# EVALUATION OF LUMINOUS EFFICACY MODELS ACCORDING TO SKY TYPES AND ATMOSPHERIC CONDITIONS

# EVALUATION DES MODÈLES D'EFFICACITÉ LUMINEUSE SUR LA BASE DES TYPES DE CIELS ET DES CONDITIONS ATMOSPHÉRIQUES

# EVALUATION VON LICHTAUSBEUTEMODELLEN BEZÜGLICH UNTERSCHIEDLICHER HIMMELSTYPEN UND ATMOSPHÄRENZUSTÄNDE

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## ABSTRACT

To be valid for a great variety of sites, a luminous efficacy model has to be able to adapt to a wide range of climatic and atmospheric conditions. Many studies focusing on the evaluation of luminous efficacy models, have based their conclusion on annual (sometimes monthly) mean bias and root mean square errors between the models and the measurements, without understanding in detail, what was the behaviour of those models under various sky conditions. In this paper, we use the data measured at the IDMP station of Vaulx-en-Velin to illustrate the variations of the beam, diffuse and global luminous efficacies with the atmospheric aerosol and water vapor content, as well as with cloudiness. We show the performance of various luminous efficacy models during five days representative of different values of turbidity and cloud cover opacity. To cover both cloudless and overcast skies, a luminous efficacy model must rely on two indices. The index characterizing the cloudless sky conditions must take into account the variations in turbidity. None of the models tested do that adequately.

## RÉSUMÉ

Pour convenir à une grande variété de sites, un modèle d'efficacité lumineuse doit être capable de s'adapter à des conditions climatiques et atmosphériques très différentes. Beaucoup d'études évaluant les modèles d'efficacité lumineuse ont basé leurs conclusions sur des écarts moyens ou des écarts types entre les modèles et les mesures, en les calculant sur une année (parfois au mois par mois), sans comprendre en détail quel était le comportement de ces modèles, sous des conditions différentes de ciels. Dans cet article, nous utilisons les mesures de la station IDMP de Vaulx-en-Velin pour illustrer les variations des efficacités lumineuses directes, diffuses et globales, avec le contenu en aérosol et en vapeur d'eau de l'atmosphère, ainsi qu'avec la couverture nuageuse. Nous présentons les performances de quelques modèles d'efficacité lumineuse durant cinq jours représentatifs de différentes valeurs de trouble et d'opacités de la couverture nuageuse. Pour couvrir aussi bien les ciels sans nuage que les ciels couverts, un modèle d'efficacité lumineuse doit avoir recours à deux indices. L'indice utilisé pour caractériser les ciels sans nuage doit pouvoir prendre en compte les variations du trouble atmosphérique. Aucun des modèles testés ne remplit parfaitement ces conditions.



## ZUSAMMENFASSUNG

Um für eine große Vielfalt an Standorten Gültigkeit zu besitzen, muss ein Lichtausbeutemodell einen weiten Bereich klimatischer und atmosphärischer Bedingungen umfassen. Viele Studien, die die Entwicklung von Lichtausbeutemodellen zum Ziel haben, ziehen Schlussfolgerungen aus der mittleren jährlichen (bzw. monatlichen) Abweichung und Standardabweichung zwischen modellierten und gemessenen Werten, ohne allerdings im Detail zu untersuchen, wie sich diese Modelle bei verschiedenen Himmelstypen verhalten. In diesem Beitrag nutzen wir Messwerte der IDMP-Station in Vaulx-en-Velin, um die Variabilität der direkten, diffusen und globalen Lichtausbeute bezüglich Aerosolgehalt, Wasserdampfgehalt und Bewölkung zu illustrieren. Wir zeigen das Verhalten von verschiedenen Lichtausbeutemodellen anhand von fünf Tagen, die unterschiedliche Werte der Trübung und der optischen Tiefe bei Bewölkung repräsentieren. Um sowohl den klaren als auch den bedeckten Himmel zu berücksichtigen, muss ein Lichtausbeutemodell sich auf zwei Indizes stützen. Der Index, der den klaren Himmel beschreibt, muss die möglichen Variationen der Trübung beinhalten. Dies wird von keinem der getesteten Modelle gewährleistet.

## INTRODUCTION

Since 1991, the international network of daylight measuring stations (IDMP: International Daylight Measurement Programme of the Commission Internationale de l'Eclairage) has grown quite a lot [IEA-17, 1994]. However, with only 50 stations, this network is far away from covering a wide variety of climatic conditions. For still a long time, the main source of information on daylight availability will lie in the use of the widely measured energetic data reduced to the visible domain, using luminous efficacy models.

The luminous efficacy of a light source is the ratio between its luminous flux and its energetic flux. Thus, it depends on the distribution of its flux between the visible and the non visible part of the spectrum. In the atmosphere, solar radiation is affected by water vapor in the infrared, while it is affected in the ultraviolet and the visible, by air molecules and aerosol particles. The luminous efficacy of the three components of the solar radiation (beam, diffuse and global) varies with the cloudiness and the content of the atmosphere in water vapor and aerosol. As the sun altitude decreases, the path of the sun rays in the atmosphere increases, leading to bigger variations.

## THE DATA USED IN THE ANALYSIS

The IDMP station located in Vaulx-en-Velin measures every minute, the global and diffuse horizontal irradiances and illuminances, the North, East, South and West global vertical illuminances, the zenith luminance, the dry bulb temperature, the relative humidity, the wind speed and the wind direction. Irradiance sensors are CM6 Kipp&Zonen. Illuminance sensors are LMT BAP 30 FCT. Diffuse components are measured with shadow bands and corrected according to sky type, using an algorithm developed by Littlefair [Daylight, 1993]. All the sensors have been calibrated with reference sensors through our participation to European [Daylight, 1993] and International research programmes [IEA-17, 1994]. A weather station located nearby, provides us with hourly cloud cover information (nebulosity in oktas and cloud type).

For the analysis of the beam, diffuse and global luminous efficacies, we combined the 1994 cloudiness information with the measurements averaged over a 10 mn period centered on the hour of the observation. The diffuse and global luminous efficacies were computed from the 10 mn averages of the horizontal illuminances and irradiances. The beam luminous efficacy was computed from the beam illuminance and irradiance deduced from the global and diffuse measurements. To provide an estimate of the atmospheric water vapor content, we computed the precipitable water thickness w from the dry bulb temperature and the relative humidity using Leckner's formula [Leckner, 1978]. In 1994, the minimum value of w was: 0.6 cm, its maximum value: 4.4 cm and its median value: 2.0 cm. To provide an estimate of the atmospheric aerosol content, we computed the Angström turbidity coefficient β (representative of the quantity of aerosols) using a methodology developed by Louche [Louche, 1987]. In 1994, the minimum value of β was: 0.04, its maximum value: 0.40 and its median value: 0.13.

For the evaluation of the day to day performance of the luminous efficacy models, we used 5 mn averages of our measurements.

## THE BEAM LUMINOUS EFFICACY

Figure 1 shows the variations of the beam luminous efficacy (Effs) with respect to the sun altitude. The diffusion by the air molecules and the aerosol particles removes radiation in the visible, thus reducing the luminous efficacy of the beam. This reduction gets larger and larger, as the length of the sun path in the atmosphere increases (i.e. as the sun altitude decreases). The large variations observed for the same sun altitude are mostly due to variations in the aerosol content of the atmosphere. Figure 2 shows the variations of Effs with the sun altitude, for various bins of the Angström turbidity coefficient (low β values correspond to low aerosol content). From left to right, the cloud of points moves down indicating that the beam luminous efficacy decreases as the aerosol content increases.

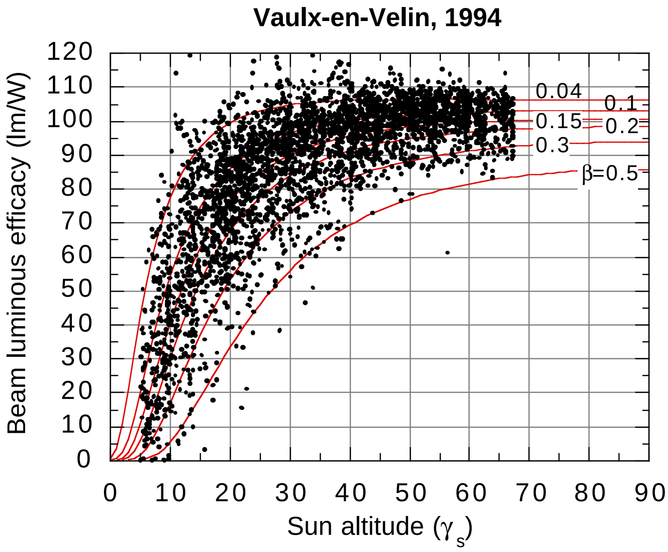


**Figure 1:** Variations of the beam luminous efficacy with the sun altitude, Vaulx-en-Velin, 1994.

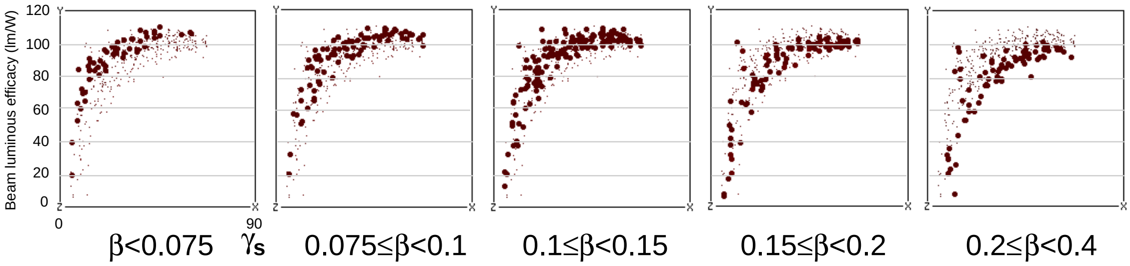


**Figure 2:** Variations of the beam luminous efficacy with the aerosol content and the sun altitude, N=0 and N=1, Vaulx-en-Velin, 1994. From left to right the aerosol content increases.

The absorption and the diffusion of solar radiation by water vapor removes part of the infrared of solar radiation, increasing the beam luminous efficacy and playing the opposite role of the diffusion by the aerosols. Figure 3 shows indeed that when the aerosol content is low (first two graphs to the left), the beam luminous efficacy increases when the water vapor content increases. However, when the aerosol content is high (the two graphs to the right), the effect of water vapor disappears. This had also been observed by Perez [Perez, 1990].

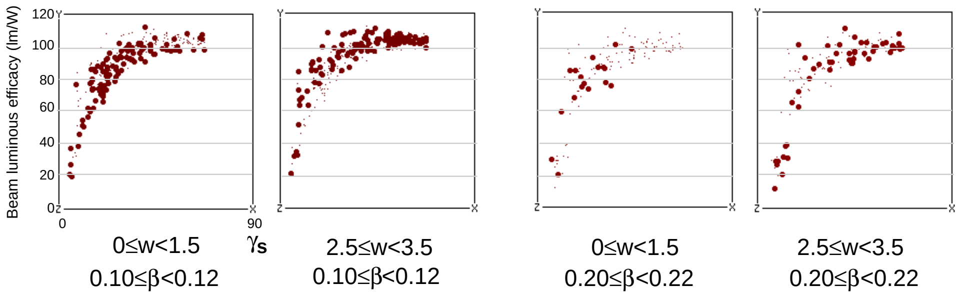


**Figure 3:** Variations of the beam luminous efficacy with the water vapor content, the aerosol content and the sun altitude, N=0 and N=1, Vaulx-en-Velin, 1994. The two graphs to the left correspond to low aerosol content, the two graphs to the right correspond to high aerosol content.

## THE DIFFUSE LUMINOUS EFFICACY

Figure 4 shows the variations of the diffuse luminous efficacy (Effd) with respect to the sun altitude. Two extreme sky conditions are represented: cloudless skies (N=0) and overcast skies (N=8). On each graph, a line indicates the general trend of these variations. For overcast skies, the diffuse luminous efficacy decreases when the sun altitude decreases, following the same trend as the luminous efficacy of the beam located above the cloud layer. The luminous efficacy of the overcast sky increases with the depth of the cloud layer, since the absorption of the infrared also increases. This explains why for the same sun altitude, Effd varies by as much as 20 lm/W.

On the opposite, the diffuse luminous efficacy of cloudless skies increases when the sun altitude decreases. For those skies, the diffusion of solar radiation by the air molecules and the aerosol particles play a major role and increases when the sun altitude decreases. However, Figure 5 shows that these variations depend on the aerosol content. If the content in aerosol is low, Effd increases strongly when the sun altitude decreases, (in that case, the diffusion on the air molecules is predominant). If the aerosol content is high, Effd is almost independent of the sun altitude. The water vapor content does not seem to have an impact on the diffuse luminous efficacy.

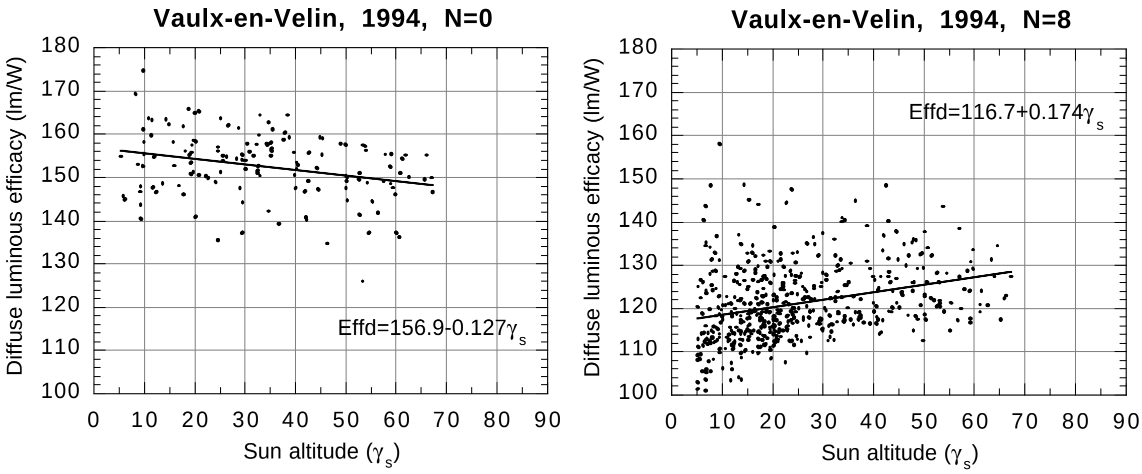


**Figure 4:** Variations of the diffuse luminous efficacy with the sun altitude, Vaulx-en-Velin, 1994. Cloudless skies N=0 (left) and overcast skies N=8 (right).

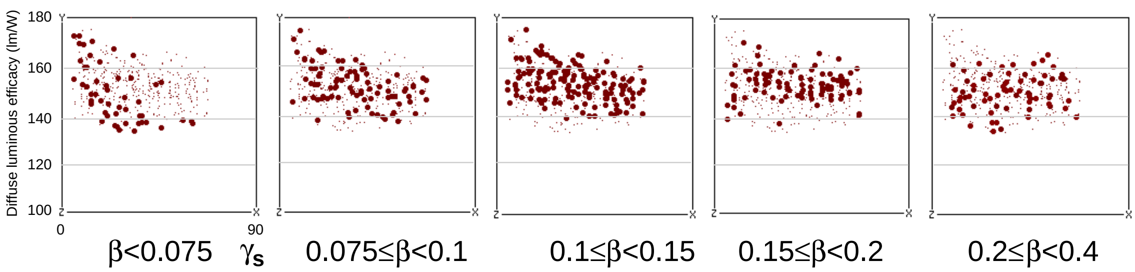


**Figure 5:** Variations of the diffuse luminous efficacy with the aerosol content and the sun altitude, N=0 and N=1, Vaulx-en-Velin, 1994. From left to right, the aerosol content increases.

## THE GLOBAL LUMINOUS EFFICACY

Figure 6 shows the variations of the global luminous efficacy (Effg) with respect to the sun altitude, for cloudless skies (N=0) and overcast skies (N=8). On each graph, a line indicates the general trend of these variations. For overcast skies, Figure 6 is almost identical to Figure 4, the small differences are only due to the use of the shadow band correction. For overcast skies, Effg is almost constant at sun altitudes above 30° (about 110 lm/W). Below 30°, Effg has wide variations, in some cases it decreases when the sun altitude decreases, in other cases it increases. Figure 7 shows that the aerosol content does not seem to explain these discrepancies. Figure 8 shows that water vapor content seems to be the key element. When the atmosphere is dry (graph to the extreme left), the global luminous efficacy increases when the sun altitude increases, following the same trend as the beam luminous efficacy. When the water vapor content is larger (graph to the extreme right), the global luminous efficacy is higher at low sun altitudes because of the additional infrared absorption.

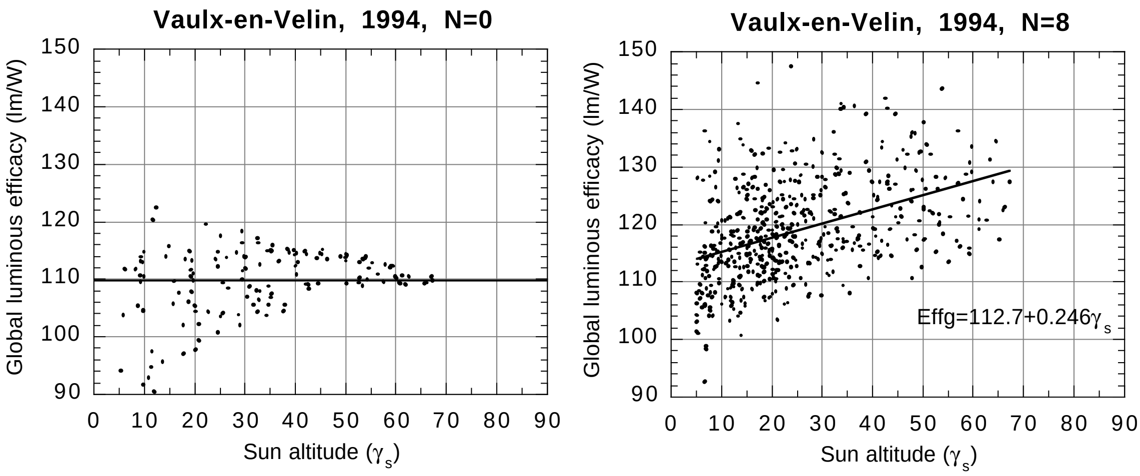


**Figure 6:** Variations of the global luminous efficacy with the sun altitude, Vaulx-en-Velin, 1994. Cloudless skies N=0 (left) and overcast skies N=8 (right).

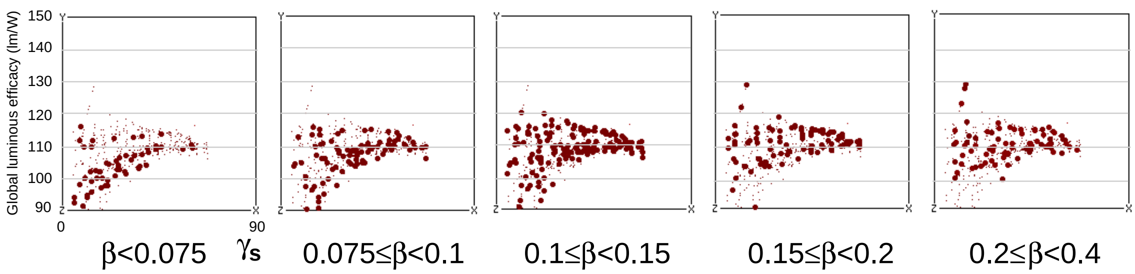


**Figure 7:** Variations of the global luminous efficacy with the aerosol content and the sun altitude, N=0 and N=1, Vaulx-en-Velin, 1994. From left to right, the aerosol content increases.

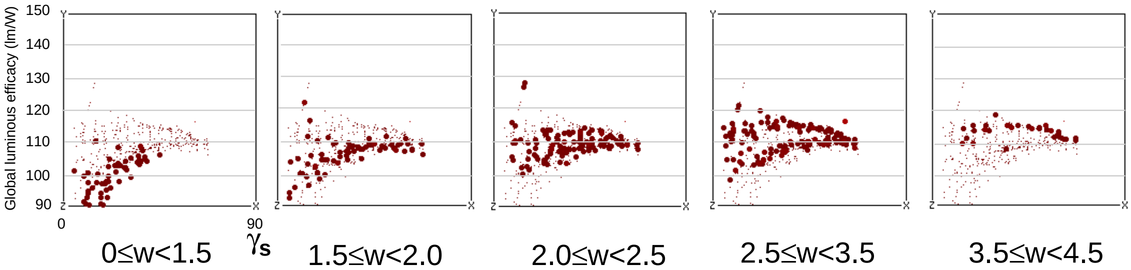


**Figure 8:** Variations of the global luminous efficacy with the water vapor content and the sun altitude, N=0 and N=1, Vaulx-en-Velin, 1994. From left to right, the water vapor content increases.

## DAY TO DAY PERFORMANCE OF LUMINOUS EFFICACY MODELS

We have seen in the previous sections how the luminous efficacy of the three components of solar radiation varies with sun altitude, aerosol and water vapor content, and cloud opacity. To be used in a wide range of climates, a luminous efficacy model has to take into account these variations. A first step in checking the validity of the model, is to look at its performance during days characterized by different atmospheric conditions. On the basis of a day by day analysis of our 1994 database, we have selected five days representative of different aerosol and water vapor content (March 10, 13 and 14, see Figure 9), and different cloud opacity (March 17 and 27, see Figure 9). This analysis was made easier by using TimeLUX: a computer programme designed for the graphical representation of IDMP data and distributed as shareware [Dumortier, 1997].

We selected four beam luminous efficacy models to study. The CEC model [CEC, 1985] which had been considered for use in the European Daylighting Atlas [Daylight II, 1995], is a polynomial expression of the sun altitude. The Olseth and Skartveit model [Olseth, 1989] is based on results provided by a spectral model of the atmospheric transmission of solar radiation called «SPECTRAL2». It is dependent on the sun altitude and a correction factor is used to take into account the seasonal variations of the atmospheric turbidity (i.e. aerosol plus water vapor content). The Perez model [Perez, 1990] is dependent on the sun altitude, the precipitable water thickness and two indices: the clear sky index and the sky brightness index. The last model is a version of a model initially developed by Dogniaux [Dogniaux, 1976] and modified by the author [Dumortier, 1995]. The beam luminous efficacy is computed using the theoretical expressions of the beam illuminance and irradiance. The energetic and luminous turbidities which are used in these expressions are linearly dependent on the aerosol content (i.e. the Angström turbidity coefficient).

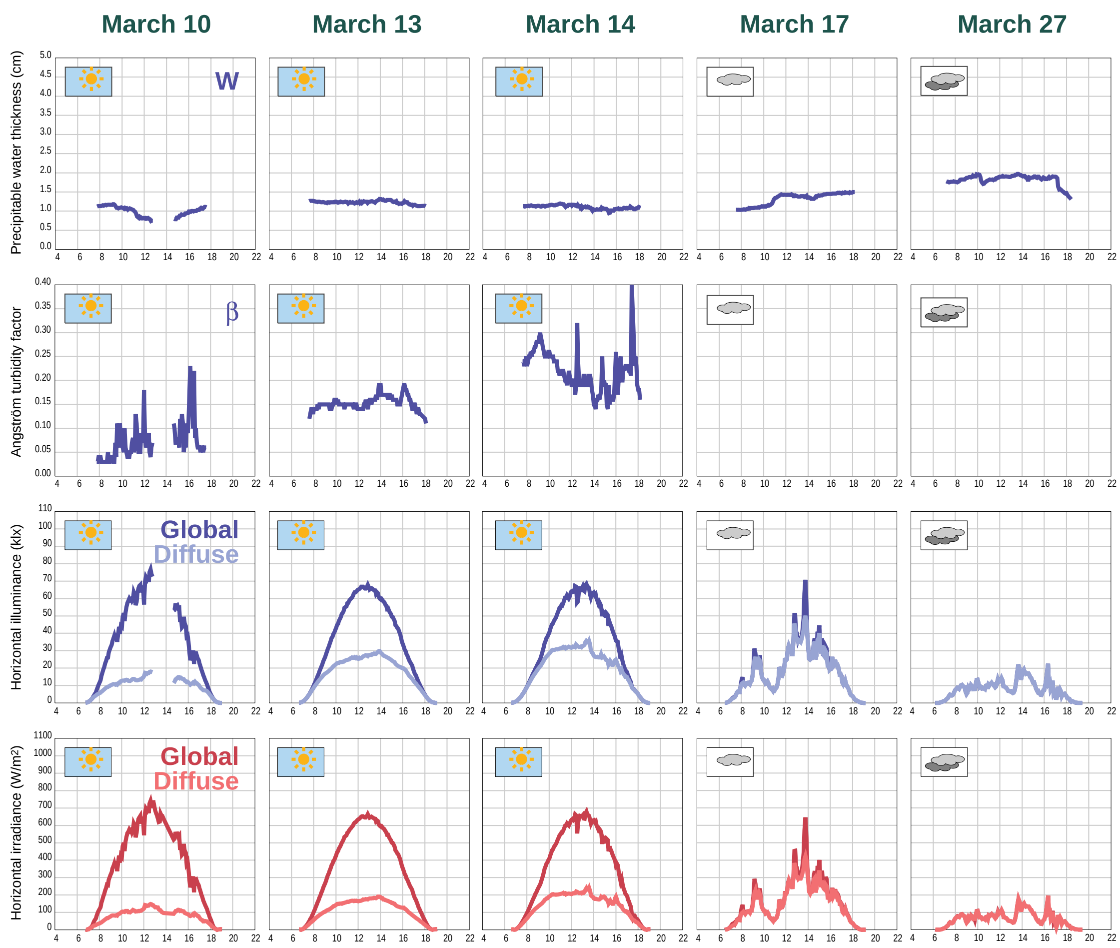


**Figure 9:** The five days selected for the evaluation of the day to day performance of luminous efficacy models. The first line shows the variations of the precipitable water thickness (w), the second line: the variations of the Angström turbidity factor (b), the third line: the variations of the global and diffuse horizontal illuminances, the fourth line: the variations of the global and diffuse horizontal irradiances.

Figure 10 shows the performance of these models. During the first three days, none of the models is able to follow the decrease in luminous efficacy, due to the increase of the aerosol content. Without being perfect, the author's model performs better than the others. This model and the Perez model are able to follow the variations of the beam luminous efficacy even during days with a non opaque cloud cover (March 17).

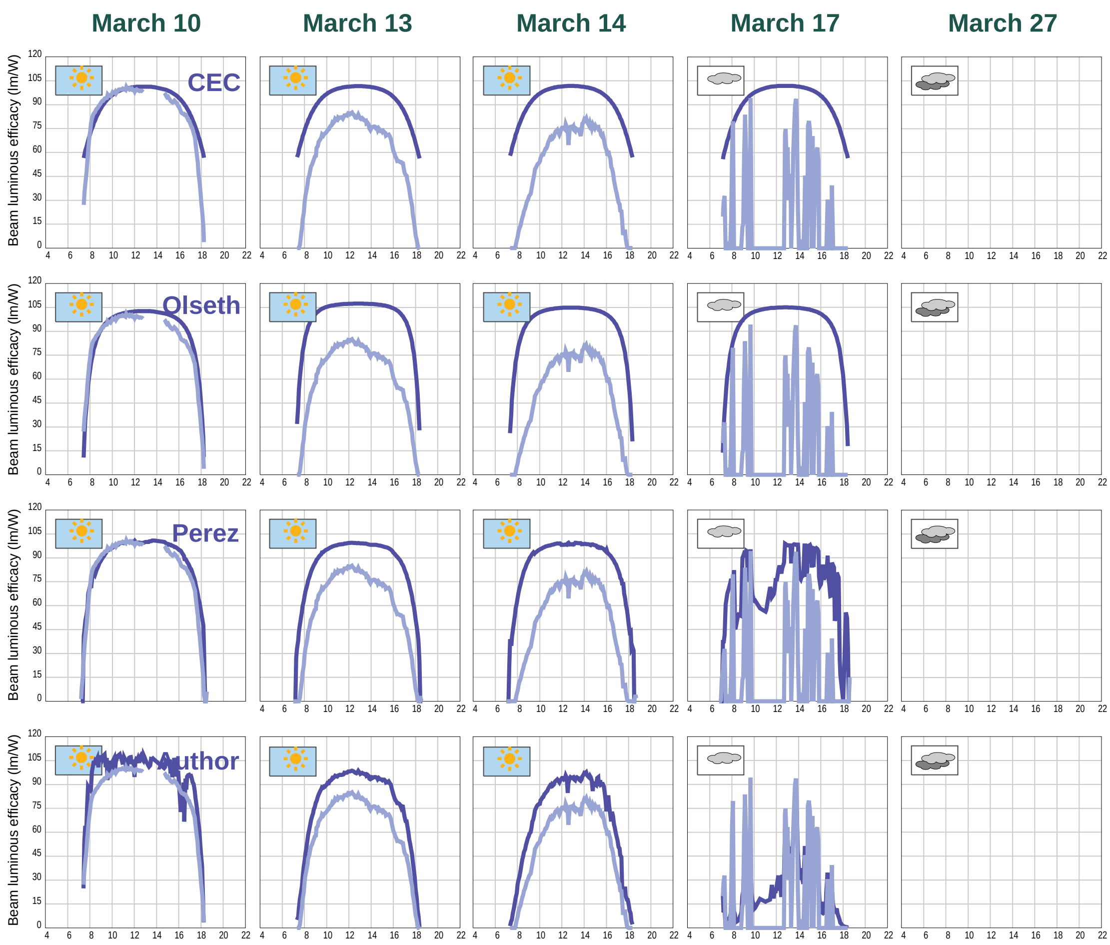


**Figure 10:** Day to day performance of the four beam luminous efficacy models. The beam luminous efficacy computed from the measurements is represented with a light shade of grey.

We then selected two diffuse luminous efficacy models to study. The first one has been proposed by Littlefair for use in the European Daylighting Atlas [Daylight II, 1995]. This model is based on a linear interpolation between the diffuse luminous efficacy of a cloudless sky and the luminous efficacy of an overcast sky. The parameter used in the interpolation is the relative nebulosity index of Perraudeau [Perraudeau, 1986]. The second one is the Perez model [Perez, 1990] where Perez uses the same parameters as for his beam luminous efficacy model.

Figure 11 shows the performance of these two models.

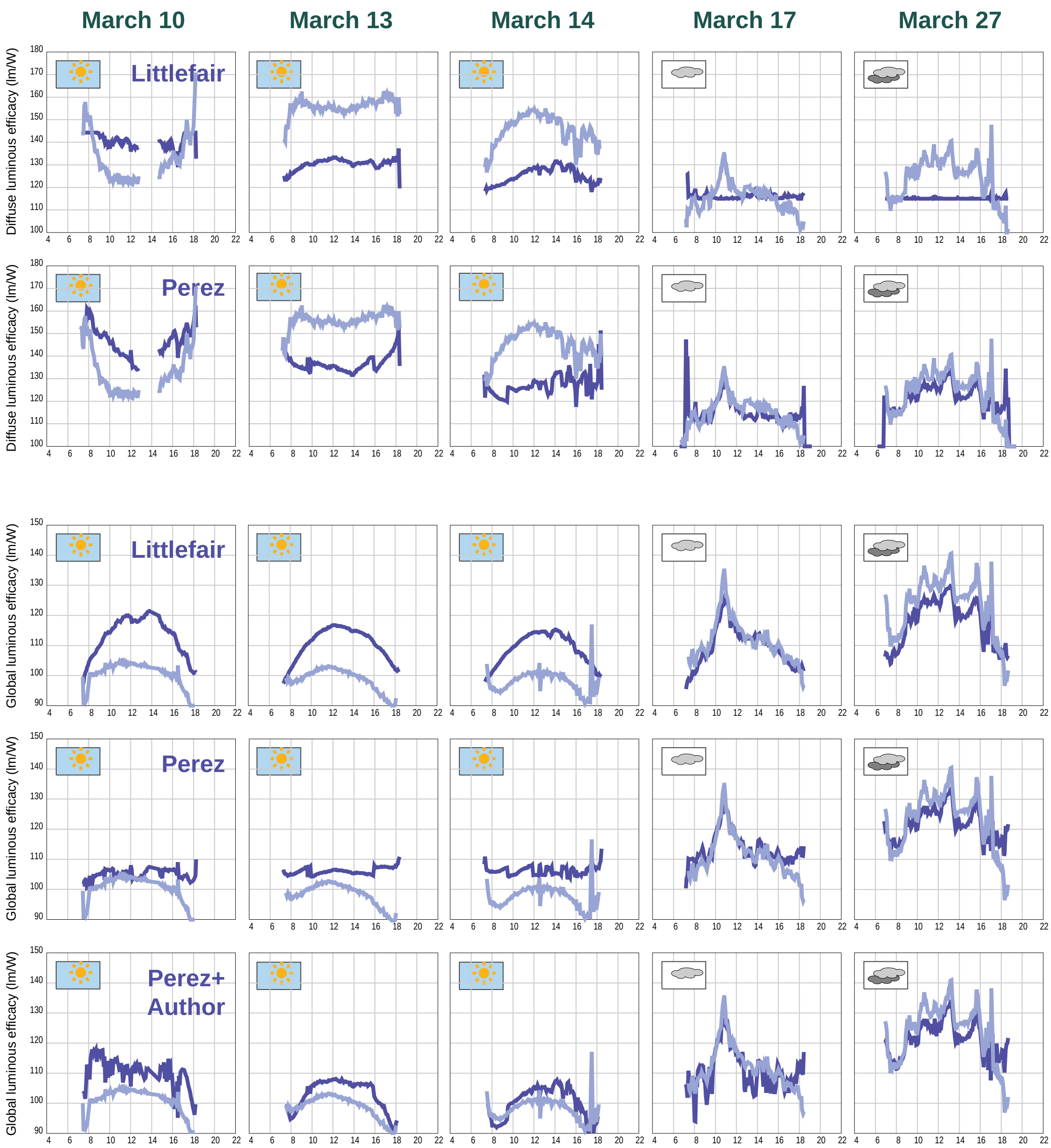


**Figure 11:** Day to day performance of two diffuse luminous efficacy models and three global luminous efficacy models. The luminous efficacies computed from the measurements are represented with a light shade of grey.

None of them is able to follow the variations of the diffuse luminous efficacy with the aerosol content. On March 10, with a low aerosol content, the two models overestimate the diffuse luminous efficacy. On March 13 and 14 with higher aerosol content, the two models underpredict the diffuse luminous efficacy. The Perez model follows the variations of the luminous efficacy with the opacity of the cloud cover: good results are obtained both on March 17 and 27. Because the relative nebulosity index is equal to 0 under overcast conditions, the model proposed by Littlefair leads to a constant luminous efficacy which is not observed with the measurements.

Finally, we selected three global luminous efficacy models to study. The first one has been proposed by Littlefair [Littlefair, 1988]. This model is based on a linear interpolation between the global luminous efficacy of a cloudless sky and the global luminous efficacy of an overcast sky. The luminous efficacy of the cloudless sky is a polynomial function of the sun altitude. The luminous efficacy of the cloudy sky is the product of the luminous efficacy of the cloudless sky by a factor depending on the brightness of the sky. The parameter used in the interpolation is the relative nebulosity index of Perraudeau [Perraudeau, 1986]. The second one is the Perez model [Perez, 1990] where Perez uses the same parameters as for his beam luminous efficacy model. The third model is a combination of the Perez diffuse luminous efficacy model and the beam luminous efficacy model proposed by the author.

Figure 11 shows the performance of these three models. The three models, especially the one proposed by Littlefair overperdict the global luminous efficacy under cloudless skies. The third model performs better than the others both on cloudless sky conditions and on cloudy conditions.

## CONCLUSION

Luminous efficacy models still need to be improved to take better into account the variety of cloudless sky conditions as well as the variety of overcast conditions. Two indices are needed, a first one which describes the cloudiness (from cloudless to overcast skies: Perez's clear sky index or Perraudeau's relative nebulosity index), a second one (such as Perez's sky brightness) which describes overcast conditions for which the first index is useless (it is equal to 0).

The Perez luminous efficacy models need to be improved to take better into account the aerosol content. The author has shown in another work that the clear sky index does not allow to distinguish between turbid cloudless skies and intermediate skies [Dumortier, 1995]. There is a need to modify this index to make it less dependent on the sun altitude. The theoretical expression of the beam luminous efficacy such as the one used by Dogniaux and modified by the author should also be used, it performs better than empirical expressions.

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