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ATMOSPHERIC TURBIDITY MEASUREMENTS IN TORINO: A COMPARISON BETWEEN 1975 AND 2010

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1. Introduction

Torino is a large industrial city located in Northwestern Italy. It is the seat of the largest Italian car factory, although recently most production plants have been moved to other sites. In the last 35 years coal and heavy oil-fuelled heating systems have been progressively replaced by district heating and natural gas installations. Private and public transportation on the other hand has increased, although the specific pollutant emissions in terms of CO, NOx, SOx and particulates have been dramatically reduced with enforcing of more and more stringent EU limits. A comparison between nowadays and 1975 situation under the chemical and health points of view can be easily made because concentrations of the main pollutants are regularly monitored since a long time. However, it is interesting to evaluate how changing emission patterns have affected the optical quality of the atmosphere, namely its turbidity.

In order to make this comparison, direct normal solar irradiance has been continuously measured during year 2010 at the Polytechnic site in Torino city centre and its values have been compared to those measured by one of the authors during the period September 1975 – July 1976.

Direct normal solar irradiance data have been also employed to validate some widely spread atmospheric models both for the calculation of direct normal irradiance and for splitting total horizontal radiation into its direct and diffuse components.

2. Turbidity: definitions

The intensity of a monochromatic beam of solar radiation crossing a homogeneous plane-parallel atmospheric layer is given by the so called Bouguer-Lambert Law:

$$G_\lambda = G_{0\lambda} \exp(-\tau_\lambda \sec z)$$

Eqn 1

where

G_λ = monochromatic solar irradiance at the ground

$G_{0\lambda}$ = monochromatic extra-atmospheric solar irradiance

τ_λ = optical thickness of the atmospheric layers

z = Zenith angle of the Sun (angle between the solar beam and the local Zenith

An ideal atmosphere in which only molecular scattering from nitrogen and oxygen molecules occurs would have an optical thickness which was determined by Rayleigh in his fundamental works in the early 1870’s giving an explanation for the blue colour of the sky.

He showed that the optical thickness of this ideal atmosphere, called “Rayleigh atmosphere” can be determined as a function of wavelength and height above sea level by the following formula:

$$\tau_{m\lambda} = \frac{32\pi^3 (n-1)^2 H_0}{3\lambda^4 N_0}$$

Eqn 2

where

n = refraction index of the air (function of wavelength)

H_0 = thickness of the homogeneous atmospheric layers

N_0 = number of molecules per unit volume

Introducing the values for H_0, π and N_0 one obtains:

$$\tau_{m\lambda} = 1.044\, 10^5 (n-1)^2 \lambda^{-4}$$

From the above one may obtain the value of the ideal beam irradiance through a Rayleigh atmosphere, once the values of monochromatic extra-atmospheric irradiance $G_{0\lambda}$ are known (see Figure 1):

$$G_R = G_0 \exp\left(-\bar{\tau}_m \sec z\right) = \int_0^\infty G_{0\lambda} \exp\left(-\tau_{m\lambda} \sec z\right) d\lambda \qquad \textbf{Eqn 3}$$

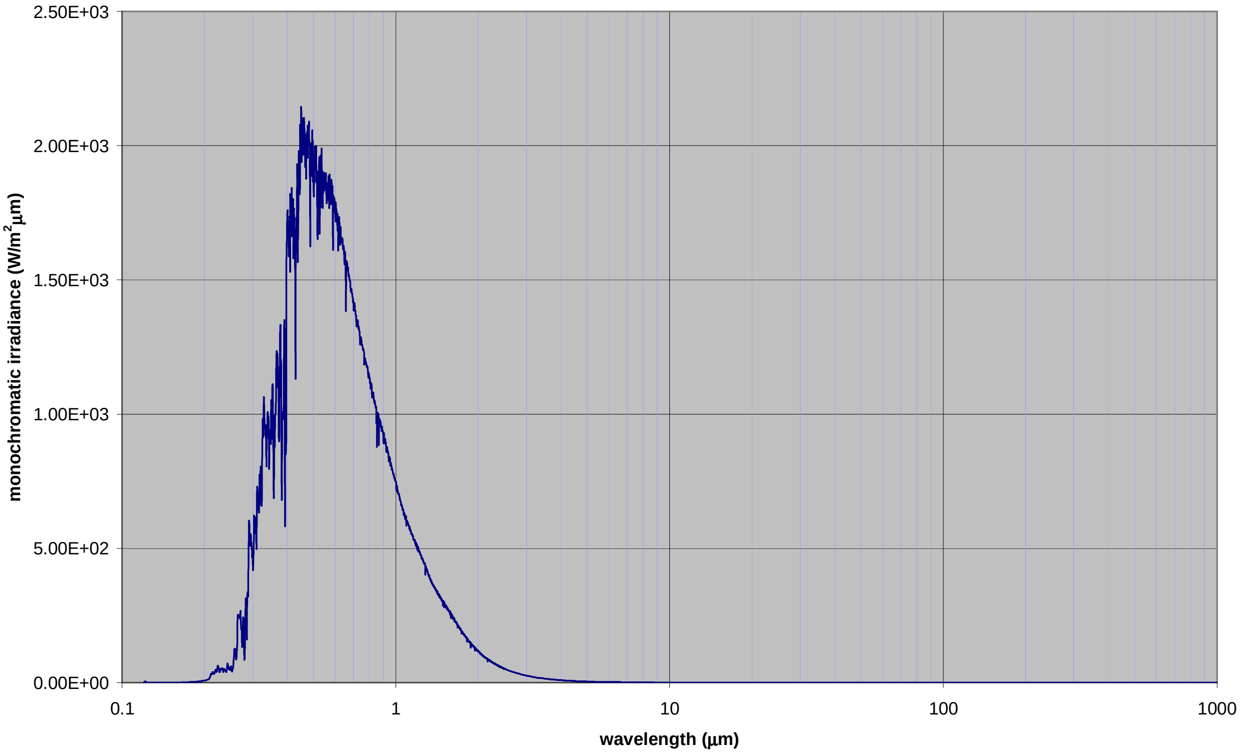

Figure 1 - Extra-atmospheric solar irradiance (G_0 = 1368 W/m^2)

For a real atmosphere in clear sky conditions the following applies:

$$G_{bn} = \frac{1}{S} G_0 \exp\left(-\bar{\tau} \sec z\right) = G_0 \frac{1}{S} \exp\left(-T\ \bar{\tau}_m \sec z\right) \qquad \textbf{Eqn 4}$$

where S takes into account the yearly variation of the extra-atmospheric irradiation G_0 and T, i.e., the number of Rayleigh atmospheres producing the same beam radiation extinction as the real atmosphere, is called “*Linke turbidity factor*”. In spite of its limits, namely its slight variation with air mass due to wavelength-dependent water-vapour and aerosol absorption, the Linke turbidity factor is useful for comparison of atmospheric transparency under different conditions (Coulson, 1975).

3. Atmospheric turbidity measurements in 1975-76 (Torino and Pino Torinese)

Starting from October 1975 until July 1976 a measurement campaign (Fracastoro, 1976, 1977) of beam solar radiation was simultaneously carried on in Torino (1.17 million inhabitants, 240 m above sea level) and Pino Torinese (about 5,000 inhabitants, 620 m a.s.l). Two Kipp & Zonen Moll thermopiles previously calibrated at the “Colonnetti” Metrological Institute were used. One was placed on top of the main Politecnico building (Torino), while the other was placed at the Astronomical Observatory of Torino, located in Pino Torinese.

Pino Torinese is a small location on the hills about 10 km East of Torino centre, 380 m above the city. Its atmosphere tends to be unaffected by typical pollution problems which characterize the industrial city of Torino.

The summary of these results is shown in figure 3.

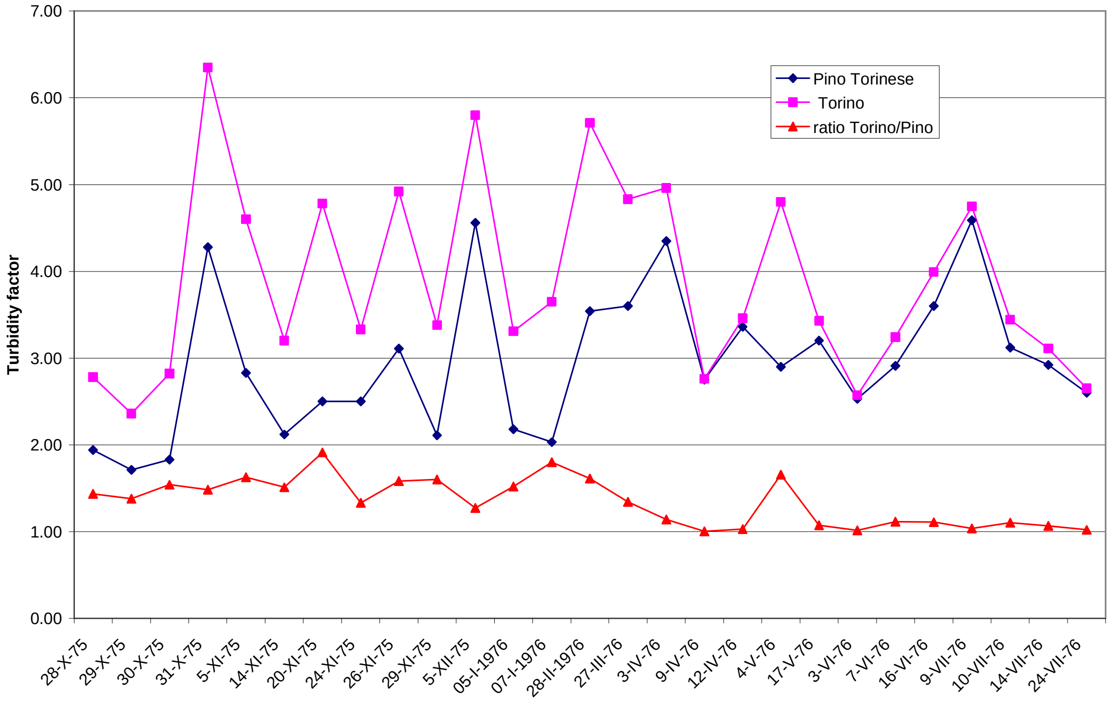

Figure 2 - 1975-76 turbidity values in Torino and Pino Torinese.

As it could be expected, turbidity data in Pino Torinese were always lower than in Torino. However, while in the late spring and summer months the difference (less than 5%) may considered “physiological”, i.e., justified by the different thickness of the atmospheric layers, during the heating season (from October to April) the difference between the two locations was much higher than in the rest of the year (up to 100% for November 20).

This different seasonal behaviour may be explained with the heavy polluting combustion appliances (heavy oil and coal) used for heating plants and industrial premises in those years in Torino. The specific climatic conditions of the Torino area, with very low winds and frequent winter thermal inversions, were and still are rather unfavorable to pollutants dispersion. As a result, air quality was very poor, and would absolutely be considered unacceptable under the present, both legal, cultural and environmental, points of view.

4. Comparison of atmospheric turbidity data in 1975 and 2010

From February 2010 to December 2010 solar beam radiation was measured every day at Torino, exactly at the same location as in 1975-76 measurement campaign. The measurement instrument was an Eppley Pyrheliometer with solar tracker, with a time sampling of 10’. Unfortunately, this time no beam radiation data were available at Pino Torinese, which could have been a useful reference also for the new data.

During the period 1975 to 2010, the city of Torino experienced a profound change in its socio-economical situation: the largest Italian carmaker left only a few productive premises and its headquarters in its birthplace, and moved most of its plants to Southern Italy and abroad (Brazil, Poland, Turkey, etc.). Torino municipality population in its turn decreased by about 250,000 inhabitants (from 1.15 to 0.9 million). On the other hand, mobility increased by about 30% (from 415,000 to 545,000 private cars during the same period), although this increase was compensated by more and more stringent EU pollutant emission limits.

In the last years, even Torino energy structure radically changed: while mobility increased, the switch to natural gas and district heating (nowadays, 410,000 Torino inhabitants are district-heated) led to consistent reduction of pollutant emissions. As an example, the SO_2 time history is shown in figure 3 (Comune di Torino, 2011).

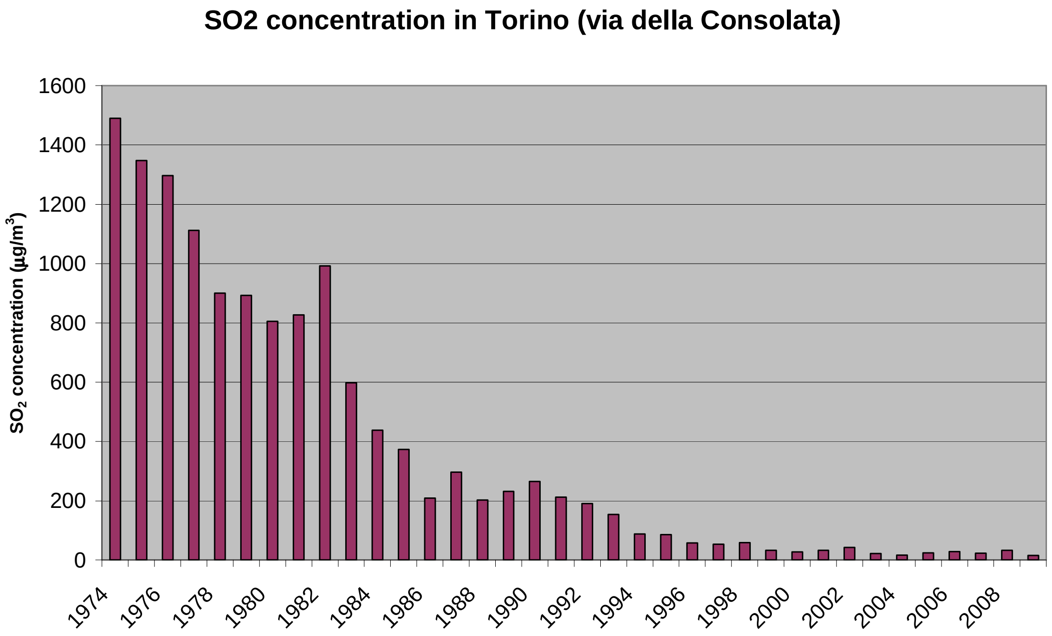

Figure 3 – SO_2 Concentration time history in Torino centre,

While SO_2 concentration is now just 1% of 35 years ago levels, the air quality in Torino is still poor, compared to other Italian and European cities, with higher than acceptable frequency of days in which pollution levels are beyond threshold, especially in terms of NO_x, and Particulate Matter (PM). For instance, PM decreased only by a factor four from 190 µg/m^3 in 1974 to values around 40-50 µg/m^3 in these last years.

A comparison of turbidity measurements in Torino and Pino (1975-6) and Torino (February 2010-December 2010) is shown in figure 4. Eighteen daily sets of data were chosen from this measurement campaign as examples of clear sky days. Daily averages were calculated considering only the clear part of the day.

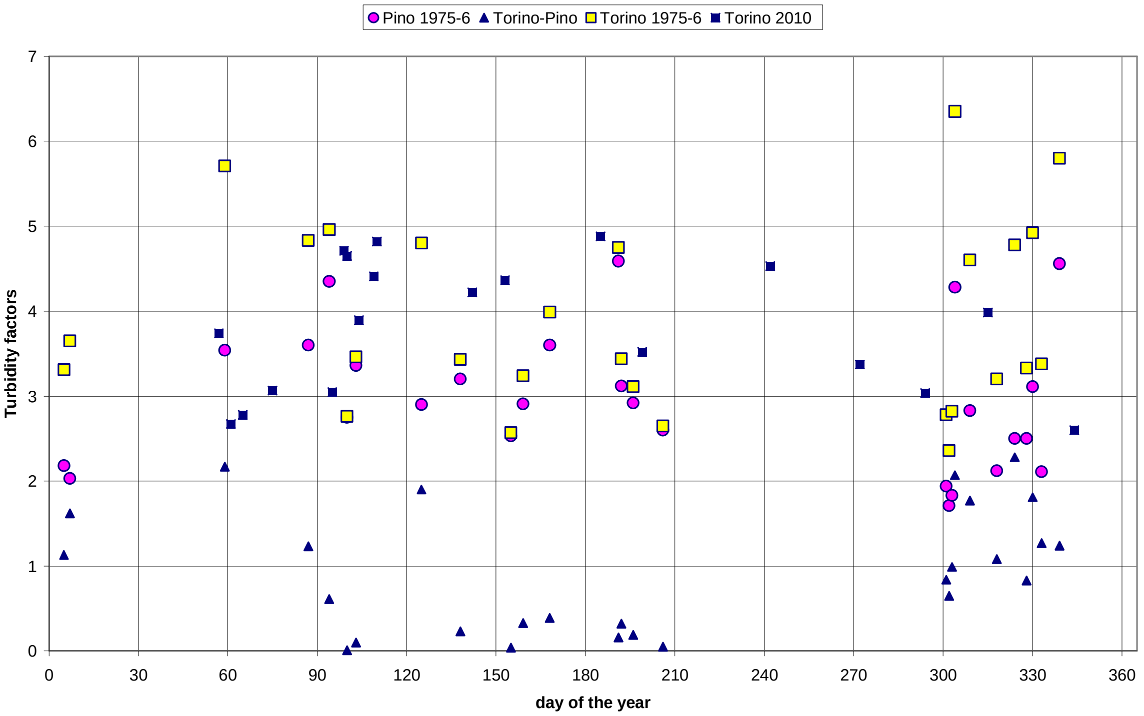

Figure 4 – Turbidity factors in 1975-6 and in 2010.

The conclusion which may be drawn looking at figure 4 is that turbidity values have not radically changed during the last 35 years in Torino. They appear slightly below the old data during the heating season, while they seem somehow higher during the rest of the year (April 15 to October 15, or days 105-288).

5. Validation of clear sky theoretical models: beam normal and diffuse horizontal irradiance

Starting from the measured beam and total horizontal irradiance other considerations were made, with two main goals:

- Verify the well known ASHRAE model (ASHRAE, 1985) for clear sky beam normal irradiance G_{bn}
- Verify ASHRAE model for diffuse horizontal irradiance G_{dh}

The ASHRAE clear sky model was originally developed by Moon (1940), and was later modified by Threlkeld and Jordan (1958) and Stephenson (1967). The ASHRAE model is still widely used, especially for engineering calculations, and may be described as follows:

$$G_{bn} = A \exp(-B\, m) = A \exp(-B \sec z) \qquad \textbf{Eqn 5}$$

$$G_{dh} = C\, G_{bn} \qquad \textbf{Eqn 6}$$

where the apparent solar constant (A, W/m^2), the extinction coefficient (B) and the diffuse coefficient (C) vary during the year, as reported by ASHRAE (1985).

As an example, both the measured and calculated data have been reported for March 6.

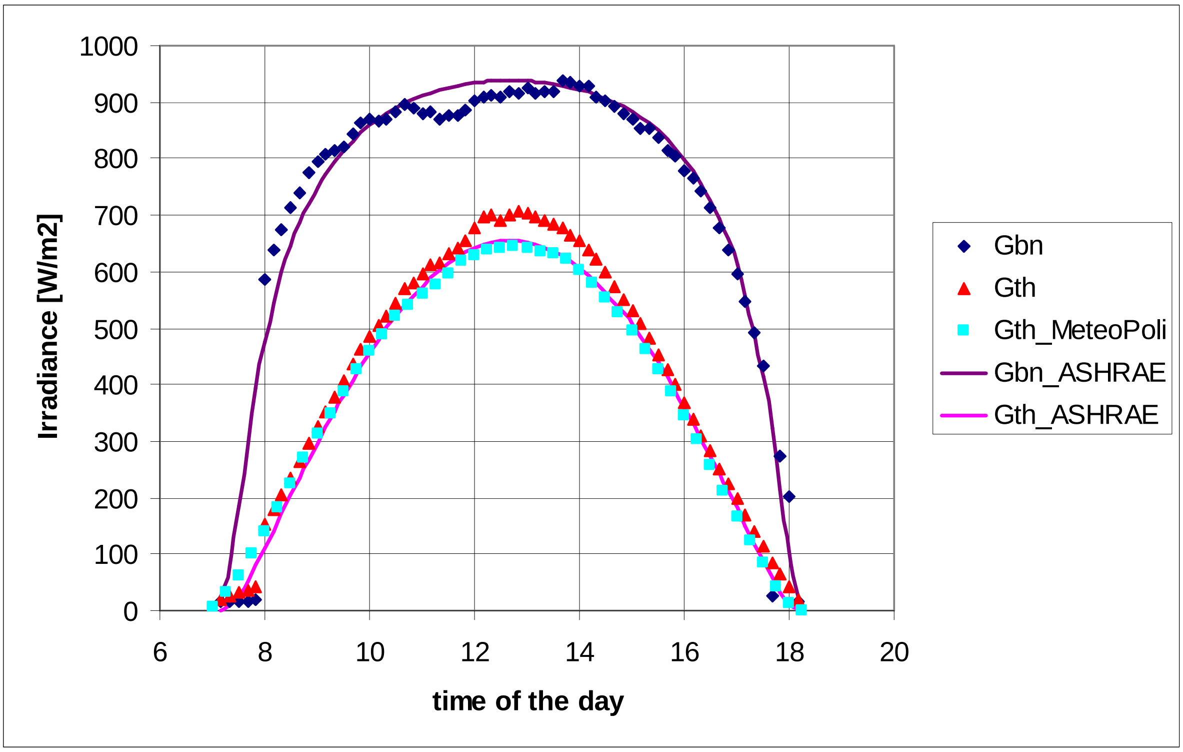

Figure 5 – Measured and calculated (ASHRAE model) solar irradiances for March 6, 2010.

The example above shows a good agreement between the measured and calculated G_{bn} values, except for some unavoidable shading of both the pyrheliometer and the pyranometer on the Department roof in the early morning time. On the other hand, the G_{th} values calculated by the ASHRAE model are in perfect agreement with data taken at the central weather station of Politecnico (G_{th}_MeteoPoli), while they appear underestimated whether compared to the data taken at the Department. A maximum 8-9% difference between the two occurred at noon. This difference will become a possible important source of errors when the diffuse component will be calculated.

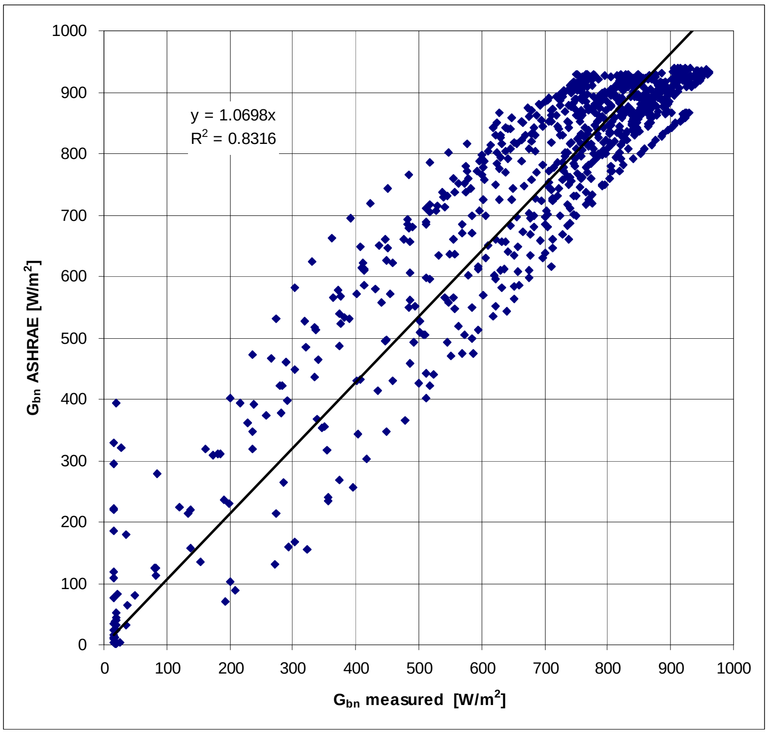

Figure 6 - Measured and calculated (ASHRAE model) G_{bn} values.

The figure above shows the comparison between instantaneous 10’ measured and calculated values of G_{bn} for the 18 clear sky days. A regression coefficient of 0.84 and a slight systematic overestimate (7%) are an evidence of the substantial acceptability of the ASHRAE model for most engineering purposes. The refinement of the method is beyond the scope of this paper, also due to the modest quality level of the experimental data. Main sources of errors were morning shading from buildings, limited duration of the measurement campaign, and non regular calibration of the instrument.

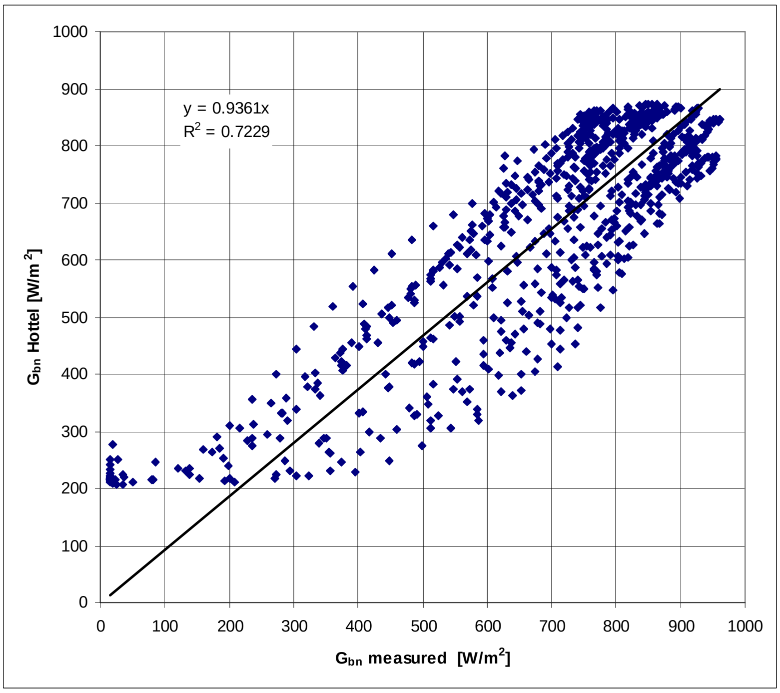

Figure 7 - Measured and calculated (Hottel model) G_{bn} values.

Other theoretical models, like Hottel (1976), provided (see Figure 7) a less satisfactory correlation ($r^2 = 0.73$), but a similar – in absolute terms - error on the estimate (-6.4%). Hottel’s model main drawback is the fact that the atmospheric transmittance is never zero, and this leads to a minimum value of around 200 W/m^2, even at very low solar altitude.

Similarly, the diffuse horizontal irradiance values G_{dh}, have been calculated from the measured data of G_{bn} and G_{th} (Department data) as follows:

$$G_{dh} = G_{th} - G_{bn}\cos(z)$$ **Eqn 7**

G_{dh} values have been compared to those predicted by the ASHRAE model (Eqn 6) both in absolute terms, and through their ratio to beam irradiance (namely, constant C in the ASHRAE model). The first comparison led to the results shown in Figure 8.

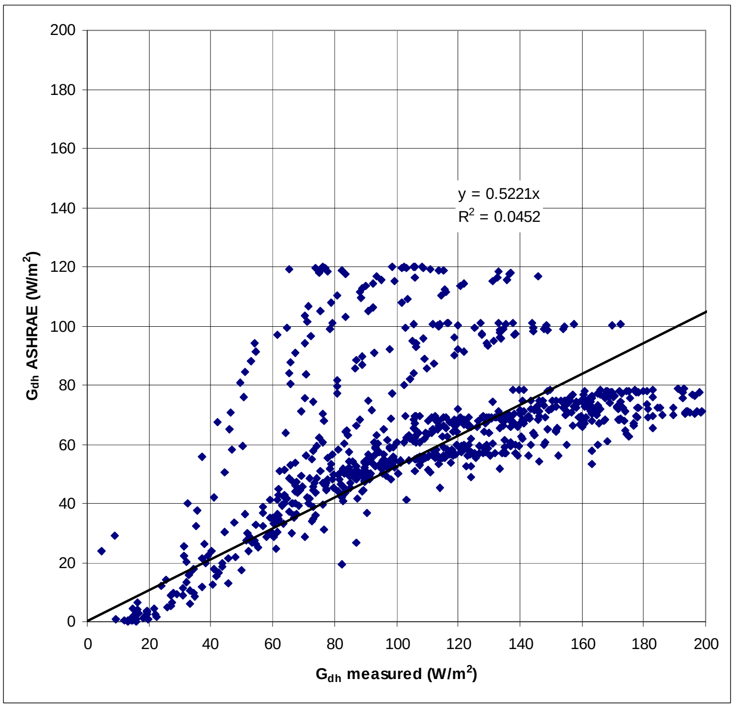

Figure 8 – Measured and calculated (ASHRAE model) diffuse horizontal irradiance.

Figure 8 is self commented: the large spread of the data (very low regression coefficient) and the systematic error (50% underestimate from theory) are immediately visible.

Similar - although slightly better - results were obtained by the Liu-Jordan model (1960), shown in Figure 9.

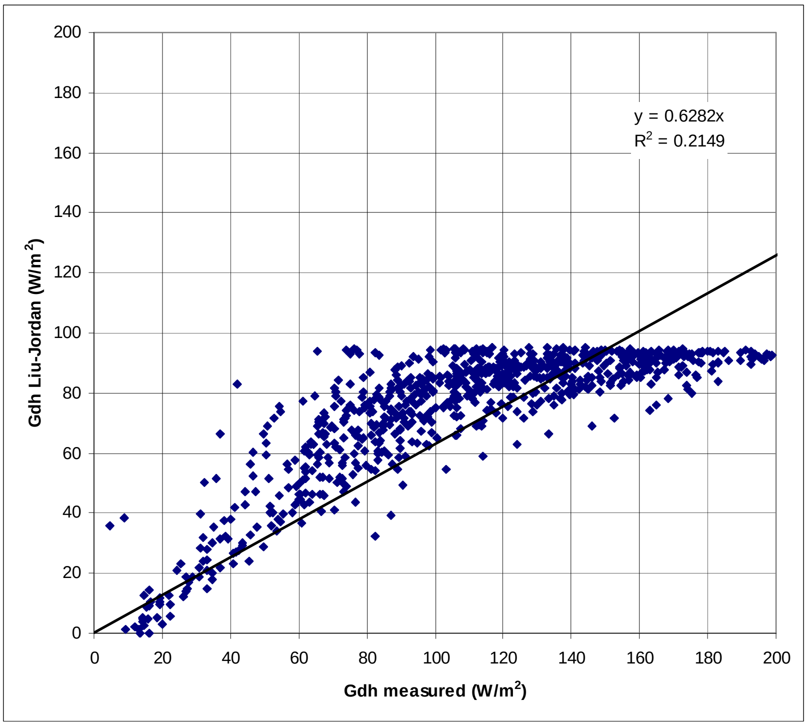

Figure 9 - Measured and calculated (Liu-Jordan model) diffuse horizontal irradiance

The ratio of diffuse horizontal to beam irradiance (namely, constant C in the ASHRAE model was calculated:

- between measured G_{dh} and calculated G_{bn} (C, blue lozenges, ASHRAE model), or
- between measured G_{dh} and measured G_{bn} (C', purple squares)

As an example, the daily variation of C for the same day as in Figure 5 (March, 6) and on April 9 are shown in figures 10 and 11.

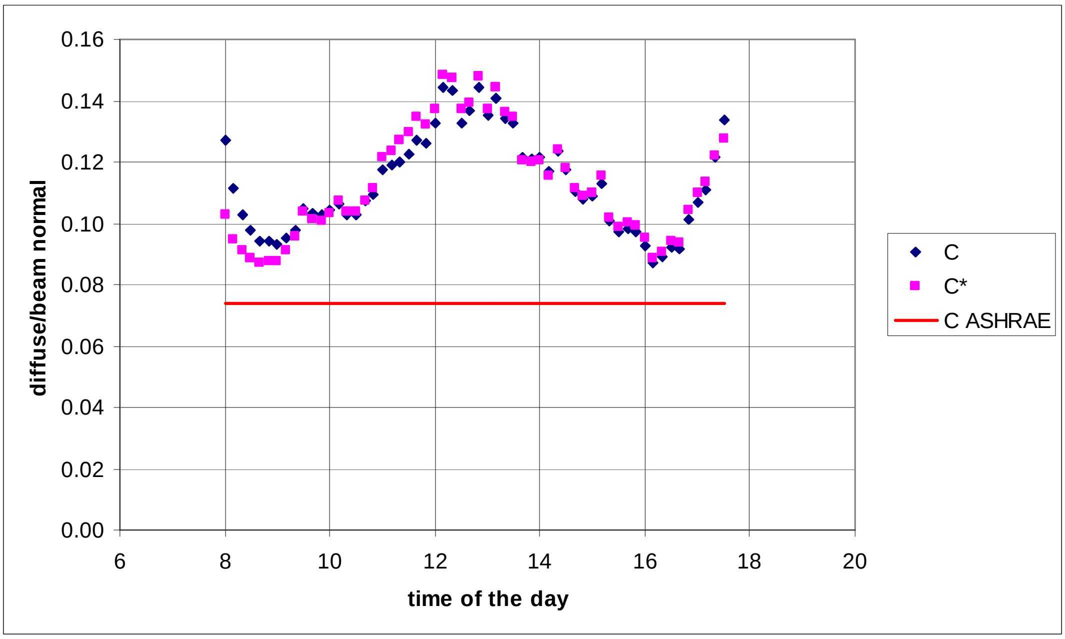

Figure 10 – Daily variation of diffuse horizontal to beam normal ratio for March, 6.

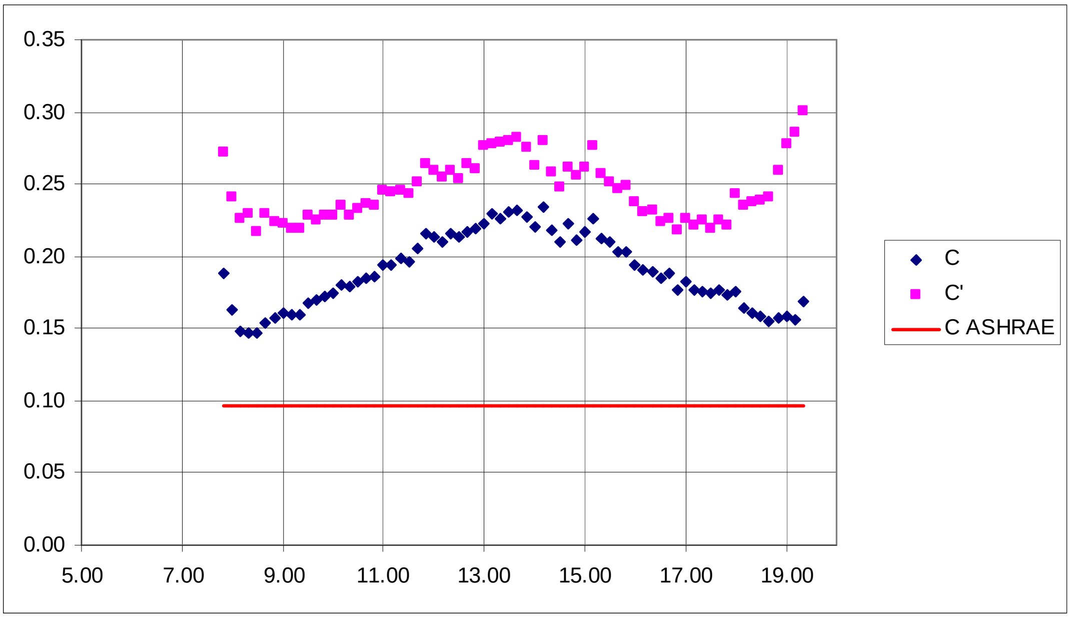

Figure 11 - Daily variation of diffuse horizontal to beam normal ratio for April, 9.

Some considerations may be drawn from the figures above:

- when G_{bn} ASHRAE values almost coincide with measured values, C and C' almost coincide as on March 6, while this does not happen on April 9.
- the experimental C and C' values are in the average well above the C predicted by the ASHRAE model, as it could be expected from the results shown in Figure 8.
- The most interesting finding is however that a daily regular oscillation of experimental C values, symmetrical to noon time, occurs, with very high values at the extremities of the day and at noon.

The last findings may be explained by the limits of the isotropy assumption implicit in the ASHRAE model: as the sun rises, circumsolar sky radiation increases in altitude, and therefore its vertical component tends to become more relevant. On the other hand, for very low altitude angles the vertical component of G_{bn} in Eqn 7 tends to decrease faster than G_{dh}, producing an asymptotical increase of C ratio up to an infinite value for $\theta_z = 90°$.

6. Conclusions

Turbidity measurements carried out 35 years ago in Torino and in the reference station of Pino Torinese showed in Torino a strong seasonal variation, with systematically higher values during the heating season, due to high pollution levels from the heavy oil and coal fuelled heating and industrial plants. Torino turbidity values were two Rayleigh atmospheres above those of Pino Torinese during winter time, while they were just a few percentage points above the reference in the late spring and summer.

The new measurements performed during 2010 have shown turbidity values comparable to those of 1975-76, but without any apparent seasonal variation: the optical quality of the atmosphere in Torino seems to have slightly improved in the winter time, and slightly worsened during the rest of the year.

The measurement campaign was also used to validate some popular engineering models for clear sky solar irradiance (namely, ASHRAE, Hottel and Liu-Jordan models) for the area of Torino. A satisfactory agreement has been found for beam normal irradiance, while calculated diffuse horizontal irradiance is usually underestimated and the ratio of diffuse to beam normal appears to be oscillating during the day.

Finding a new model for diffuse solar radiation is beyond the scope of this paper, both for the reduced number of measurements and for their arguable quality.

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