorol 1973;12:639–48.
[43] Mayer H, Matzarakis A, Iziomon MG. Spatio-temporal variability of moisture conditions within the urban canopy layer. Theor Appl Climatol 2003; 76:165–79.
[44] Richards R. Urban and rural dewfall, surface moisture, and associated canopy-level air temperature and humidity measurements for Vancouver, Canada. Bound Layer Meteorol 2005;114:143–63.
[45] Kim K, Kwon T, Kim Y-H, Koo H-J, Choi B-C, Choi C-Y. Restoration of an inner-city stream and its impact on air temperature and humidity based on long-term monitoring data. Adv Atmos Sci 2009;26:283–92.
[46] Rousseau D. Paris temperatures: monthly means 1676 to 2008. La Météorol 2009;67:43–55 [in French].
[47] Prata A. A new long-wave formula for estimating downward clear-sky radiation at the surface. Quart J Roy Meteor Soc 1996;122:1127–51.
[48] Swingedouw D, Terray L, Cassou C, Voldoire A, Salas-Mélia D, Servonnat J. Natural forcing of climate during the last millennium: fingerprint of solar variability. Clim Dyn; 2010; doi:10.1007/s00382-010-0803-5.

Documents from Nantes municipal archives, ancient collection before 1790

Historical information used in this study mainly came from plans and illustrations. Statutory texts, for example, were used as a basis on the assumption that they were the expression of what was done in the city. This was the case for the regulations for paving the streets, the use of stone for rebuilding and the limits on the height of buildings.

- All the ancient plans are listed in: CHAPALAIN-NOUGARET, Ch. (1985). Cartes et plans des séries anciennes de Nantes (AA-II), Impr. de la Ville de Nantes, ARCHIVES MUNICIPALES DE NANTES.
- Series C 325: town planning and general plans
- Series C 327 to 330, 334 to 337, 340 to 344, and 348 to 355: by quarter
- Series Fi 2 to 20: photographs of ancient plans of the city of Nantes.
- Series II: series comprising maps, plans and picture documents
- Series DD: construction and maintenance works for buildings, highways, water courses, civil engineering constructions.
- Series I: police and public health regulations.
- Series O: technical services, civil engineering and road works.