Multi-Resolution Sky Visualization: Daylight Design and Design Tools

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Abstract

This paper describes how building designers make sense of the sky and modern visualization techniques for representing them. The dialectic approach addresses technological innovation with respect to existing social practices. This is done for two reasons—to illustrate where practices are and how they can be extended with innovative technologies. It is shown that building designers maintain various levels of expertise for managing daylight design. Visualization prototypes are introduced also with different degrees of precision. The paper concludes with implications for the development of design tools and use by building designers.

Keywords: *information visualization, daylighting, building performance, energy efficiency*

1 Introduction

This paper presents preliminary results on how building designers make sense of the sky and the development of modern visualization techniques for representing them. The twofold thrust of this paper respects user-centered trends in technological development—namely that examining people and practices is key to making usable interfaces (Beyer and Holtzblatt 1998). In the domain of architectural lighting, there are numerous participants, each with distributed (Hutchins 1995) responsibilities, skills, and backgrounds. For example, the architect, who is largely responsible for a building's fenestration system, is certified and trained differently than the electrical engineer installing the electric lighting system. As a result, understanding the "user" is more complex due to distributed nature of the problem.

In recent years, the field of human-computer interaction has adopted methods to account for larger social systems for designing technical artifacts for. For example, activity theory (Nardi 1996), considers socio-historical aspects of the structure of lighting design. This perspective recognizes macro forces such as divisions of labor as well as individuals and relations to tools. Understanding the activity structure of a system can lead to effective technological development.

In this paper, we will use the term ***multi-resolution*** to characterize how different communities consider the sky as a source of illumination. This reflects different skills and expertise of the professions involved. Sky models and tools are also ***multi-resolution*** since they have varying degrees of complexity. Section 1 reviews historical aspects of sky representations. Section 2 of this paper describes how different types of users understand daylight while section 3 describes technical development of a visualization tool for representing multi-resolution data. It concludes with a discussion on implications for design tools and practices.

1.1 Background on Sky Representations

Over decades, building researchers and designers have developed a variety of abstract models of the sky for simulating building performance (Hopkinson 1966) (Muneer and Kambezidis 1997) (Illuminating Engineering Society, Rea et al. 2000). The purposes of these reference models are both for ***predictive*** accuracy as well as maintaining ***invariant*** testing conditions. Having reliable predictive data enables building designers to assess consequences of the lighting systems such as energy consumption or visual comfort before it is built. Invariant skies enable people to compare a variety of models without fear that a change in performance is due to erratic simulation conditions.

Historically designers have used physical models to understand daylight performance (Figure 1). Although this can lead to high-quality results for current sky conditions (Benton 1990), extrapolating the

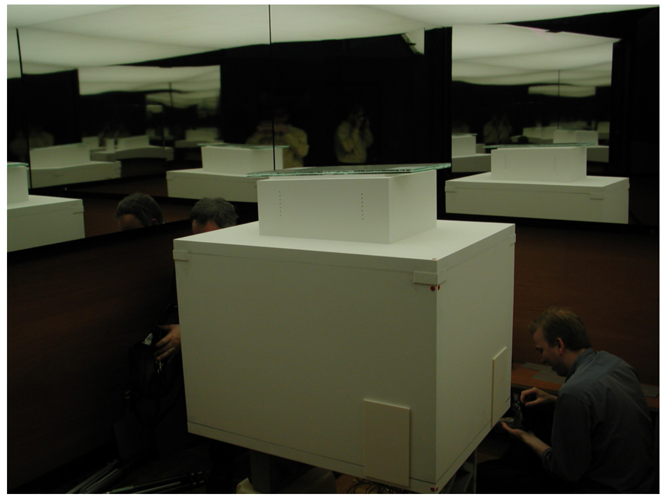


Figure 1. Artificial skies enable building designers to quickly simulate for a variety of conditions that may be difficult to control for in the real world. (left) an actual building under overcast skies and (right) a physical model in a calibrated chamber

results can be problematic. In particular, variances due to time of day, day in year, and sky conditions are not easily accounted for. Hence, symbolic representations of the sky have been created to calculate daylight performance across a variety of conditions.

During the past few decades, researchers and practitioners have described the sky in terms of idealized conditions. These skies have precise mathematical formulations (International Commission on Illumination 1996). Two skies, *clear* and *overcast*, are particularly important since they are often referred to as best and worst case scenarios respectively[1] (Figure 2). A clear sky is cloudless and is brightest at the sun location, while the darkest areas are located 180^{o} out of phase along the azimuth. For example in Figure 2, the brightest spot is located in the SW part of the sky, while the darkest crossing NE. An overcast sky scatters sunlight and varies only with respect to altitude—points highest in the sky are three times brighter than those on the horizon.

Although hourly, daily and seasonal variations can be modeled with these sky descriptions and locational data such as latitude, zenith illumination etc, having real sky data is important since actual conditions are dependent upon climate and weather. For example, changing cloud conditions can

[1] This characterization can be reversed in practice. For example, sunny skies can be “worse” than overcast when trying to minimize glare although they typically provide greater illumination.

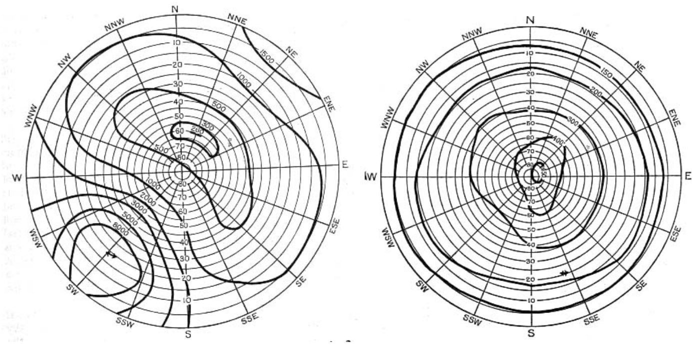


Figure 2. Charts illustrating illuminance distributions for two skies. (left) one close to CIE idealized clear and (right) overcast sky conditions. From (Hopkinson 1966).

make a winter day as bright as an overcast summer in a matter of minutes. Also, climate zones may bias the availability of daylight—for example, winters may provide more overcast skies than summers for tropical zones. As a result, sky databases have been created to provide input for the idealized skies. One such database, Solar and Meteorological Surface Observation Network (SAMSON), contains 30 years of hourly-recorded values of different sky parameters. This high-resolution dataset can be used in conjunction with idealized skies to reconstitute multiple simulation environments.

Although SAMSON contains fine-grained measurements, statisticians developed the reduced dataset Typical Meteorological Year 2 (TMY-2), to show *typical* performance of a single year. A TMY-2 year consists of 12 "typical" indivisible months selected from the 30 sampled years. This simplification enables designers and design tools to manage one year of past performance instead of 30. This reduction, though, comes at a cost since it hides large portions of the data. For example, it may contain all of January 1975, February 1983, March 1967, and nine other months. As a result, 348 months are omitted from this data set since they are less "typical"! Hence, TMY-2 data has characteristic sky variations within it, but it does not have full resolution data. TMY-2 is also limited in its expressiveness since it does not provide aggregate values either.

Table 1 summarizes the different types of sky models. A key point is that each model describes only part of a reference sky. Idealized skies describe distributions of light for a hemisphere, but without specifying intensity across time. SAMSON and TMY-2 describe sky conditions across time, but without a hemispheric distribution.

Sky Model	How Obtained	Parameterization	Temporal Resolution
CIE Idealized Skies	Empirically determined	Three types: *clear*, *overcast*, or *intermediate* with distinct hemispheric distributions	With additional calculations
SAMSON	Measured at discrete times by observatories	Many variables, horizontal direct and diffuse irradiance; cloud cover most relevant to lighting simulation	Multiple years, hourly
TMY-2	Derived from databases such as SAMSON	Many variables, horizontal direct and diffuse irradiance, cloud cover most relevant to lighting simulation	Single year, hourly (derived from multiple years)

Table 1. Summary comparing different sky models.

The next section describes how current practices use different sky models.

2 User Studies

Four groups of building designers and daylighting experts were asked how they incorporated sky information into their designs. Small samples of students, architects, educators, and daylighting consultants were included in this study. These groups were not mutually exclusive; most of the building science educators were also daylighting consultants. Interviews focused on how people differentiated between ***direct*** and ***diffuse*** components of daylight. The direct component relates to the light emitted directly from the sun, while the diffuse accounts for all the other parts of the sky. The ratio between the two can widely vary depending on factors like cloud cover.

2.1 Architects and Graduate Students

Three architects and four graduate students in architecture were interviewed. They were asked the following questions:

1. What is your background in design?

2. How long have you worked in the field? have you taken a building science course before?

3. Have you ever thought about sky conditions with respect to building design? if yes, please illustrate how you did on a specific project.

The architects all had 15 years or more experience, but little or no formal building science background. In general, they limited the term 'sky condition' to sun orientation and profile angles—they did not differentiate the direct component of daylight from diffuse. For instance, one of the architects mentioned the location of the skylights can balance light in the interior space:

> *I like to use skylight to balance spaces and rooms. I think skylights should not be placed at the center of the room, instead, it should be placed on the surfaces that can be washed accordingly. Light reflects off the wall and thus bounces back to the interior space. To decrease the issue of glare, windows and daylight are taken into great account.*

Only one out of the three architects was able to address the question in some detail:

> *There are several issues to address when applying different sky conditions. For instance, in a clear sky, the light is more "contrasty". When a sky is overcast, the light is more even. When both conditions occur, we need a high contrast as well as an even light. As a result, the quality changes. All of the quality depends on surfaces, without the surfaces, you can't see the light.*

The graduate students represented a population recently educated about building science concepts. Some of the graduate students stated that they did not consider sky conditions in their designs. Others thought they did, but although those students said they were aware of and designed for varying sky conditions, they in fact considered only visual and thermal aspects of direct beam sun (Figure 3).

2.2 Building Science Survey and User Test

To inquire about expert representations, a survey was posted to an international building science educator list and one expert provided comments during a user test. The survey questions related to what types of simulations they ran, the skies they used, and for what purpose. The user test was for an early prototype described in (Glaser and Ubbelohde 2002). For the survey, four educators responded, three of which had performed notable consulting work.

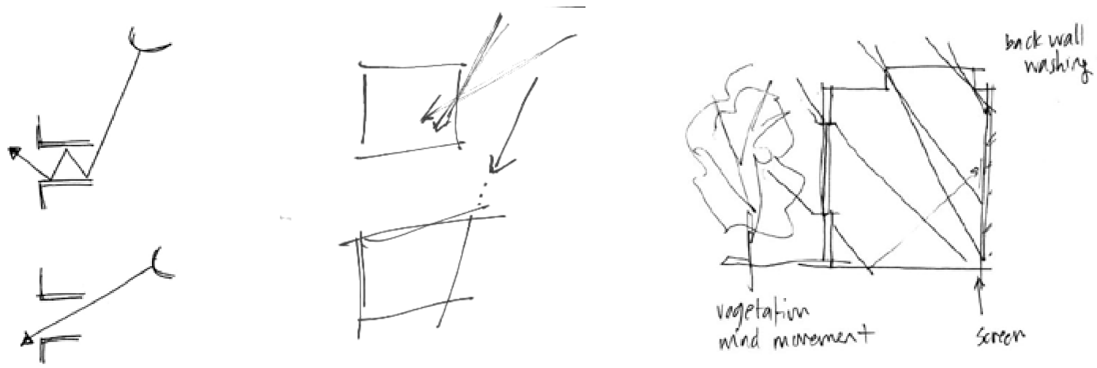


Figure 3. Sample student drawings when asked to show how the sky affects the lighting in a building. The responded only by illustrating ideas related to *direct* beam sun instead of atmospheric or *diffuse* effects.

These experts simulated daylight for three main applications. All four used daylight simulation tools for analyzing window and skylight placement during schematic design. Two specifically addressed simulation for daylight and electric light integration. Only one described how they used daylight simulation to identify zones for electric lights and estimating energy savings through the use of lighting controls. It should be noted, though, that the resolution of data working with lighting controls was very low—predicting daylight sensor performance from a single point with a single idealized sky. This result was only displayed numerically and did not allow the expert to inspect its accuracy.

A variety of tools were used to assess the lighting conditions. “I look at daylighting from as many perspectives as possible”. Physical models, high-quality computer renderings, and illuminance plots were all cited. Nevertheless, none of these representations could provide meaningful contexts for high-resolution data “I personally believe that daylight resource design data are woefully inadequate and/or hard to find” one expert said.

Currently professionals only simulated for a limited set of sky conditions. CIE clear and overcast were cited by three of them along with actual skies with physical modeling. One expert justified the limited simulation context as follows:

> *We usually use a clear sky and 9:00, noon and 3:00pm, December, March, and June. That’s Los Angeles’ weather and we don’t wait for something else*

It is important to note that the expert made a simplification of the Los Angeles sky distribution for the year. The consequences for this type of assumption are illustrated in Section 3.

Only two of these experts discussed using sky conditions with respect to daylight/electric light integration. It is unclear from the tools that they specified how useful the information was. For example, one program, DOE-2, enabled them to estimate daylight availability by a single representative point for large areas in the architectural plan with a uniform sky. This enables the consultant to determine the savings a daylight sensor would provide for the electric lighting system. No expert referenced SAMSON level data for their design problems.

As part of an earlier user study of visualiztion prototypes described in Section 3, an expert consultant was shown the interface and inquired about the sky conditions. At the time of the test, the only sky condition implemented was clear sky. He was able to identify the limitations of the interface and asked to see data from a “TMY tape”. Hence, his level of understanding of skies was similar or above the other consultants on the mailing list.

2.3 User Summary

User models of the sky were ascertained through three sources of empirical data. The first sample composed of graduate students and architects did not describe the sky outside of its direct component. The second sample of building science experts described more detailed sky descriptions, but still worked with a range of sky types that the next section will show is limited. They noted, though, that technologies were not yet capable of helping them in their analysis. The third was a single expert who described, in detail during a design situation, how he would like to see high-resolution representations. Table 2 summarizes the results of the user studies.

Sky Model	Used by Novices?	Used by Experts?
CIE Idealized Skies	Some	Yes
SAMSON	No	No
TMY-2	No	Most

Table 2. Summary of understandings of different sky models by different populations. Architects and graduate students are considered novices while building science educators and consultants experts.

3 New Representations

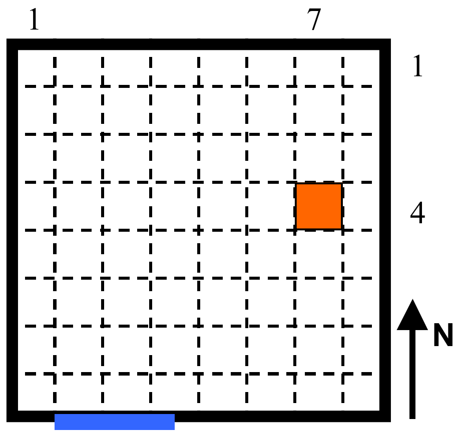
We have extended an existing visualization environment (Glaser and Ubbelohde 2002) to account for varying sky conditions. This environment now consists of four basic parts. One is the advanced visual display that is currently under development. The second are links to a simulation environment described in (Ward 1994) and to sky databases. Finally, it consists of a sketch-modeling environment for creating an architectural model for analysis.

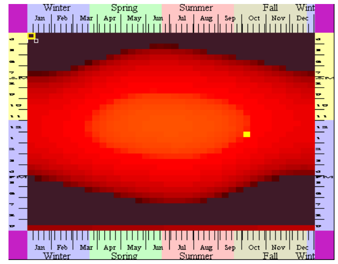
A challenge with this research is to provide mechanisms for displaying the high-resolution data that the sky models can provide. To our knowledge, no techniques have been developed to visualize such complex data. The video Lightscapes (Sumption, Haglund et al. 1991) illustrates innovative techniques through a cinematic type experience for one building across a variety of times and sky conditions. Radiance (Ward 1994) has the facilities for simulating these various sky conditions, but does not have built in visualization capabilities for managing temporal changes. The commercial program Lightscape has facilities to enter TMY-2 type data, but not for multivariate visualization. Hence, extending the visualization environment described in (Glaser and Ubbelohde 2002) will offer the necessary functionality for examining different sky models.

3.1 Visualizing Idealized and TMY-2 Defined Sky Conditions

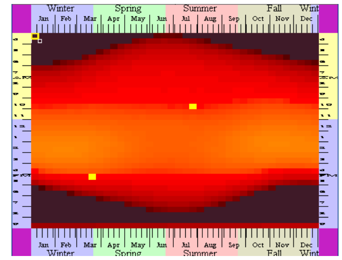
Figure 4 visually illustrates a model's performance under varying sky conditions. On the left is a rectilinearly shaped architectural model. It has a single south-facing window and has 64 sensors at workplane height (2.5 feet) for sampling daylight performance (in an 8x8 grid). A sensor on the east side is highlighted red and the temporal performance is drawn in the four graphs in the right. The axes in all four graphs are time of day (4am to 10pm; from top to bottom) and day in year (Jan 1 to Dec 31; from left to right). Values of higher illuminance are drawn in yellow while darker regions are red. Times of no data (nighttime) are drawn in black.

It can be seen that the plots generated from CIE idealized skies are smoother than that of TMY-2 data. Idealized skies are defined with smooth parameterizations while TMY-2 data is measured and can be highly variable. There also is large variation among the three idealized sky conditions. For example, the sensor under overcast sky will not receive high (orange) amounts of sunlight during the winter months like the clear and intermediate skies do.

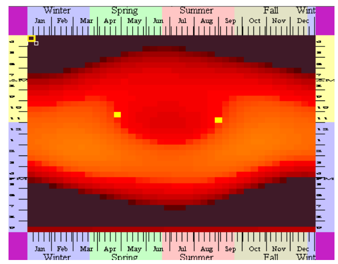




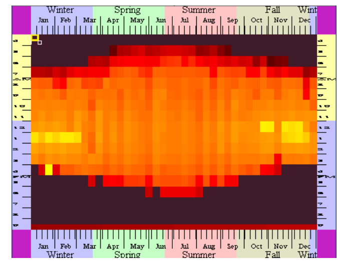
CIE Overcast Sky



CIE Clear Sky



CIE Intermediate Sky

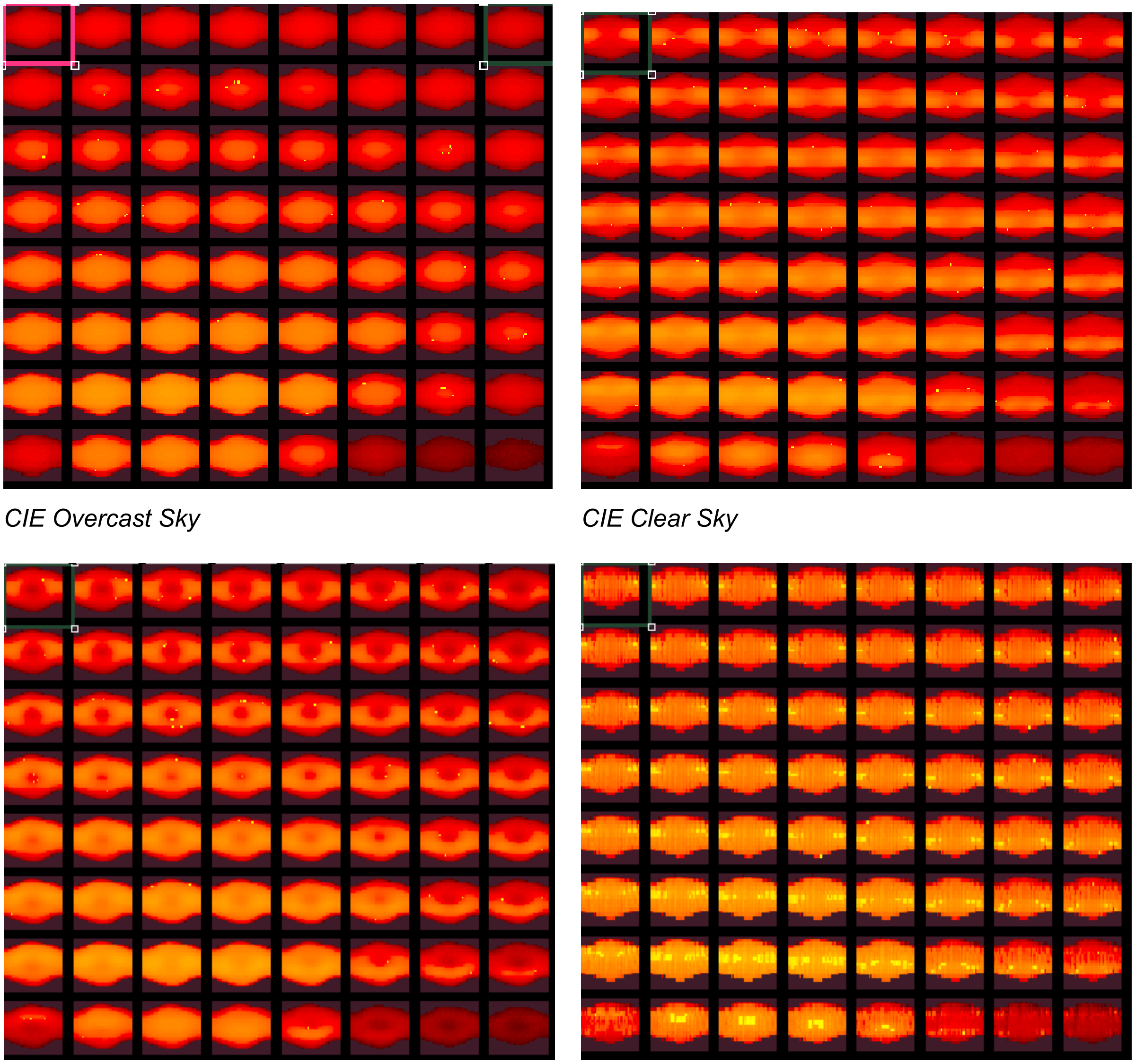


TMY-2

Figure 4. (left) A rectangular model with a single South-facing window. (right) The performance under four sky conditions across the year.

One result that this visualization makes apparent is that the conditions displayed with the intermediate sky do not fall between the clear and overcast sky. For example, at noon in the summer, the point's performance under intermediate skies is *less* than both overcast and clear. Hence, the idealized distribution of the intermediate sky differs from the clear and overcast and can lead to lower "worst case" results. This is important to note since designers who want to see worst cast lighting, should also simulate for intermediate skies. (this model was dropped from the standards).

Figure 5 shows a denser layout of the data. Instead of showing a single sensor's performance as in Figure 4, temporal graphs of all 64 sensors are simultaneously charted keeping its spatial order. For example, in the CIE overcast day, the top row of values are dark red since the north side of the room does not receive any direct sunlight. In contrast, under CIE clear sky, points on the north side receive direct sunlight during the winter months (due to the lower position of the sun which enables it to penetrate deeper in the room). It should be noted that the purple and green rectangles are interface controls, unrelated to the display of the data.

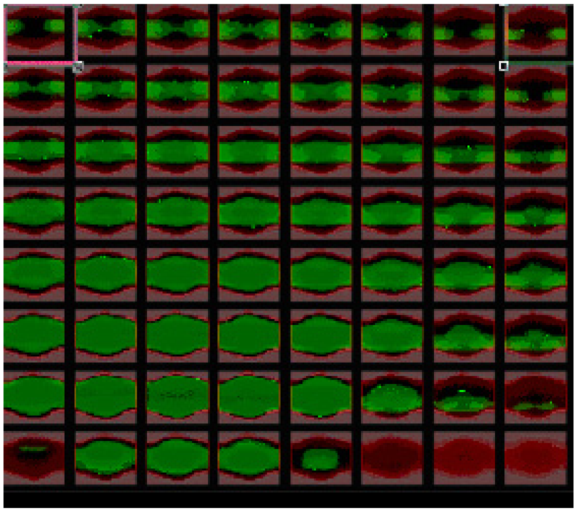


CIE Overcast Sky *CIE Clear Sky*

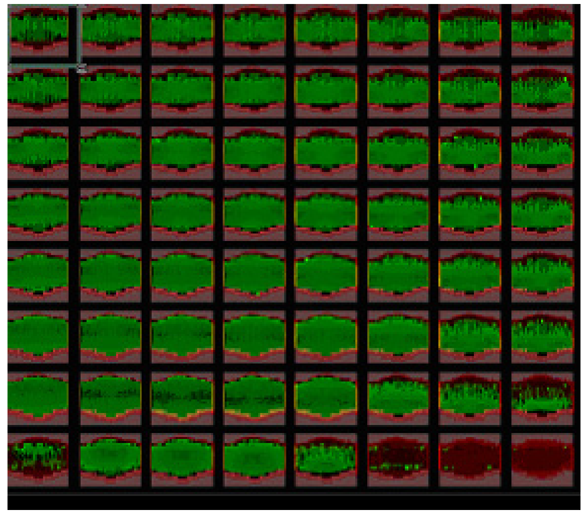
CIE Intermediate Sky *TMY-2*

Figure 5. Temporal charts at each 64 sensor points for various sky conditions. Note north is at the top of this page.

Figure 6 shows differences for running simulations with different sky models. The lighter the green shade, the larger the differences between simulation results. In Figure 6 (left), there are significant differences between clear and overcast skies throughout the year. This is both as a result of more sunlight available in the southeast portion of the room throughout the year as well as seasonal differences in the north and northeast parts of the room. Figure 6 (right) illustrates discrepancies between highly variable TMY-2 and static clear skies.



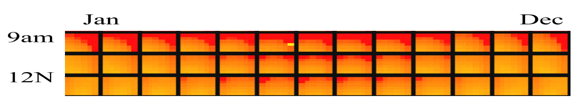
Difference between CIE Clear and Overcast sky models



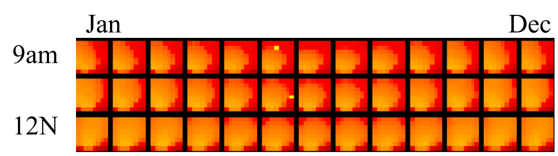
Difference between CIE Clear and TMY-2 sky models

Figure 6. Difference plots between sky models. This figure was produced through a third-party image processing program.

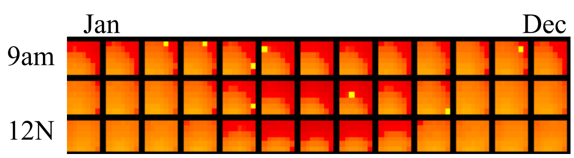
Figure 7 shows another multivariate plot of the same data, but with different axes. Each small square represents the room as depicted in Figure 4 (with slightly different proportions). This room is plotted through time of day (y-axes) and day of year (x-axes). The set of rooms illuminated by an overcast sky have a fairly even lighting distribution across time. Clear skies allow for bright, direct sun penetration with higher variance. Models simulated under intermediate skies are muted, but also allow for direct sun penetration. TMY-2 generated skies show a wide variety of conditions.



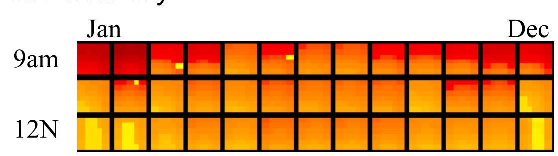
CIE Overcast Sky



CIE Clear Sky



CIE Intermediate Sky



TMY-2

Figure 7. Spatial charts for a square room under four sky conditions. Note that a square room (North facing up on this page) is plotted 39 (3x13) different times were plotted for each sky condition.

3.2 Visualizing Sky Conditions with SAMSON Data

Currently, visualization routines are under development for managing complex SAMSON data. With modern computers and visualization methods, there is no reason that high resolution SAMSON data and simulation results cannot be worked with directly. Since SAMSON data is multi-year, it can be displayed with two main strategies. The first is to extend the existing visualization routines to manage more years by simply adding them to the display (Figure 8). In this example, values of higher illuminance are colored yellow and white while lower values are blue. In Figure 8 (left), approximately five years of data are displayed in a way similar to Figure 5 (5 of 30 SAMSON years are selected). Figure 8 (center) and (right) are close-ups of individual regions. Within these cells, differences between yearly performances are apparent. For example, in Figure 8 (right), summers have noticeable amounts of light within and between years. Other routines for displaying full resolution data are currently under development.

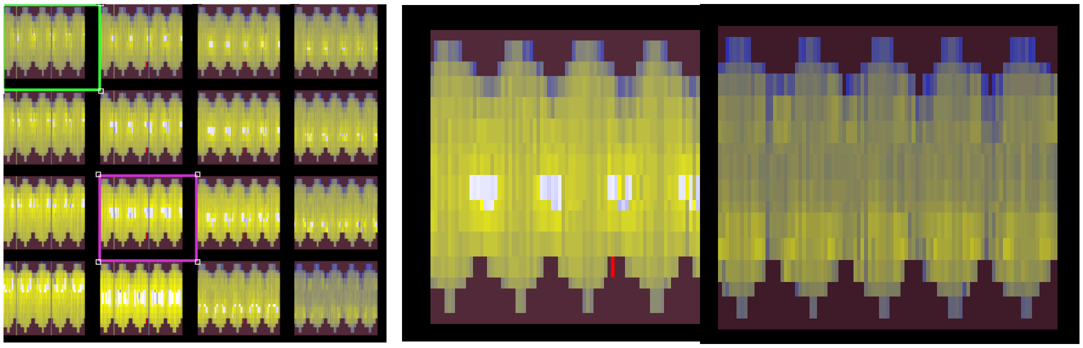


Figure 8. Multi-year SAMSON data displayed contiguously. (left) image similar to Figure 5, (center) close-up of a central cell (right) close-up of the SE most cell. Note the differences among (spatial variation) and within (temporal variation) cells.

The second strategy for managing the data is through aggregation. For example, a year of performance results can be obtained by averaging of all 30 SAMSON years. A month constructed this way will almost certainly differ from that by TMY-2 (since it will be smoother). Other aggregation functions such as finding worst and best cases could potentially be useful to different types of building designers.

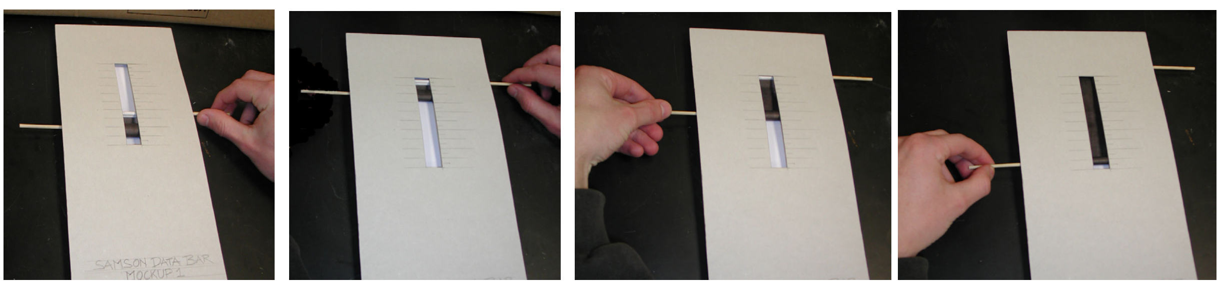


Figure 9. Range sliders under development to manage multi-year data. (from left to right) initial positioning to select the worst year; sliding the right control up to select the best year; unrolling the left control to select a range of years; further unrolling left control to see range of years.

To facilitate managing multi-year data a control has been prototyped for selecting and aggregating data (Figure 8). Two main levers organize this control. On the right is a slider to change the index of the selected year while the left is a roller to select a range. In Figure 8 (left), the user has selected one year with low illumination values. This would show a single year performance like the CIE idealized or TMY-2 skies. In (left center), the best-case year is instead selected by moving the slider further up. In (right center), the user unrolls the left lever to select multiple years. These years could be averaged or displayed in full. In (right) the user extends the roller further down to select all years for display. Although the prototype is a physical model, it could either directly be instrumented to communicate with the visualization program or be used as a reference to a software implementation.

3.3 Visualization Summary

Similarities and differences among sky conditions are made apparent by developing the visualization routines described in (anonymous cite). Depending on the sky used, there is considerable variation in the lighting performance for the sample room described in Figure 4. Hence, these visualization routines can enable designers to work with sky data at different levels.

4 Conclusions, and Future Research

From an organizational perspective, there are significant opportunities for advancements in the field of lighting visualization. The user work in section 2 illustrates that both novices and experts can both benefit from more advanced representations. In the case of architects, recognizing that the sky contributes more than just the direct beam component of the sun as a source of light can be of significant consequence. Experts, in turn, can use fine-grained simulation data to improve the performance of work that they already do. In particular, the different distributions provided under the advanced representations has consequences to the performance of the electric lighting system. This performance is related to both visual for the occupants and energy conservation with respect of the building. Hence, the proposed visualization routines can fit and expand upon exiting socio-historical networks to model the sky more accurately.

There are a number of areas planned for future study. First a set of algebraic functions are being implemented to compare different distributions shown in the visualization plots. This will enable, for example, a person to see the difference between clear and overcast skies through generating a difference plot. Second, advanced sky models developed through the field of computer graphics (e.g. (Preetham, Shirley et al. 1999)) are also being examined. User testing is planned to see how different professionals and students use the visualization tools to improve upon their design capacity for managing daylight under different sky conditions.

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