NOTES AND CORRESPONDENCE

Deep Soil Temperature Trends and Urban Effects at Paris

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1. Introduction

The local warming of air near the ground in large cities is reflected by nearly concentric mean isotherms around the city with the maximum value located about at the center of the urban area. Many authors have published studies on various aspects of these “urban heat islands,” and their results generally estimate that large cities have an annual mean temperature 0.8–2.0°C higher than their rural environs. The temperature increase depends on the extent of the urbanized area, the population density, industrial activity, and the climate itself.

This urban temperature increase results principally from heat sources (vehicles, and domestic and industrial fires), an abundance of vertical walls, and the expanse of macadamized surfaces which store sufficient heat during the day to remain relatively warmer during the night, especially in summer. In Paris, the roadways and pavement surfaces are 26 km², 25% of the total urban area of 105 km².

As precipitation is rapidly drained off streets and roofs, less heat is used in evaporation than in rural areas. Pollution also contributes to the local warming, principally during the nocturnal hours.

The amount of global temperature change over a period of years and the amount of warming in this period due to urban influences have been difficult to establish because most long-term temperature records have been made in growing and often large urban centers, thus making it difficult to separate the two effects. However, deep soil temperatures are not usually affected by urban warming and may afford a means to monitor the global increase in temperature during the first half of the 20th century. For instance, Changnon (1964), using data from 1889–1947 at Urbana, Ill., found an increase of 1.2°F at the 3-ft depth, while the air temperature increased 2.3°F, indicating an urban effect increase of about 1.1°F.

Temperature measurements made at a depth of 28 m near the center point of Paris (Paris Observatory cellar) and begun in the 18th century, are summarized in this paper and compared with air temperature trends. Although there are some breaks in the soil temperature series, it affords an interesting comparison owing to the relatively long period of record in a place where there has been no major modification in the neighboring buildings or in the subsoil for 200 years. The physical reasoning for the exchange of heat from the surface to the 28 m depth is also presented.

2. Data

a. Cellar

On 3 December 1670, Abbe Mariotte set a thermometer in the cellar of the Paris Observatory at a depth of 28 m. This cellar was part of a very old stone-quarry system under the city. Many measurements were made during the 18th century. While it is possible to find the data (Arago, 1855), we know very little about the instruments, the scales, and their accuracy.

The first available value was 11.76°C given by Messier in 1776, the reading being made with a very good thermometer carefully checked a few days before setting it in the cellar. At the end of the 18th century, Cassini blocked the cellar corridors except for one which was closed with a door. Later measurements, however, indicated that the temperature was not affected by opening or closing this door.

After 1782, a highly sensitive thermometer was installed by Lavoisier at the same point in the cellar. There are some doubts about 1782–1816 results, especially because of a slow deviation arising from the aging of glass of this second thermometer. However, there were at least three thermometers in service, the first being broken on 13 January 1792 (Arbey, 1952).

In the year 1817, in order to check the values of Lavoisier’s thermometer and to eliminate errors from instrumental aging, Arago installed a thermometer forged by Gay-Lussac. Values of the two instruments were read simultaneously from 1817 until 1852. Differences between these two series remain practically invariable with a mean annual deviation of 0.302°C (86% of the deviations are between 0.294 and 0.342°C).
As shown in Fig. 1, the annual mean temperature for 1817–52 was near 11.88°C, ranging between the lowest value of 11.71°C (1817) and the highest of 11.98°C (1838). It is worth noting that there is no diurnal variation and a negligible seasonal variation at this depth.

Unfortunately, the cellar observations between 1853 and 1921 have been lost. Nevertheless, we have two reports available in Rayet’s (1867, 1868) and Eble’s (1919) studies.

In the years 1865 and 1867, Rayet measured the temperature in a small pool of water spread out on the cellar ground and noted that the difference between the air and water temperature was less than 0.02°C. He found a mean annual water temperature of 11.72°C for 1865 and 11.74°C for 1867 (Fig. 1).

Eble, between 1912 and 1917, noted air temperatures between 12.8 and 13.2°C, values which were clearly too high; however, he reported that these results were due to the heat emitted by a small petroleum lamp left without interruption during his cellar activities. After putting out the lamp in early 1917, he found the air temperature rapidly decreased to 12.3°C and became steady at 12.1°C (Fig. 1).

Since 1922, the cellar temperature has always been read at the same point using thermometers set under five bell glasses which protect the “Bureau International de l’Heure” pendulums. There are some data gaps after 1947 and the series was broken in 1954. The latest data point, from measurements made in April 1969, is plotted only for information.

The dashed-dotted line in Fig. 1 does not constitute data; it only aids the eye in following the global temperature evolution which seems probable with these measured annual values. After relative stability during a long period (about 1775–1890), we can clearly see a gradual increase of temperature, roughly 1.5°C in the last 70–80 years.

b. Air temperature

For comparison with the cellar temperatures, three curves of annual mean air temperatures are also drawn in Fig. 1. These were obtained from good long-period homogeneous data from two stations probably not affected by any “urban effect,” Nantes and Besançon, and one which was affected, Paris St. Maur, which was in the rural countryside at its inception in 1873 but is now enclosed in the Paris suburbs. The St. Maur values for the years prior to 1873 were computed from the Paris Observatory air temperatures. These estimated mean annual temperatures are believed good since 1800. Values of another Paris station, Montsouris, were omitted in Fig. 1 because its curve would be superimposed on the St. Maur curve (the urban growing rate of St. Maur and Montsouris is about the same).

If the artificial fluctuations resulting from the running-mean process are disregarded, the general temperature trend is clearly reflected in Paris where the air temperature increase is about 1.0°C in the last 70 years.

Adjusting the individual mean annual temperatures by the least-squares method over the 78 years from 1891–1968, we find the trend values for five stations shown in Table 1. The calculation of confidence limits (P = 0.95) of the correlation coefficients between temperature and time (the years being numbered from 0 to 77) points out that the warming is significant only for the two Parisian stations, the data at Lyon probably being affected in part by local urban effects. It is reasonable to believe that the urban effect reflected in the St. Maur and Montsouris data is due to a general increase of 1.0°C in the annual temperatures.

### Table 1. Seventy-eight year air temperature trends in France.

<table>
<thead>
<tr>
<th>Place</th>
<th>Trend (°C)</th>
<th>Distance and direction from center of Paris</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paris St. Maur</td>
<td>+1.16</td>
<td>14 km ESE</td>
</tr>
<tr>
<td>Paris Montsouris</td>
<td>+1.06</td>
<td>4 km S</td>
</tr>
<tr>
<td>Lyon</td>
<td>+0.39</td>
<td>400 km SE</td>
</tr>
<tr>
<td>Besançon</td>
<td>+0.15</td>
<td>320 km ESE</td>
</tr>
<tr>
<td>Nantes</td>
<td>+0.08</td>
<td>350 km WSW</td>
</tr>
</tbody>
</table>

3. Discussion

A succinct spatial temperature analysis for the Paris area (Fig. 2), using mean annual isotherms only for the last 10 years to preserve measurement homogeneity, corroborates the temporal analysis. The “urban heat island,” assumed near the center of Paris where the mean is 12.3°C at La Tour St. Jacques (the shelter is in
a small garden), has an excess of about 1.7°C over the rural country based on temperatures "reduced" to the 50 m level [using a lapse rate of 0.45°C (100 m)\(^{-1}\)], and an excess of \(\sim 2°C\) if not reduced.

By interpolation of the values in Fig. 2, this annual air temperature excess at the Paris Observatory location appears to be about 1.3°C, approximately the same as the 1.5°C increase of the cellar temperature in the 70–80 years noted in Fig. 1.

It may be surprising that increases in air temperature give a warming trend in the soil at a depth of 28 m, since the air temperatures remained lower than those in the cellar. However, it should be emphasized that mean soil temperatures at the surface or slightly below are generally higher higher than shelter values. On asphalt, for instance, daytime surface temperatures are often higher than those in the air, by amounts ranging up to 15–20°C in summer. Thus, the mean heat flux is downward.

Analysis of the cellar mean-monthly temperatures and the results of Becquerel's (1879) studies of data down to a depth of 36 m show that the annual temperature range is \(\sim 0.05–0.10°C\) at 28 m. Using these data we can calculate an average value of the thermal diffusivity of soil of 0.025 cm\(^2\) sec\(^{-1}\) and an annual phase lag of the 28 m temperature with respect to that at the surface of about 1 year. These abnormally high values suggest that a large part of the heat is transferred by infiltration of water, since the cellar is very humid and water oozes along its walls. The phase lag and annual temperature range at 28 m are thus probably connected closely with rainfall.

Since moderately deep rural soil temperatures are not usually affected by urban warming, Changnon (1964) was able to discern values for global warming at Urbana. However, at Paris, a very deep soil temperature site, which has had a long-term urban environment, and heavy water infiltration, reveals that its temperature increase closely matches the urban air temperature increase. Both indicate an urban warming of more than 1°C.

REFERENCES


