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Welcome to the Daylighting Handbook II. The book is a continuation of the Daylighting Handbook I: Fundamentals and Designing with the Sun, which comprises chapters 1–8. The second volume is also divided into two parts, Daylight Simulations and Dynamic Façades. Chapters 9–12 discuss how to predict the overall amount of daylight in and around buildings at any given site using manual methods and computer simulations. Chapters 13–16 present an integrated design analysis framework to evaluate façades with dynamic shading and lighting systems that negotiate between occupant comfort and energy efficiency.

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As for the previous volume, I have made every effort to ensure that the information presented is accurate and relevant. Should you nevertheless find any errors, typos or have divergent opinions, I sincerely invite you to share them with me at tito@mit.edu.

Christoph Reinhart
Cambridge, September 2018

Fig 9.1 Harvard Art Museum Expansion, Cambridge, Massachusetts, by Renzo Piano, 2014
Daylight Simulations

Chapters 9–12 discuss how to predict the overall amount of daylight in and around buildings at any given site using manual methods and computer simulations. Chapter 9 provides an overview of sky models and radiation maps followed in chapter 10 by a historic account of algorithms used for point-in-time daylight simulations. Chapter 11 discusses illuminance-based daylight availability metrics including methods of how to model daylighting levels under multiple sky conditions (dynamic daylight simulations). Chapter 12 introduces measurement techniques for characterizing the optical properties of opaque and transparent objects.

Fig 9.2 Simulation-based map showing the photovoltaic potential for MIT buildings around Killian Court in Cambridge, Massachusetts
(Source: mapdwell)
Part two of the *Daylighting Handbook I* dealt with the question of how to consider direct sunlight during the design of a building, acknowledging the fact that direct sunlight can – in extreme cases – be responsible for up to 80% of global annual solar radiation falling on a horizontal surface. However, depending on climate and surface orientation, diffuse daylight may not only constitute a significant fraction of incident annual global solar radiation but – for façades facing away from the equator – almost all incident solar radiation. Given the ensuing relevance of diffuse radiation, this chapter reviews a family of *sky models*, that describe the sky luminous distribution under different sky conditions. These models constitute one of the inputs used for the physically based daylight simulation methods discussed in chapter 10. Another use of sky models is to sum up instantaneous sky conditions over extended periods of time. The resulting *cumulative skies* can be used to generate *radiation maps*\(^1\) to assess the potential of a building design or site for photovoltaic power generation and passive solar heating through windows.

**Sky Models**

In chapter I-3 in *Daylighting Handbook I* sky conditions were classified into three categories: clear, intermediate and overcast. Sky models are used to mathematically approximate the complexity of real skies. Typical model inputs are site latitude and longitude, date and time as well as measured or simulated global and diffuse solar irradiance. A source of hourly solar radiation data are the Typical Meteorological Years from chapter I-3 or local weather station data. Using Equ 6-3 and 6-4, the position of the solar disk can be derived at any given moment in time. The luminance of the solar disc corresponds to the direct normal irradiance, \(I\), divided by the disc’s solid angle. \(I\) is either measured by a tracking sensor that directly faces the sun (Fig I-3.19) or derived from global horizontal irradiance \(G\) and horizontal diffuse irradiance \(D\) as follows.

\[
I = \frac{G - D}{\cos (\text{solar altitude})}
\]

Equ 9-1

Over the past 100 years, a succession of increasingly refined standardized sky luminance distributions have been presented which consider diffuse daylight as well as direct sunlight. These distributions are two-dimensional
mathematical functions of the relative luminous/radiative distribution at a particular sky element with respect to the zenith luminance/radiance. Local radiation levels need to be combined with sky luminous efficacy models (see below) to translate a relative sky luminous distribution into absolute values. While one could use azimuth and altitude angles as input variables for sky luminous distribution functions (Fig 1-6.4), the natural composition of actual sky conditions favors the coordinate system shown in Fig 9.4. The system uses two angles, \( c \) and \( Z \). \( c \) constitutes the shortest angular distance between a given sky element and the sun. \( Z \) and \( Z_{\text{sun}} \) are the angular distances between the zenith and the sky element and the sun, respectively. All established sky models then rely on the same basic set of functions to describe the ratio of the luminance/radiance \( L \) of a sky element to the zenith luminance/radiance, \( L_{\text{zenith}} \):

\[
\frac{L}{L_{\text{zenith}}} = \frac{f(c)}{f(Z_{\text{sun}})} = \frac{\varphi(Z)}{\varphi(0)} \quad \text{with} \quad \varphi(Z) = 1 + a e^{b \cos(Z)} ; \ f(c) = 1 + c \left[ e^c - e^{c/2} \right] + e \cos^2(c)
\]

Equ 9-2

Parameters \( a \) to \( e \) are modified in the different sky models to adopt the sky luminous distribution function to a range of different skies. What the practically minded reader may want to retain from Equ 9-2 is the physical meaning of the two functions: \( \varphi(Z) \) and \( f(c) \). \( \varphi(Z) \) is called the luminance

\( j(Z) \) is called the luminance gradation function. It defines the changes of luminance from the zenith to the horizon. For a uniform sky this function corresponds to unity (\( a=0 \)). \( f(c) \) is the scattering indicatrix. It relates the changes of luminance of a sky segment to its angular distance from the sun. Its main purpose is to define the luminance in the circumsolar region surrounding the sun. Both effects can be seen in the hemispherical fisheye HDR photograph of a clear sky over Berkeley in Fig 9.5 even though lens flaring partially occludes the circumsolar region. The interested reader may further consult the HDR sky movies provided by Lawrence Berkeley National Laboratory at URL http://flexskycam.lbl.gov.

CIE and Perez Skies

The earliest approach to model an overcast sky dates as far back as 1909 to Peter Waldram who defined the uniform sky, a simple isotropic sky luminance distribution without any direct sunlight (Fig 9.6).\(^3\) In 1942, Parry Moon and Domina Spencer at MIT replaced the uniform sky with the CIE overcast sky, a rotationally invariant sky which has a zenith brightness three times higher than the horizon with a sine dependant fall-off (Fig 9.7).\(^4\) The relevance of (initially) the uniform and later the CIE overcast skies is that they consecutively served as the basis for the Daylight Factor metric which is being used to this day and which will be further discussed in chapters 10 and 11. While the CIE overcast sky may do a semi-decent job at mimicking...
Fig 9.6 Hemispherical fisheye view of a uniform sky on April 15 at 10am in Boston

Fig 9.7 Hemispherical fisheye view of a CIE overcast sky on April 15 at 10am in Boston

Fig 9.8 Hemispherical fisheye view of a CIE clear sky on April 15 at 10am in Boston

Fig 9.9 Hemispherical fisheye view of a Perez all-weather sky on April 15 at 10am in Boston (intermediate sky condition)
the sky luminous distribution under select overcast skies, a clear sky model was also required, especially for climates with predominantly sunny skies. The CIE clear sky was hence formalized by the CIE in 1973. As shown in Fig 9.8, the CIE clear sky consists of a pronounced circumsolar region and a slightly brightened horizon.

The CIE overcast and clear skies served for several decades as two extreme sky conditions under which architects could evaluate a particular building design. Then, during the mid-1990s, a new generation of skies, the CIE standard general sky as well as the Perez all-weather sky,10 were introduced to “cover the spectrum of intermediate and cloudy skies between the two already standardized clear and overcast sky distributions.” Interestingly, both skies still rely on the mathematical functions from Eq 9-2.

The difference between them is that the CIE general sky defines 15 discrete parameters sets for variables a to e whereas the Perez sky model continuously changes those parameters as a function of sky clearness and brightness. Sky clearness and brightness are derived from horizontal diffuse and direct normal solar irradiances. CIE general and Perez all-weather sky models expand upon and include the earlier mentioned “old” CIE overcast and clear skies. Same as Perez, the CIE general sky requires direct and diffuse irradiance pairs along with latitude, longitude, date and time to identify which of the 15 standardized general skies best matches a particular sky condition for a given set of date, time, location and irradiation data. Fig 9.9 shows a hemispherical fisheye view of an intermediate sky according to Perez on April 15 at 10am in Boston. Visual comparison to the CIE overcast and clear skies in Fig 9.7 and 9.8 confirms that Perez constitutes an intermediate between the two extreme skies.

Sky Luminous Efficacy Models
As mentioned in chapter I-3, weather stations increasingly measure global irradiance, which can be used to derive diffuse and direct irradiance via separation methods such as the Reindl model.9 To convert solar irradiances into their photometric equivalent, luminous efficacy models for direct, diffuse and global solar irradiances are required. Within the Radiance/DAYSIM simulation suite, the author regularly uses a set of conversion models by Richard Perez, Pierre Ineichen and others.10 Same as the Perez all-weather sky model, these models use sky clearness and brightness as key input parameters to select between polynomial fitting functions which were derived and validated based on measurements taken at 13 sites in the US (10) and Europe (3). The measured diffuse luminous efficacy for these sites varied from less than 110lm/W for bright overcast skies to above 150lm/W for clear skies. Measured solar beam luminous efficacy was mostly around 100lm/W and only decreased for low solar altitudes due to increased scattering caused by longer beam paths through the atmosphere.

A point worth noting is that the above mentioned sky models perform well when mimicking luminance distributions under clear or overcast sky conditions. However, their ability to predict “discontinuous” effects such as clouds is low. While the effect of clouds on overall radiation levels is captured through global and diffuse irradiance measurements, spatially resolved phenomena – such as a highly reflective cloud to the north of a building that may trigger glare – are being ignored. An interesting proposal by Richard Perez in 1993 to add the effect of clouds to sky models has – to the author’s knowledge – not been further pursued.12

Sky luminous efficacy models, combined with the earlier discussed sky luminous distribution models, effectively treat the sky and sunlight as “gray” light sources, meaning that they ignore their spectral composition. If all surfaces in a scene are also gray (have the same reflectance/transmittance throughout the visible range) this approach is justifiable. However, if one models an interior space with color-tinted windows, assuming a constant reduction factor for all wavelengths leads to significant
More importantly, as one tries to get a sense of the lighting quality in a space or aims to model health-related effects linked to circadian response, introducing sky models with a physically based color gradient becomes necessary. An example spectral model, which has been implemented into the Radiance simulation suite, is the *Utah sky model*. The model’s predominant current use is to generate superior scene visualizations.

Finally, as physically accurate HDR photography is becoming more widely used, it may at one point become common practice to replace sky luminous efficacy and distribution models with time series of HDR fisheye images of the sky over a given location (see Fig 9.5). These HDR images can then be used as simulation input for the sky in daylight simulations. As a proof of concept, Fig 9.11 shows a Radiance visualization by Mark Stock of a mirrored sphere under HDR photographs of an intermediate sky during midday and sunset.

**Radiation Maps**

As mentioned before, the standard use of sky models is to feed the resulting sky luminous distributions into a global illumination program to calculate illuminances within a scene. Another useful mode of analysis is to add up a series of different sky conditions on top of each other and to then use the resulting, nonphysical sky to understand the annual or seasonal amount of solar radiation falling onto different surfaces. In order to sum up several continuous sky luminance distribution functions, it is customary to divide the celestial hemisphere into disjoint sky patches and to record the mean luminance across each patch for a given sky condition. A typical division for diffuse daylight follows a convention introduced by Peter Tregenza in 1987 which consists of 145 sky patches. As shown in Fig 9.12, the division is rotationally symmetric around the zenith as well as the north-south and east-west planes. While Tregenza introduced the division for sky scanners with a mechanically moving luminance meter, the division remains the de facto standard for computer simulations today. The contribution of direct sunlight may either be merged with the diffuse daylight or binned separately into a number of representative sky positions throughout the year. Once an individual sky has been binned accordingly, one just has to add up all sky conditions of interest to get a *cumulative sky*. An example cumulative sky for a whole year based on the Boston TMY3 file is shown in Fig 9.12. The sky was generated using the *GenCumulativeSky* program by Darren Robinson and Andrew Stone. The cumulative sky can be combined with a global rendering algorithm (chapter 10) to yield a false color visualization of a scene in which every pixel corresponds to the solar radiation falling on the surface underlying the pixel within the time frame represented by the cumulative sky. This type of visualization is called a *radiation map*. Fig 9.13 shows an annual radiation map of the MIT buildings surrounding Killian Court. Two particularly useful design applications for radiation maps are discussed in the following sections on photovoltaic and passive solar heating potentials.