Hugo Hens

Applied Building Physics

Boundary Conditions, Building Performance and Material Properties

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Printed in the Federal Republic of Germany.
Printed on acid-free paper.

To my wife, children and grandchildren

In remembrance of Professor A. de Grave
who introduced Building Physics as a new discipline
at the University of Louvain, K. U. Leuven, Belgium in 1952

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Applied Building Physics: Boundary Conditions, Building Performance and Material Properties. Hugo Hens

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Preface

Overview

Until the first energy crisis of 1973, building physics existed as a shadow field in building engineering, with seemingly limited applicability. While soil mechanics, structural mechanics, building materials, building construction and HVAC were seen as essential, designers only sought advice on room acoustics, moisture tolerance, summer comfort or lighting when really needed or when, after construction, problems arose. Energy was not even a concern, while indoor environmental quality was presumably guaranteed thanks to ever present infiltration, window ventilation and the heating system. The energy crises of the seventies, persisting moisture problems, complaints about sick buildings, thermal, visual and olfactory discomfort, and the move towards more sustainability changed that all. The societal pressure to diminish energy consumptions in buildings without degrading usability acted as a trigger that activated the whole notion of performance based design and construction. As a result, building physics and its potential to quantify performances was suddenly pushed to the forefront of building innovation.

As all engineering sciences, building physics is oriented towards application, which is why, after a first book on fundamentals, this second volume examines the performance rationale and performance requirements as a basis for sound building engineering. Choices have been made, among others to limit the text to a thorough discussion of the heat-air-moisture performances only. The subjects treated are: the climate outdoors and conditions indoors, the performance concept, performances at the building level, performances at the building enclosure level and heat-air-moisture material properties. The book incorporates thirty five years of teaching architectural, building and civil engineers, bolstered by forty years of experience, research and consultancy. Where needed information and literature from international sources has been used, which is indicated by an extensive list with references at the end of each chapter.

The book is written in SI-units. It should be usable for undergraduate and graduate students in architectural and building engineering, although mechanical engineers studying HVAC, and practising building engineers who want to refresh their knowledge, will also benefit from it. The level of presentation assumes that the reader has a sound knowledge of the basics treated in the first book on fundamentals, along with a background in building materials and building construction.

Acknowledgments

A book of this magnitude reflects the work of many, not only that of the author. Therefore, I want first of all to thank my thousands of students. They gave us the opportunity to test the content and helped us in upgrading with the corrections they proposed and the experience they offered in pointing out which parts should be better explained.

The book could not have been written in this form without standing on the shoulders of those who preceded me. Although I started my career as a structural engineer, my predecessor, Professor Antoine de Grave planted the seeds that slowly nurtured my interest in building physics and its applications. The late Bob Vos of TNO, the Netherlands, and Helmut Künzel of the Fraunhofer Institut für Bauphysik, Germany, showed the importance of experimental work and field testing for understanding building performance, while Lars Erik Nevander of Lund University, Sweden, showed that application does not always correspond to extended

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modelling, mainly because reality in building construction is much more complex than any model may be.

During the four decades at the Laboratory of Building Physics, several researchers and PhD-students got involved. I am very grateful to Gerrit Vermeir, Staf Roels and Dirk Saelens who became colleagues at the university; to Jan Carmeliet, professor at the ETH-Zürich; to Piet Standaert, a principal at Physibel Engineering; to Jan Lecompte at Bekaert NV; Filip Descamps, a principal at Daidalos Engineering and part-time professor at the Free University Brussels (VUB); Arnold Janssens, professor at the University of Ghent (UG); Hans Janssen, associate professor at the Technical University Denmark (TUD); Rongjin Zheng, associate professor at Zhejiang University, China, and Bert Blocken, associate professor at the Technical University Eindhoven (TU/e), who all contributed by their work. The experiences gained by operating four Annexes of the IEA, Executive Committee on Energy Conservation in Buildings and Community Systems, also forced me to rethink the performance approach. The many ideas I exchanged in Canada and the USA with Kumar Kumaran, Paul Fazio, Bill Brown, William B. Rose, Joe Lstiburek and Anton Ten Wolde, were also of great help. A number of reviewers took time to examine the book. Although we do not know their names, we thank them here.

Finally, I want to acknowledge my family. My loving mother who died too early. My late father, who reached a respectable age. My wife, Lieve and my three children who managed living together with a busy engineering professor, and my many grandchildren.

Leuven, May 2010 *Hugo S. L. C. Hens*

0 Introduction

0.1 Subject of the book

This is the second volume in a series of books on Building Physics and Applied Building Physics:

- Building Physics: Heat, Air and Moisture
- **Applied Building Physics: Boundary Conditions, Building Performance and Material Properties**
- Applied Building Physics and Performance Based Design 1
- Applied Building Physics and Performance Based Design 2

In this volume the subjects are: indoor and outdoor climate, the performance concept, performances at the building and building enclosure level and heat-air-moisture material properties. The book thereby functions as a hinge between 'Building Physics: Heat, Air and Moisture' and 'Applied Building Physics and Performance Based Design 1 and 2'. Although acoustics and lighting are not treated in detail, they form an integral part of the performance array and are mentioned where and when needed.

In Chapter 1 outdoor and indoor conditions are described and design and calculation values discussed. Chapter 2 specifies the performance concept and its hierarchical structure, from the urban environment over the building level down to the material's level. Aspects typical for performances are definability in an engineering way, their predictability at the design stage and controllability during decommissioning. In Chapter 3, the main heat, air, moisture related performances at the building level are discussed. Chapter 4 analyzes the hygrothermal performance requirements of importance for a good building enclosure design, while Chapter 5 treats the material properties needed for predicting the heat, air, moisture response of buildings and building enclosures.

A performance approach helps designers, consulting engineers and contractors to guarantee building quality. However physical requirements are not the only track that adds value. Although functionality, spatial quality and aesthetics, i.e. aspects belonging to the architect's responsibility, are of equal importance, they should not become an argument for neglecting the importance of a highly performing building and building services design.

0.2 Building Physics and Applied Building Physics

For the readers who like to know more about the engineering field of 'Building Physics', its importance and history, we refer to 'Building Physics: Heat, Air and Moisture'. Honestly, the term 'applied' may be perceived to be a pleonasm. Building Physics is by definition applied. But by inserting the word, the focus is unequivocally directed towards usage of the knowledge building physics generates, in building and building services design plus building construction.

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0.3 Units and symbols

The book uses the SI-system (internationally mandated since 1977). The base units are the meter (m), the kilogram (kg), the second (s), the Kelvin (K), the ampere (A) and the candela. Derived units, which are important when studying building physics and applied building physics, are:

Unit of force: Newton (N); $1\ \mathrm{N} = 1\ \mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-2}$
Unit of pressure: Pascal (Pa); $1\ \mathrm{Pa} = 1\ \mathrm{N/m^2} = 1\ \mathrm{kg} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-2}$
Unit of energy: Joule (J); $1\ \mathrm{J} = 1\ \mathrm{N} \cdot \mathrm{m} = 1\ \mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-2}$
Unit of power: Watt (W); $1\ \mathrm{W} = 1\ \mathrm{J} \cdot \mathrm{s}^{-1} = 1\ \mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-3}$

For the symbols, the ISO-standards (International Standardization Organization) are followed. If a quantity is not included in these standards, the CIB-W40 recommendations (International Council for Building Research, Studies and Documentation, Working Group 'Heat and Moisture Transfer in Buildings') and the list edited by Annex 24 of the IEA, ECBCS (International Energy Agency, Executive Committee on Energy Conservation in Buildings and Community Systems) are applied.

Table 0.1. List with symbols and quantities.

Symbol	Meaning	Units
a	Acceleration	$\mathrm{m/s^2}$
a	Thermal diffusivity	$\mathrm{m^2/s}$
b	Thermal effusivity	$\mathrm{W/(m^2 \cdot K \cdot s^{0.5})}$
c	Specific heat capacity	$\mathrm{J/(kg \cdot K)}$
c	Concentration	$\mathrm{kg/m^3}$, $\mathrm{g/m^3}$
e	Emissivity	–
f	Specific free energy	J/kg
	Temperature ratio	–
g	Specific free enthalpy	J/kg
g	Acceleration by gravity	$\mathrm{m/s^2}$
g	Mass flow rate, mass flux	$\mathrm{kg/(m^2 \cdot s)}$
h	Height	m
h	Specific enthalpy	J/kg
h	Surface film coefficient for heat transfer	$\mathrm{W/(m^2 \cdot K)}$
k	Mass related permeability (mass may be moisture, air, salt.)	s
l	Length	m
l	Specific enthalpy of evaporation or melting	J/kg
m	Mass	kg
n	Ventilation rate	$\mathrm{s^{-1}}$, $\mathrm{h^{-1}}$
p	Partial pressure	Pa
q	Heat flow rate, heat flux	$\mathrm{W/m^2}$
r	Radius	m
s	Specific entropy	$\mathrm{J/(kg \cdot K)}$

Symbol	Meaning	Units
t	Time	s
u	Specific latent energy	J/kg
v	Velocity	m/s
w	Moisture content	$\mathrm{kg/m^3}$
x, y, z	Cartesian co-ordinates	m
A	Water sorption coefficient	$\mathrm{kg/(m^2 \cdot s^{0.5})}$
A	Area	$\mathrm{m^2}$
B	Water penetration coefficient	$\mathrm{m/s^{0.5}}$
D	Diffusion coefficient	$\mathrm{m^2/s}$
D	Moisture diffusivity	$\mathrm{m^2/s}$
E	Irradiation	$\mathrm{W/m^2}$
F	Free energy	J
G	Free enthalpy	J
G	Mass flow (mass = vapour, water, air, salt)	kg/s
H	Enthalpy	J
I	Radiation intensity	J/rad
K	Thermal moisture diffusion coefficient	$\mathrm{kg/(m \cdot s \cdot K)}$
K	Mass permeance	s/m
K	Force	N
L	Luminosity	$\mathrm{W/m^2}$
M	Emittance	$\mathrm{W/m^2}$
P	Power	W
P	Thermal permeance	$\mathrm{W/(m^2 \cdot K)}$
P	Total pressure	Pa
Q	Heat	J
R	Thermal resistance	$\mathrm{m^2 \cdot K/W}$
R	Gas constant	$\mathrm{J/(kg \cdot K)}$
S	Entropy, saturation degree	J/K, –
T	Absolute temperature	K
T	Period (of a vibration or a wave)	s, days, etc.
U	Latent energy	J
U	Thermal transmittance	$\mathrm{W/(m^2 \cdot K)}$
V	Volume	$\mathrm{m^3}$
W	Air resistance	m/s
X	Moisture ratio	kg/kg
Z	Diffusion resistance	m/s
α	Thermal expansion coefficient	$\mathrm{K^{-1}}$
α	Absorptivity	–
β	Surface film coefficient for diffusion	s/m
β	Volumetric thermal expansion coefficient	$\mathrm{K^{-1}}$

Symbol	Meaning	Units
η	Dynamic viscosity	$N \cdot s/m^2$
θ	Temperature	°C
λ	Thermal conductivity	$W/(m \cdot K)$
μ	Vapour resistance factor	–
ν	Kinematic viscosity	m^2/s
ρ	Density	kg/m^3
ρ	Reflectivity	–
σ	Surface tension	N/m
τ	Transmissivity	–
ϕ	Relative humidity	–
α, ϕ, Θ	Angle	rad
ξ	Specific moisture capacity	kg/kg per unit of moisture potential
Ψ	Porosity	–
Ψ	Volumetric moisture ratio	m^3/m^3
Φ	Heat flow	W

Table 0.2. List with suffixes and notations.

Symbol	Meaning
Indices	
A	Air
c	Capillary, convection
e	Outside, outdoors
h	Hygroscopic
i	Inside, indoors
cr	Critical
CO_2, SO_2	Chemical symbol for gasses
m	Moisture, maximal
r	Radiant, radiation
sat	Saturation
s	Surface, area, suction
rs	Resulting
v	Water vapour
w	Water
ϕ	Relative humidity
Notation	
[ ], bold	Matrix, array, value of a complex number
dash	Vector (ex.: $\overline{a}$)

0.4 References

[0.1] CIB-W40 (1975). Quantities, Symbols and Units for the description of heat and moisture transfer in Buildings: Conversion factors. IBBC-TNP, Report No. BI-75-59/03.8.12, Rijswijk.

[0.2] ISO-BIN (1985). Standards series X02-101 – X023-113.

[0.3] Kumaran, K. (1996). *Task 3: Material Properties.* Final Report IEA EXCO ECBCS Annex 24. ACCO, Louvain, pp. 135.

1 Outdoor and indoor conditions

1.1 Overview

In building physics, the in- and outdoor conditions have a role comparable to the loads in structural mechanics, reason why the term ‘environmental loads’ is often used. A good knowledge of that load is essential, if one aims making environmentally correct design decisions.

The different parameters that make up the load are:

Outside		**Inside**	
Air temperature	θ_e	Air temperature	θ_i
		Radiant temperature	θ_R
Relative humidity	ϕ_e	Relative humidity	ϕ_i
(Partial water) vapour pressure	p_e	(Partial water) vapour pressure	p_i
Solar radiation	E_S		
Under-cooling	q_{rL}		
Wind	v_w	Air speed	v
Rain and snow	g_r		
Air pressure	$P_{a,e}$	Air pressure	$P_{a,i}$

In the next paragraphs, each parameter is discussed separately. One should however keep in mind that in- and outside conditions are coupled. The more decoupling is demanded, the more severe the envelope and HVAC performance requirements become and the more energy will be needed. Predicting future outdoor conditions is also not possible. Not only are most parameters measured in a few locations only, but the future never is an exact copy of the past. The weather in fact does not obey the paradigm ‘the more data available, the better the forecast’. Moreover, glooming global warming may disturb any such trial. A typical way of by-passing that problem is using reference values and reference years for each performance evaluation needing outside climate data, such as quantifying the heating and cooling load, predicting end energy consumption, evaluating overheating, judging moisture performance, looking to durability issues others than moisture induced, etc.

In the paragraphs that follow, data from the weatherstation of Uccle, Belgium, 50° 51′ North, 4° 21′ East, are used to illustrate statements and trends. Reason for that is we disposed of a rich documentation analyzing the measurements done there during the last century.

1.2 Outdoor conditions

Weather patterns are to a large extent defined by the geographical location – northern or southern latitude –, proximity to the sea and height above sea level. But micro-climatic factors

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also intervene. Thanks to the urban heat island effect, the air temperature in city centres is higher than at the country side whereas air pollution makes solar radiation less intense and relative humidity is lower. Table 1.1 illustrates the differences by listing the monthly mean air temperatures measured under thermometer hut in Uccle and Sint Joost for the period 1901–1930.

Table 1.1. Monthly mean dry bulb temperature in Uccle and Sint-Joost, Brussels, for the period 1901–1930 (°C).

Location	**Month**											
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Uccle	2.7	3.1	5.5	8.2	12.8	14.9	16.8	16.4	14.0	10.0	5.2	3.7
Sint Joost	3.8	4.2	6.8	9.4	14.6	16.7	18.7	18.0	15.4	11.2	6.4	4.7

Both stations are situated in Brussels but Uccle faces a green area, while ‘Sint Joost’ lays straight in the centre of the city.

The outside climate varies periodically with as main cycles:

- The year with its succession of winter, springtime, summer and autumn in moderate regions and the wet and dry season in the equatorial band. The annual cycle is governed by the earth’s elliptic orbit around the sun
- The sequence of low and high pressure fronts. In moderate and cold climates, high pressure stands for warm weather in summer and cold weather in winter. Low pressure instead gives cool, wet weather in summer and fresh, wet weather in winter
- Day and night. The daily cycle is a consequence of the earth’s autorotation.

Reference years and standardised quantities are focusing on annual and daily cycles and daily values. Meteorological reference data instead consider 30 year averages, for the 20–21 century: 1901–1930, 1931–1960, 1961–1990, 1991–2020. Per period the averages vary due to long term climate changes such as induced by global warming, relocation of meteorological stations, more accurate measuring apparatus and the way averages are calculated. Between 1901 en 1930, the daily mean temperature was the average between the daily minimum and the daily maximum, the one logged with a minimum and the other logged with a maximum mercury thermometer. Today, the air temperature in many weather stations is logged each 10′ and the daily average is calculated as the mean of these 144 values.

1.2.1 Dry bulb (or air) temperature

The air temperature plays an important role in the heating and cooling load and the annual end energy use for heating and cooling. The load fixes the HVAC-investment, while the energy consumed defines part of the annual costs. The air temperature is also linked to overheating and participates in the heat, air, and moisture load the envelope experiences. Measurement proceeds in open field under thermometer hut, 1.5 m above ground level. The accuracy as imposed by the WMO (World Meteorological Organization) is ≤ ±0.5 °C. Table 1.2 gives monthly mean values for several weather stations in Europe. All are quite well represented by an annual mean and a first harmonic, although two harmonics give better results:

Table 1.2. Monthly mean dry bulb temperatures for several locations in Europe (°C).

Location	Month											
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Uccle (B)	2.7	3.1	5.5	8.2	12.8	14.9	16.8	16.4	14.0	10.0	5.2	3.7
Den Bilt (NL)	1.3	2.4	4.3	8.1	12.1	15.3	16.1	16.1	14.2	10.7	5.5	1.2
Aberdeen (UK)	2.5	2.7	4.5	6.8	9.0	12.1	13.7	13.3	11.9	9.3	5.3	3.7
Eskdalemuir (UK)	1.8	1.9	3.9	5.8	8.9	11.8	13.1	12.9	10.9	8.5	4.3	2.7
Kew (UK)	4.7	4.8	6.8	9.0	12.6	15.6	17.5	17.1	14.8	11.6	7.5	5.6
Kiruna (S)	–12.2	–12.4	–8.9	–3.5	2.7	9.2	12.9	10.5	5.1	–1.5	–6.8	–10.1
Malmö (S)	–0.5	–0.7	1.4	6.0	11.0	15.0	17.2	16.7	13.5	8.9	4.9	2.0
Västerås (S)	–4.1	–4.1	–1.4	4.1	10.1	14.6	17.2	15.8	11.3	6.3	1.9	–1.0
Lulea (S)	–11.4	–10.0	–5.6	–0.1	6.1	12.8	15.3	13.6	8.2	2.9	–4.0	–8.9
Oslo (N)	–4.2	–4.1	–0.2	4.6	10.8	15.0	16.5	15.2	10.8	6.1	0.8	–2.6
München (D)	–1.5	–0.4	3.4	8.1	11.9	15.6	17.5	16.7	13.9	8.8	3.6	–0.2
Potsdam (D)	–0.7	–0.3	3.5	8.0	13.1	16.6	18.1	17.5	13.8	9.2	4.1	0.9
Roma (I)	7.6	9.0	11.3	13.9	18.0	22.3	25.2	24.7	21.5	16.8	12.1	8.9
Catania (I)	10.0	10.4	12.0	14.0	18.0	22.0	25.2	25.6	23.2	18.4	15.2	11.6
Torino (I)	1.6	3.5	7.6	10.8	15.4	19.0	22.3	21.6	17.9	12.3	6.2	2.4
Bratislava (Sk)	–2.0	0.0	4.3	9.6	14.2	17.8	19.3	18.9	15.3	10.0	4.2	0.1
Copenhagen (Dk)	–0.7	–0.8	1.8	5.7	11.1	15.1	16.2	16.0	12.7	9.0	4.7	1.1

1 harmonic

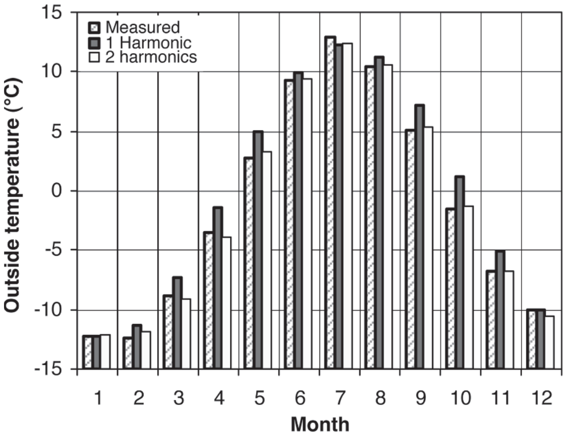
$$\theta_e = \overline{\theta}_e + A_1 \sin\left(\frac{2\,\pi\,t}{365.25}\right) + B_1 \cos\left(\frac{2\,\pi\,t}{365.25}\right) \tag{1.1}$$

2 harmonics

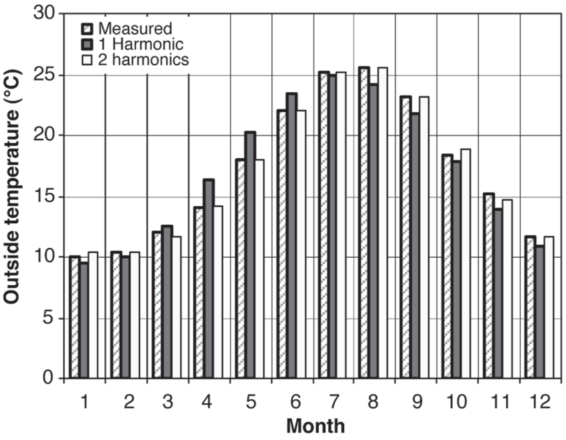
$$\begin{aligned}\theta_e = \overline{\theta}_e &+ A_1 \sin\left(\frac{2\,\pi\,t}{365.25}\right) + B_1 \cos\left(\frac{2\,\pi\,t}{365.25}\right)\\ &+A_2 \sin\left(\frac{4\,\pi\,t}{365.25}\right) + B_2 \cos\left(\frac{4\,\pi\,t}{365.25}\right)\end{aligned} \tag{1.2}$$

where $\overline{\theta}_e$ is the annual mean dry bulb temperature. t is time and d the phase shift in days. For three of the locations listed in Table 1.2 one gets (see also Figure 1.1):

	$\overline{\theta}_e$ °C	A_1 °C	B_1 °C	A_2 °C	B_2 °C
Uccle	9.8	–2.3	–6.9	0.45	–0.1
Kiruna	–1.2	–4.2	–11.6	1.2	0.5
Catania	17.2	–4.1	–6.6	0.8	0.2



Kiruna



Catania

Figure 1.1. Outside air temperature: annual course, one and two harmonics.

For Uccle the average difference between the monthly mean daily minimum and maximum ($\theta_{\text{e,max,day}} - \theta_{\text{e,min,day}}$) during the period 1931–1960 looked like:

J	F	M	A	M	J	J	A	S	O	N	D
5.6	6.6	7.9	9.3	10.7	10.8	10.6	10.1	9.8	8.0	6.2	5.2

Combination with the annual course gives (time in hours):

$$\begin{aligned}\theta_{\text{e}} &= \bar{\theta}_{\text{e}} + \hat{\theta}_{\text{e}} \cos\left[\frac{2\,\pi\left(t-h_1\right)}{8766}\right] \\ &+ \frac{1}{2}\left\{\Delta\bar{\theta}_{\text{e,dag}} + \Delta\hat{\theta}_{\text{e,dag}} \cos\left[\frac{2\,\pi\left(t-h_2\right)}{8766}\right]\right\} \sin\left[\frac{2\,\pi\left(t-h_3\right)}{24}\right]\end{aligned} \tag{1.3}$$

with:

$\Delta\overline{\theta}_{\mathrm{e,dag}}$	$\Delta\hat{\theta}_{\mathrm{e,dag}}$	h_1	h_2	H_2
°C	°C	h	h	h
8.4	2.8	456	–42	8

Equation (1.3) assumes the daily values fluctuate harmonically. This is untrue. The difference between the minimum and maximum daily value swings considerably without even a glimpse of a harmonic course. To give an example, the difference for January and July 1973 in Leuven, Belgium, was purely stochastic, with average values of 4.0 °C and 8.9 °C respectively and a standard deviation mounting to 60% of the average in January and 39% of the average in July.

A question of particular importance is if the dry bulb temperature recorded during the last decades reflects global warming. For that, we turned to the data recorded by a weather station in Leuven, Belgium, between 1997 and 2007. The annual means are shown in Figure 1.2.

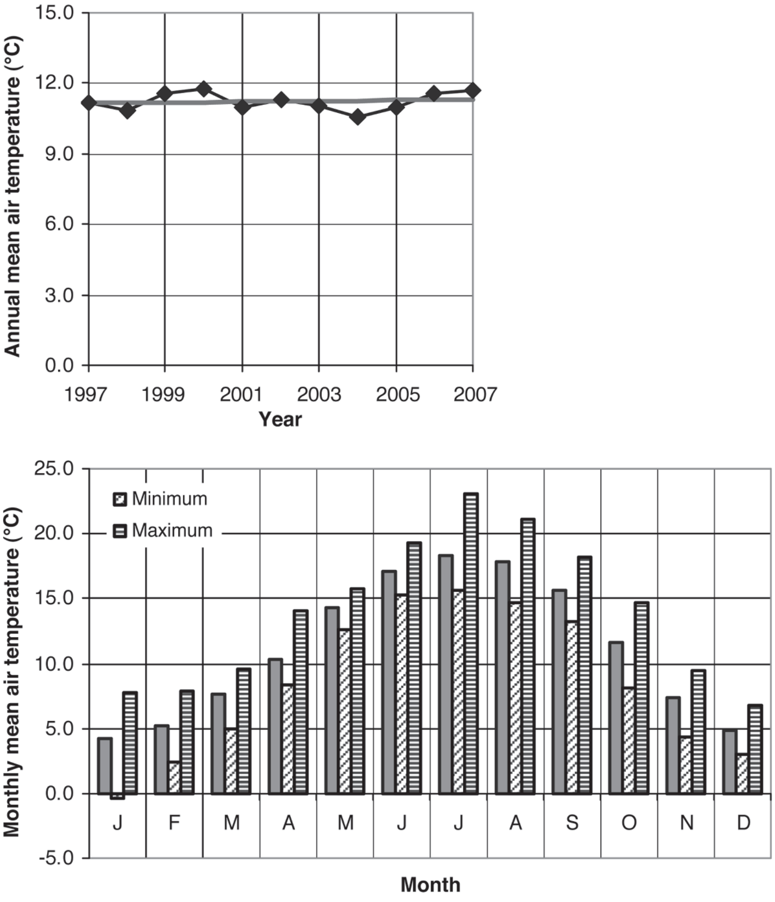


Figure 1.2. Weather station, Leuven, Belgium: annual mean dry bulb temperature (left), average, minimum and maximum monthly mean recorded between 1996 and 2007 (right).

With an average of 11.2 °C and the slope of the least square line close to 0.02 °C, a recorded increase seems hardly present. However, in Uccle, which is 30 km South West of Leuven, the average annual mean between 1901 and 1930 touched 9.8 °C, i.e. 1.4 °C lower than the value measured in Leuven between 1997 and 2007. Between 1952 and 1971, a same 9.8 °C was recorded. Since then, however, the moving 20 years average increased slowly, with the highest values noted between 1988 and 2007.

1.2.2 Solar radiation

Solar radiation means free heat gains. These decrease the end energy needed for heating but increase the end energy needed for cooling. Too much gain may also cause overheating. The sun further increases the outside surface temperatures the irradiated envelope parts experience. Although enhancing drying, these higher temperatures activate solar driven diffusion to the inside of moisture stored in the exterior rain buffering layers. In air-dry outer layers in turn, the higher temperature and accompanying drop in relative humidity aggravates hygrothermal stress and strain.

The sun acts as a 5762 K hot black body at a distance of 150 000 000 km from the earth. That large distance allows considering solar radiation as being emitted by a flat body with the rays in parallel. Above the atmosphere the solar spectrum looks as drawn in Figure 1.3 with a mean irradiation equal to:

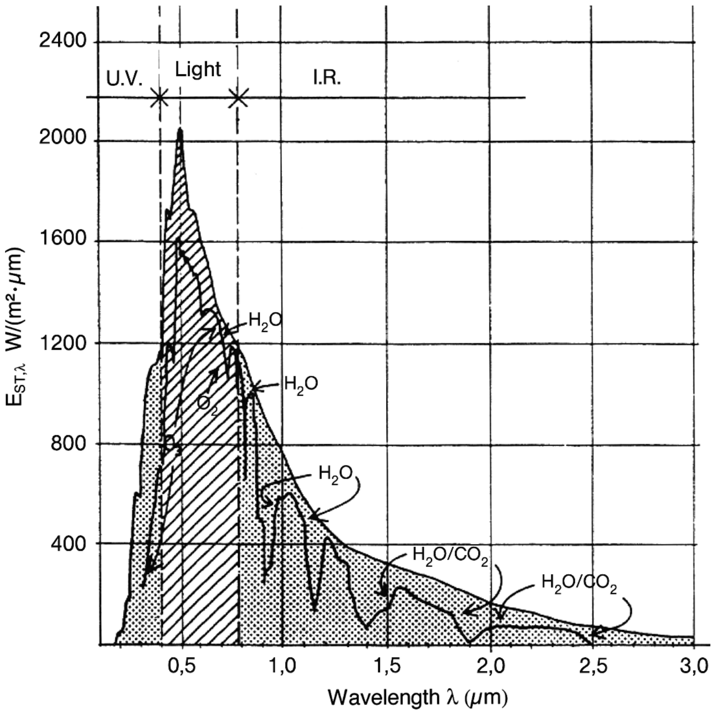


Figure 1.3. Solar spectrums outside and after passing the atmosphere.

$$E_{\mathrm{ST}} = 5.67\left(\frac{T_{\mathrm{S}}}{100}\right)^4\left(\frac{r_{\mathrm{S}}}{D_{\mathrm{SE}}}\right)^2 = 5.67\cdot(57.64)^4\cdot\left(\frac{0.695\cdot 10^6}{1.496\cdot 10^8}\right)^2 = 1332\ \mathrm{W/m^2} \quad (1.4)$$

In that formula r_{S} is the radius of the sun and D_{SE} the distance between earth and sun, both in km. The value 1332 W/m^2 is called the average solar constant (E_{STo}). It reflects the mean solar radiation per square meter the earth should receive upright the beam if no atmosphere existed. That intensity is quite thin. Burning one litre of fuel for example gives $4.4 \cdot 10^7$ J. To collect that amount of energy a square meter large terrestrial surface upright the beam should need constant solar irradiation during nine hours. That thinness explains why large collecting surfaces are needed when the aim is using solar energy for heat or power production.

A more exact description of the solar constant accounts for the annual variation in distance between earth and sun and the annual cycle in solar activity (with d the number of days beyond December 31/Januari 1, at midnight):

$$E = 1373\left\{1 + 0.03344\cos\left[\frac{2\pi}{365.25}(d - 2.75)\right]\right\}(\mathrm{W/m^2}) \quad (1.5)$$

The azimuth (a_{s}) and solar height (h_{s}) or the time angle (ω) and declination (δ) which is the angle between the sun's highest position and the equator plane, fix the solar position in the sky, see Figure 1.4. The first two describe the sun's movement as seen locally whereas the second two relate that movement to the equator. The time angle varies from 180° at 0 p.m. over 0° at noon to –180° at 12 a.m. One hour thus corresponds to 15°. The declination in radians is given by:

$$\delta = b\,g\,\sin\left\{-\sin\left(\frac{\pi}{180}23.45\right)\cos\left[\frac{2\pi}{365.25}(d + 10)\right]\right\} \quad (1.6)$$

where 23.45 is the latitude in degrees between the equator and the tropics. The maximum solar height in radians follows from:

$$h_{\mathrm{s}} = \frac{\pi}{2} - \varphi + \delta \quad (1.7)$$

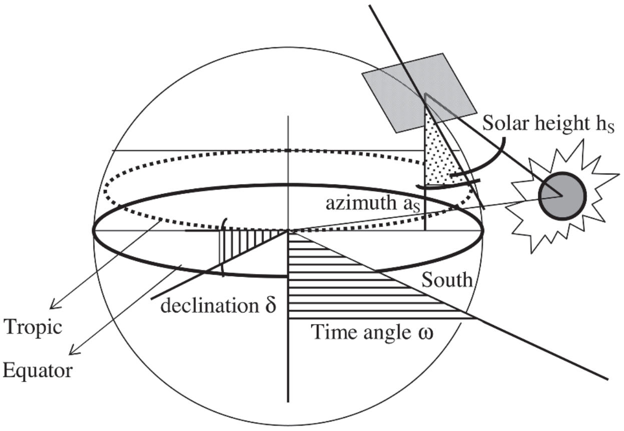


Figure 1.4. Solar angles.

φ being the latitude in radians (positive in the northern, negative in the southern hemisphere).

1.2.2.1 Beam insolation

During its trek through the atmosphere, selective absorption by the ozone, oxygen, hydrogen, CO_2, CH_4 present tempers the radiation and changes its spectrum, while scatter transforms the beams into beam and diffuse radiation. The longer the distance the solar beam has to traverse through the atmosphere, the larger that tempering. She intervenes in the equation for beam insolation through the air factor m: the ratio between the real distance traversed and the distance to sea level if the sun stood in zenith position (Figure 1.5). As an equation (solar height h_s in radians):

$$m = \frac{1 - 0.1\,z}{\sin(h_s) + 0.15\left(\frac{180}{\pi}\,h_s + 3.885\right)^{-1.253}} \tag{1.8}$$

where z is the height above sea level in km.

Beam insolation on a surface upright the solar rays is then given by:

$$E_{\mathrm{SD,n}} = E_{\mathrm{STo}} \exp\left(-m\, d_{\mathrm{R}}\, T_{\mathrm{Atm}}\right) \tag{1.9}$$

with d_{R} the optic factor (a measure for the scatter of the beam per unit of distance traversed through the atmosphere) en T_{Atm} the turbidity of the atmosphere. The optic factor follows from (solar height h_s in radians):

$$\begin{aligned} d_{\mathrm{R}} &= 1.4899 - 2.1099\cos(h_s) + 0.6322\cos(2\,h_s) + 0.0253\cos(3\,h_s) \\ &\quad - 1.0022\sin(h_s) + 1.0077\sin(2\,h_s) - 0.2606\sin(3\,h_s) \end{aligned} \tag{1.10}$$

Atmospheric turbidity on a clear day is given by (solar height h_s in radians):

Mean air pollution $T_{\mathrm{Atm}} = 3.372 + 3.037\,h_s - 0.296\cos(0.5236\ \mathrm{mo})$

Minimal air pollution $T_{\mathrm{Atm}} = 2.730 + 1.549\,h_s - 0.198\cos(0.5236\ \mathrm{mo})$

where mo is the month's ranking (1 for January and 12 for December).

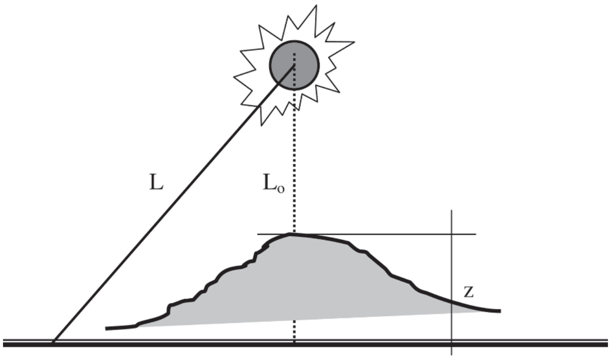


Figure 1.5. *L* is the atmospheric distance traversed, *z* the height in km and *m* the air factor equal to L/L_o.