“In and Out Air Strategies. From Climate Change to Microclimate. Library, Archives and Museum Preservation Issues”

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http://www.ifla.org/VI/4/pac.htm
Microclimate and air pollution in the Louvre Palace

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### The Louvre: some historical data

The construction of the Louvre has been performed in a continuous manner from the 12th to the 20th Century, from *Philippe-Auguste* to *Mitterrand*.

- **1180**: construction of a fortress along the river Seine by *Philippe-Auguste*.
- **1546**: destruction of the fortress, construction of the first aisle of the future Cour Carrée by *François Ier*.
- **1624-1670**: the Cour Carrée is completed by *Louis XIII* and *Louis XIV*…

- **1852-1870**: the Pavillon Richelieu and the Cour du Ministre (future Cour Marly) are constructed by *Napoléon III*…

- **1958-1962**: 1rst general cleaning of the Louvre façades planned by *A. Malraux*.
- **1984-1988**: “Grand Louvre Programme” and construction of the “Louvre Pyramid” ordered by *Mitterrand*. The Cour Marly is dedicated to the sculptures originally at the Marly Castle near Saint Germain and Versailles.
- **1985-1996**: 2nd general cleaning of the façades and statues.
1- Statue of Apollo: Air pollution

2- Cour Marly: Microclimate

Philippe-Auguste fortress
1 - The statue of Apollo: a record of the Parisian air pollution history

- In Carrara marble
- Dating from the middle of the 19th Century
- Exposed in a niche, *sheltered from rain*

- 1985: *white* because cleaned by dry sandblasting
- 1985 to 1994: turned to *grey* by dust deposition (soiling)
- 1994: the right hand was broken by a vandal and found at the foot behind the statue
In 1994...

...the surface of the statue is grey...

...except the broken arm which is white...

...and the hollow of the hand, which is black...

In 2004...

...the section of the arm has turned from white to grey due to new dust deposition (soiling)...

In 2009
The black crust in the hollow of the Apollo’s hand

Probably formed before the 1st cleaning (1962) or, less probably, between the 1st and the 2nd cleaning (1962 to 1985)

- 200 µm in thickness
- In gypsum (CaSO₄, 2H₂O) cementing particles
- Containing numerous micrometric fly-ash:
  - Alumino-silicated or iron-rich produced by coal combustion
  - Carbonaceous and spongy produced by heavy fuel-oil combustion
The grey deposits on the arm section

Formed by dust deposition:

- on the entire statue after the 1st cleaning campaign (1985)
- on the broken section between 1994 and 2009

- Thinner than the black crust: 50 µm
- CaSO₄, 2H₂O crystals
- Containing nanometric carbonaceous soot, present in the grey deposit and in the air
In 1994, the year of the breaking of the hand of Apollo statue, *a campaign of air filtration* was performed *rue de Rivoli*, outside the Cour Carrée.
Presence of numerous *carbonaceous soot*:

- individual spheres of 50 nm forming clusters of 1 to 15 µm
- containing Sulphur
- emitted by combustion of light fuel-oil or gasoline in engines, or natural gas in urban heating system

That confirms the predominant contribution of *traffic* to air pollution in the last decades:

- less SO$_2$ and fly-ash
- more NO$_x$ and fine carbonaceous soot
Modeling the evolution of the *sulphation* of the Parisian monumental limestones *under* their surface

**Hill model:**

\[ Y(t) = B + \frac{K}{1 + \left( \frac{M}{t} \right)^H} \]

\[ [S]\% (t) = 0.08 + \frac{2}{1 + \left( \frac{1056}{t} \right)^{2.73}} \]
Modeling the evolution of the soiling of the monumental surfaces in Paris

Hill model: \[ Y(t) = B + \frac{K}{1 + \left(\frac{M}{t}\right)^H} \]

Soiling \( t \) = \( B + \frac{26,16}{1 + \left(\frac{8,97}{t}\right)^{2.14}} \)
Conclusions concerning the statue of Apollo

1 - The particle content of the old black crust and of the recent grey deposits records the changes in fuel used in Paris:

- coal and heavy-fuel oil until the second half of the 20th century: micrometric fly-ash
- light-oil, gasoline and natural gas since the middle of the 20th century: nanometric carbonaceous soot

2 - Sulphation and soiling reach saturation with time
2 - The microclimate in the Cour Marly

1- Statue of Apollo: Air pollution

2- Cour Marly: microclimate
The Cour Marly gathers the original sculptures ordered by Louis XIV and Louis XV for the Castle of Marly near Saint Germain and Versailles.

The most famous sculptures are:

“Les Chevaux de Marly” by Coustou (1745)

“Les Chevaux ailés” by Coysevox (1702)

Nowadays copies are displayed around the Concorde Square at the entrance of the Champs Elysées and the Tuileries Garden.
The Cour Marly, open in 1993, has been covered with a glass dome designed by Peter Rice which creates a particular microclimate, with marked *daily* and *seasonal cycles*.

The Cour is made in *three levels* and is connected through doors and windows to the Pyramid and the French Sculpture Department.

Indoor temperature and humidity are controlled by an air conditioning system.

The Cour has *trees* that simulate the Marly Castle environment but stimulate *micro-organisms* growth which might infect the Museum.
The Cour Marly in the Louvre

View from E to W

View from W to E

To the French Sculpture Department

Air conditioned slits

To the Pyramid

Air conditioned slits
Solar radiation falling on the Cour Marly at Mid August

Solar beams calculated after astronomic formulae and the architectural shield of the building
In summertime and by day: hot roof

- greenhouse effect and air layering under the roof
- near the floor: air mixing

Hot air penetrates by the corridor from the Pyramid
Temperature distribution on the floor *in summer*:
- Bottom level warmer than top level
- Very unstable situation
- But remains more or less the same from the morning to the evening
In Summer Relative Humidity is unbalanced

August 14:30
In wintertime and by night: cold roof

- Cold air layering on the floor
- Cold air sinking along walls.
- Cold air penetrates by the corridor
Temperature distribution on the floor *in winter* is singular:

- In the morning: bottom level cold and top warmer (normal)
- In the afternoon: situation radically changed by the rise of temperature in the corridor
Air particulate pollution in the Cour Marly

<table>
<thead>
<tr>
<th>Elemental Composition</th>
<th>Carbonaceous Particles</th>
<th>Non-Carbonaceous Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nanosoot</td>
<td>Biological</td>
</tr>
<tr>
<td>SUMMER Cour Marly</td>
<td>C</td>
<td>C+P</td>
</tr>
<tr>
<td>Rue de Rivoli</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>WINTER Cour Marly</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Rue de Rivoli</td>
<td>++++</td>
<td>+</td>
</tr>
</tbody>
</table>
Air particulate pollution in the Cour Marly: Conclusions

1-Different *types* of particles of different *origins* penetrate the Cour Marly: *anthropic, marine, continental, biogenic*

2-They follow *cyclic trends*:
   - daily and seasonal variations of *air pollution* (car traffic, domestic heating…)
   - *Seasonal biological cycles* (pollens, spores)

3-The weak penetration of fine and coarse airborne particles has proven the real *efficiency* of air filtration system

4-The transportation of external particles by *mass tourism* is negligible (very low concentrations)

5-The sculptures are not in danger of rapid soiling
The risk from plants

Plants require humidity and fertilizers, i.e. the ideal habitat for bacteria colonisation.

Bacteria can eventually migrate, being transported and spread by air motions, and may infest other areas in the museum.

Plants constitute a potential risk to conservation, which should be carefully and regularly controlled.
The top level and some trees
The top level and the French Sculpture Department
Cour Marly microclimate: Conclusions and perspectives

Although the indoor microclimate is controlled in both temperature and humidity it varies daily and seasonally being mainly forced by 4 factors:

1- Solar radiation and nocturnal cooling from the glass ceiling

2- Inflows of treated air from the climatisation intakes

3- Exchange of air through the 4 doors connecting the bottom level to the Pyramid area

4- Exchange of air with the Mediaeval Sculpture Department at the top level

...But this situation might be in evolution due to climate change scenario
The future climate of Paris according to two climate models

*Hadley Centre Model, HadRM3H, Scenario A2 in 2070*

*Météo-France Model, Arpège, Scenario A2 in 2070*

Background: mean annual temperature in the present climate

After S. Hallegatte, 2008
Thanks for your attention
The top level and the French Sculpture Exhibition
The Mid floor
The underground floor
The underground floor
1 – The statue of Rigaud
1 – Statue of Rigaud

2 – Statue of Apollo

3 – Cour Marly

4 – Salon Carré
1- Statue of Rigaud

2- Statue of Apollo

3- Salon Carré

4- Cour Marly
Humidifiers should not be placed near paintings because fluctuations in moisture concentration will damage artworks.

Humidifiers supply moisture to the entire room. They form clouds of vapour which moist artworks, and dissipate after operation. These cycles are repeated several times every day.
The Aisle Denon and Salon Carré
21 February 1995, h 09:30
1- Statue of Rigaud

2- Cour Marly

2- Statue of Apollo

4- Salon Carré
La Cour Marly

Un grand nombre de sculptures extérieures sera déplacé dès la fin des années 1710, notamment aux Tuileries. La dispersion se poursuivra au cours de la Révolution et jusqu'au début de l'Empire. La plupart des œuvres exposées dans la cour Marly proviennent de ces terres d'accueil. Nombre d'entre elles prélevées aux Tuileries, ainsi que les Chevaux de Marly, ont été remplacées par des moulages après leurs déplacements.

La nouvelle cour, inaugurée en 1993, offre un éclairage naturel grâce à une verrière conçue par Peter Rice.
Statues brought in in the past have preserved their black crusts with pollution particles generated centuries ago.
Long-term forecasting of weathering: the impact of climate change

Application of the Dose-Response Function method:

\[
Soiling = \left(0.184.[SO_2] + 0.094.[PM_{10}] + 0.212.[T^\circ] + 0.017.[HR]\right) / \left(1 + (245/t)^{1.3}\right)
\]