THERMAL AND LIGHTING PERFORMANCE OF TOPLIGHTING SYSTEMS IN THE HOT AND HUMID CLIMATE OF THAILAND

A Thesis

by

SIRITIP HARNTAWEEWONGSA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Architecture

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Approved by:

Chair of Committee, Liliana Beltran
Committee Members, Terry Larsen
Richard Furuta
Head of Department, Phillip J. Tabb

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ABSTRACT

Thermal and Lighting Performance of Toplighting Systems

in the Hot and Humid Climate of Thailand. (August 2005)

Siritip Harntaweewongsa, B. Arch., Chulalongkorn University

Chair of Advisory Committee: Dr. Liliana Beltran

This study evaluated the potential of toplighting systems in the hot and humid tropics by using Bangkok, Thailand (latitude 13.7°N) as a test location. The analysis tested both the thermal and lighting performance of three toplighting systems.

Toplighting, designed for use in one-story buildings or on the top floor of taller buildings, yields a uniformly distributed light throughout a space. However, in lower latitude locations, where there is no heating period, heat gain is a critical design issue since it significantly affects the annual energy consumption of the building. Accordingly, the decision to use toplighting in these locations needs to be carefully examined before any design considerations occur.

In this study, the thermal and lighting performance of three toplighting systems were compared. For the thermal performance, total cooling loads, heat gains and losses, and interior temperature were evaluated. The lighting performance parameters examined were daylight factor, illuminance level, light distribution, and uniformity. EnergyPlus was used as the thermal analysis tool, and RADIANCE, along with a physical scale model, was used as the lighting performance analysis tool. The sky conditions tested were overcast, clear sky, and intermediate sky.

Results have shown that, for locations with hot and humid climates with variable sky conditions such as Bangkok, Thailand, the roof monitors perform better than the other two systems in terms of the thermal and lighting performance. With similar cooling loads, the roof monitor provides better illuminance uniformity than the skylights and lightscoops, with adequate illuminance level (at mostly higher than 500 lux).

To Dad, Mom, Nga, and Ngern

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Liliana Beltran, my committee chair, who gave me the inspiration to study in the area of architectural daylighting. I am very thankful for all her help and support during my master's study and my research. I found her comments very informative and have helped broaden my viewpoint and my knowledge in this field. I would also like to thank Prof. Terry Larsen for his help with the settings and simulation of RADIANCE, and to Dr. Richard Furuta for his valuable comments and time.

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CHAPTER I

INTRODUCTION

1.1. Background

The use of daylighting in architectural design is an efficient way to create sustainable design, which helps to reduce both the energy consumption of a building and energy consumption on a national scale. This is because daylight is abundant and free. More importantly, it comes from a renewable resource: the sun.

The advantages of using daylight are more pronounced and more challenging as the location gets closer to the equator, mainly due to the increased availability of daylight. Bangkok, Thailand, which is at latitude 13.7°N, is in a hot and humid climate that has no heating period (Fig 1.1).

Two types of daylighting applications are used in introducing daylight into a space: sidelighting and toplighting. Sidelighting, which is more commonly seen, is an aperture in the wall elements of the building or, more simply, a window opening. Toplighting is an opening in the ceiling or roof elements of building. The most common application of toplighting is the skylight, lightscoop, or roof monitor. Toplighting is, in general, designed for used in one-storey buildings or on the uppermost floor in contact with the roof. It is now used in industrial building, factories, schools, museums, and art galleries.

This thesis follows the style and format of Energy and Buildings.

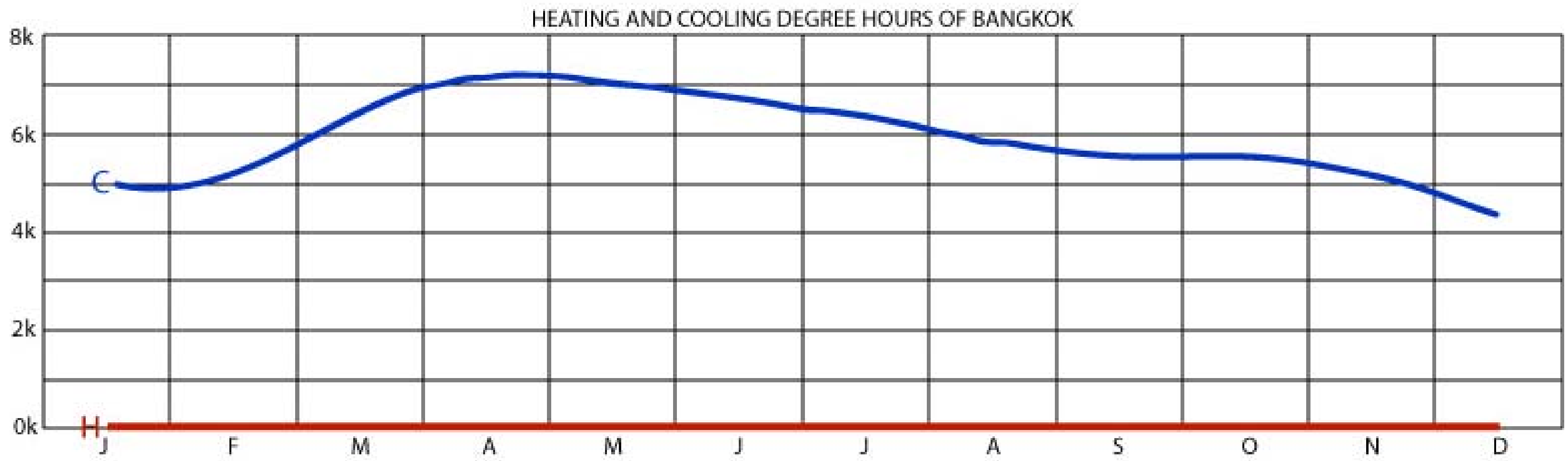

Fig. 1.1 Comparison chart between heating (H) and cooling (C) degree hours of Bangkok, Thailand

While toplighting yields more uniformly distributed daylight throughout the space than sidelighting, the use of toplighting is avoided by many architects in Thailand because of the heat gain problem. The central design consideration when using toplighting in a hot and humid climate is the associated heat gain which is more significant as the location gets closer to the equator. This is one of the variables that makes toplighting much harder to design than sidelighting even with regards to its lighting performance effectiveness.

As a consequence, at the present time, in Thailand, the use of large area of sidelight glazing or curtain walls is very popular and can be found increasingly in newly built projects, causing even more heat gain problems than it might be with the use of proper design of toplighting. Frequently, however, toplighting is not used, even when it is applicable. The most popular type of sidelighting is designed after modern buildings in cold-climate countries, which, when applied to hot and humid climates, adds unnecessary heat gains to the interior space. An oversized air conditioning system then has to be designed to nullify heat gain problems, resulting in more electricity consumption.

One solution to alleviate the heat gain problem is to use dark coatings with low visible transmittance, which inhibit the entry of daylight. However, the building then has to rely solely on electric lighting. In addition, some buildings are over-shaded to protect them from excess heat gains, thereby reducing the amount of daylight that can be efficiently used to illuminate the interior space.

As a result, electric energy has to be used to remove the heat gains and for electric lighting as well, due to the amount of daylight entering the space. This then increases the energy bill.

While studies on ways to improve the design of sidelighting for locations like Thailand have been done, research on integrating toplighting in hot and humid climates is scarce. For this reason, this study examines toplighting in hot and humid climates in terms of its thermal and lighting performance.

1.2. Research Objectives

The main objective of this research is to evaluate three simple toplighting systems in terms of their thermal and lighting performance when used in a hot and humid climate. Bangkok, Thailand is used as the test location. The following tasks for achieving this objective have been identified:

1) Develop three simple toplighting prototypes, as single units and as a series of units, which introduce similar amounts of heat gain into the space.

2) Test and evaluate the thermal performance of each toplighting system.

3) Test and evaluate the lighting performance of each toplighting system.

4) Summarize and provide design guidelines for using toplighting in buildings in hot and humid climates.

1.3. Significance of the Study

This study will be useful for designers in their decision making process when using toplighting in designs. It will also serve as proof that toplighting systems can be used in hot and humid climates without having to pay the heat penalty—if the design is done properly.

1.4. Assumptions and Delimitations

1.4.1. Assumptions

The first assumption is that Bangkok, Thailand (latitude 13.7°N) is representative of a hot and humid, low-latitude location.

The second assumption is that the prototypical building used in this study is representative of a typical building in a low-latitude location.

1.4.2. The Delimitations

This study will not attempt to evaluate toplighting performance in aspects other than lighting and thermal performance.

This study will be limited to the study of daylight only and will not test the effects of the integration of daylight and electric lighting.

This study will be limited to the hot and humid, low-latitude locations where there is mostly no heating period all year. The test location used is Bangkok, Thailand.

1.5. Organization of the Thesis

This thesis is comprised of 6 chapters. Chapter I, Introduction, provides the research background information, research objectives, assumptions, and the significance of the study.

Chapter II discusses the related literature which is about daylighting and toplighting, including previous studies on toplighting performance and potential of toplighting use in Thailand.

Chapter III provides the information on a research methodology which covers the base case building information, thermal performance and lighting performance methodology, and the development of toplighting prototypes.

Chapter IV discusses the evaluation of the thermal performance of each case. It comprises of the thermal performance test of single toplighting unit, the prototype series of 1.5 to 1 spacing-to-height ratio, and the prototype series of 1 to1 spacing-to-height ratio.

Chapter V discusses the evaluation of the lighting performance of each case. It comprises of the lighting performance test of single toplighting unit, the prototypical series of 1.5 to 1 spacing-to-height ratio, and the prototypical series of 1 to1 spacing-to-height ratio.

Chapter VI summarizes the results of the study in terms of thermal and lighting performance. Design recommendations are given to designers when implementing toplighting use for buildings in hot and humid climates. Recommendations for future studies relating to this research area are proposed.

CHAPTER II

REVIEW OF THE LITERATURE

The literature review will examine the following two areas:

1. Daylighting

2. The Study of Toplighting

2.1. Daylighting

2.1.1. Daylighting and Architecture

Daylighting has been an important technique for illuminating interior spaces since ancient Egypt. Daylight not only illuminates, but also defines the abstract qualities of a space, which can be seen in religious buildings [1]. It has been used in many building types from small residential homes to larger buildings, such as temples and churches. According to Moore (1985), the use of daylight has changed over time from an opening at the spot where light is needed to the use of abundant glazed areas. This modern usage, resulting from new materials and structural development, adds heat gains to the interior space. Moreover, for areas far from the building perimeter, electric light must be used, increasing the energy consumption of a building.

At the present time, when energy is expensive and sustainable development is an important consideration in architectural design, daylight is once again seen as an important technique to help obtain energy savings.

2.1.2. Benefits of Daylighting

Daylight has many benefits and many articles have discussed the advantages of integrating daylight into design. The benefits of daylighting are discussed in the following section.

The quality of daylight is superior to that of electric lights. Robbins (1986) stated that daylight has a high quality, because it is the one light source that is full-spectrum and that closely matches human visual perception [2]. It is also considered the best light source for its color rendering quality, which is also superior to electric light. It can be said that daylight helps create a visually comfortable space and enhances the visual quality of that space.

The luminous efficacy of daylight is higher than that of electric light. The luminous efficacy of a light source is the ratio between light output to heat produced (in lumen/watt). In Lechnor, the efficacy of various light sources is compared in a chart [3]. Here, daylight introduces heat 6 times less than incandescent light with the same light level.

Another benefit of daylighting, mentioned by Robbins, is that it connects occupants with the exterior environment. Building with daylight aperture provides occupants with views, creating visual connections between the interior and exterior, and satisfying the human need for contact with the outdoor environment.

Daylight has shown to help increase sales rates, occupant productivity, and student attention in classes, because people prefer daylight. In a study by the Heschong Mahone Group on daylight and retail sales [4], it was found that the increased rate of retail sales is strongly associated with increased daylight during the day. Another study from this group suggests that daylight can increase worker performance in the areas of mental function and memory recall by 10-25% [5]. When applied in schools, daylighting increases student attention by 21% when compared with classrooms with less access to daylight [6].

One of the most pronounced benefits of daylight is that it helps save energy by reducing the use of electric lighting. Since energy crisis of the early 1970’s, people have begun to realize the significance of energy savings found in the use of renewable energy resources. In the United States alone, lighting energy consumes about 30% of electricity use in commercial buildings [7]. According to the Illuminating Engineering Society of North America (IESNA), the use of daylight can reduce by 30% the amount of electricity used for interior lighting [8]. In Thailand, according to the study by Busch et al., has referred to the paper of the National Energy Administration in 1990 that, in Thailand in 1987, the energy used for lighting accounts for 31% of electricity use for commercial buildings [9].

Given these benefits, it is apparent that daylight should be utilized to its full potential to help create a visually pleasant environment and a sustainable architecture.

2.1.3. Daylighting Design Strategies

In this section, two simple daylighting design strategies (i.e., sidelighting and toplighting) will be discussed according to the definition of Ander [10].

Sidelighting uses the walls of a building to admit daylight into interior spaces. It is a convenient strategy for building and provides both views and options for ventilation.

It gives light with a strong directionality, but which diminishes as the distance from the aperture increases. In addition, it is good for horizontal work plane surfaces. The disadvantage of sidelighting is that it may cause glare, as the illuminating area is in the field of view of the occupants, and there are often high contrast ratios between the aperture and the surrounding surfaces.

Toplighting uses the upper part of the building element: the roof or another element above the ceiling line. The advantage of toplighting is that it gives designers flexibility in arranging the geometry and orientation of daylight apertures according to the lighting needs of the occupants and is not limited to wall orientations like sidelighting [11]. As a result, the uniformity of light distribution is more easily achieved with toplighting. In addition, large quantities of light can be provided through relatively small openings.

While toplighting can help reduce the electric energy used in artificial lighting, at the same time, potential heat gains from inappropriate design have to be avoided. This challenge in designing with toplighting has to be closely examined, especially in buildings in low-latitude, hot and humid climates without a heating period [12].

2.2. The Study of Toplighting

2.2.1. Previous Studies

There have been only a few studies of toplighting design that treat both thermal and lighting performance.

One study, conducted in 1984, tested three toplighting systems using a simulation and concluded that the skylight is the most efficient system in terms of lighting and thermal performance. A study by S. Treado, G. Gillette, and T. Kusada (1984) examined the impact of window, skylight, and clerestory daylighting systems on the annual energy performance of buildings [13]. The authors concluded that the skylight is the most efficient system in terms of minimizing the overall energy used for the heating, cooling, and lighting of a building. This study, however, tested the efficiency of each system for latitude 38ºN (i.e., Washington DC), and the results could be different if tested in other latitudes and climates.

A study by the Lawrence Berkeley National Laboratory (LBNL) (W. Place et al., 1984) tested the effects of roof aperture design on the energy performance of buildings and found that a combination of east-facing and west-facing glazing reduced energy cost more than a south-facing glazing [14]. Specifically, this study examined the daylighting performance of various orientations of roof apertures and then chose two roof lighting options in order to test their energy cost benefits using the BLAST building simulation program. In their conclusion, the authors stated the need for testing more design options, as they only tested a south-facing glazing and a combination of a east- and west-facing glazing. However, they also concluded that the total annual energy cost can lowered by a combination of east-facing and west-facing glazing.

It is important to note that the test locations in these papers were in the U.S. in high-latitude locations. The results might vary in a low-latitude, hot and humid climate, since there is no heating period. In the LBNL study, the south-facing glazing was chosen, because it admitted more light in the winter than in summer. This criterion will be less important in hot and humid climates, as heat is not needed at any time of year.

A study by R. Cabus and F. Pereira (1996) has proved that the energy performance of a daylighting system differs based on location and weather conditions. Their study tested the performance of toplighting systems, including a skylight, clerestory, and roof monitor, along with their associated heat gains for locations in the tropics (at latitude 0º) [12]. By using the ratio of light output to heat gain (SSLE), the authors showed that the skylight has the lowest SSLE ratio among the three options tested.

The test in this paper, however, used only clear sky conditions. Thus, the optimum system for overcast sky was not examined. In addition, visual comfort parameters were not analyzed, because the emphasis was on energy performance rather than visual performance. With the use of the same glazing area for all cases, it can be predicted that the skylight will perform the poorest on visual performance. This is due to the fact that the skylight sees more of the sun than the other cases, which are vertical openings.

A study by V. Garcia-Hansen et al. (2002) analyzed both the visual and energy performance of three toplighting systems: skylights, clerestories, and monitors. The test location in the study was at latitude 35°S in Argentina [15].

The conclusion of this study was that, for thermal aspects, the systems that could save the most energy are clerestories, monitors and skylights, respectively. This paper also suggests that skylights should be used for locations with predominantly overcast sky conditions but not for locations with heat gain problems. For predominant clear sky conditions, the authors recommended clerestories. For visual and thermal performance, however, the monitor rooflight is the most efficient and is also suggested for use under variable sky conditions. In this study, a physical scale model with no glazing was used for the lighting analysis. As a result, the authors suggested that further study with translucent glazing is needed.

The test cases for this study, however, would be more comparable if they were thermally comparable cases. In keeping thermal performance constant across the test cases, visual performance could have been analyzed more efficiently.

E. J. Dewey and P. J. Littlefair (1998) also discussed lighting performance, but again not the thermal performance, of different rooflight systems [16]. The objective of their study was to analyze the lighting performance, in terms of the uniformity of illuminance level, of six toplighting systems, including skylight, clerestory, and roof monitor systems. By testing different spacing-to-height ratios for each toplighting system, the authors examined which system gave the most flexibility in meeting CIBSE uniformity criteria. This study used a physical scale model with a replaceable roof to test the various toplighting designs. The authors concluded that the roof monitor system provides better uniformity than other systems, since it had the largest spacing-to-height ratio that still met the uniformity criteria. Still, this study is for lighting performance only. A thermal test was not included, and, therefore, the systems are not comparable thermally. In addition, the test was done under overcast sky conditions, the predominant sky type of the United Kingdom. Because of this, the results might be different if tested under other sky types and at other latitudes.

2.2.2. Toplighting Potential in Thailand

For Thailand, no studies have been conducted on toplighting performance in terms of thermal and lighting aspects. Toplighting uses in the country are similar to those in other locations, that is, for commercial buildings, industrial buildings, or in the top floor of office buildings. In general, its uses are very limited.

The Thai sky has a lot of potential for daylighting applications due to the high daylight availability. According to a study by S. Chirarattananon et al. (2002), during office hours (8:00am-16:00pm), global, beam, and diffuse illuminance are typically at more than 20 Klux [17]. Only a 2.5% daylight factor is needed then for the interior illuminance to reach 500 lux, which is the recommended illuminance level for office use [18]. Moreover, the study found that the differences of the illuminance availability between each month are small, as compared with those of locations far from the equator. The efficacy of daylight is also high at about 105-115 lumen/watt [19].

The sky type of Bangkok, as studied by S. Chirarattananon et al. (2003), is 40% cloudy sky, 40% intermediate, and 20% clear sky [19]. Accordingly, the optimum system for this location should perform well in both overcast and clear sky conditions, without adding excessive heat gains to the space.

2.3. Summary of the Literature Review

The literature review provided an overview of the research on daylighting design. The discussion in the literature review can be summarized as follows:

- The benefits of daylighting are that it has a better visual quality and luminous efficacy than general electric lights. It also provides views to the outside environment and increases the occupant's satisfaction and productivity.
- One of the most pronounced benefits of daylight is that it helps save energy from the use of electric lighting and has the potential to reduce the energy used for heating and cooling.
- Two simple daylighting strategies are sidelighting and toplighting.
- Some studies have been conducted to test the performance of toplighting in terms of thermal and lighting performance. However, no test has been conducted for hot and humid climates. The results could be different for this climate, due to the lack of a heating period.
- The majority of studies failed to analyze both thermal and lighting performance. Therefore, the total system performance cannot be ascertained.
- Thailand, which is in a hot and humid climate, has a high potential for daylighting because of daylight availability. However, heat gain is a major concern.

CHAPTER III

RESEARCH METHODOLOGY

This chapter describes the methodology used in the current research study, including the development of toplighting prototypes, the thermal performance methodology, and the lighting performance methodology. Figure 3.1 summarizes the methodologies used in this study.

3.1. The Development of Toplighting Prototypes

3.1.1. Base Case Building Descriptions

A prototypical base case building was created to test various toplighting options in terms of thermal and lighting performance. The base case building used is comparable in size to a small industrial building, a convenience store or an art gallery. It has a floor area of 375 sq m. (4,100 sq ft). The dimensions of the space were 15.00 m (50 ft) wide by 25.00 m (82 ft) deep by 4.50 m (14.8 ft) floor-to-ceiling height (Fig. 3.2). The construction materials chosen are those available in Thailand. More details about the materials and construction of the building are provided later in this chapter.

3.1.2. Toplighting System Variations

Using the base case building, a comparison between the three simple toplighting systems is made. The selected systems, skylight, lightscoop, and roof monitor, are generally found in Thailand. In addition, their performance has been studied for latitude 35°N [9]. Figure 3.3 shows a cross section for each of these three systems.

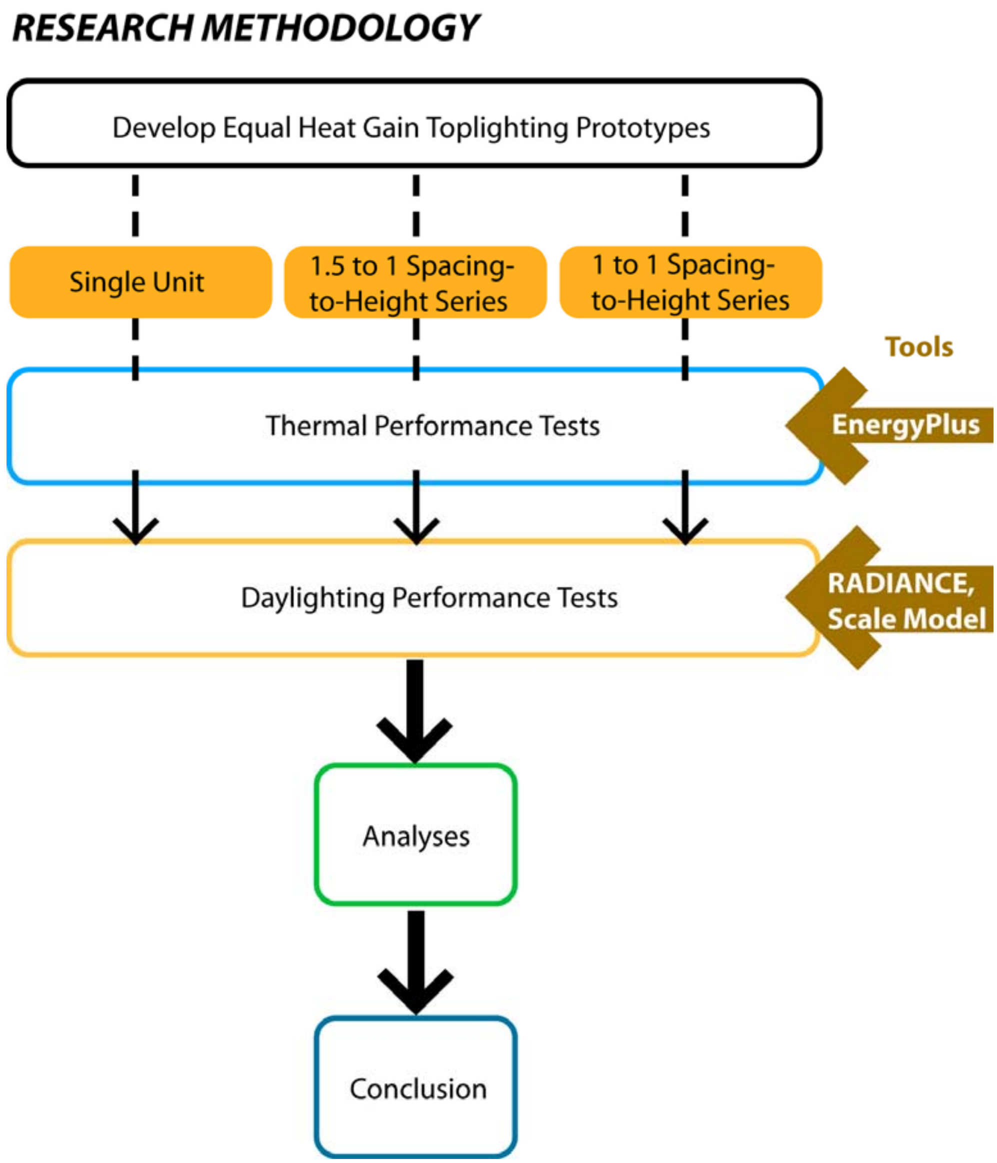

Fig. 3.1 Research methodology

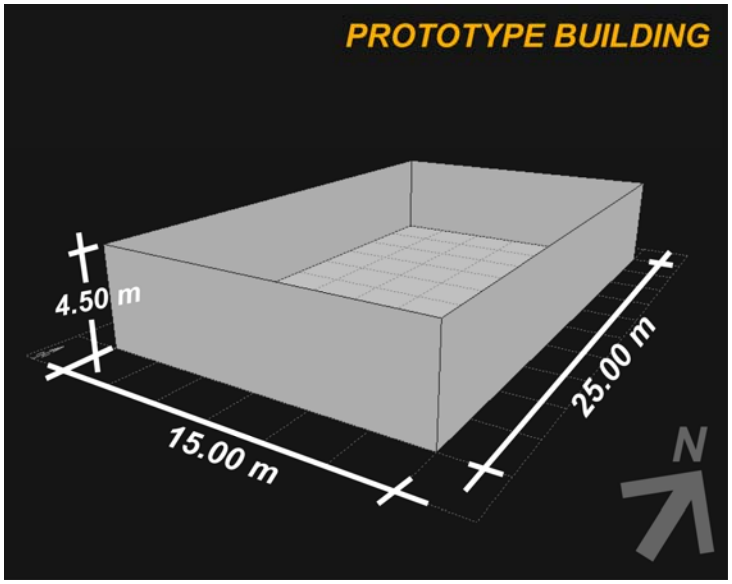

Fig. 3.2 Prototype building dimension

Fig. 3.3   Cross sections of toplighting systems

3.1.3. Development of Single Unit Toplighting Prototypes

In order to compare the performance of each toplighting prototype, each case has to be thermally comparable. Equal glazing areas are not appropriate for this kind of test, since, if equal glazing areas are employed, one could easily predict that the skylight prototype will have the worst performance. It sees the whole hemisphere of the sky dome and hence will receive more heat gain as compared with the other systems.

The average cooling load will be used as a parameter to determine the thermal performance of each toplighting prototype and whether it could be considered thermally comparable. Since the cooling load is the energy used to take out the heat stored in the building, it is a good performance parameter for the development of thermally comparable prototypes.

3.1.4. Prototypes Design

The prototype development methods are given in more detail in Appendix B.

Developed Prototypes

The glazing dimensions for each prototype, which yield similar cooling loads, were 0.15m for the skylight, 0.95m for the lightscoop, and 0.55m for both sides of the roof monitor looking towards the north and south (with a length of 12.00m along the center line of the space). The difference without shading devices is that, after the shading devices are installed, the roof monitor can have more glazing area but the glazing area of the skylight had to be reduced. With the shading installed, a roof monitor has the largest glazing area as compared with the other prototypes. This calculation and test is based on the lightscoop glazing height which remains the same since it is a reasonable height for an actual building.

The developed prototypes, which will be used in all the simulation runs in this study, are presented in Figure 3.4. The section of the prototypes is given in Figure 3.5. The glazing area comparison of each prototype is presented in Figure 3.6. The design of the shading devices for each prototype is presented later in this section after the initial cooling load test results.

Cooling Load Test for Each Prototype

In the initial tests of the three toplighting prototypes, the average cooling load of each case was similar, with a difference of less than 2%. This verified that all the prototypes are comparable thermally. From the data presented, the average cooling load of the skylight, lightscoop, and roof monitor is about 5.8 kW per month. The thermal performance of each case in terms of average monthly cooling load is presented in Figure 3.7. More details about the results are given in Chapter IV, as the goal of the initial test was simply to verify that the systems are comparable in terms of thermal performance. EnergyPlus inputs can be found in Appendix C.

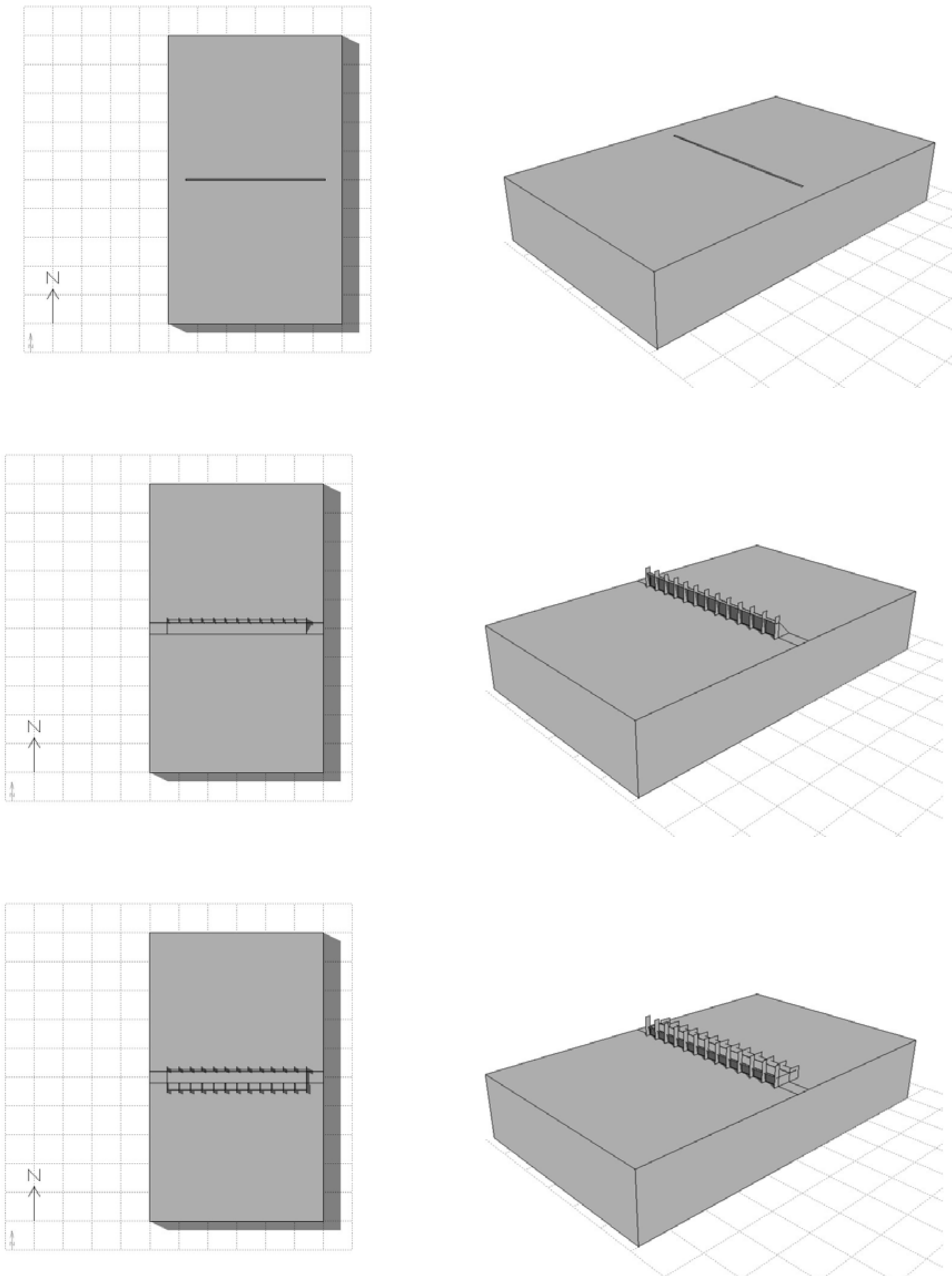

Fig. 3.4 Roof plan and perspective view of single unit prototypes; skylight, lightscoop, and roof monitor

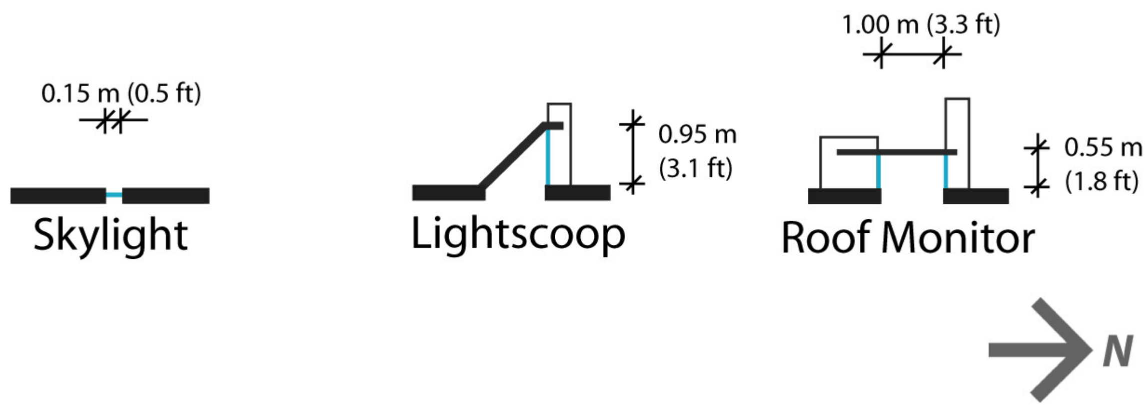

Fig. 3.5 Sections of single unit prototypes

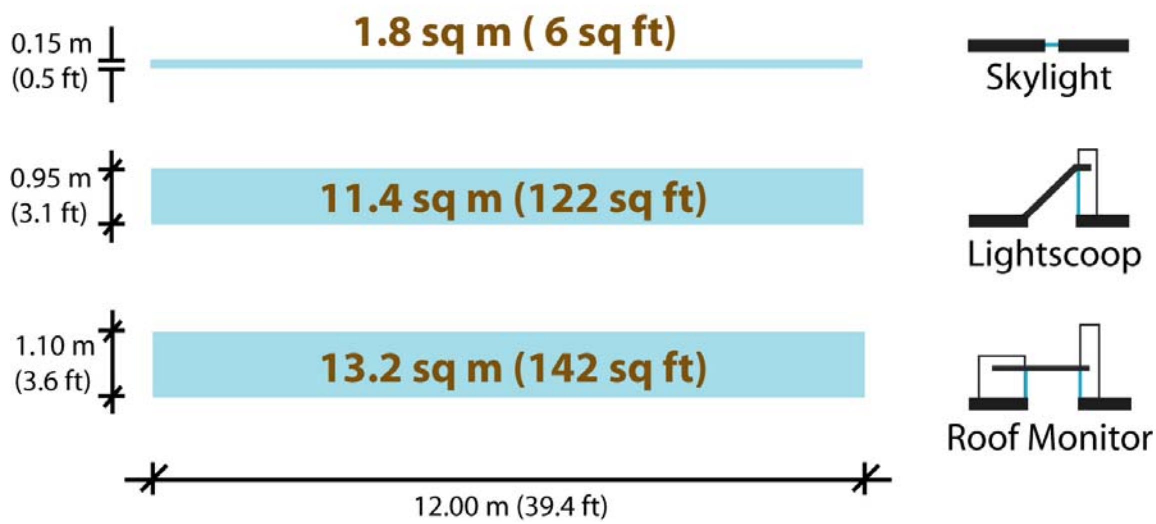

Fig. 3.6 Glazing area comparison of single unit prototypes

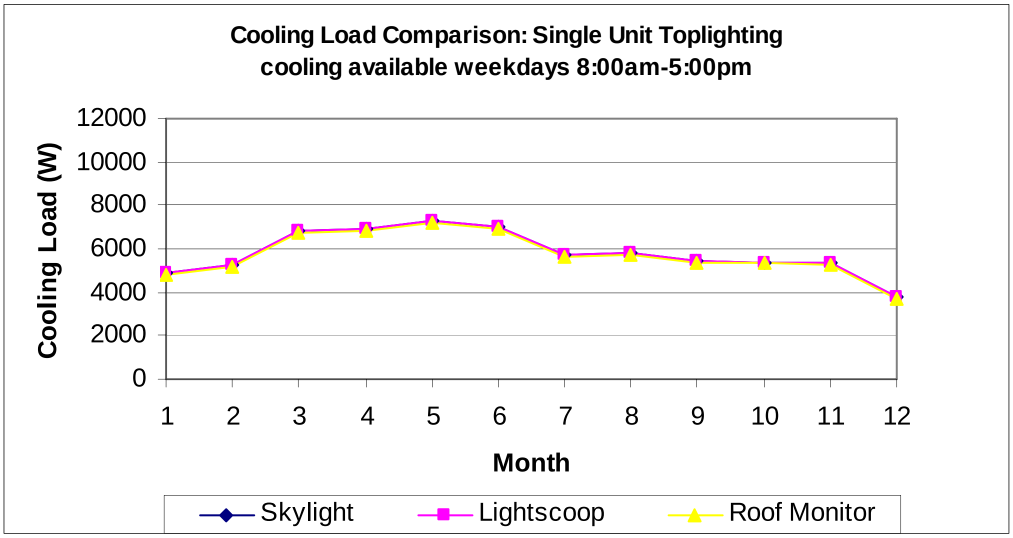

Fig. 3.7 Single unit prototypes: initial test of cooling load

3.1.5. Series of Apertures Design

A series of apertures with a ratio of spacing to height of 1.5 to 1 were tested first. According to E. J. Dewey and P. J. Littlefair (1998), a 1.5 to 1 ratio in a flat skylight and vertical sawtooth can yield daylight uniformity, meeting the uniformity criteria of CIBSE [16]. Even though the test cases in the current study are not exactly of the same geometry as the prototypes in Dewey and Littlefair, their ratio is reasonable and will be tested first. However, IESNA suggests that, for the toplighting system, the rule of thumb is a spacing-to-height ratio of 1 to 1 [8]. Therefore, this ratio will be tested as well. A plan view of the 1.5 to 1 spacing-to-height ratio is shown in Figure 3.8 and the section in Figure 3.9. Figure 3.10 presents each prototype’s plan and perspective for this ratio. Plan view of the 1 to 1 ratio is shown in Figure 3.11 and the section in Figure 3.12. Each prototype’s plan and perspective for the 1 to 1 ratio is given in Figure 3.13.

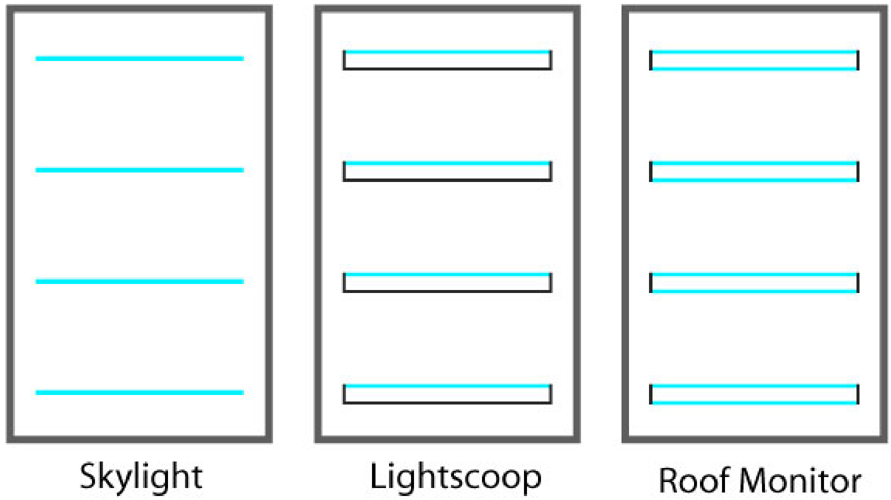

Fig. 3.8 Roof plans of 1.5 to 1 spacing-to-height ratio prototypes showing glazing position

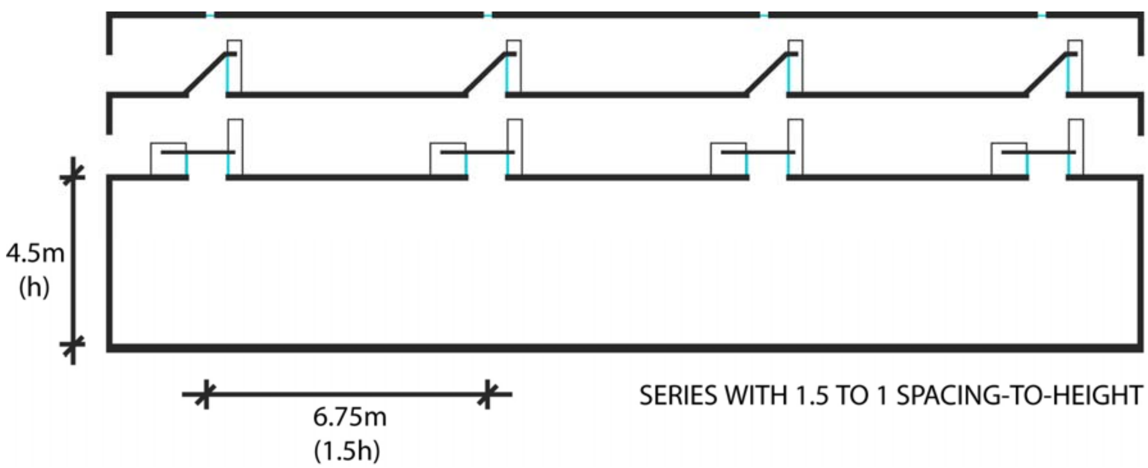

Fig. 3.9 Sections of 1.5 to 1 spacing-to-height ratio prototypes

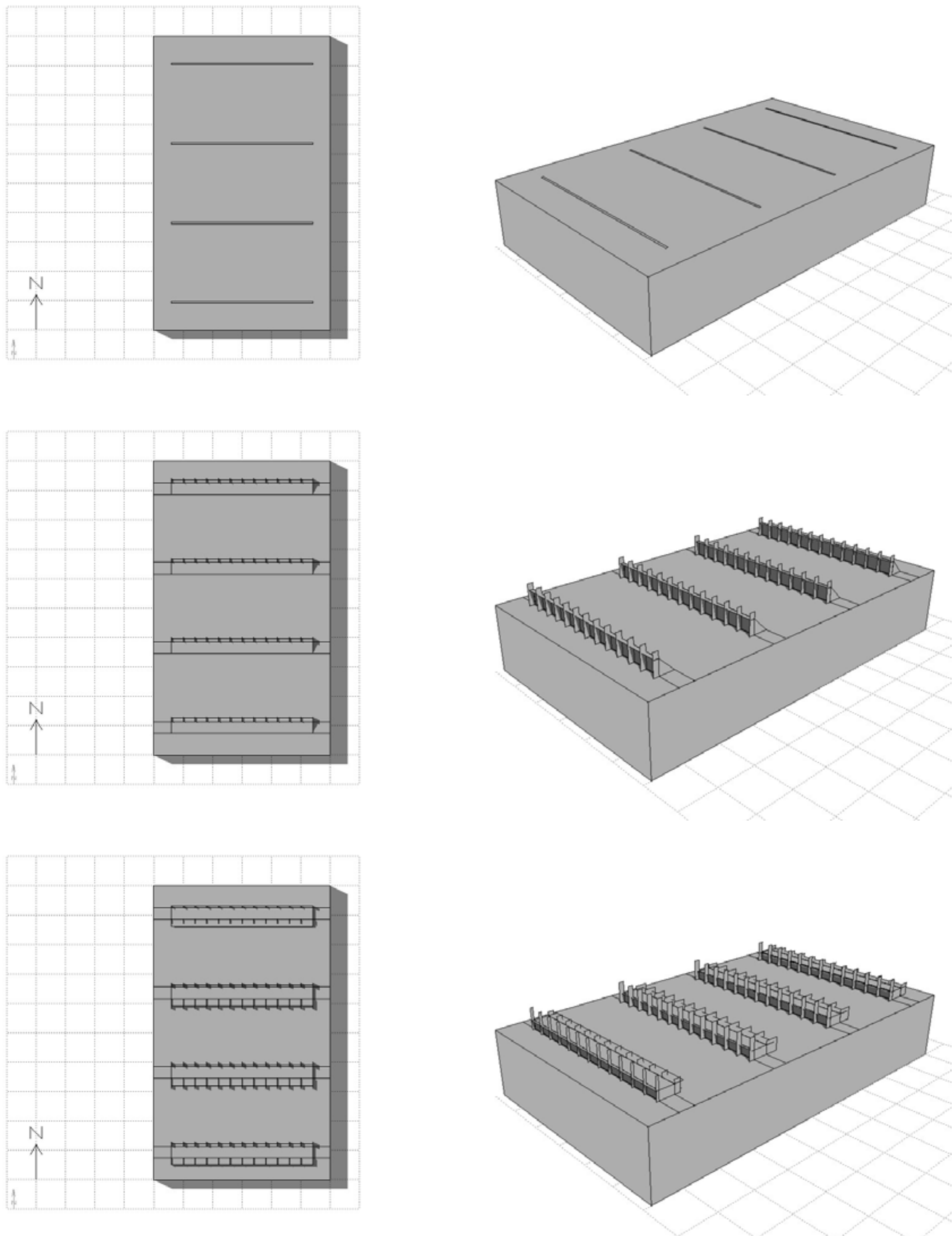

Fig. 3.10 Roof plan and perspective view of 1.5 to 1 spacing-to-height prototypes; skylight, lightscoop, and roof monitor

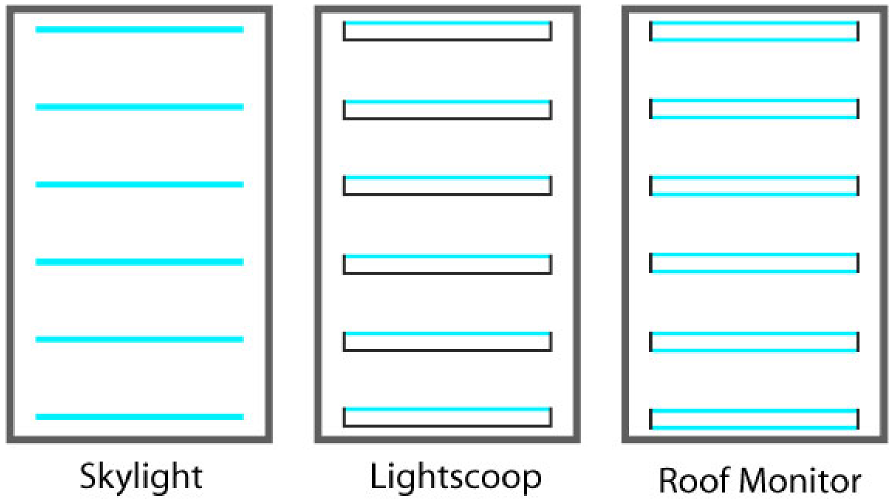

Fig. 3.11 Roof plans of 1 to 1 spacing-to-height ratio prototypes showing glazing position

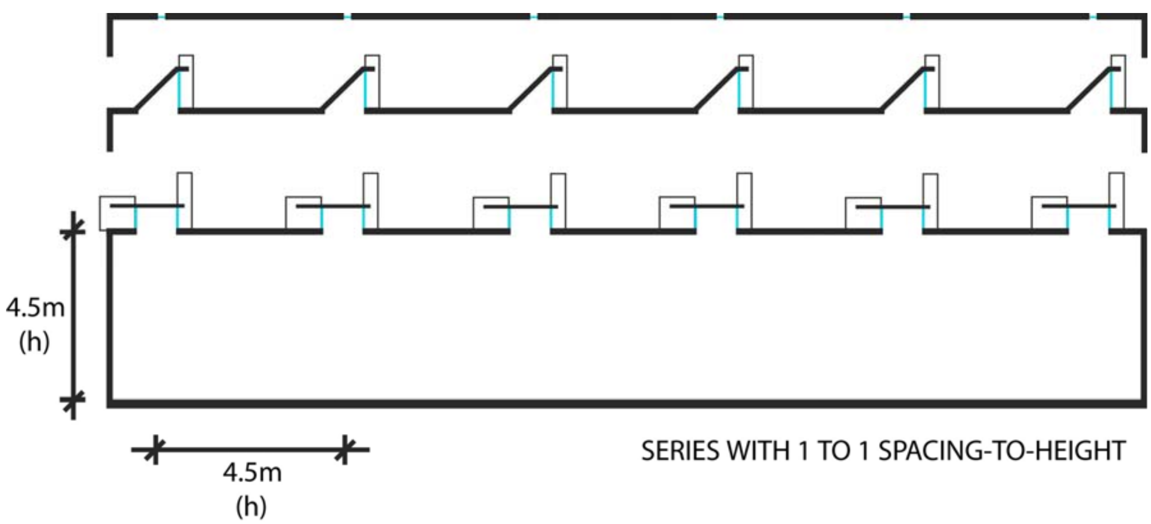

Fig. 3.12 Sections of 1 to 1 spacing-to-height ratio prototypes

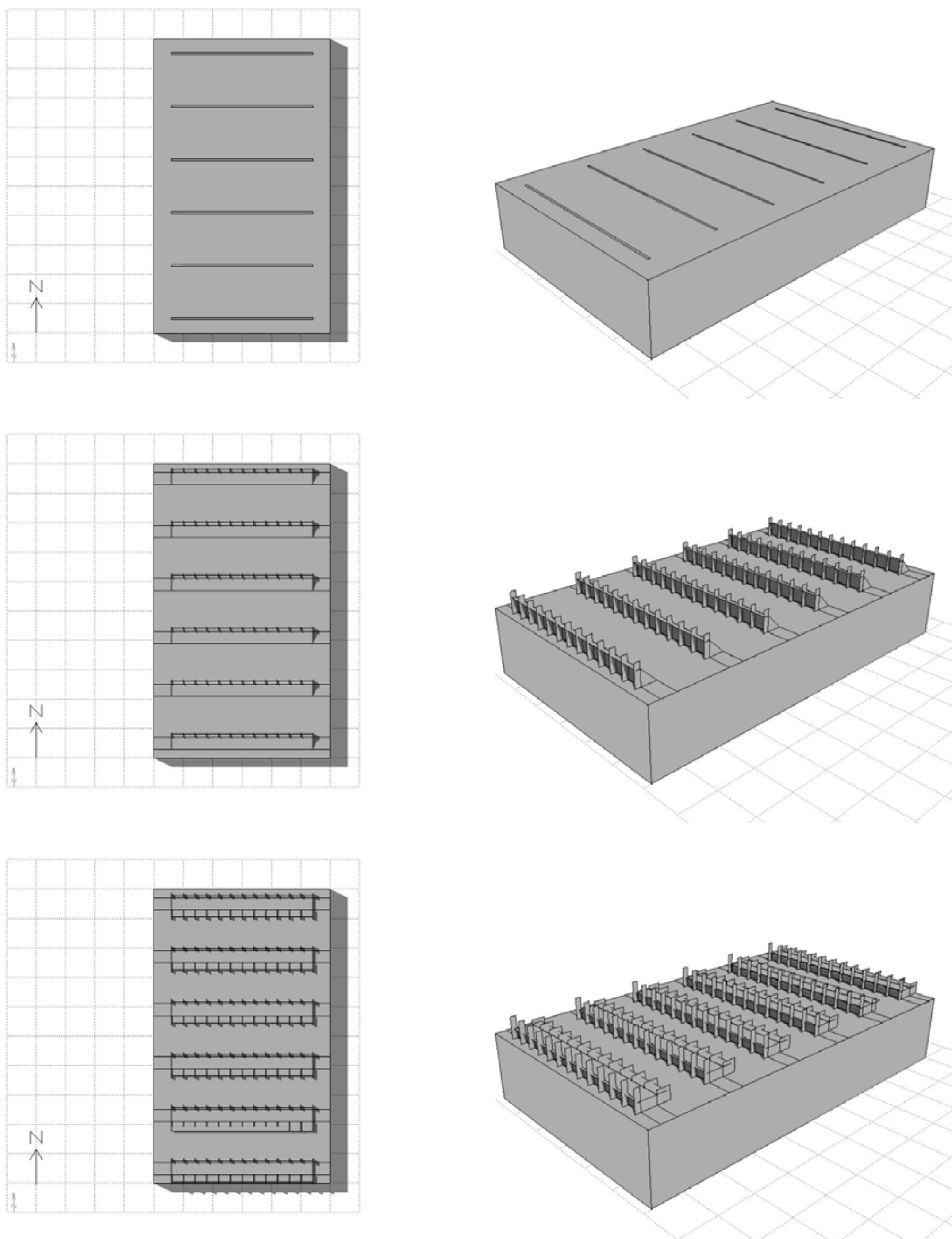

Fig. 3.13 Roof plan and perspective view of 1 to 1 spacing-to-height prototypes; skylight, lightscoop, and roof monitor

3.2. Thermal Performance Methodology

The thermal performances of all the cases were tested using EnergyPlus. The analyses of thermal performance are based on the results of EnergyPlus simulations. All the prototypes used the same materials and a similar construction style, so the only difference was in the design of the toplighting system.

3.2.1. Instrumentation: EnergyPlus

EnergyPlus is a building thermal simulation program created by the Lawrence Berkeley National Laboratory (LBNL) with the support of the U.S. Department of Energy. It is a fully integrated building and HVAC simulation program, which is based on the best features and capabilities of two other building energy simulation programs, DOE-2 and BLAST. The input and output of EnergyPlus are ASCII text files, and the validity of the program as a reliable building simulation engine has been tested [20]. This study uses version 1.2.1 of EnergyPlus to simulate the thermal performance of the prototypes to see the energy efficiency potential in each toplighting system. EnergyPlus was initially going to be used to simulate the illuminance value of the developed prototypes to compare the results with RADIANCE. The problem occurred with this version of EnergyPlus when working on the illuminance calculation. As a result, the illuminance value simulation was not completed.

3.2.2. EnergyPlus Input Parameters

The thermal input files for EnergyPlus in this study were initially created with the Ecotect program and adjusted to the selected design parameters before running EnergyPlus. However, the EnergyPlus input files (.idf) created from Ecotect had many errors and needed additional adjustments after being exported. The input files created later for this thesis are manually input into idf files or using IDF Editor rather than relying on Ecotect.

The following details the parameters taken into consideration for the inputs into EnergyPlus.

Weather Data

The weather file of Bangkok used in the simulation was downloaded from the EnergyPlus website. It can be accessed at http://www.eere.energy.gov/buildings/energyplus/weatherdata.html.

Ground Temperatures

The ground temperature inputs were derived from the program slab.exe, which is provided with EnergyPlus.

Purchased Air Parameters

Purchased air parameters were placed into the EnergyPlus input files in order to estimate the cooling load needed to cool the building to the cooling temperature set point. The simulated space did not include any HVAC systems, because the primary research objective is to analyze the effect that each daylighting system has on the thermal performance of the building. Therefore, the purchased air concept in EnergyPlus was used. Purchased air is a fictitious simple system that can be used in EnergyPlus to derive the heating and cooling loads [21]. It is a supply of hot and cold air that maintains the interior set point temperature.

Cooling Setpoint Schedule

The cooling setpoint is set at 25°C at all time.

Electric Lighting

Electric lighting and energy savings from the use of daylighting are not included because the lightscoop and roof monitor with shading are complex fenestration systems and EnergyPlus needs the data of the bi-directional transmittance distribution function in order to use the DELight object to calculate the energy savings [21]. With the time limits of this study, this test could not be completed.

EnergyPlus input parameters are presented in Tables 3.1-3.3 and Figures 3.14-3.16.

Table 3.1
EnergyPlus input: LOCATION

Parameters	Value
Latitude (deg)	13.7
Longitude (deg)	100.5
TimeZone (hr)	7
Elevation (m)	10

Table 3.2
EnergyPlus input: GROUNDTEMPERATURE

Month	Ground Temp (C)	Month	Ground Temp (C)
January	24.27	July	24.26
February	24.23	August	24.27
March	24.22	September	24.32
April	24.18	October	24.38
May	24.17	November	24.36
June	24.23	December	24.26

Table 3.3
EnergyPlus input: materials and construction

Building Elements	Material User Name	Materials	Construction Name	Source
Wall	HF-A6	FINISH	BRICK_TH	DOE2.1E materials
	HF-B2	INSULATION 1IN		
	HF-C4	COMMON BRICK 4IN		
	AL21	Air Layer 3/4 in		
	HF-C4	COMMON BRICK 4IN		
	HF-E1	3/4IN PLAS-3/4IN GYPS		
Ceiling and roof	HF-C10	CONCRETE HW 8IN	ASHI-38	DOE2.1E construction
	HF-E4	CEILING AIR SPACE		
	HF-E5	ACOUSTIC TILE		
Floor	ConcSlab_OnGround-0	Finish	ConcSlab_OnGround	Ecotect
	ConcSlab_OnGround-1	Concrete Slab		
Glazing (Low-E)	E178-4.CIG	Low-E glazing	Asahi_Low-E	Window5
	AIR 12.7MM	Air space		
	CLEAR_6.DAT	clear glazing layer		

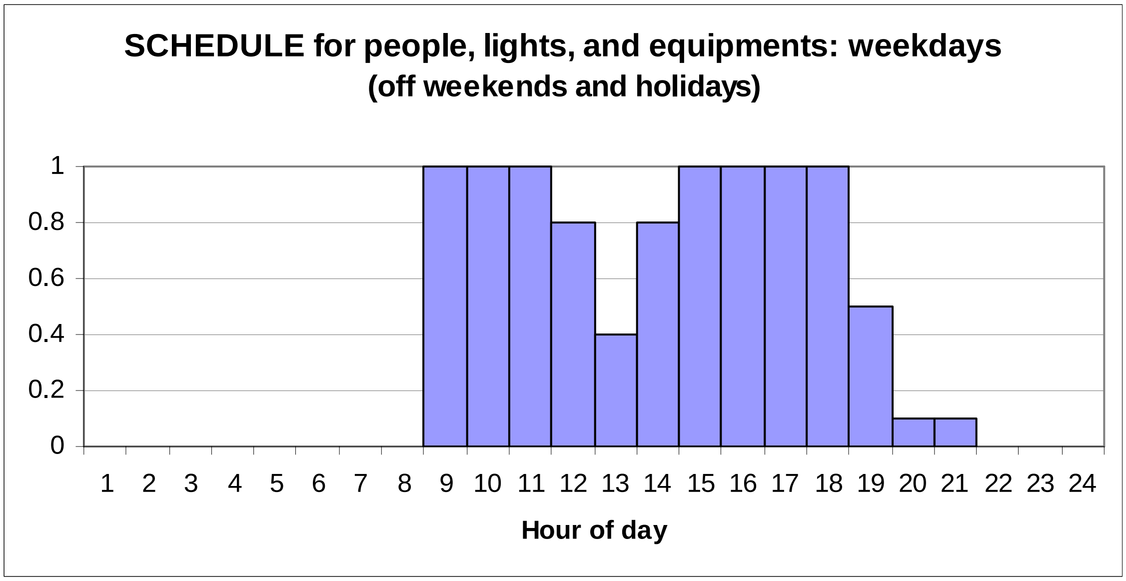

Fig. 3.14 EnergyPlus input: simplified SCHEDULE for people, lights, and equipments

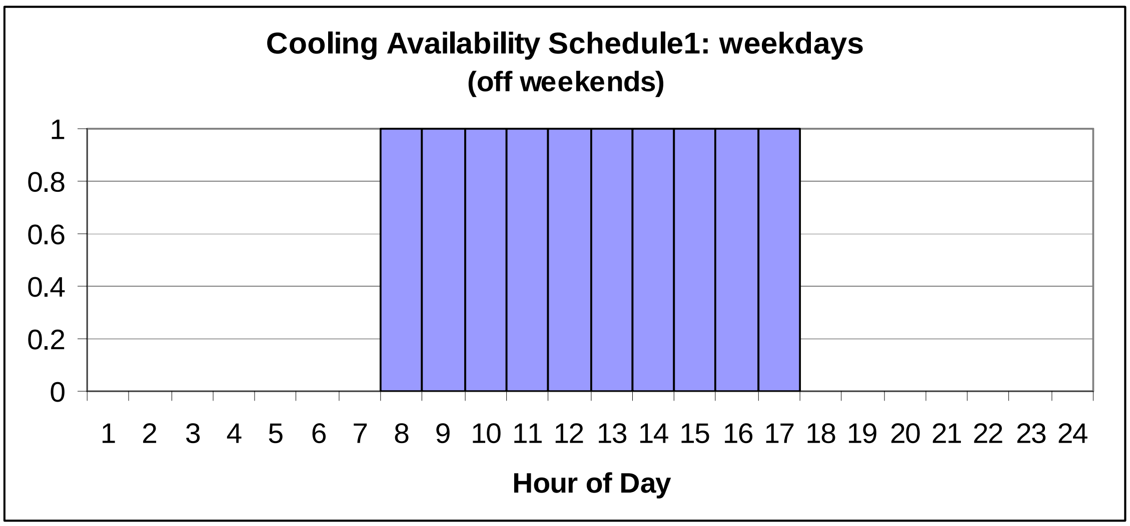

Fig. 3.15 EnergyPlus input: cooling availability schedule1: cooling not available nights and weekends

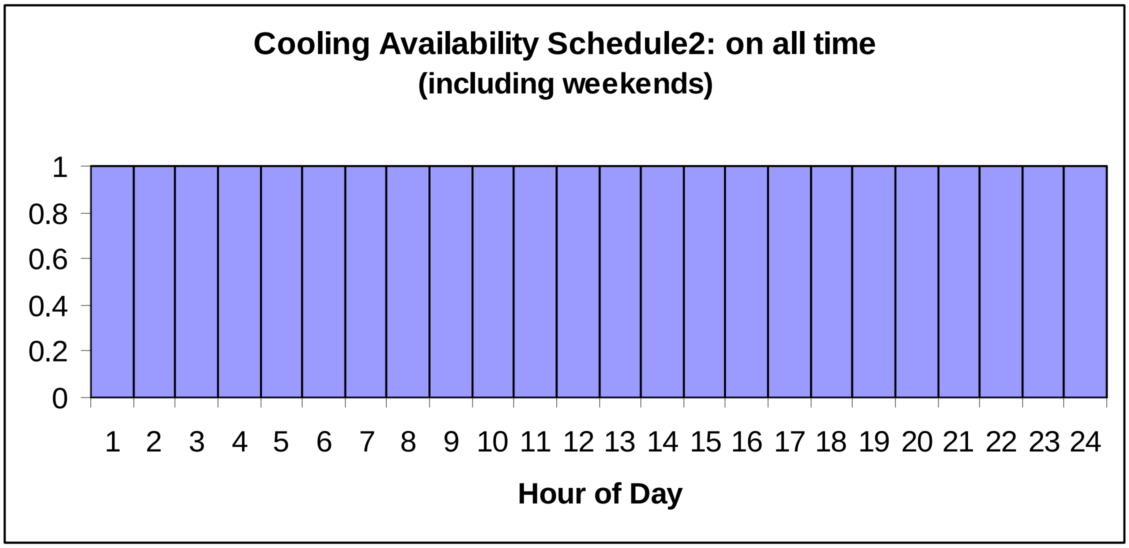

Fig. 3.16 EnergyPlus input: cooling availability schedule2: cooling available 24 hours

3.2.3. Thermal Analysis Variables

The output variables requested from EnergyPlus and their descriptions are as follows:

1. Purchased Air Total Cooling Rate (watt) is the total (both sensible and latent) energy needed to remove heat from the outside and return air streams. This can be called the cooling load of a system. The difference between Purchased Air Sensible Cooling Rate and Purchased Air Total Cooling Rate gives the amount of energy needed for moisture removal. This is the total cooling load.

2. Purchased Air Sensible Cooling Rate (watt) is the rate that energy is removed from the outside and return air streams to lower the temperature to the interior set point temperature. It ignores the energy needed for moisture removal (latent cooling). This is the sensible cooling load.

3. Zone Window Heat Loss (watt) is the sum of the heat flows into a space from all the windows in a zone when the sum is negative.

4. Zone Window Heat Gain (watt) is the sum of the heat flows into a space from all the windows in a zone when the sum is positive.

5. Mean Air Temperature (°C) is the average temperature within a thermal zone at a specified time step. Since EnergyPlus uses the zone heat balance to calculate the heat transfer, there is only one temperature within one thermal zone. Separate EnergyPlus input files have to be created to get this variable by excluding the purchase air input parameters. The EnergyPlus input files are provided in Appendix A.

3.3. Lighting Performance Methodology

The lighting performance test was done using a physical scale model and RADIANCE. The physical scale model tests were done to compare the results with the outputs from RADIANCE and to estimate the discrepancy resulting from the RADIANCE calculation. RADIANCE is used for detailed lighting calculations and scene rendering.

The prototypes were tested by physical scale model and RADIANCE a single and series of: skylight, lightscoop, and roof monitor with no glazing (using a special illum material in RADIANCE which has 100 % visible transmittance).

The lighting performance parameters for the RADIANCE simulations will be discussed later in this section. The prototypes tested were a single unit and series of units of a skylight with diffuse glazing, a lightscoop, and a roof monitor with typical low-E glazing. A diffuse skylight was used instead of typical low-E glazing, because, with a clear glazed skylight, direct sun can penetrate the space directly. This, in turn, can cause the interior illuminance at peak points to be very high, and hence the lighting performance could not be compared to the lightscoop and roof monitor, which have shading devices. Diffuse glazing in the skylight prototype helps diffuse the direct sunlight that enters the space and make the cases more comparable in terms of their lighting performance. This diffuse glazing is assumed to have the same thermal performance as the base case skylight. and also same visible transmittance as the typical low-E glazing used for other cases which is 76.1 percent.

3.3.1. Overcast, Intermediate, and Clear Sky Test Conditions

The tests of the physical scale model and RADIANCE were done under overcast and clear sky conditions. Only the test for lighting performance using RADIANCE was done under all three sky conditions; that is, the sky types found in Bangkok, Thailand.

For intermediate and clear sky conditions, the tested dates and times are summer solstice (June 21), equinoxes (March 21/September 21), and winter solstice (December 21) at 9:00am, 12:00pm, and 3:00pm solar time. The test dates and times are based on LBNL's paper on skylight systems [22]. The equinoxes were added to see the variation of the lighting performance throughout the year.

3.3.2. Instrumentation: RADIANCE

RADIANCE

RADIANCE is an advanced physically based rendering and simulation engine for lighting and daylighting. It was created by The Window and Daylighting Program at LBNL and employs a backward ray-tracing method to calculate the lighting.

RADIANCE is chosen for this study, because it has the ability to model a geometrically complex environment and precisely simulate light behavior within a space with numerical results and sophisticated rendered images [23]. It has been tested for validity under real sky conditions and is able to predict interior light levels with a high degree of accuracy [23].

This study will use RADIANCE to predict the interior illuminance level for different toplighting systems and also to generate images for each variation.

Two versions of RADIANCE are used in this study. The first is Desktop Radiance 2.0 Beta which is based on an older UNIX version. The second is RADIANCE version 3.6, the latest version available from LBNL, which runs in a UNIX environment. Desktop Radiance is used for generating the models because the models can be easily generated using an AutoCAD interface. However, there are only 2 releases of AutoCAD that can be used with Desktop Radiance and those are release 14 and AutoCAD 2000. This study uses AutoCAD release 14.

The UNIX version of the program is used for detailed lighting calculation because the simulation parameters can be adjusted manually and the scripting can be used to speed up the calculation process. This is not possible in Desktop Radiance. This study uses Cygwin, a UNIX emulator for Windows environments, to run RADIANCE. The compiled zip file of RADIANCE version 3.6 for use in Cygwin can be downloaded at http://www.dream.unipa.it/dream/pub/dot/anselmo/radiance/cygwin/.

3.3.3. RADIANCE Input Parameters

The geometry of each prototype is generated using AutoCAD command 3D face within Desktop Radiance. The materials and glazing are then assigned to each surface and the light sensors are placed within the model to do the initial runs. If Desktop Radiance runs without any errors, it will create an octree file which is located within the project folder for the individual case. This octree file can then be used to run the UNIX version to speed up the process.

Some of the important input parameters for RADIANCE are provided in Tables 3.4 and 3.5. For the turbidity factor input, the value is obtained from www.helioclim.net. For the rtrace input parameters, the values used are a compromise between the calculation time and accuracy of lighting analyses. The test dates and times are June 21, March 21, September 21, and December 21, at 9:00am, 12:00pm, and 3:00pm solar time. A conversion has to be performed since RADIANCE uses local time. The sky input file, which contains the information on date and time, can be specified as solar time if it is manually input. This method is used with the UNIX version of RADIANCE. In Desktop Radiance, the time cannot be entered as solar time. Therefore, the local time has to be calculated. Since the method employed in this study is to get the octree file from Desktop Radiance and run the calculation in UNIX, the time conversion has to be made in order have a correct input for Desktop Radiance. The formula for converting between local time and solar time is $T_{local} = T_{solar} + ((Longitude - Longitude_{ref}) * 4)$. The local time used in this thesis is calculated using a solar position calculator (available from http://www.squ1.com). Local time data is presented in Table 3.6.

Table 3.4
Desktop Radiance input: location

Parameter	Input
Location	Bangkok, Thailand
Latitude	13.7
Longitude	100.5
Turbidity	4.5
Standard Meridian	105

Table 3.5
RADIANCE input: rtrace parameters

Parameter	Description	Value
ab	ambient bounce	5
aa	ambient accuracy	0.2
ad	ambient division	1024
as	ambient super-samples	64
ar	ambient resolution	128

Table 3.6
RADIANCE input: local time

Date/ Solar Time	9:00am	12:00pm	3:00pm
21-Jun	9:20am	12:20pm	3:20pm
21-Mar	9:26am	12:26pm	3:26pm
21-Dec	9:16am	12:16pm	3:16pm

<u>Glazing Input for EnergyPlus and RADIANCE Using LBNL's WINDOW5 and Optics5 Programs</u>

WINDOW5 and Optics5 were used to input the glazing parameters into EnergyPlus and RADIANCE. WINDOW5 and Optics5 are distributed by LBNL and are based on the glazing database of the National Fenestration Rating Council (NFRC).

WINDOW5 calculates window thermal performance indices. The given variables can be used as an input to EnergyPlus. Optics5 calculates the optical data that the glazing layer generates and can be exported to the Desktop Radiance glazing library.

The glazing selected for the test cases are based on the low-E glazing from Thai-Asahi Glass Company, a glazing manufacturer in Thailand. The data provided by the manufacturer’s website [24,25] does not cover all the parameters needed for WINDOW5 and Optics5. As a result, glazing layers were selected from the program database in order to obtain the closest match to the company’s glazing.

The optical and thermal data in Tables 3.7 and 3.8 were calculated from the two programs and used as inputs into EnergyPlus and RADIANCE. The glazing is a double pane with 12 mm air gap in the center, low-E glazing on the outer pane, and a visible transmittance of 76%. More detailed information on the thermal and optical properties of the glazing system is provided in Appendix E. This diffuse glazing had to be manually generated since is not included in the glazing database of WINDOW5 and Optics5. Currently, there is no method for calculating the spectral characteristics of diffuse glazing.

Table 3.7
Summary of thermal performance of glazing from WINDOW5

Parameters	Value
Tilt	90
Glazings	2
KEFF	0.0328
Uvalue	1.75
SHGCc	0.57
SCc	0.65
Vtc	0.76
RHG	426.04

Table 3.8
Optical properties for glazing system from Optics5

Layer	#1	#2	System
Filename	E178-4.CIG	CLEAR_6.DAT	Ngao_try1
Solar, T	0.607	0.771	0.489
Solar, Rf	0.194	0.070	0.226
Solar, Rb	0.253	0.070	0.208
Photopic, T	0.860	0.884	0.763
Photopic, Rf	0.054	0.080	0.113
Photopic, Rb	0.048	0.080	0.118
EmitF	0.840	0.840	0.840
EmitB	0.083	0.840	0.840

3.3.4. Instrumentation: Physical Scale Model

For lighting analysis, a scale model can be used to test the lighting performance of an actual building due to the physical properties of light, which penetrate and reflect in a scale model as they would in a real building [2]. A model can be used to assess both the qualitative and quantitative performance of a daylighting system. A scale model test can be performed with an overcast or clear sky and can be done with actual daylight or in a daylighting laboratory. For clear sky conditions, the model has to be tilted to match the reference days of the tested latitude. By using a sundial, the model can be tilted to match the date and time for the tested location. This study examined the lighting performance of toplighting systems at latitude 13.7°N. Therefore, the sundial used in this thesis was set for latitude 13.7°N. This study uses a physical scale model and compares these results with the results from RADIANCE using actual sky.

3.3.5. Construction of a Physical Scale Model and Measurement Instruments

A physical scale model was constructed at a scale of 1:40 for lighting tests. A replaceable roof was used to test various toplighting options. Pictures of the scale model are provided in Figures 3.17 and 3.18. It was constructed of opaque board on the outside and crescent board on the inside. Details of the material reflectance are presented in Appendix D.

Measurement Instruments

Two illuminance meters were used for the light measurements of the scale model. A cosine corrected Konica Minolta Illuminance Meter model T-10M (Fig. 3.19) was used for the measurements inside the model. This meter can measure the illuminance level at ranges from 0.01-299,900 lux (0.001-29,990 footcandles). It has a mini receptor head which makes it very convenient to use with the reference points in the model. When taking measurements inside the scale model, the sensor is locked into the constructed base, which is 1.50m high in true scale (Fig. 3.20). The horizontal illuminance measurements are taken along the center line of the model.

Another illuminance meter was used for measuring the exterior illuminance value of the scale model. This meter was a Konica Minolta Illuminance Meter model T-10 with a standard sensor head (Fig. 3.21). It has the same specifications as the model T-10M.

A luminance meter, a Minolta LS-100, was used along with Kodak Gray Card to take the luminance measurement of the crescent board paper when calculating the reflectance value. The picture of the luminance meter is presented in Fig. 3.21 which is adapted from the manufacturer's website at konicaminolta.com.

Fig. 3.17 Exterior view of the scale model

Fig. 3.18 Exterior view of the scale model with the replaceable roof

Fig. 3.19 An illuminance meter Konica Minolta T-10M

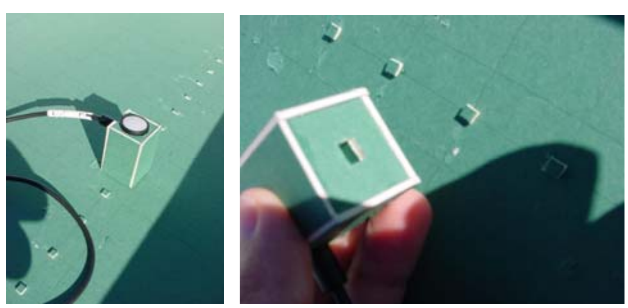

Fig. 3.20 The base of the light sensor and connection

Fig. 3.21 An illuminance meter Konica Minolta T-10 and a luminance meter Minolta LS-100

<u>Reflectance Values of Materials Used in RADIANCE and the Physical Scale Model</u>

Each toplighting system was tested for visual performance by comparing RADIANCE with the scale model. The material reflectance is based on LBNL's study of daylighting [26].

The reflectance value in RADIANCE was generated to match those of the physical scale model (see Table 3.9). A table of reflectance values of crescent board, the material used in constructing the physical scale model, is provided by LBNL for some colors [2]. For colors with no reflectance values, the luminance meter and the Kodak gray and white cards were used for testing the reflectance value of each material.

The scale model materials and reflectance values are presented in Table 3.10. Details on the reflectance measurements of the crescent board are provided in Appendix F.

Table 3.9
Reflectance values used in this thesis and reference

Building Components	LBNL paper	RADIANCE	Scale Model
floor	21%	20.10%	20.10%
walls	44%	44%	44%
ceiling	76%	75%	75%

Table 3.10
Scale model materials and reflectance values

Crescent Board color	Building elements	Reflectance Value	reflectances provided by LBNL/measured
Light Gray 916	walls	0.44	measured
French Gray 962A	ceiling and roof components	0.75	LBNL
Ivy Green 919A	floor	0.201	LBNL

<u>Sensor Locations for RADIANCE and Scale Model Tests</u>

Sensor locations for the different tests are given in Figures 3.22-3.24. Seven points between RADIANCE and the scale model were compared. For the illuminance level analysis in RADIANCE, 13 points of the middle grid sensor are used. For the RADIANCE illuminance uniformity analysis, rectangular reference grids (1m x 1m) are used.

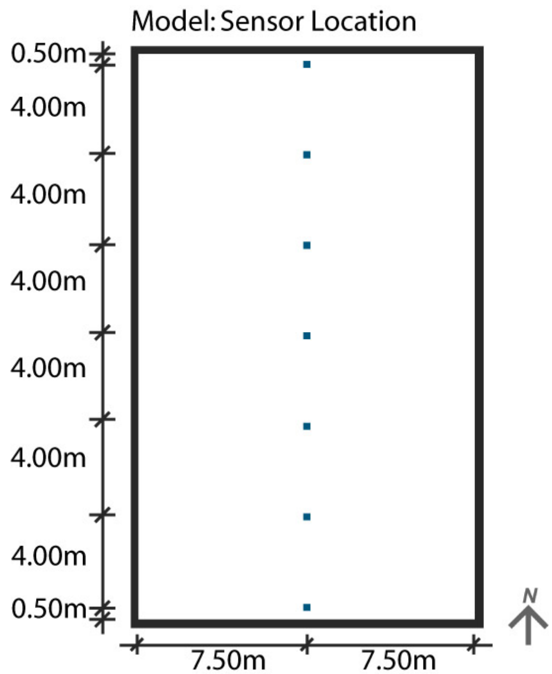

Fig. 3.22 Sensor locations for comparison of a physical scale model and RADIANCE

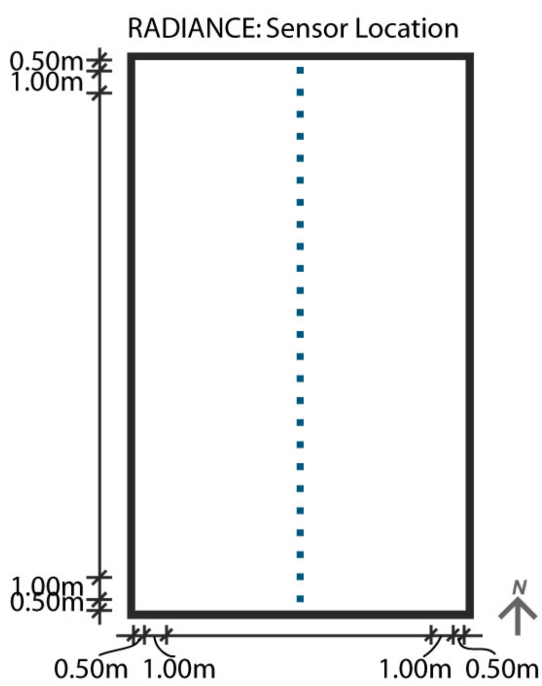

Fig. 3.23 Sensor locations for RADIANCE: illuminance level and daylight factor analysis

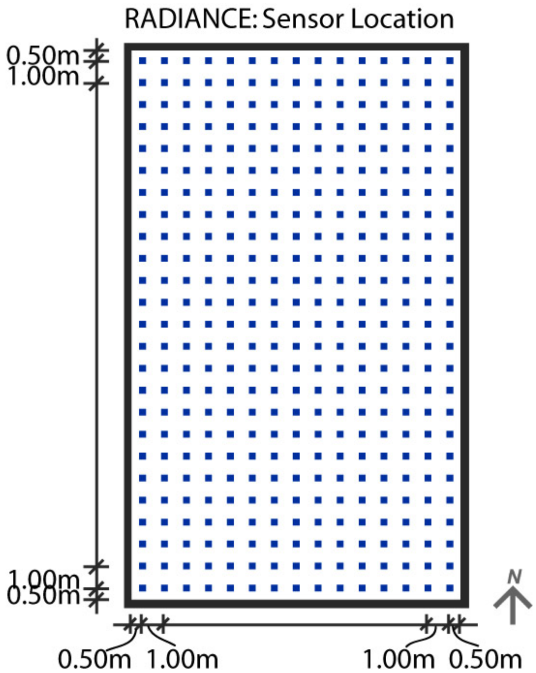

Fig. 3.24 Sensor locations for RADIANCE: uniformity analysis

3.3.6. Lighting Analysis Variables

The variables which this thesis uses to assess the lighting performance of each toplighting prototype are as follows:

1. Illuminance value (Lux)

Illuminance value is the visible energy (light) incident on a surface, measured in lux. IESNA has made recommendations for the illuminance level for various tasks and building types [18]. However, since the prototype building is not assigned any building type, the illuminance values are mostly analyzed for comparison between the performances of each of the toplighting prototype.

2. Daylight factor level (%)

Daylight factor is the ratio of interior illuminance level to exterior illuminance level. This parameter is used in the overcast sky condition.

3. Light distribution and uniformity

The light distribution and uniformity can be described as the relative illuminance at different points in space. If the light level differs too much in a space, it may cause eye fatigue.

For the uniformity of light distribution, the CIBSE code for interior lighting [27] is used as a standard to test the performance of each design. Other studies of toplighting have also used CIBSE parameters to test roof light uniformity [16].

In CIBSE code, the uniformity of illuminance is measured using the ratio of minimum illuminance to average illuminance, which should be more than 0.8.

Another parameter is the diversity of illuminance or the ratio of the maximum to minimum illuminance level of the area 0.5m off the wall perimeter. This ratio should not exceed 5 to 1. The diversity of illuminance is considered a more relaxed parameter.

This study will use the diversity of illuminance parameters as the primary measurements of light uniformity, since the model does not take in account people or equipment. These standards are based primarily on horizontal illuminance levels.

4. Glare

Glare is produced by excessive brightness relative to the adaptation of the eye [18] and can be caused by occupants looking directly at a light source or when the light source is simply in their field of view (i.e., direct glare). Glare can also be caused by surfaces that reflect bright areas into the field of view. This is known as reflected glare or veiling reflection. Control of glare can be achieved in various ways, such as with the use of shading devices or in the design of daylighting systems to hide the source of light from the occupant's field of view.

The luminance ratio is calculated to assess the presence of glare. This is the ratio between task and its surroundings, and recommendations for brightness ratios have been given by Stein and Reynolds [28]. As no tasks are defined in this study, a ratio of 20 to 1 for fenestration and adjacent surfaces and of 40 to 1 for anywhere within the field of view will be used.

CHAPTER IV

THERMAL PERFORMANCE EVALUATION

After the development of the prototype cases and the heat gains tests for each system to ensure that all the cases are thermally comparable, each toplighting system is tested for its thermal performance using EnergyPlus. The variables tested for are total cooling load, heat gain, heat loss, and interior temperature.

4.1. Single Toplighting Prototypes Analysis

The prototypes are a building with a single unit skylight, lightscoop, or roof monitor. For a picture of each case as generated from the input files of EnergyPlus see Fig. 3.4 of Chapter III.

4.1.1. Total Cooling Load Comparison

From the initial testing, the single unit prototypes proved to be comparable thermally. They yielded a similar total cooling load all year and had a difference of less than 2%. The cooling load comparison chart for all the cases is divided into 2 parts. The first chart uses a cooling availability schedule of 8:00am-5:00pm on weekdays and off during weekends, which is typical for office or industrial buildings. The second chart gives the total cooling load of the prototypes with a cooling availability schedule for building like a museum or an art gallery, where the air conditioning system has to be turned on at all time to preserve valuable artworks.

Figs. 4.1 and 4.2 present the comparison charts. An average cooling load per month for the first cooling availability schedule is about 5,700 Watt (5.7 kW). For the second scenario, the average cooling load per month is about 8,000 watt (8kW). Similar cooling loads can be achieved through the prototypes, because the heat stored in the building has similar characteristics.

In these results, the difference between the cooling loads of the two schedules is about 140%. The second scenario has a higher cooling load but a similar trend.

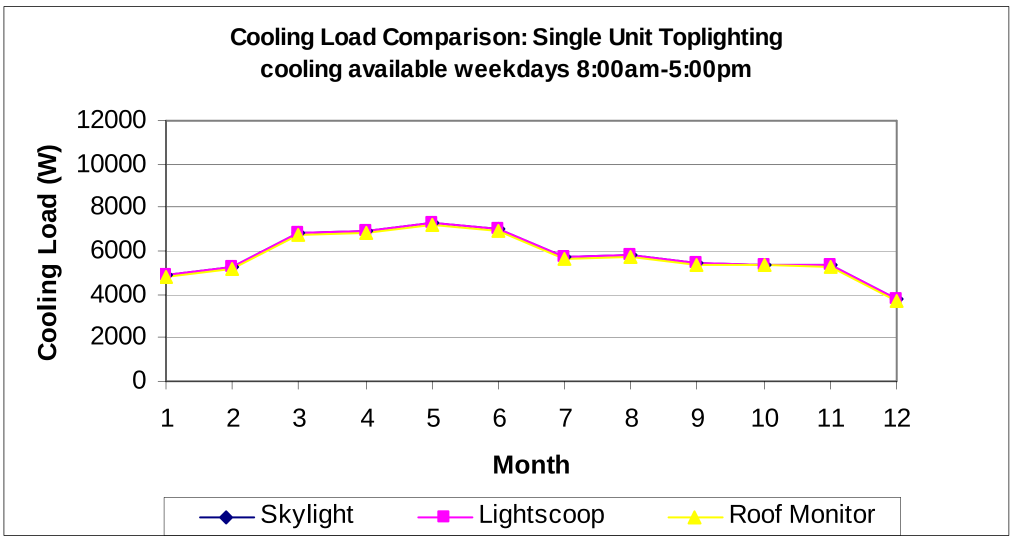

Fig. 4.1 Single unit toplighting: cooling load comparison, cooling available weekdays from 8:00am-5:00pm

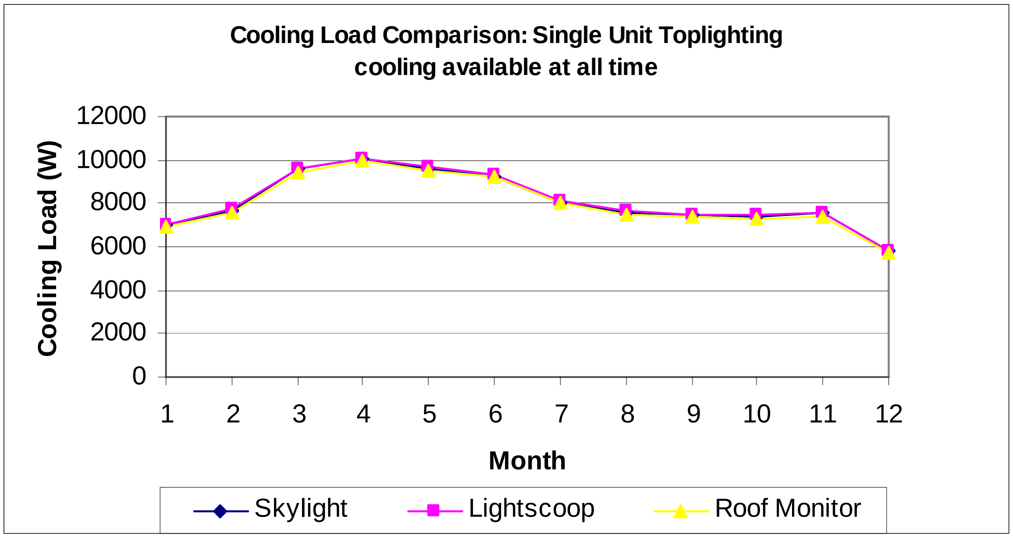

Fig. 4.2 Single unit toplighting: cooling load comparison, cooling available at all time

Hourly cooling load results when cooling is always available are presented as a reference to the characteristics of heat gain in the prototype building, which, from the results, each case represents similar trend. The charts for the first scenario give the character of the cooling load, which reflects the heat gain behavior of the building.

Comparison charts are presented in Figs. 4.3 and 4.4 for two extreme days of the year: average hottest (April 30) and average coldest (January 25). It should to be noted that these results do not reflect internal gains from people and equipment. Therefore, these results reflect the loads from the surface gains only. The results with internal gains, where cooling load reflects the dissipation of heat stored in the building from surface gains, people, and equipment, are given in Figs. 4.5 and 4.6.

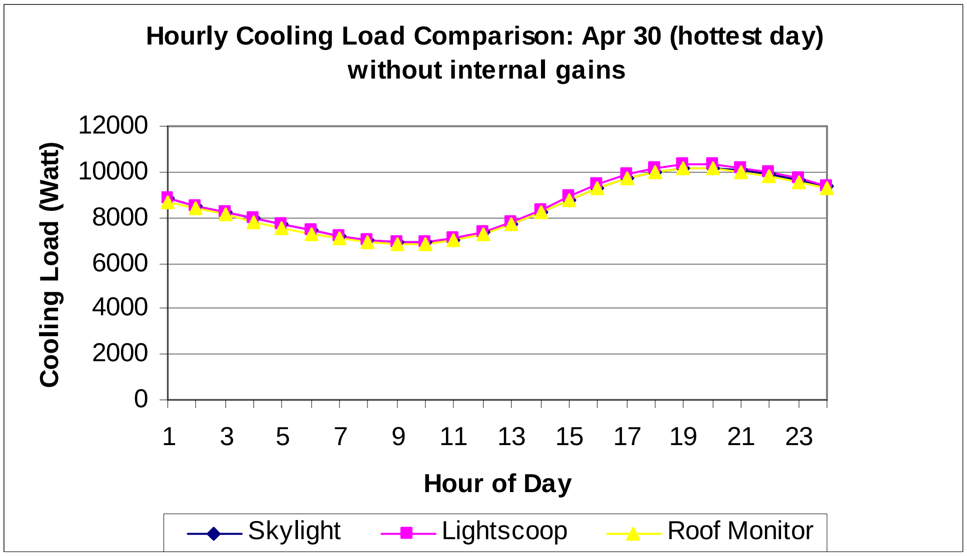

Fig. 4.3 Single unit toplighting: hourly cooling load comparison, Apr 30, without internal gains, when cooling is always available

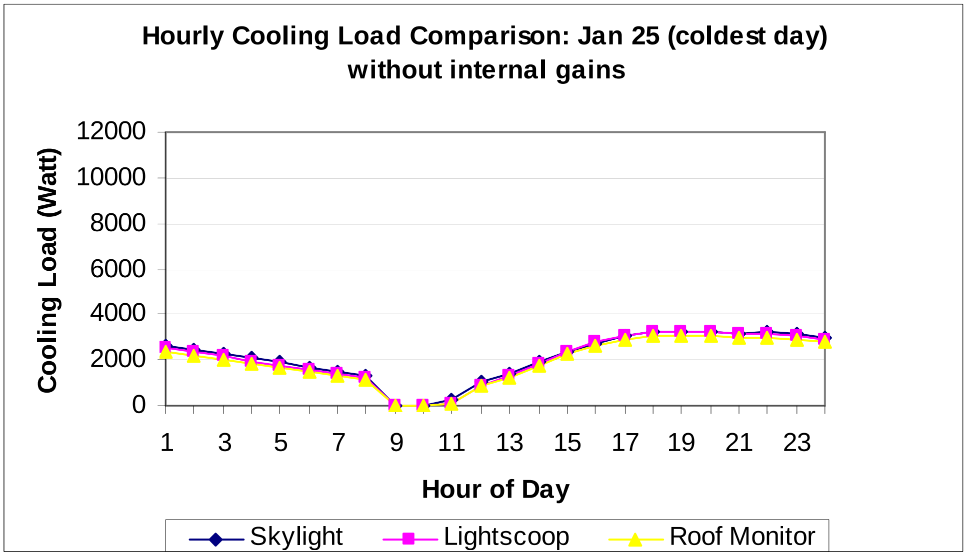

Fig. 4.4 Single unit toplighting: hourly cooling load comparison, Jan 25, without internal gains, when cooling is always available

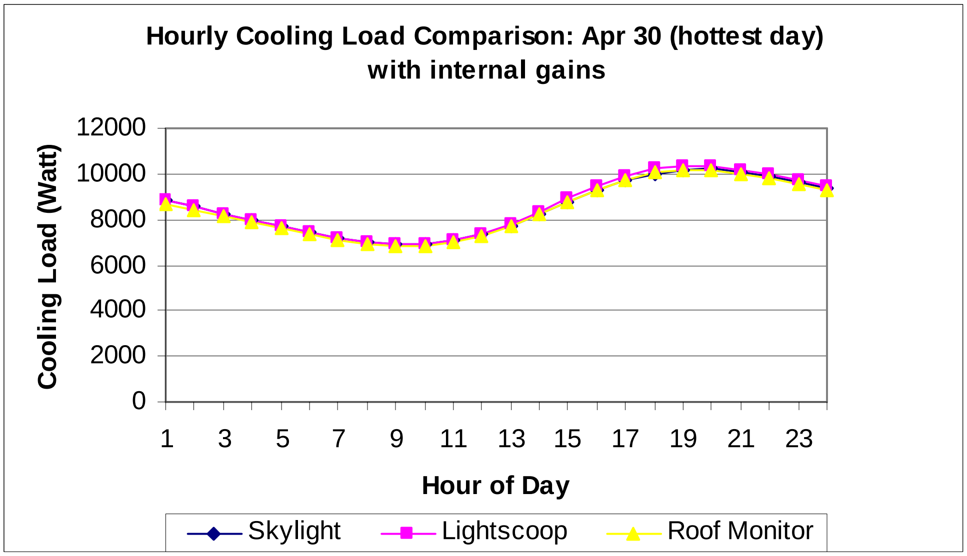

Fig. 4.5 Single unit toplighting: hourly cooling load comparison, Apr 30, with internal gains, when cooling is always available

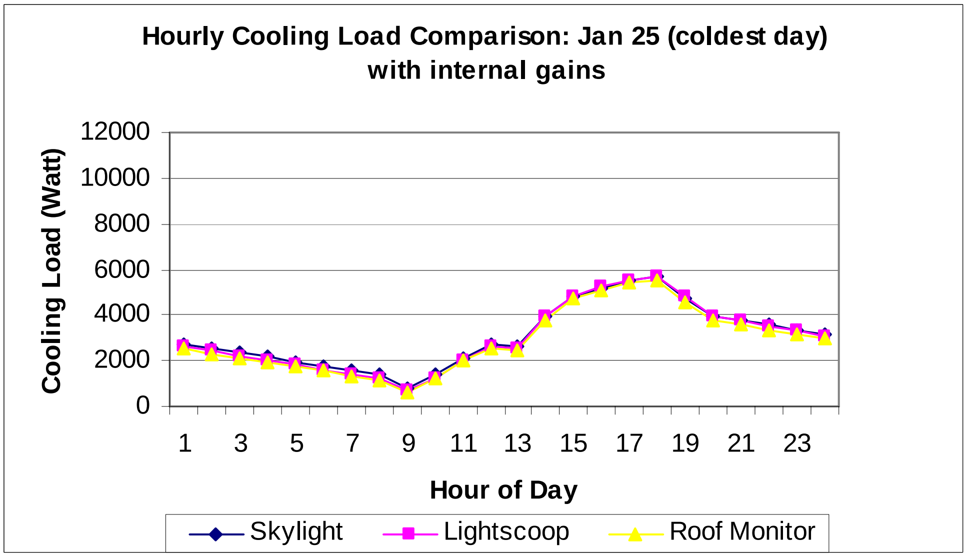

Fig. 4.6 Single unit toplighting: hourly cooling load comparison, Jan 25, with internal gains, when cooling is always available

From the charts, similar characters for both the hottest and coldest day can be seen in hourly cooling load without internal gains. In both, the cooling load decreases during morning time, increases in the afternoon, and begins to decrease again at night starting at about 7:00pm. This indicates that the thermal mass of the building stores heat in morning and releases heat in the afternoon. By 7:00pm the heat begins to be released from the building, and only by 9:00am the next morning is it fully released.

In the winter, internal gains result in an increase of cooling load at about two times the cooling load without internal gains. In the summer, the internal loads do not seriously affect the cooling load. This indicates that surface gains occur in the summer.

4.1.2. Sensible and Total Cooling Load Comparison

Monthly sensible cooling load is plotted compared to the total cooling load of each case in order to analyze the amount of energy required for moisture removal. Figs. 4.7-4.9 present the results from each of the toplighting designs for a cooling availability of 8:00am-5:00pm (typical thermal input files).

From the results, the cooling energy necessary for moisture removal represents about one-third of the total cooling energy needed to cool the building to the temperature set point of 25°C (77°F). The difference between sensible and total cooling load increases in March through June, which are the summer months in Thailand. Maximum discrepancy occurs in May and June, and the minimum discrepancy during winter in December, which corresponds to the time of minimum relative humidity.

These results emphasize the importance of latent cooling energy in a hot and humid climate. However, as the units of aperture increase in each of the toplighting designs, the difference in cooling load might become greater.

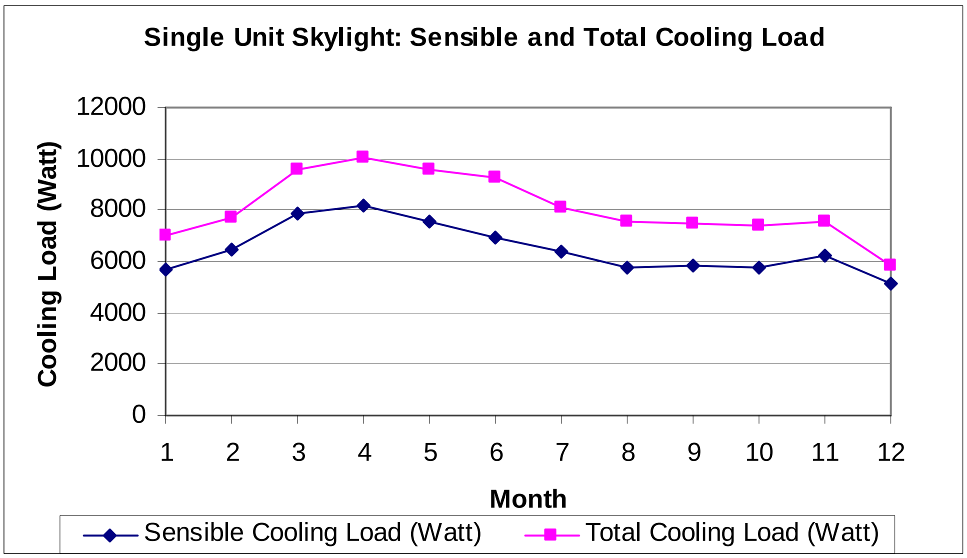

Fig. 4.7 Single unit skylight: sensible versus total cooling load comparison

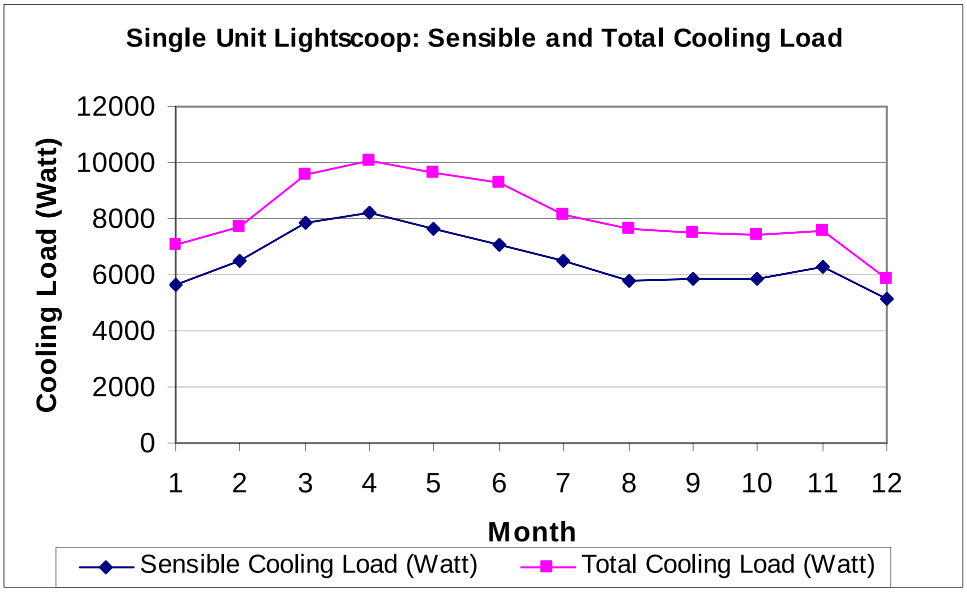

Fig. 4.8 Single unit lightscoop: sensible versus total cooling load comparison

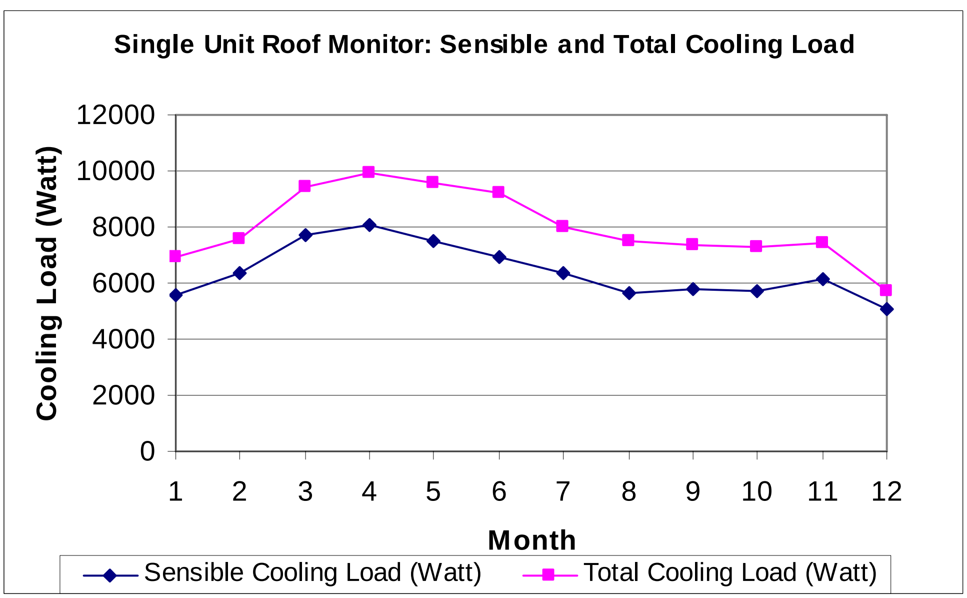

Fig. 4.9 Single unit roof monitor: sensible versus total cooling load comparison

4.1.3. Window Heat Gain and Loss Comparison

Monthly average window heat gain and loss charts are presented in Figs. 4.10 and 4.11. It can be seen that all the prototypes have a similar behavior in window heat gain. The skylight, even though it has less heat gain than other systems, also has less heat loss. Therefore, the overall average cooling loads of all the systems are similar.

Hourly heat gain and loss charts are plotted in order to compare the thermal character of each of the single unit prototypes. The heat loss amount is insignificant as compared with the amount of heat gain entering the space. Hourly heat gain and loss data are plotted for two extreme days: the average hottest (April 30) and the average coldest (January 25). This is done to compare the heat gain characteristics of the apertures. The hourly heat gain and loss comparison charts are given in Figs. 4.12-4.15.

As seen in Figs. 4.12-4.15, the heat gain and loss of the three prototypes are similar, with more heat gain during summer and more heat loss in winter. In summer, the heat gain seen in the skylight could result from the position of the sun, as the skylight has no shading device installed. The sun can then directly enter the space and thereby introduce more heat gain during daytime. The lightscoop and roof monitor introduce more heat gain than the skylight in winter, but they also have more heat loss. In winter, when the sun hits the building at an oblique angle, the skylight, which has the least glazing area, provides less heat gain and loss than the other systems.

All the systems yield a similar amount of cooling load, since the amount of heat stored in the building for each is similar.

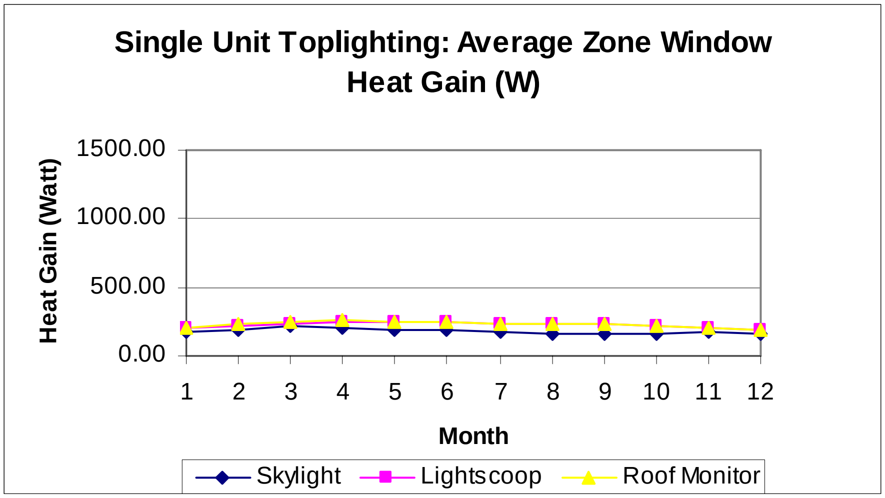

Fig. 4.10 Single unit toplighting: average monthly zone window heat gain

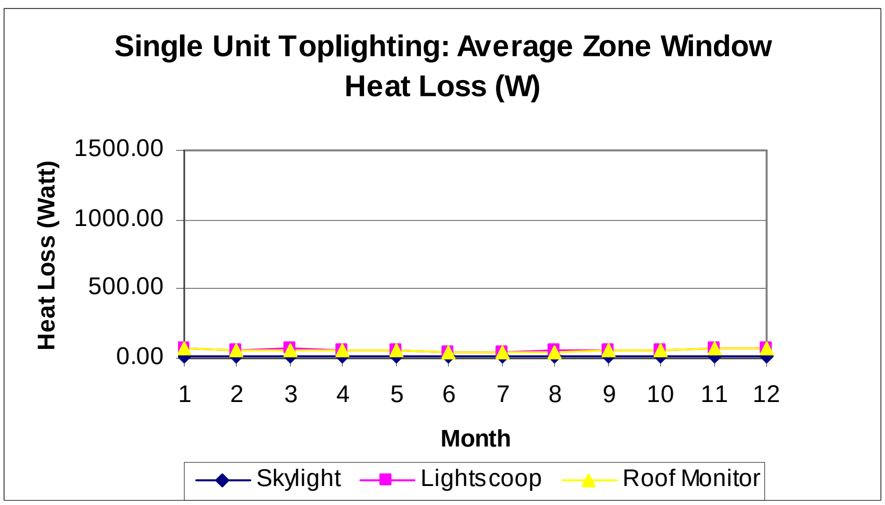

Fig. 4.11 Single unit toplighting: average monthly zone window heat loss

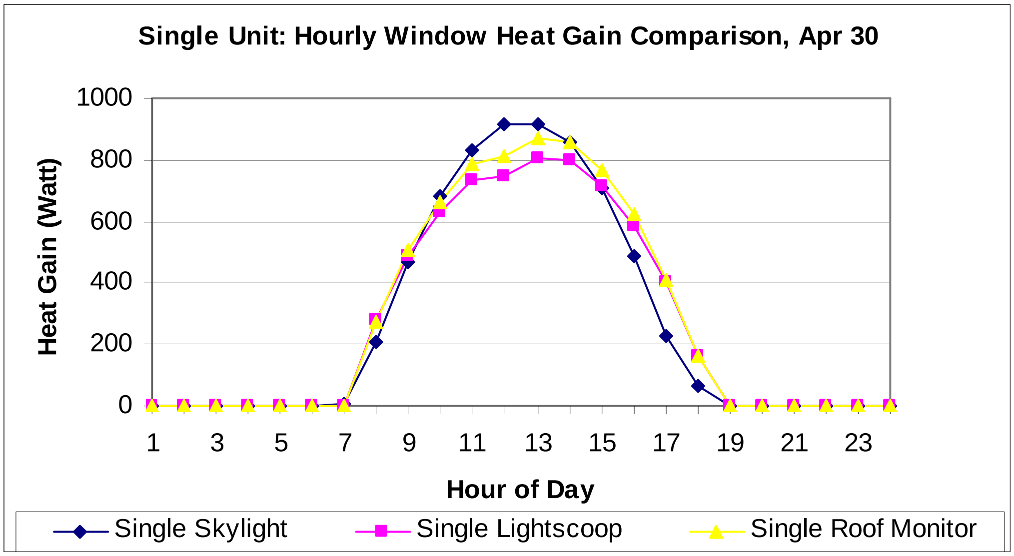

Fig. 4.12 Single unit toplighting: hourly window heat gain, Apr 30

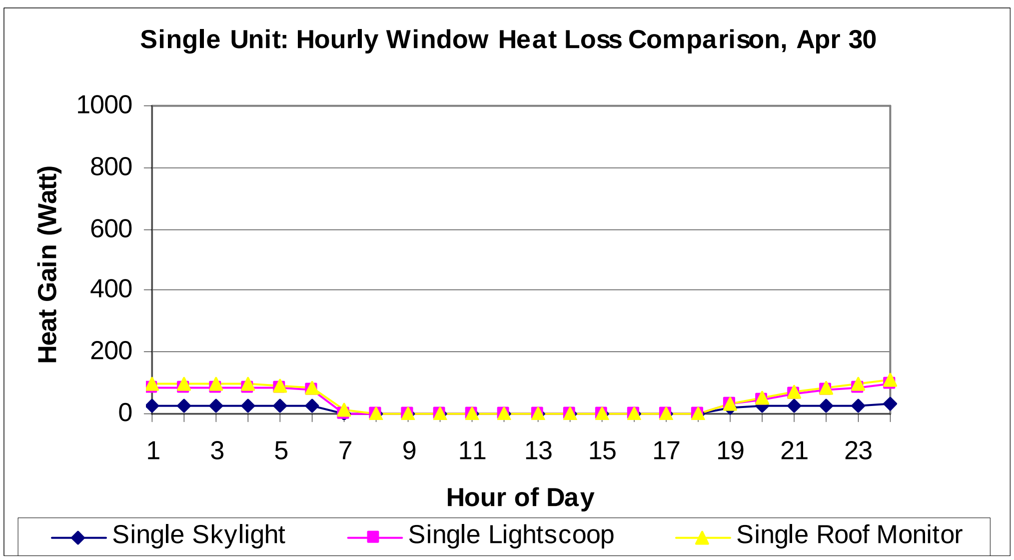

Fig. 4.13 Single unit toplighting: hourly window heat loss, Apr 30

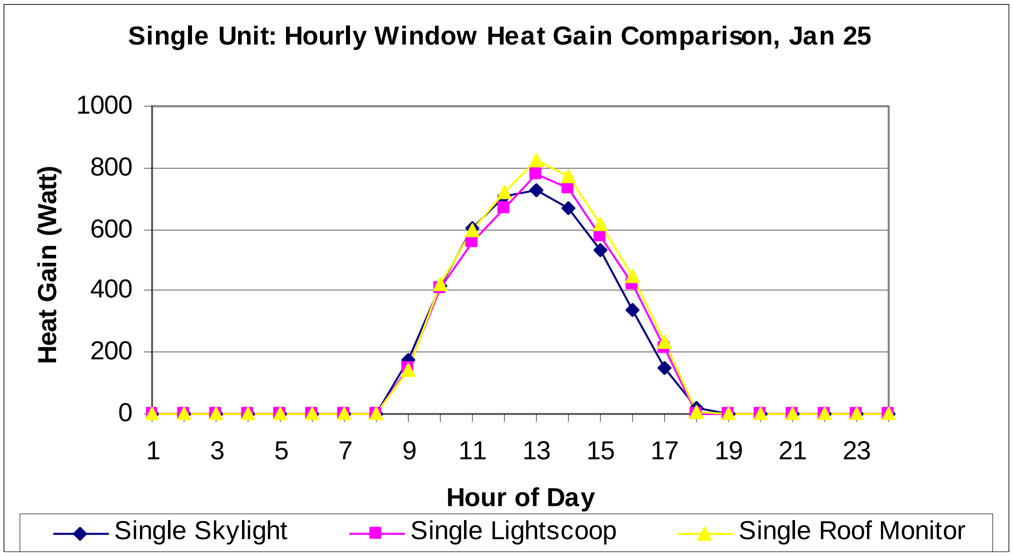

Fig. 4.14 Single unit toplighting: hourly window heat gain, Jan 25

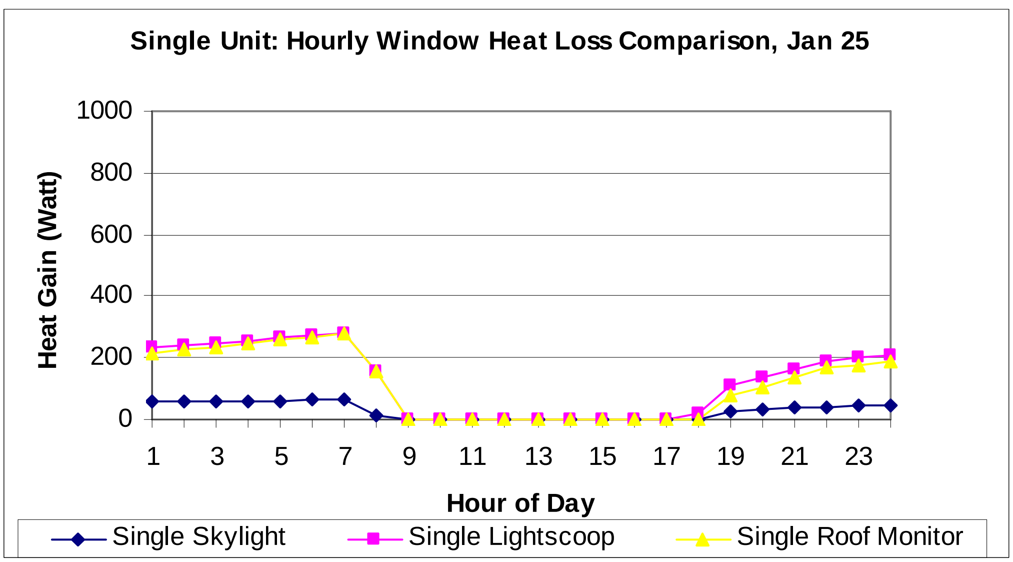

Fig. 4.15 Single unit toplighting: hourly window heat loss, Jan 25

4.1.4. Exterior and Interior Temperature Comparison

The indoor and outdoor temperatures are plotted by month in order to analyze the differences between each system. The results are similar in all the cases. It should be noted, however, that, to get the interior temperature data, the input files do not include any systems. More details concerning the input files used to obtain the interior temperature are provided in Chapter III.

A comparison chart for the outdoor and indoor temperatures from each toplighting system is given in Fig. 4.16. In general, the indoor temperature is higher than the outdoor temperature during the day, but the ranges between these two values are quite constant throughout the day. In addition, the indoor temperatures of each case are similar and fluctuate according to the outdoor temperatures.

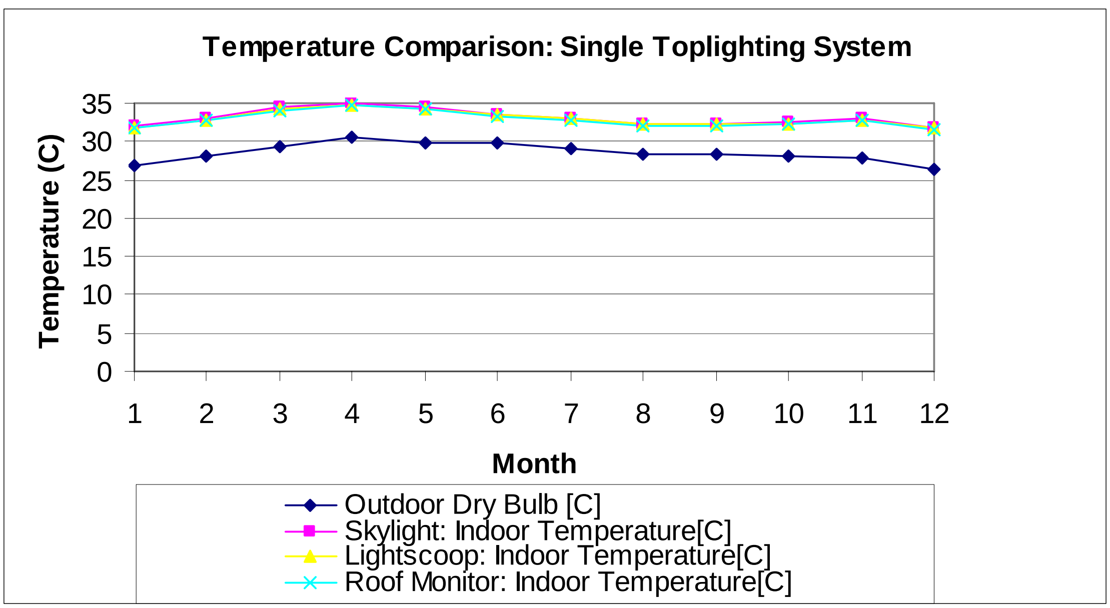

Fig. 4.16 Single unit toplighting: monthly average temperature comparison

Hourly temperature comparison plots are made for two extreme days: average hottest (April 30) and average coldest (January 25). These are presented in Figs. 4.17 and 4.18.

From these charts, it can be seen that the hourly interior temperatures, in all the cases, are similar and are constant throughout the day. On the hottest day, from 9:00am-5:00pm, the hourly interior temperatures are lower than the exterior dry bulb temperature. However, at night, the interior temperature is higher than the exterior. During working hours, the interior temperature is almost constant at 36°C (97°F), while the outdoor temperature reaches 38°C (100.4°F) in the afternoon.

To remedy this situation, the windows could be opened at night to help release the heat stored in the building during daytime. Even though the exterior temperature is not within a comfort zone, it is still lower than the interior would be if the windows were closed. For the coldest day, the interior temperature is also constant at about 29°C-30°C (84.2-86°F). This is close to a comfort zone, but still higher than the exterior temperature which ranges from 15°C (59°F) to 27°C (80°F). In the winter time, which lasts about 2 months, the windows could be opened all day to allow natural ventilation to cool the building.

However, a test for natural ventilation was not conducted. The parameters for reliable and accurate testing of the effects of natural ventilation are complex and are beyond the scope of this study. (Complex parameters have to be input to allow for reliable and accurate results in testing the effect of natural ventilation by the use of COMIS in EnergyPlus).

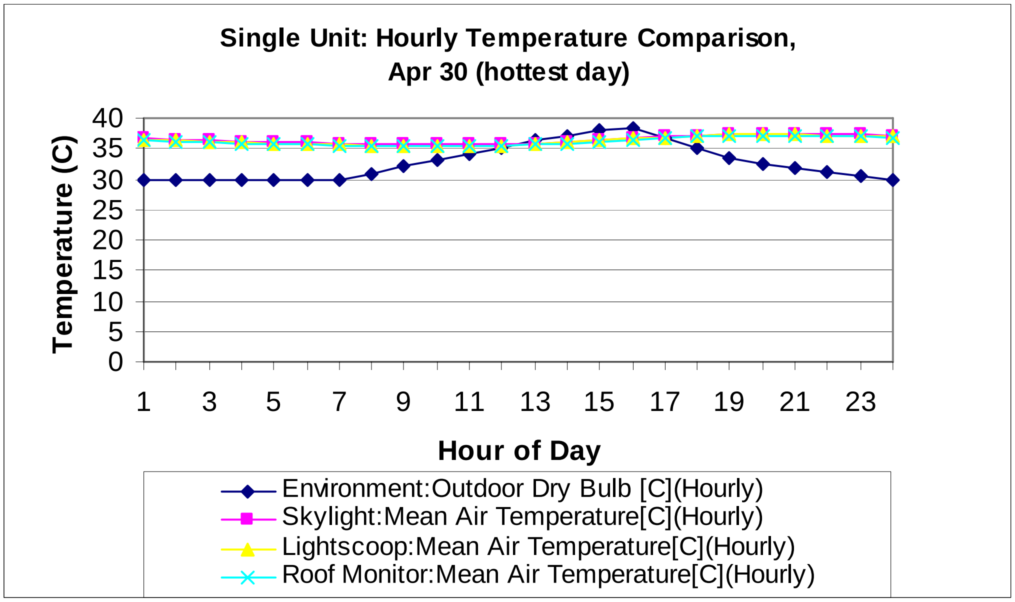

Fig. 4.17 Single unit toplighting: hourly average temperature comparison on April 30 (hottest day)

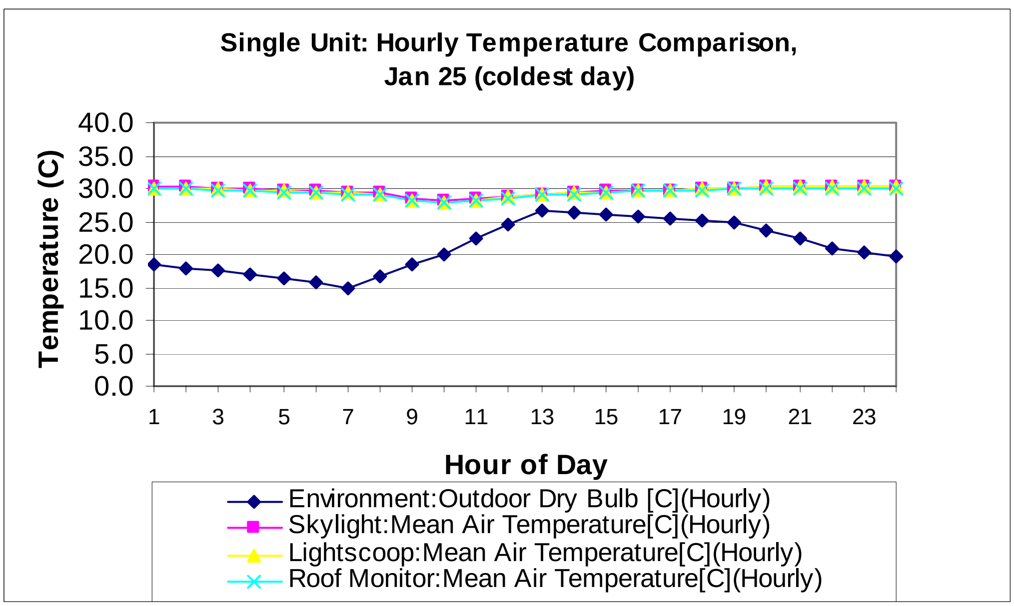

Fig. 4.18 Single unit toplighting: hourly average temperature comparison on Jan 25 (coldest day)

4.2. Toplighting Prototypes with a 1.5 to 1 Spacing-to-Height Ratio Analysis

The thermal performance of each 1.5 to 1 spacing-to-height ratio case is tested in EnergyPlus with a methodology as describe in Chapter III. The picture of each case is shown in Chapter III (Fig. 3.10). The 1.5 to 1 spacing-to-height prototype is comprised of 4 units per each toplighting system.

4.2.1. Total Cooling Load Comparison

Total cooling load of each case is close to each other less than 1 percent for typical cooling availability schedule (from 8:00am-5:00pm); therefore, these three cases are comparable in terms of their thermal performance. For the cooling availability schedule of 24 hours, the difference between total cooling loads of each prototype is 3 %. Each prototype yields the average yearly total cooling load at about 7-8 kW for the cooling availability schedule from 8:00am-5:00pm, and 15-17 kW for cases with cooling available at all time. Monthly total cooling load data of each prototype is shown in Figs. 4.19-4.20 for cooling availability schedule of 8:00am-5:00pm and 24 hours, respectively.

As can be seen from the charts, the discrepancy between the cooling loads of each prototype increases when the availability schedule is set to 24 hours.

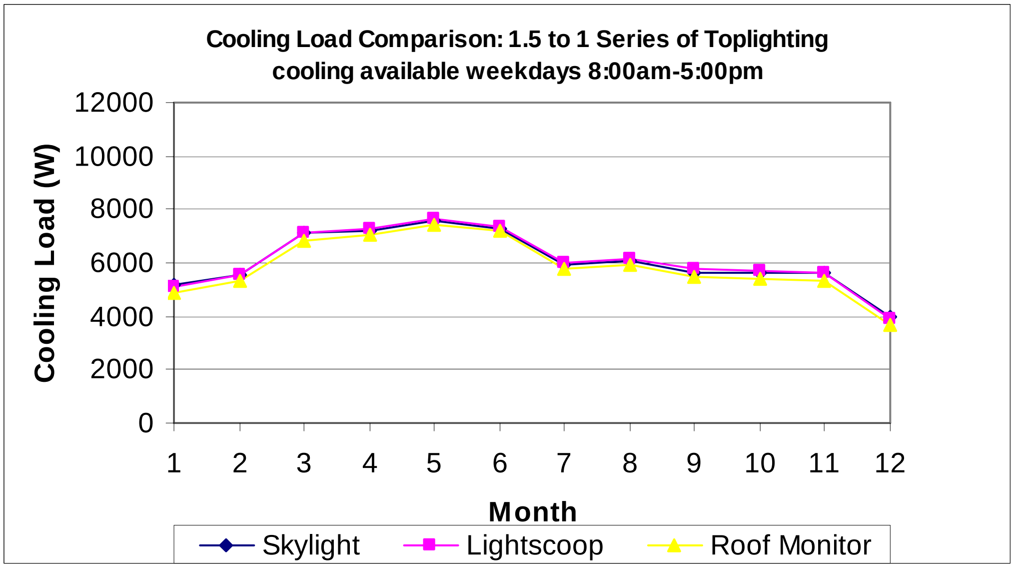

Fig. 4.19 1.5 to 1 toplighting unit: cooling load comparison, cooling available weekdays from 8:00am-5:00pm

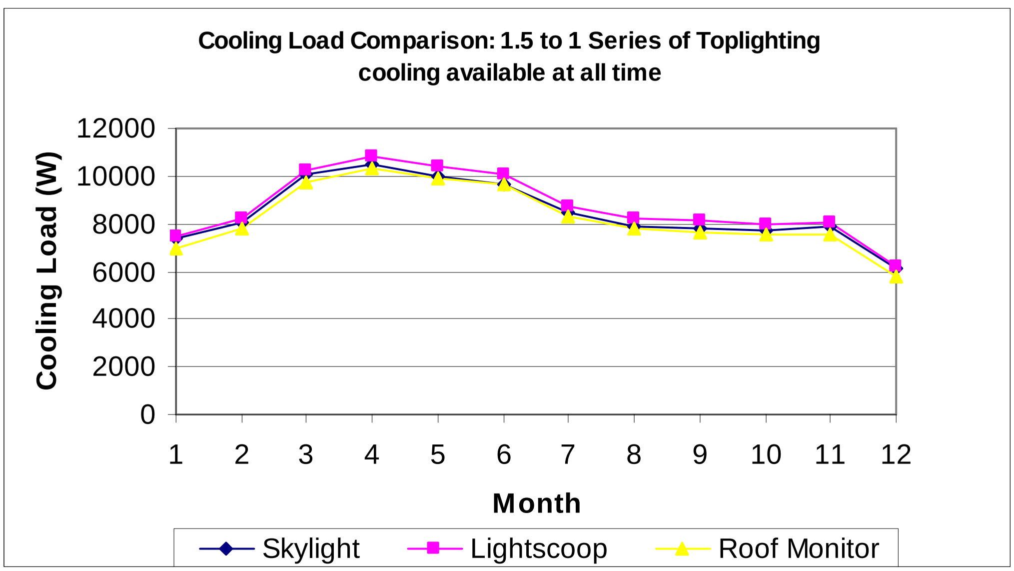

Fig. 4.20 1.5 to 1 toplighting unit: cooling load comparison, cooling available at all time

Hourly cooling loads results when cooling is always available are presented as a reference to the characteristics of heat gain in the prototype building, which, from the results, each case represents similar trend. Figs. 4.21-4.22 represent the hourly cooling load of the building without internal gains and Figs. 4.23-4.24 are the hourly cooling load of the building with internal gains.

For the cooling load without internal gains, the cooling load increases in the morning and reaches the maximum late afternoon about 6pm and then begins to decrease. This applies for both the hottest and coldest day.

For cooling load with internal gains, the average total cooling load in summer is about similar to the cases without internal gains. In summer, the cooling load begins to increase more during late afternoon hours and continues to be almost stable, then, starts to decrease in late evening at about 7pm. The cooling load for summer reaches the minimum during morning hours. For winter hours, the average total cooling loads of the cases with internal gains are higher than the cases without internal gains.

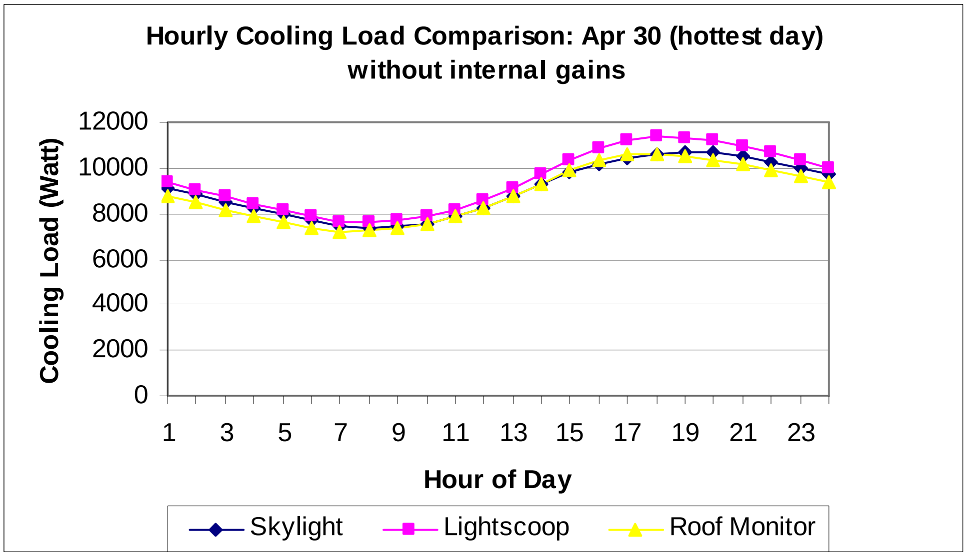

Fig. 4.21 1.5 to 1 toplighting unit: hourly cooling load comparison, Apr 30, without internal gains, when cooling is always available

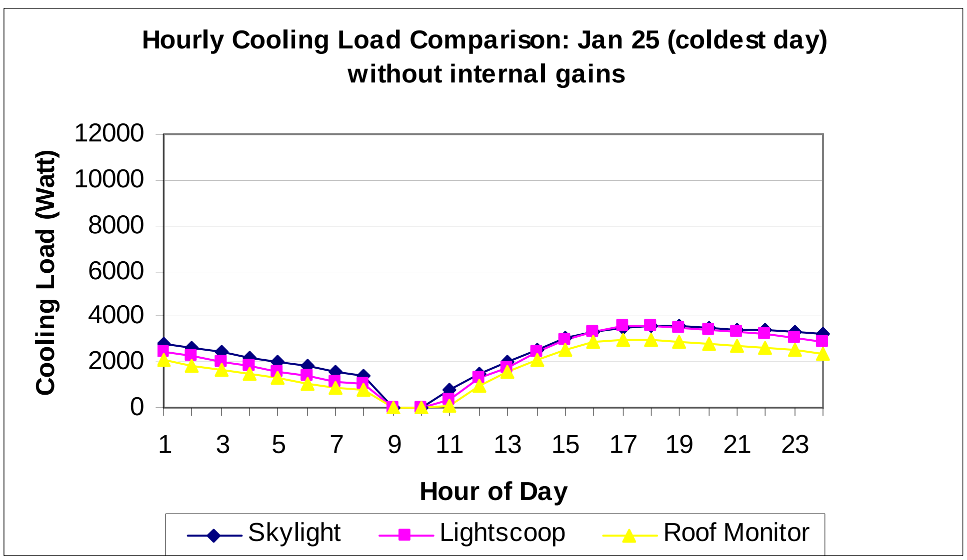

Fig. 4.22 1.5 to 1 toplighting unit: hourly cooling load comparison, Jan 25, without internal gains, when cooling is always available

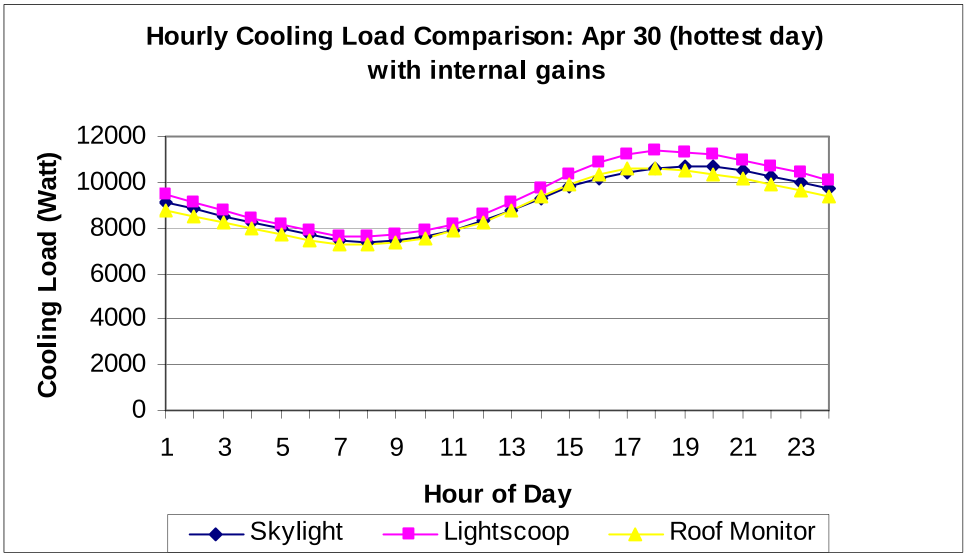

Fig. 4.23 1.5 to 1 toplighting unit: hourly cooling load comparison, Apr 30, with internal gains, when cooling is always available

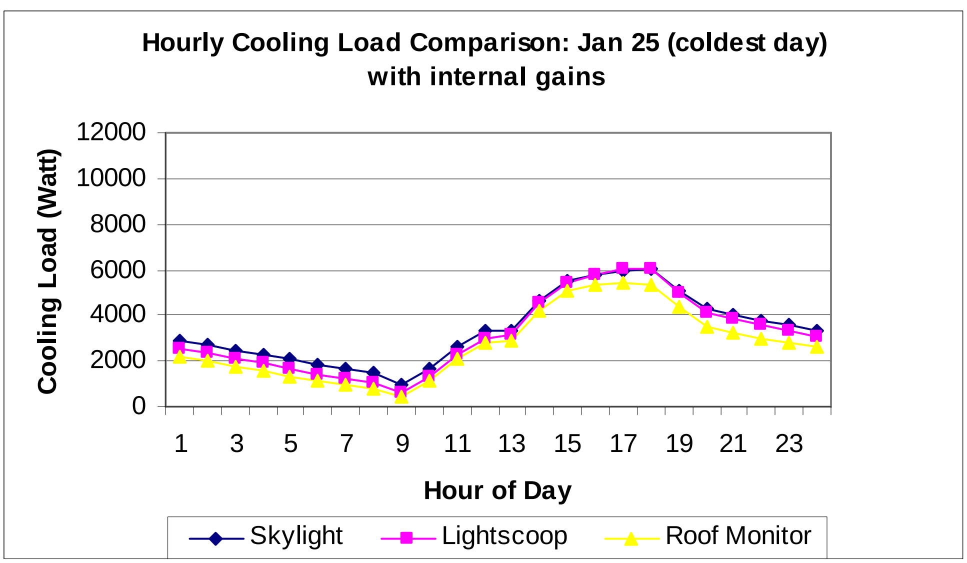

Fig. 4.24 1.5 to 1 toplighting unit: hourly cooling load comparison, Jan 25, with internal gains, when cooling is always available

4.2.2. Sensible and Total Cooling Load Comparison

Monthly sensible cooling load is plotted compared to total cooling load of each case in order to analyze the amount of energy required for moisture removal. Figs. 4.25-4.27 present the results from the 1.5 to 1 spacing-to-height toplighting cases with cooling availability from 8:00am-5:00pm (typical thermal input files).

From the results, it can be determined that the sensible cooling load still represents about one-third of the total cooling load and is following the same trend as single unit toplighting results. The highest discrepancy still in summer of May and June, and the lowest occurs in December.

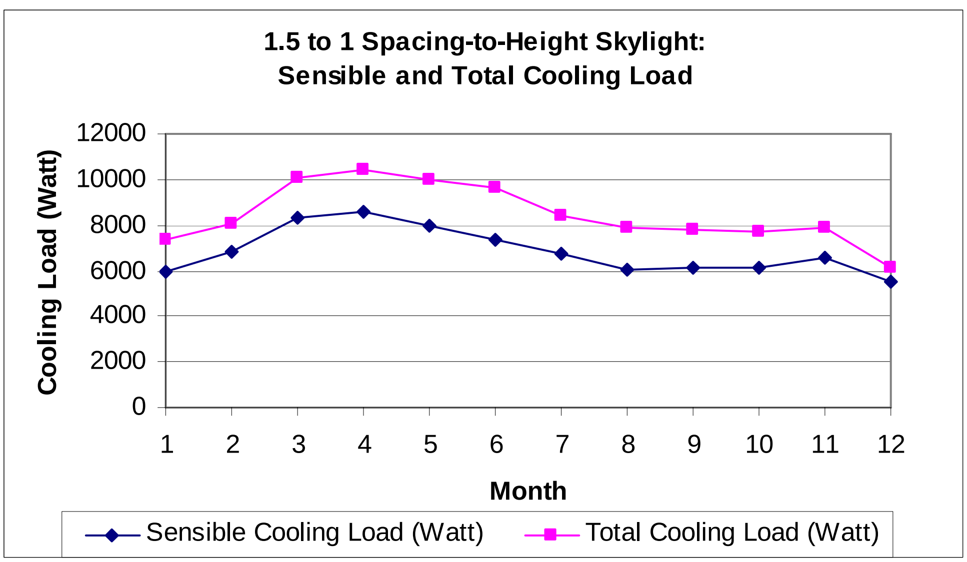

Fig. 4.25 Skylight with a 1.5 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

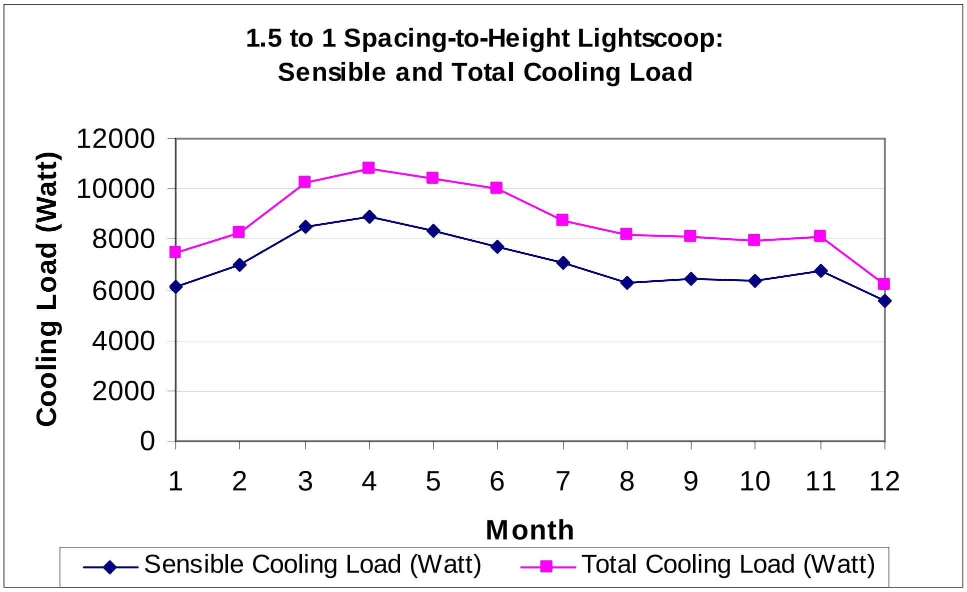

Fig. 4.26 Lightscoop with a 1.5 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

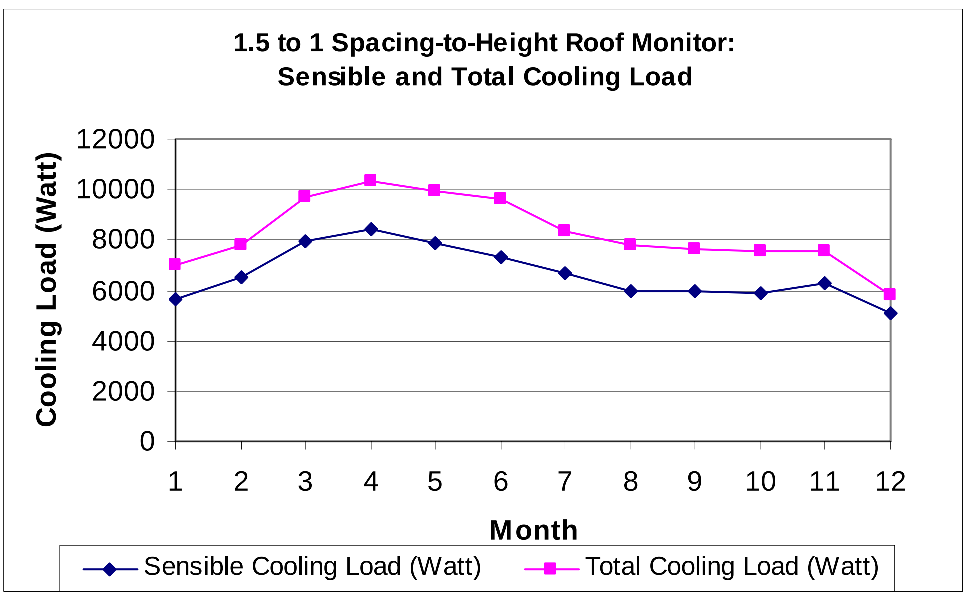

Fig. 4.27 Roof monitor with a 1.5 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

4.2.3. Window Heat Gain and Loss Comparison

Monthly average window heat gain and loss charts are presented in Figs. 4.28-4.29. The skylight has less heat gain than other prototypes but also less heat loss, resulted in similar amount of cooling load as discussed previously.

Hourly heat gain and loss charts are plotted to compare the thermal character between each single unit prototypes as a reference. The charts for hourly heat gain and loss for two extreme days: April 30 which is the hottest day and January 25 which is the coldest day are plotted and shown in Figs. 4.30-4.33.

From the data, it can be seen that the heat gains and losses for each case is similar and following the same trend, with the skylight prototype having higher heat gain in the summer and lower heat gain in winter, which is from the effect of the position of the sun entering the space. The lightscoop and roof monitor prototypes yield very close values and trends for both heat gain and loss, possibly because both cases have shading devices installed.

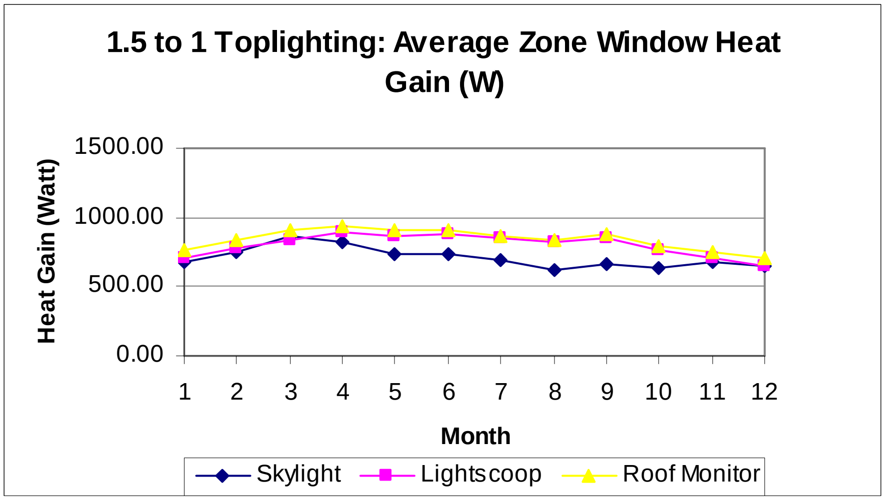

Fig. 4.28 1.5 to 1 toplighting unit: average zone window heat gain

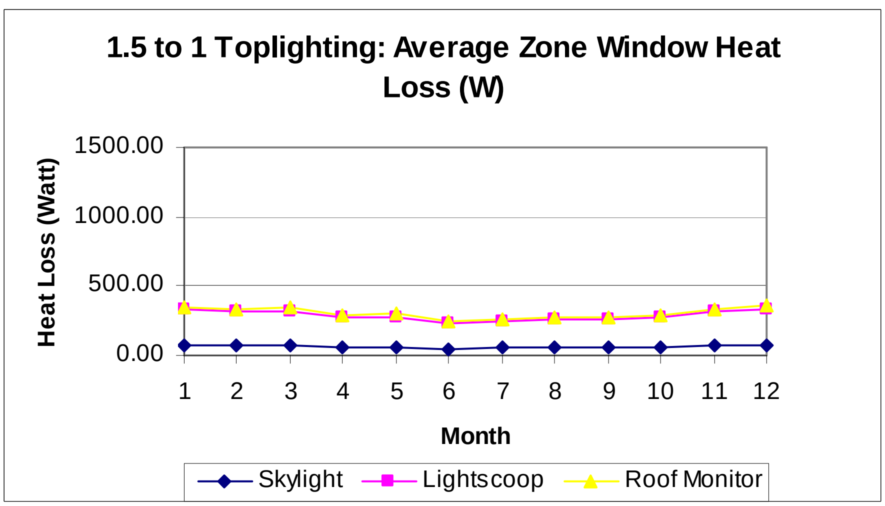

Fig. 4.29 1.5 to 1 toplighting unit: average zone window heat loss

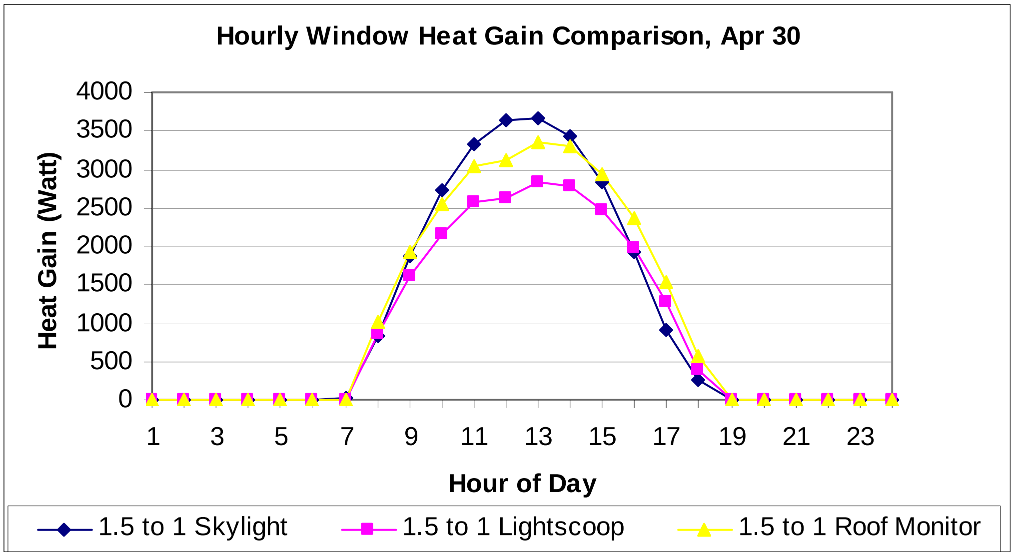

Fig. 4.30 1.5 to 1 toplighting unit: hourly window heat gain, Apr 30

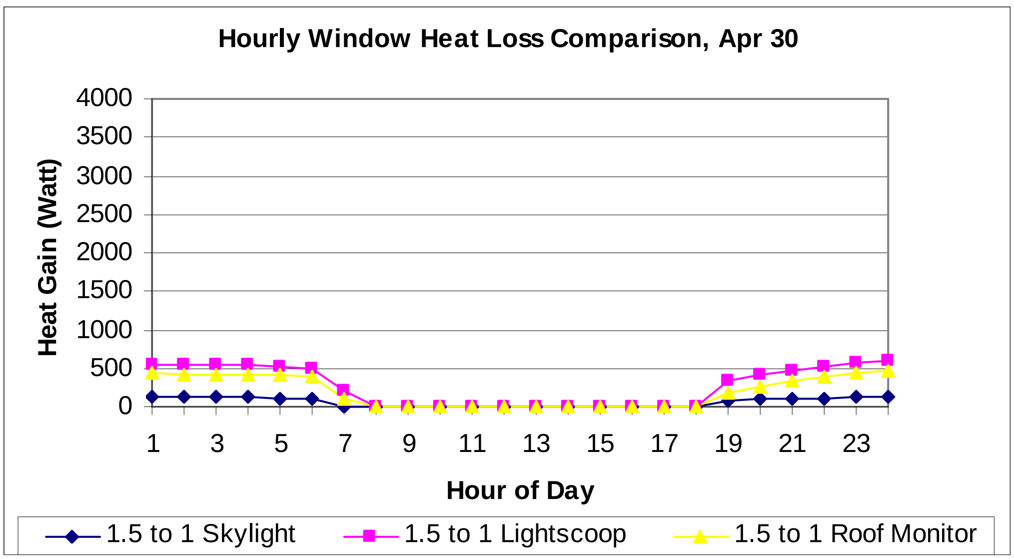

Fig. 4.31 1.5 to 1 toplighting unit: hourly window heat loss, Apr 30

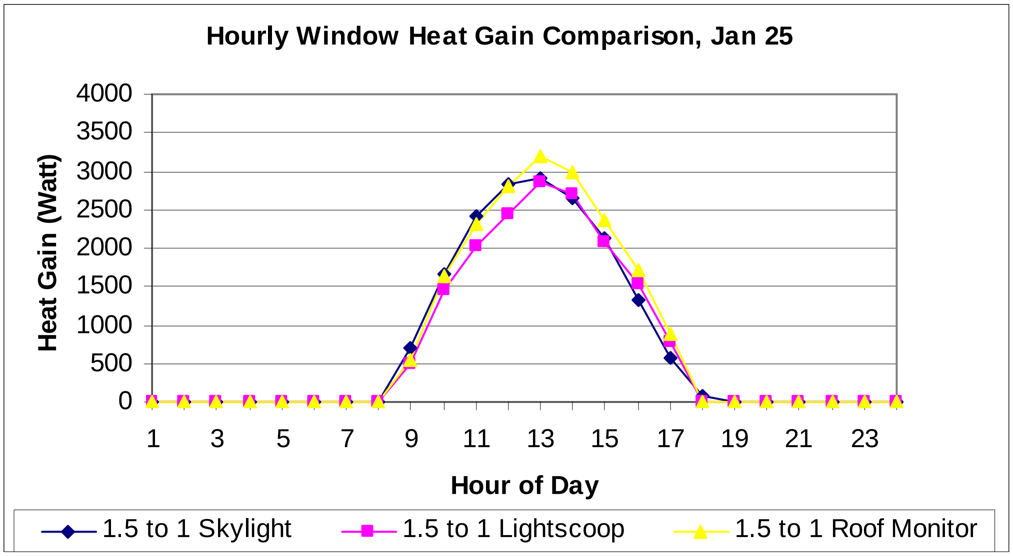

Fig. 4.32 1.5 to 1 toplighting unit: hourly window heat gain, Jan 25

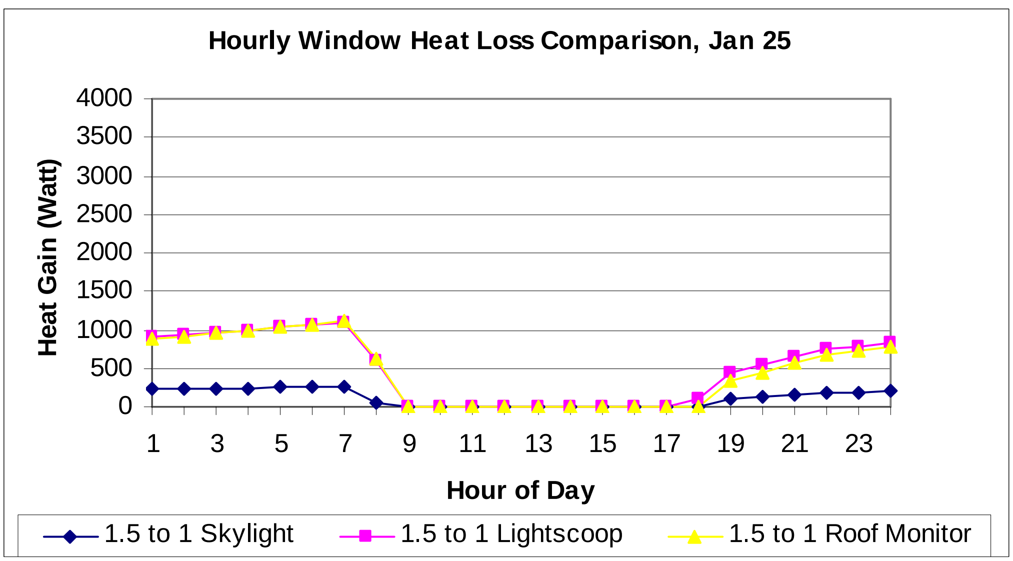

Fig. 4.33 1.5 to 1 toplighting unit: hourly window heat loss, Jan 25

4.2.4. Exterior and Interior Temperature Comparison

The average interior temperature of each case is very similar at about 4-5°C (7-9F) higher than the exterior and fluctuates according to the exterior temperature. The indoor and outdoor temperatures are plotted monthly to analyze the difference between each system with a 1.5 to 1 spacing-to-height ratio. A comparison chart for outdoor and indoor temperature from each 1.5 to 1 spacing-to-height ratio toplighting system is illustrated in Fig. 4.34.

From the chart, it can be seen that the building with three different toplighting cases have the similar trend and values for interior temperature throughout the year. The interior temperature of each case fluctuates following the exterior temperature.

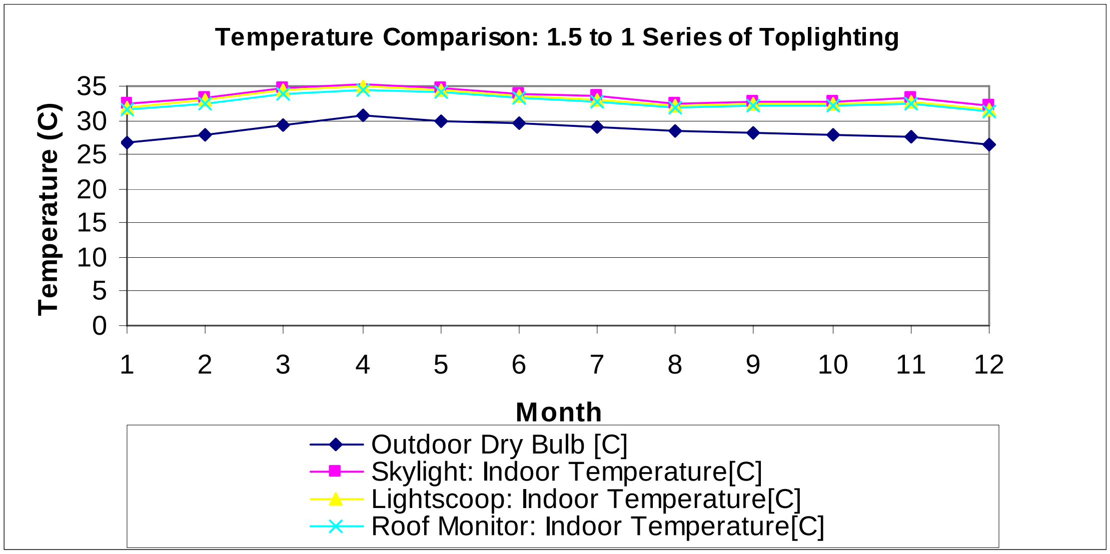

Fig. 4.34 1.5 to 1 toplighting unit: monthly average temperature comparison

Hourly temperature comparison between each case on hottest day (April 30) and coldest day (January 25) are presented in Figs. 4.35-4.36.

All cases have similar values of interior temperature on each day which is generally higher than exterior dry bulb temperature. In summer, the interior temperature reaches 36°C (96F) when the exterior is at 30°C (86F). Still, from the thermal mass of the building, the interior temperature does not fluctuate following the exterior but remains quite constant throughout the day at around 36°C (96F). In winter, where the exterior dry bulb temperatures are generally lower than 25°C (77F), the interior temperature are constant around 29-30°C (84.2-86F); 4-5 degrees higher than the exterior. Therefore, in winter, opening of windows to allow for natural ventilation might be a useful climate responsive method for this climate to reduce the interior temperature because the exterior temperature is within the comfort zone, unlike in summer. Still, the exterior temperature that is within the comfort zone (24-28°C) occurs only about 2 months per year or less.

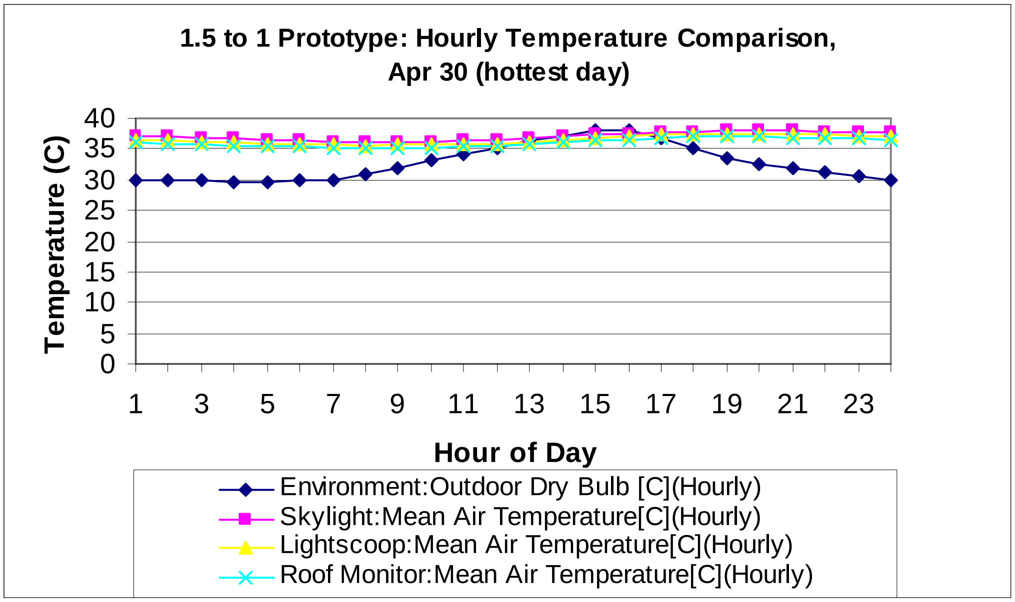

Fig. 4.35 1.5 to 1 toplighting unit: hourly average temperature comparison on April 30 (hottest day)

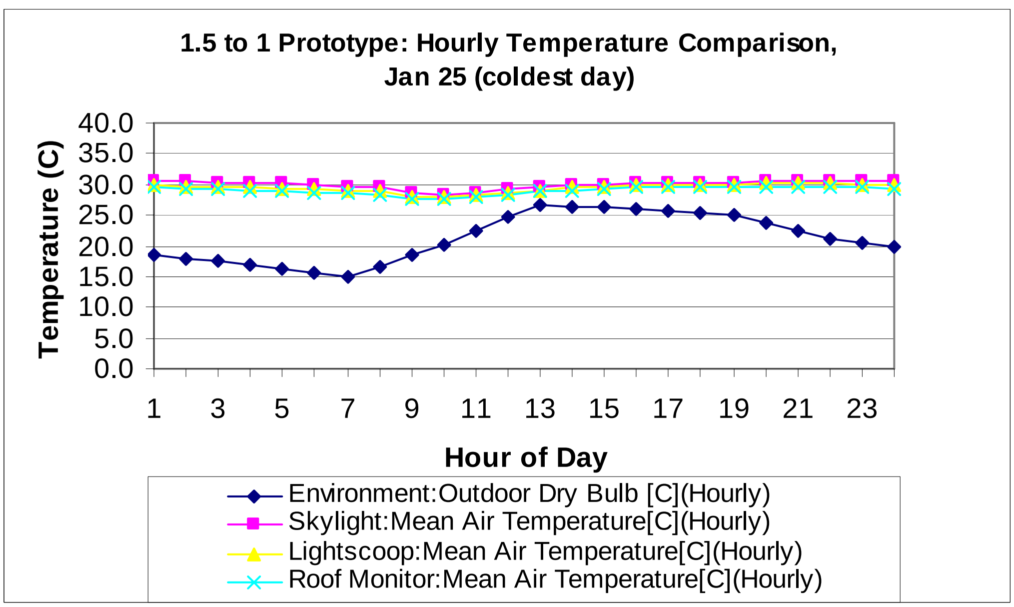

Fig. 4.36 1.5 to 1 toplighting unit: hourly average temperature comparison on Jan 25 (coldest day)

4.3. Toplighting Prototypes with a 1 to 1 Spacing-to-Height Ratio Analysis

4.3.1. Total Cooling Load Comparison

The average monthly cooling load comparison charts are presented in Figs. 4.37-4.38, for typical cooling schedule, and for cooling availability of 24 hours, respectively.

The cooling load of each case is in a close range for typical cooling schedule from 8:00am-5:00pm but more discrepancy occurs when cooling is available 24 hours. It can be seen that, the average cooling load per year of each case is around 6.2 kW and still differs less than 5 % (for typical cooling schedule of 8:00am-5:00pm files), which is considered to be thermally comparable. For cooling availability schedule of 24 hours, the cooling load between each cases differ at 7.6 %, which is 5 % higher than the 1.5 to 1 spacing to height units (which have 4 units of apertures). The average monthly total cooling load is at about 8.7 kW. For both cooling schedule, it can be seen that the most cooling load is generated in April, May, and June, which is summer time for this climate.

The pictures of the units with a 1 to 1 spacing-to-height ratio are presented in Chapter III (Fig. 3.19), with each case having 6 units of the developed prototype.

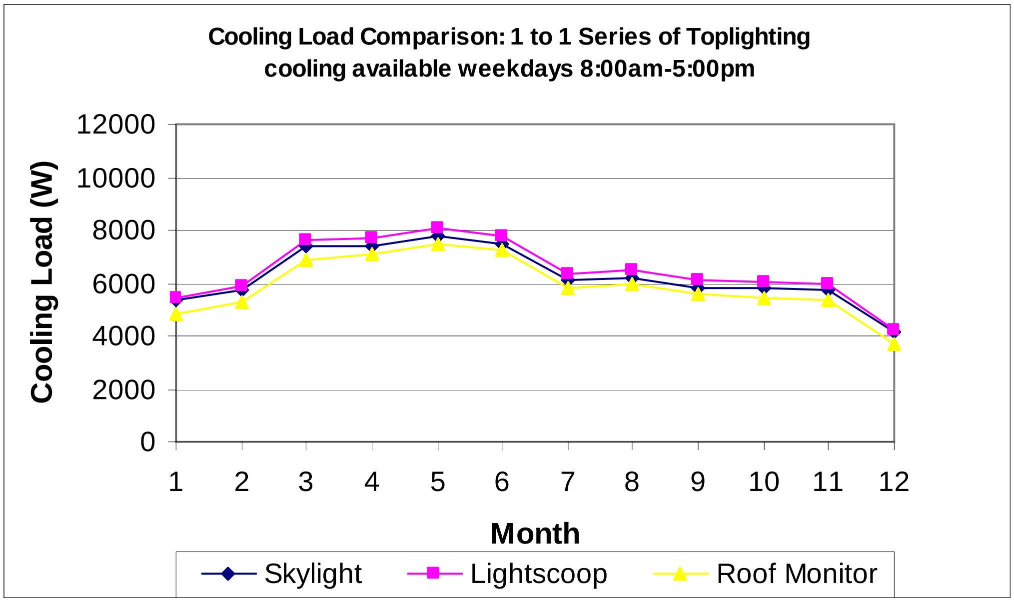

Fig. 4.37 1 to 1 toplighting unit: cooling load comparison, cooling available weekdays from 8:00am-5:00pm

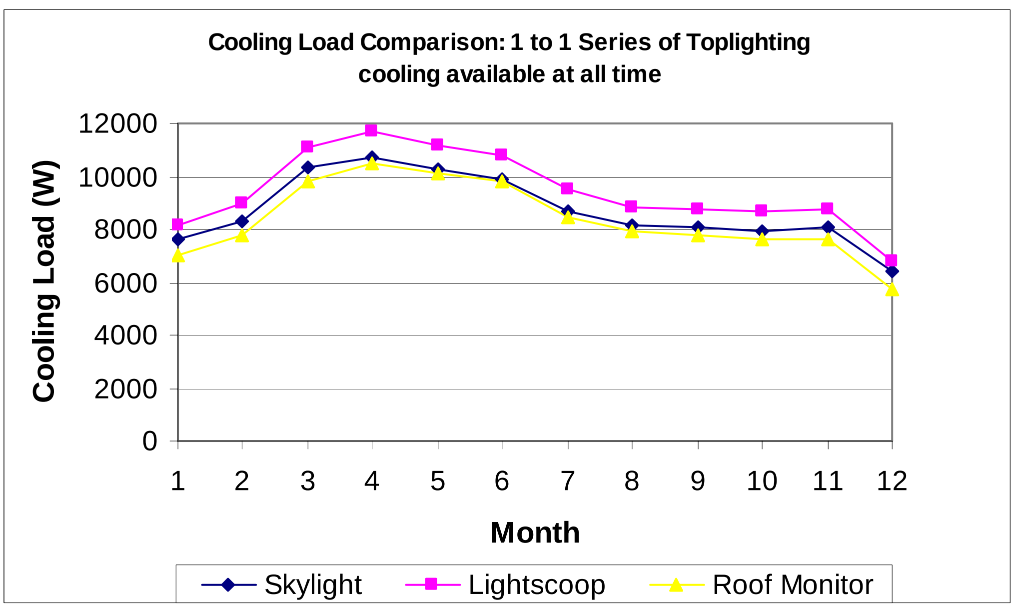

Fig. 4.38 1 to 1 toplighting unit: cooling load comparison, cooling available at all time

Hourly cooling load results when cooling is always available are presented as a reference to the characteristics of heat gain in the prototype building, which, from the results, each case represents similar trend. Figs. 4.39-4.40 are the hourly cooling load without internal gains and Figs. 4.41-4.42 are the hourly cooling load with internal gains.

Hourly cooling load of each case is similar for both hottest and coldest days for the cases with and without internal gains. The results are similar to the results from single unit and 1.5 to 1 series of prototypes, with more cooling load occur in the afternoon and less in the morning. The overall cooling load increases from a 1.5 to1 series a little, but all trends are similar.

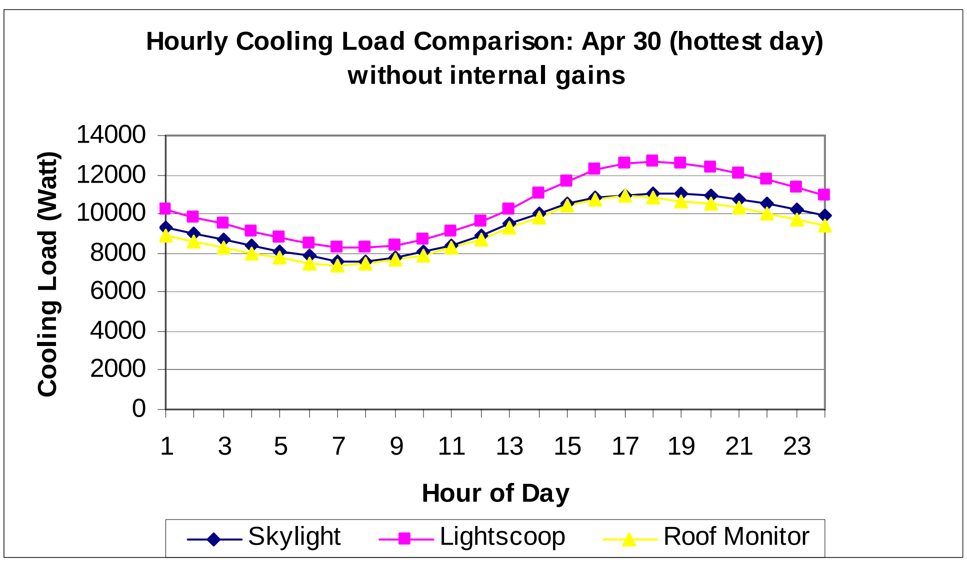

Fig. 4.39 1 to 1 toplighting unit: hourly cooling load comparison, Apr 30, without internal gains, when cooling load is always available

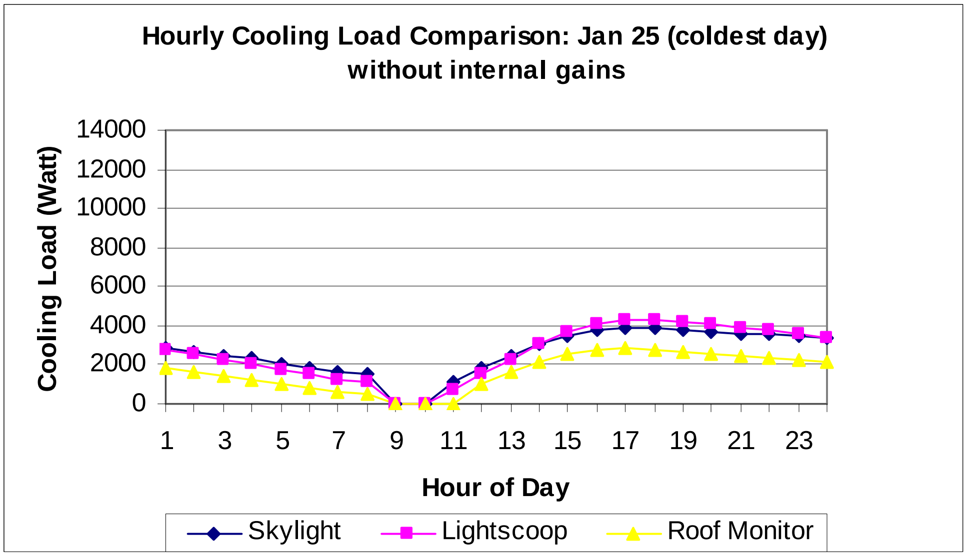

Fig. 4.40 1 to 1 toplighting unit: hourly cooling load comparison, Jan 25, without internal gains, when cooling load is always available

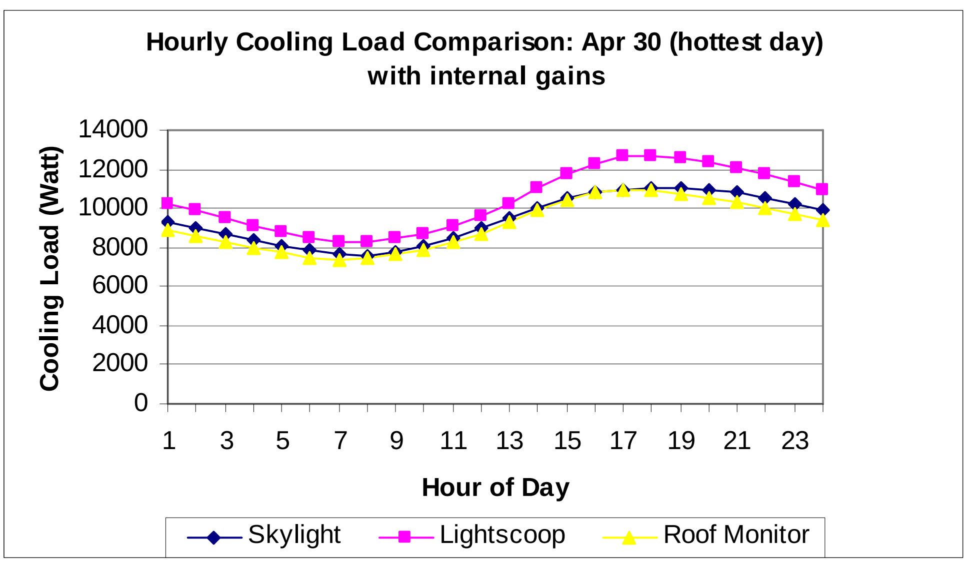

Fig. 4.41 1 to 1 toplighting unit: hourly cooling load comparison, Apr 30, with internal gains, when cooling load is always available

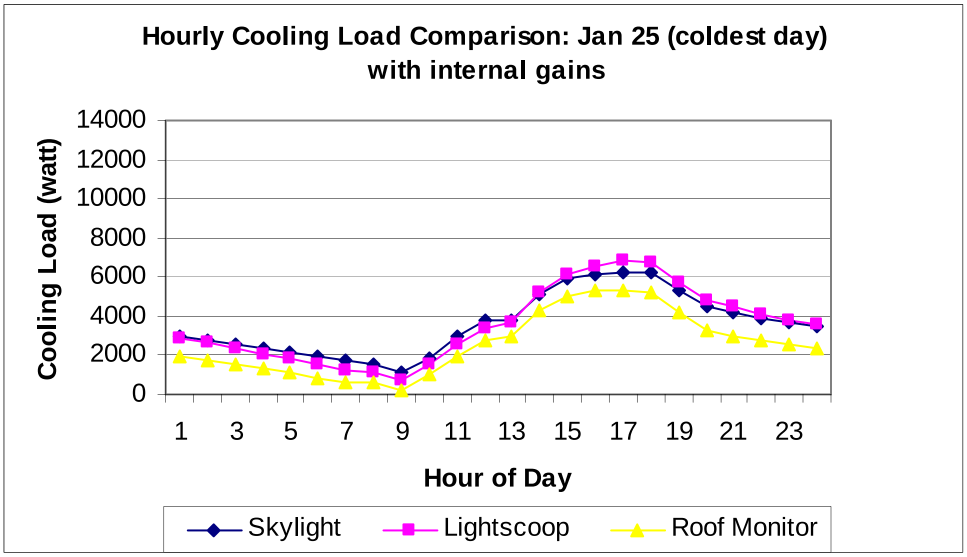

Fig. 4.42 1 to 1 toplighting unit: hourly cooling load comparison, Jan 25, with internal gains, when cooling load is always available

4.3.2. Sensible and Total Cooling Load Comparison

Monthly sensible cooling load is plotted compared to total cooling load of each case to analyze the amount of energy required for moisture removal. The results presented in Figs. 4.43-4.45 are from the 1 to 1 spacing-to-height toplighting cases with cooling availability from 8:00am-5:00pm (which are typical thermal input files).

From the charts, it can be seen that latent cooling energy still represents about one-third of the total cooling energy, with the most discrepancy in May and June, and the least in December. This emphasizes the need for moisture removal of this hot and humid climate. The data for sensible and total cooling load is following the same trend for all the cases.

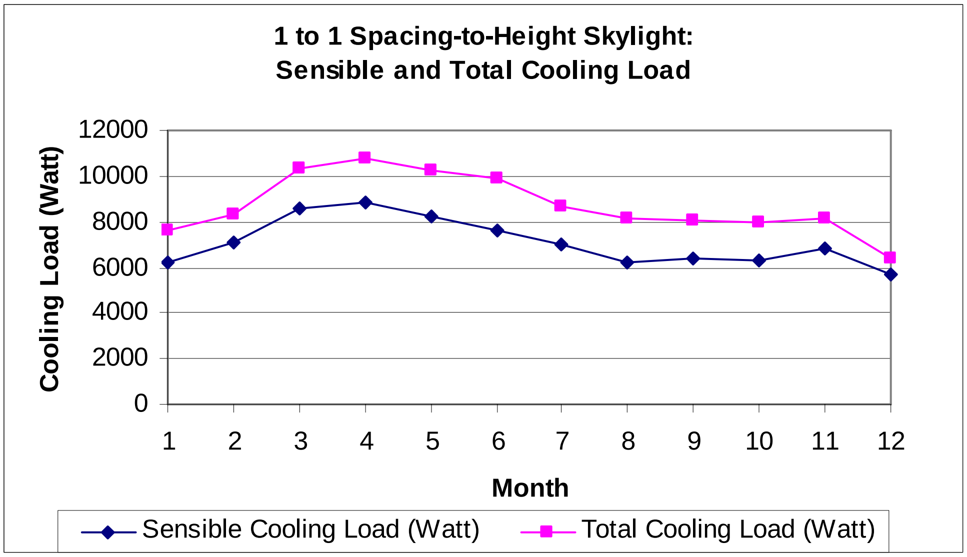

Fig. 4.43 Skylight with a 1 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

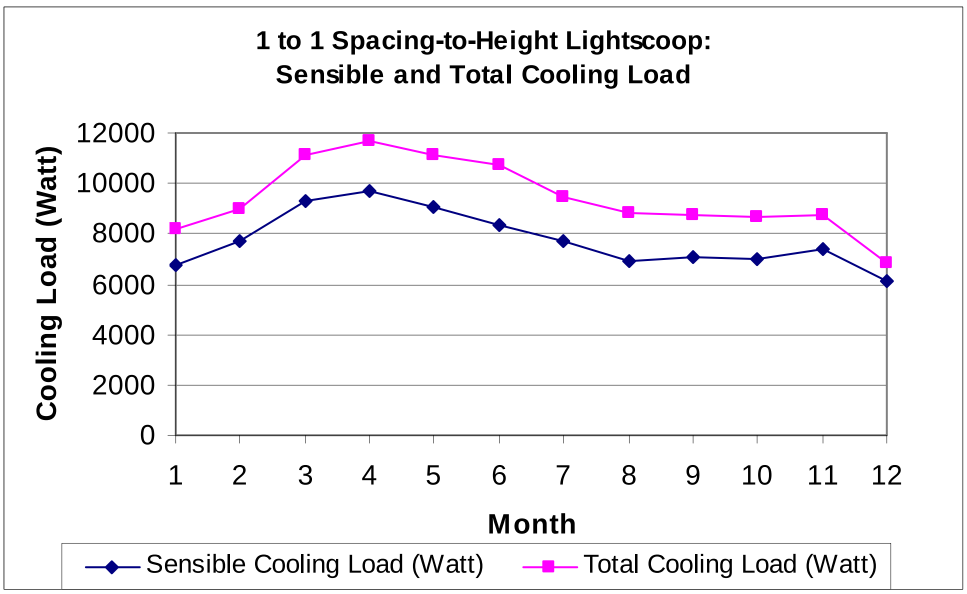

Fig. 4.44 Lightscoop with a 1 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

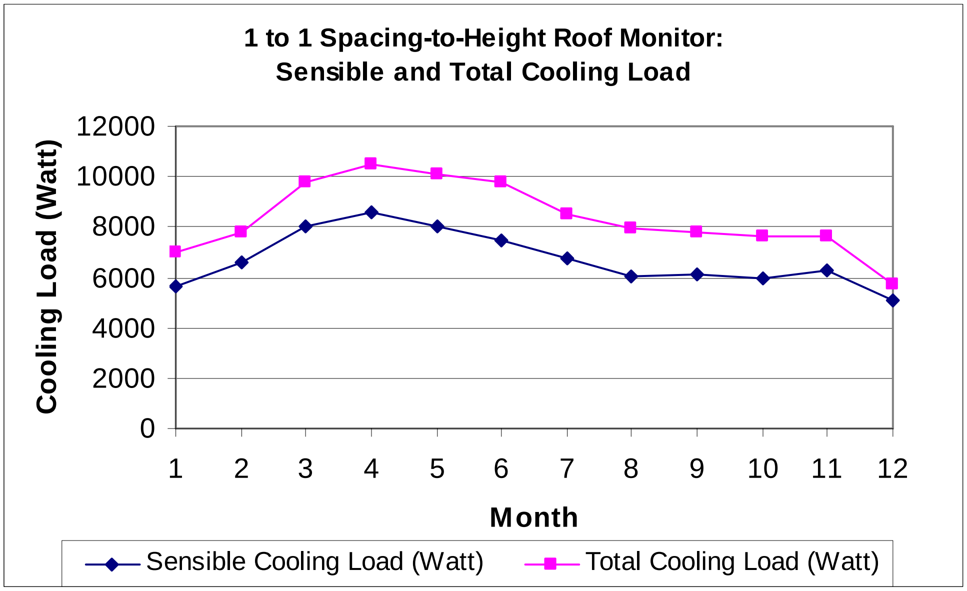

Fig. 4.45 Roof Monitor with a 1 to 1 spacing-to-height ratio: sensible and total cooling load comparison, cooling available from 8:00am-5:00pm

4.3.3. Window Heat Gain and Loss Comparison

Monthly average window heat gain and loss charts are presented in Figs. 4.46-4.47. It can be seen from the charts that the trends are very similar to those of a 1.5 to 1 toplighting prototypes, with the skylight having lower heat gain and lower heat loss. In summary, it could be said that, this trend in heat gain and loss results in similar cooling loads for all the cases.

Hourly heat gain and loss charts are plotted to compare the thermal character between each single unit prototypes as a reference. The charts for hourly heat gain and loss for two extreme days: April 30 which is the hottest day and Jan 25 which is the coldest day are plotted and shown in Figs. 4.48-4.51.

From the data, it can be seen that all the heat gains and losses character for each case is still similar and having the same trend, with the skylight case having higher heat gain in the summer. Heat gain from skylight reaches at about 5,500 watt on April 30 while lightscoop and roof monitor cases have about 4,000 watt of heat gain amount. However, the heat loss of lightscoop and roof monitor cases for both summer and winter are more than skylight which resulted in similar amount of average cooling load as presented earlier in this section. The lightscoop and roof monitor cases yield similar amounts of heat gain and loss for both April 30 and January 25.

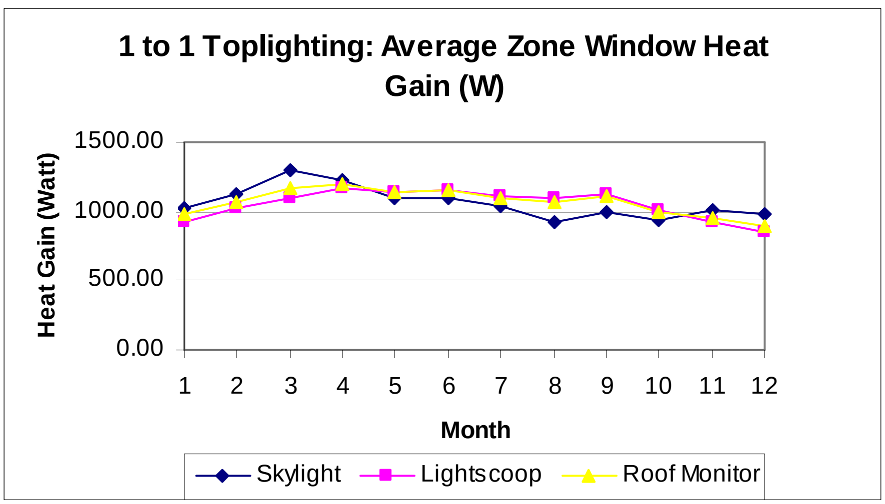

Fig. 4.46 1 to 1 toplighting unit: average zone window heat gain

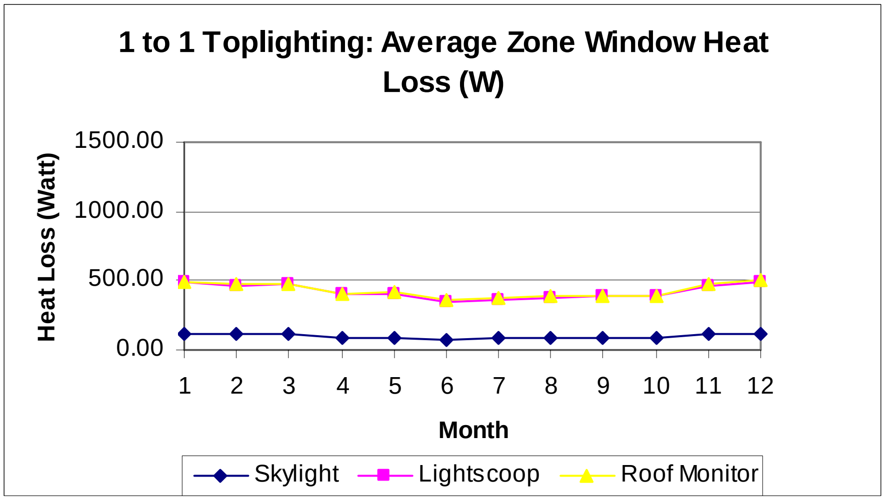

Fig. 4.47 1 to 1 toplighting unit: average zone window heat loss

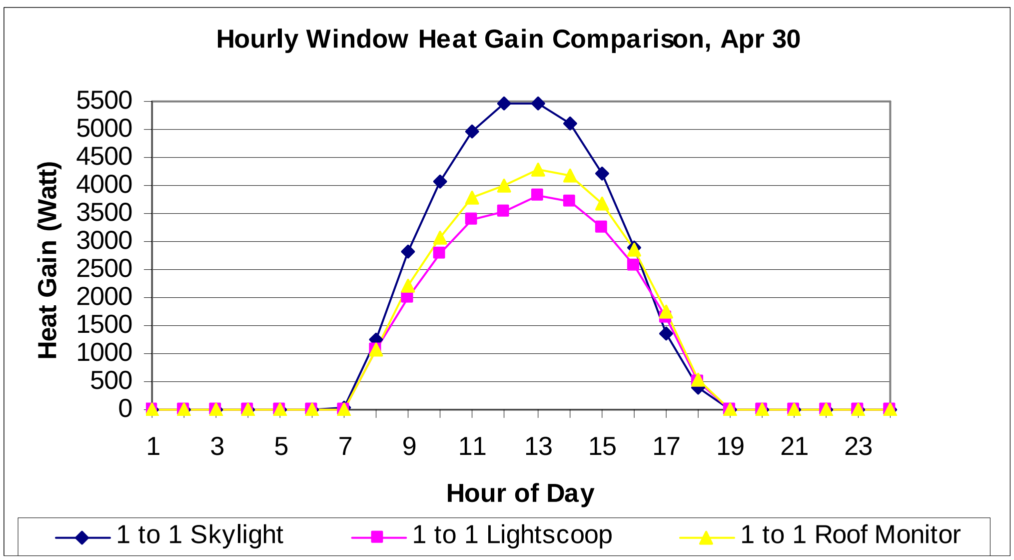

Fig. 4.48 1 to 1 toplighting unit: hourly window heat gain, Apr 30

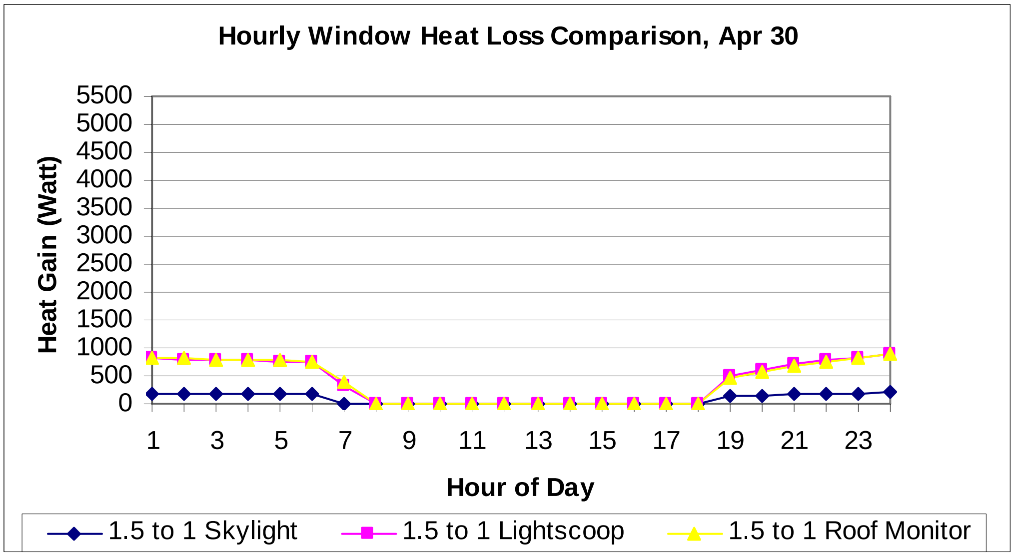

Fig. 4.49 1 to 1 toplighting unit: hourly window heat loss, Apr 30

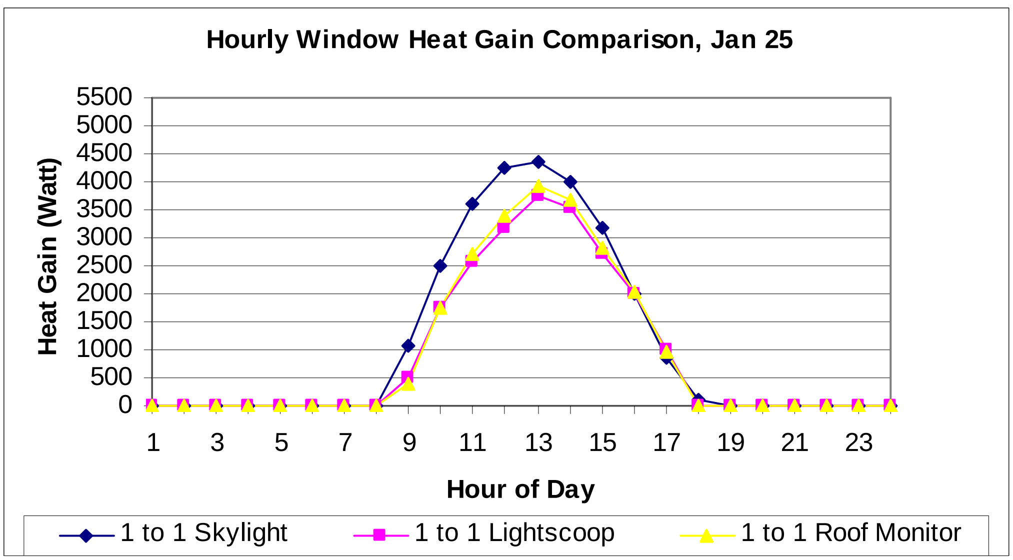

Fig. 4.50 1 to 1 toplighting unit: hourly window heat gain, Jan 25

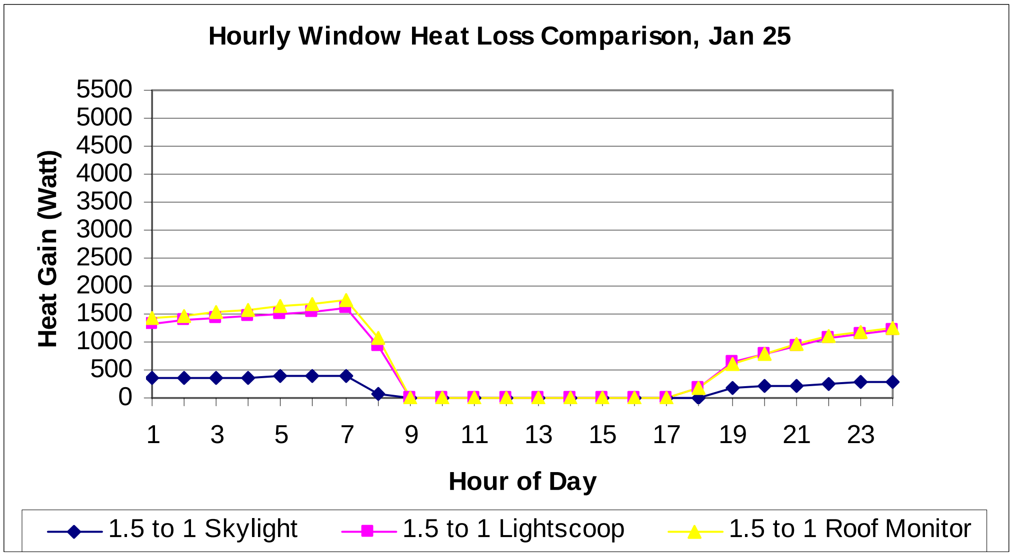

Fig. 4.51 1 to 1 toplighting unit: hourly window heat loss, Jan 25

4.3.4. Exterior and Interior Temperature Comparison

The average interior temperature of each case is very similar at about 4-5°C (7-9F) higher than the exterior and fluctuates according to the exterior temperature, similar to those from single and 1.5 to 1 spacing-to-height ratio toplighting units. The indoor and outdoor temperatures are plotted monthly to analyze the difference between each system with a 1 to 1 spacing-to-height ratio. Comparison chart for outdoor and indoor temperature from each 1 to 1 spacing-to-height ratio toplighting system is illustrated in Fig. 4.52.

The overall trend of the interior temperature is constant throughout the year; fluctuates following the exterior temperature by having a higher temperature at about 5°C. All the cases have a very close interior temperature throughout the year. The indoor temperature of a 1 to 1 series ranges from about 31°C (87.8F) to 36°C (96.8F) in April, which is the hottest month.

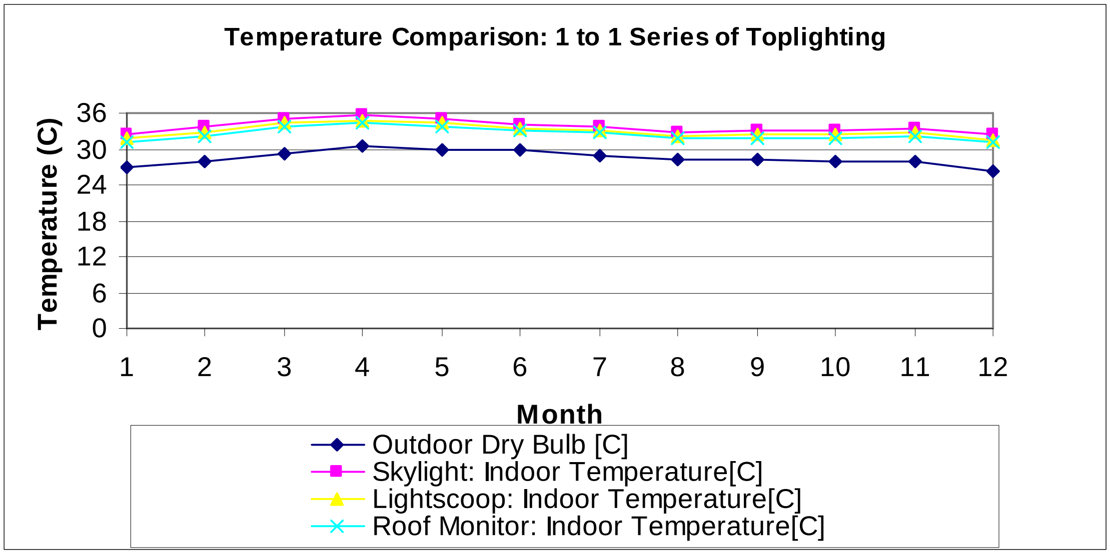

Fig. 4.52 1 to 1 toplighting unit: monthly average temperature comparison

Hourly temperature comparison between each case on the hottest day (Apr 30) and coldest day (Jan 25) are presented in Figs. 4.53-4.54.

All the cases have similar values of interior temperature on each day which is mostly higher than exterior dry bulb temperature except in the summer afternoon. The indoor temperature on the hottest day is mostly constant at around 36-38°C (97-100F) while for coldest day, the temperature is around 29-30°C (84.2-86F). The indoor temperature decreases in the morning hours, increases during the afternoon and reaches the maximum during late afternoon hours for both the hottest and coldest days. The same technique, natural ventilation, which is recommended as in the previous section for single toplighting unit and 1.5 to 1 spacing-to-height series could help lower indoor temperature.

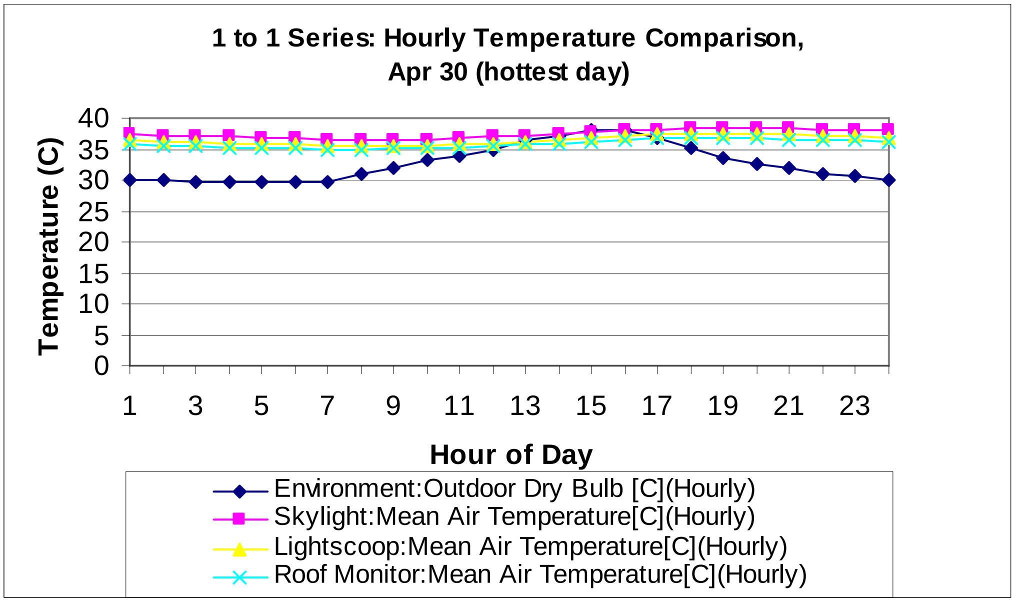

Fig. 4.53 1 to 1 toplighting unit: hourly average temperature comparison on April 30 (hottest day)

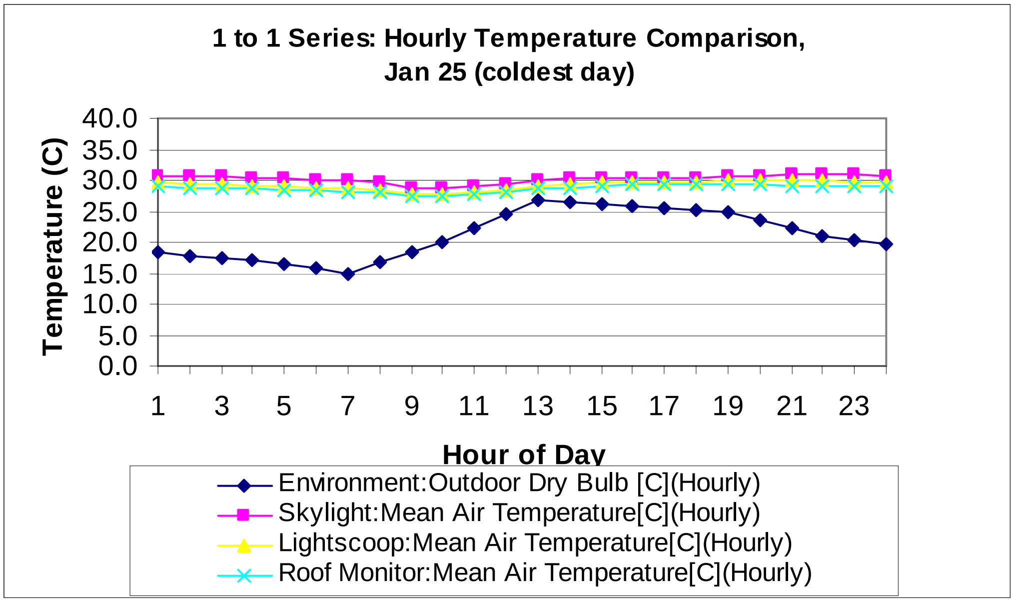

Fig. 4.54 1 to 1 toplighting unit: hourly average temperature comparison on Jan 25 (coldest day)

4.4. Cooling Load Analysis between a Single and Series of Units

The analysis of total cooling load, when the glazing area increases from a single unit to series of units, is provided in order to study the impact of daylight on the thermal performance of the building. The cooling load comparison charts when the number of units increases from 1 to 4, and then again to 6, are given in Figs. 4.55 and 4.56 for both cooling availability schedules.

The increased amount of daylight (a result of the increased glazing area) entering the space does not affect the cooling load much. As the number of units increases from 1 to 4 in the first cooling scenario, the cooling load increases 4%, 5%, and 2% for the skylight, lightscoop, and roof monitor, respectively. With 6 units, the average cooling load increases 4%, 7%, and 3% for the skylight, lightscoop, and roof monitor, respectively. When the 6-unit prototypes (with a 1 to 1 spacing-to-height ratio) are compared with the 4-unit prototypes (with a 1.5 to 1 spacing-to-height ratio) in the first cooling scenario, the glazing area increases 150% but the cooling load increases only 3%, 5%, and 1% for the skylight, lightscoop, and roof monitor, respectively. For the second cooling scenario, the increases are 3%, 8%, and 1% for the skylight, lightscoop, and roof monitor, respectively.

This is significant proof that toplighting can be efficiently utilized in buildings in hot and humid climates, if proper design considerations are made.

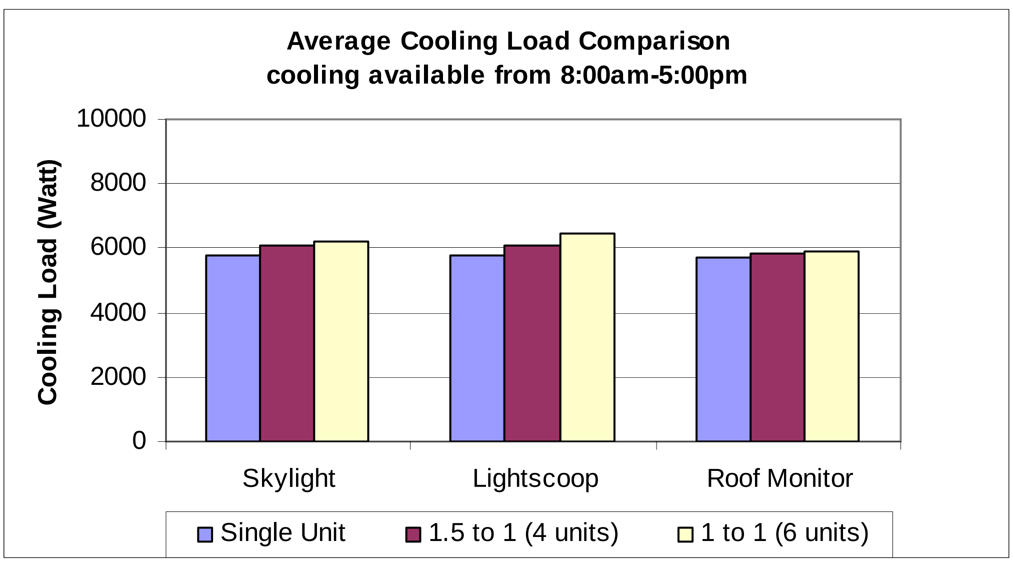

Fig. 4.55 Average cooling load comparison between single, 4-unit, and 6-unit prototypes, when cooling is available from 8:00am-5:00pm

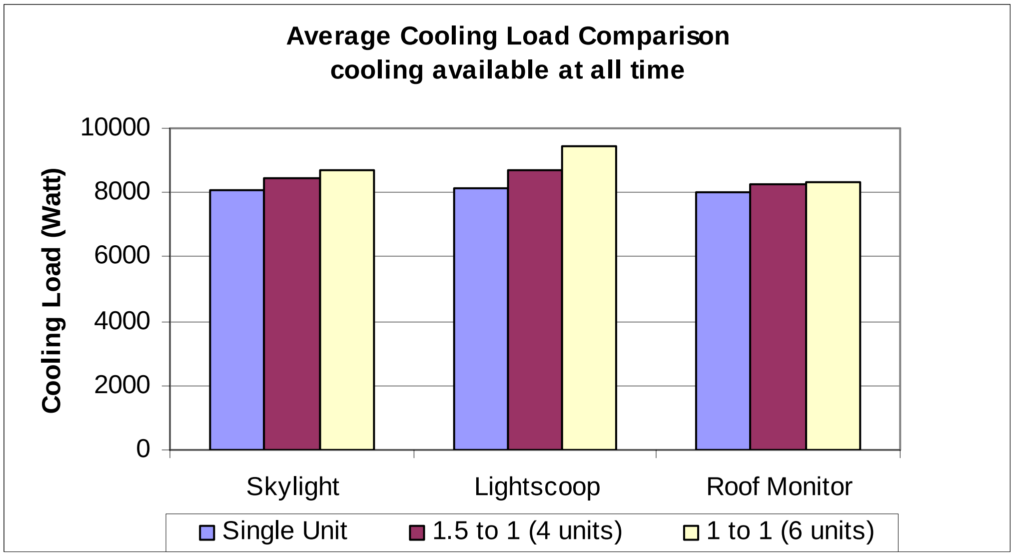

Fig. 4.56 Average cooling load comparison between single, 4-unit, and 6-unit prototypes, when cooling is available at all time

4.5. Summary on Thermal Performance Evaluation

In the tests of the single units and the series of units, each toplighting prototype yields a similar amount of cooling load per month. This indicates that they are thermally comparable. Therefore, these prototypes can then be tested for lighting performance.

Increasing the number of units to 4 and again to 6 results in an increase in the cooling load around 11%. For the single toplighting unit (with a typical schedule), the average cooling load per month is about 5.7 kW in each case. For a 1.5 to 1 spacing-to-height series, the average cooling load per month is about 6 kW. For a 1 to 1 series of toplighting units, the average cooling load per month is 6.2 kW. Both of these cooling loads are for a typical schedule.

For the indoor average temperature, the results indicate that the indoor temperature of each case is very similar and fluctuates according to the outdoor temperature at a range of 5°C. Single unit prototypes and series of prototypes perform similarly in terms of indoor temperature when the windows are closed. Summer average indoor temperature is about 36°C (96.8°F), while winter average indoor temperature is about 30°C (86°F). It is recommended that natural ventilation be tested as a way of decreasing the indoor temperature when the outdoor temperature is within a comfort zone.

The overall heat gains and losses from the different toplighting prototypes resulted in similar trends. Higher values were seen as the number of units increased from 1 to 4 units (1.5 to 1 spacing-to-height) and from 1 to 6 units (1 to 1 spacing-to-height). The skylight introduced more window heat gains in the summer than the other cases but had less heat loss in both winter and summer.

Alternate building materials to decrease in the indoor temperature and the reduce the cooling load were not conducted in this study because the objective was simply to have the cases be thermally comparable.

If thermal performance is less of a priority in the design consideration and if a difference in thermal performance of 5-10% is acceptable, then, the decision whether to use a 4-unit series or a 6-unit can be based on the lighting performance of each system. The lighting performance of each system is discussed in the subsequent chapter.

CHAPTER V

LIGHTING PERFORMANCE EVALUATION

After the development of the prototypical cases and heat gain test of each system to ensure that all the systems are thermally comparable, each toplighting system is then tested for its thermal performance using EnergyPlus. Each system is tested for the variables described in Chapter III: illuminance level, illuminance distribution, and uniformity.

5.1. Comparison between a Physical Scale Model Measurement and RADIANCE Simulation

Illuminance measurements are taken for the physical scale model in order to compare them with the RADIANCE results and develop a context for any discrepancies that may occur. The tests are done for overcast and clear sky conditions using real sky in College Station, TX. The measurement method was described previously in Chapter III and more details can be found in Appendix D. For the overcast sky, a daylight factor comparison is made, while for the clear sky, an illuminance comparison is made.

Comparisons between the physical scale model measurements and RADIANCE are done for each single-unit prototype: skylight, lightscoop, and roof monitor without any glazing (using a special illum glazing in RADIANCE).

5.1.1. Overcast Sky Test Results

The tests show that, in the overcast sky condition, the daylight factor results from the physical scale model and from RADIANCE are similar. The scale model measurements are slightly higher than the daylight factor generated from RADIANCE, with an overall discrepancy of about 10%. It appears then that RADIANCE, for the test location of latitude 13.7°N under overcast sky, might underestimate the daylight factor value and that the real overcast sky in Thailand might generate a daylight factor value 10% greater.

For the single unit prototypes, the scale model measurements yield a higher daylight factor value than the results from RADIANCE but within a closed range. The average discrepancy is 27%, 8%, and 7% for the skylight, lightscoop, and roof monitor, respectively. However, as can be seen from the chart, the values of the scale model and RADIANCE are very close and have the same pattern of distribution.

For the 1.5 to 1 spacing-to-height prototypes, the scale model measurements are close to the values from RADIANCE but yield higher daylight factor values. The average discrepancy is 4.7%, 4.9%, and 14% for the skylight, lightscoop, and roof monitor, respectively. However, as can be seen from the chart, the values of the scale model and RADIANCE are very close and still have the same pattern of distribution.

For the 1 to 1 spacing-to-height prototypes, the scale model measurements are again close to the values from RADIANCE but also yield increased daylight factor values. The average discrepancy is 12%, 10%, and 20% for the skylight, lightscoop, and roof monitor, respectively. However, the chart demonstrates again that the values of the scale model and RADIANCE are very close and have the same pattern of distribution.

Some possible causes of the discrepancy could be the following:

- The overcast sky tested is real sky and not CIE overcast sky as in the sky model used in the RADIANCE calculations.
- The real sky tested is in College Station, TX which might have different characteristics as compared with the overcast sky in Bangkok, Thailand.
- The measurements were taken on the roof of the Langford Architecture Building where there are obstructions from surrounding buildings. This is different from the conditions modeled in RADIANCE where there are no building obstructions.

5.1.2. Clear Sky Test Results

The results show that, for the clear sky condition, the illuminance values from the physical scale model and from RADIANCE are similar, with the scale model measurements being slightly higher than the illuminance values generated from RADIANCE. The overall discrepancy is about 20%.

It appears that RADIANCE, for the tested location of latitude 13.7°N in a clear sky condition, might underestimate the illuminance value by about 20%. This figure increases to as much as 30% during afternoons in the winter. Moreover, the actual clear sky in Thailand might produce more illuminance value than calculated in RADIANCE.

For the clear sky test, horizontal exterior illuminance (HEI) is measured as a reference to the interior horizontal illuminance value. The value as generated from the sky file in RADIANCE is calculated for comparison and is presented in Table 5.1.

Table 5.1 Horizontal exterior illuminance (HEI) level generated from RADIANCE

Date/Time	9:00am	12:00pm	3:00pm
Jun 21	82622	103934	61986
Mar21	79576	99505	56653
Dec 21	63373	79556	40989

The charts and detailed analyses of the comparison for each prototype between the scale model measurements and RADIANCE are presented in Appendix F.

Some possible causes of the discrepancy in clear sky conditions include the following:

- The clear sky tested is real sky and not CIE clear sky as used in the sky model for RADIANCE calculations.
- The real sky tested is in College Station, TX which might have different characteristics as compared with clear sky in Bangkok, Thailand.
- The measurements were taken on the roof of the Langford Architecture Building where there are obstructions from surrounding buildings. This is different from the conditions modeled in RADIANCE where there are no building obstructions.
- The test is done by tilting the model to match the date and time of Bangkok's latitude. As a result, some discrepancies might occur from tilting the model.

The apertures in the model do not see the whole sky but only some parts of the ground and the surrounding buildings. In the results, the time with the greatest discrepancy is December 21, which is also the time of the greatest tilting of the model.

5.2. Single Toplighting Prototypes Analysis

5.2.1. Daylight Factor, Illuminance Level, and Daylight Distribution Analysis

The daylight factor comparison is used for overcast sky conditions and the illuminance level comparison for clear sky conditions. Both of these parameters are analyzed for light level and distribution. The methods for obtaining these values are presented in Chapter III (in the lighting performance methodology section). The tests for intermediate sky are used as a reference to identify the percentage that the light level decreases from clear sky conditions. Intermediate sky tests are done only at solar noon on all the solstices.

The daylight factor comparison chart for the single unit toplighting prototypes is presented in Figure 5.1. The illuminance level comparisons for clear sky conditions are presented in Figures 5.2-5.4. Intermediate sky results are presented in Figures 5.5-5.7. The prototypes analyzed are single-unit diffuse skylight, lightscoop, and roof monitor. A normal skylight is not included since direct sun could penetrate into the space causing the peak illuminance levels to be much higher than in the other prototypes and hence incomparable (see Chapter III).

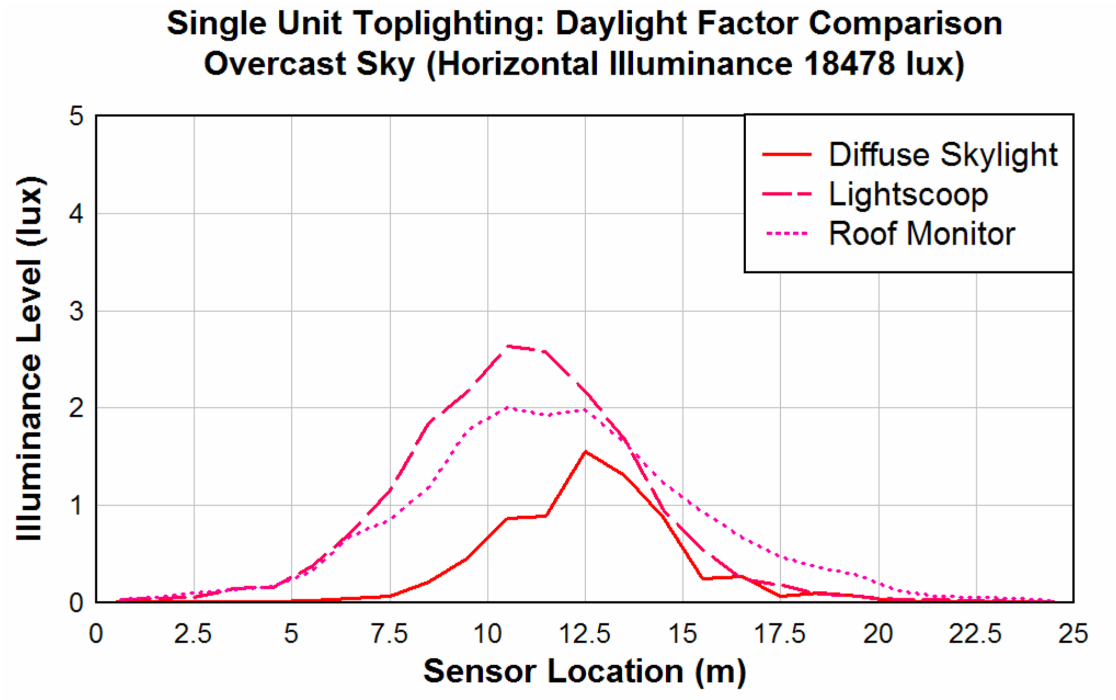

Fig. 5.1 Single unit toplighting: daylight factor comparison, overcast sky (Horizontal Exterior Illuminance from RADIANCE is 18478 lux)

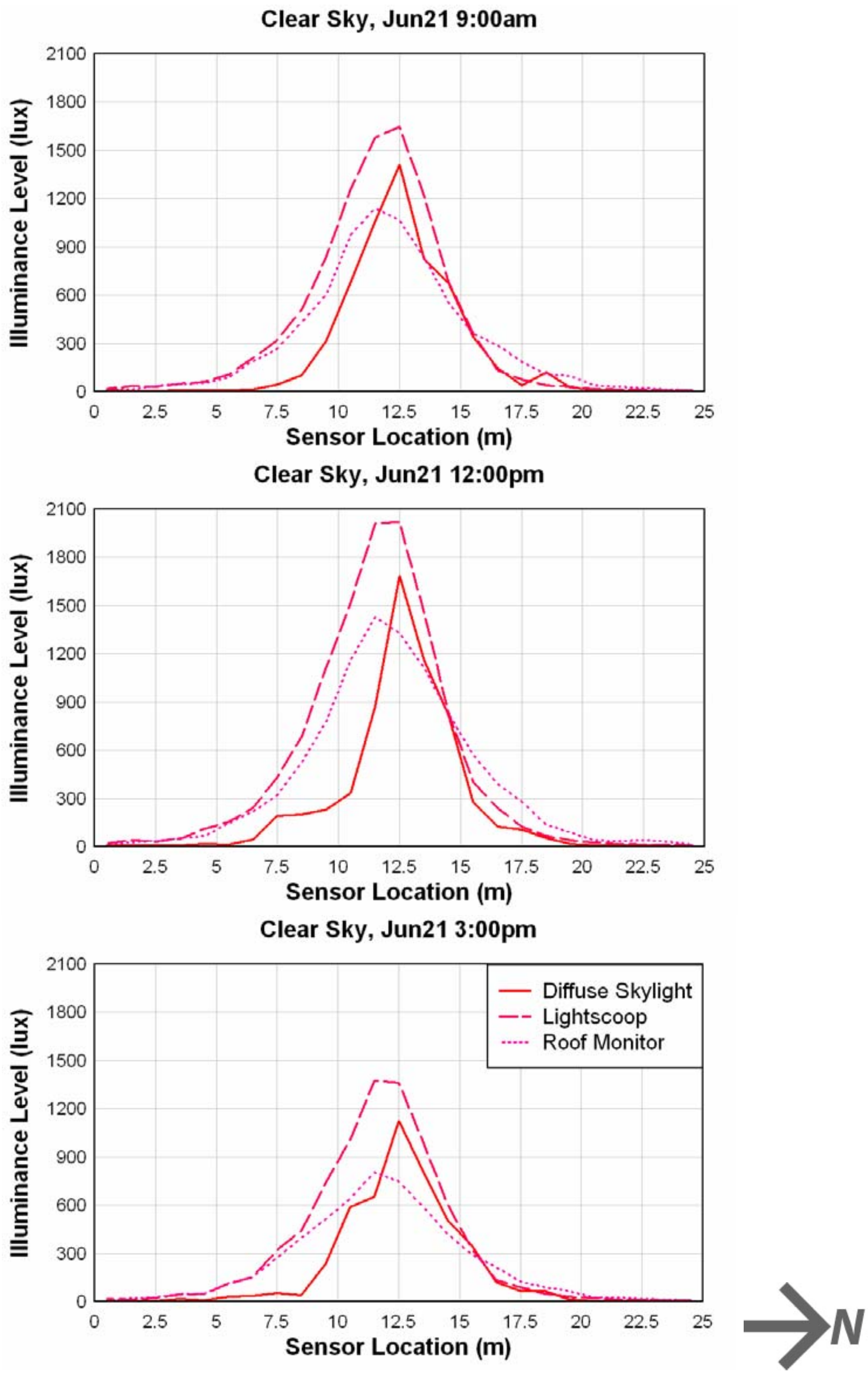

Fig. 5.2 Single unit toplighting: illuminance level comparison, clear sky, June 21

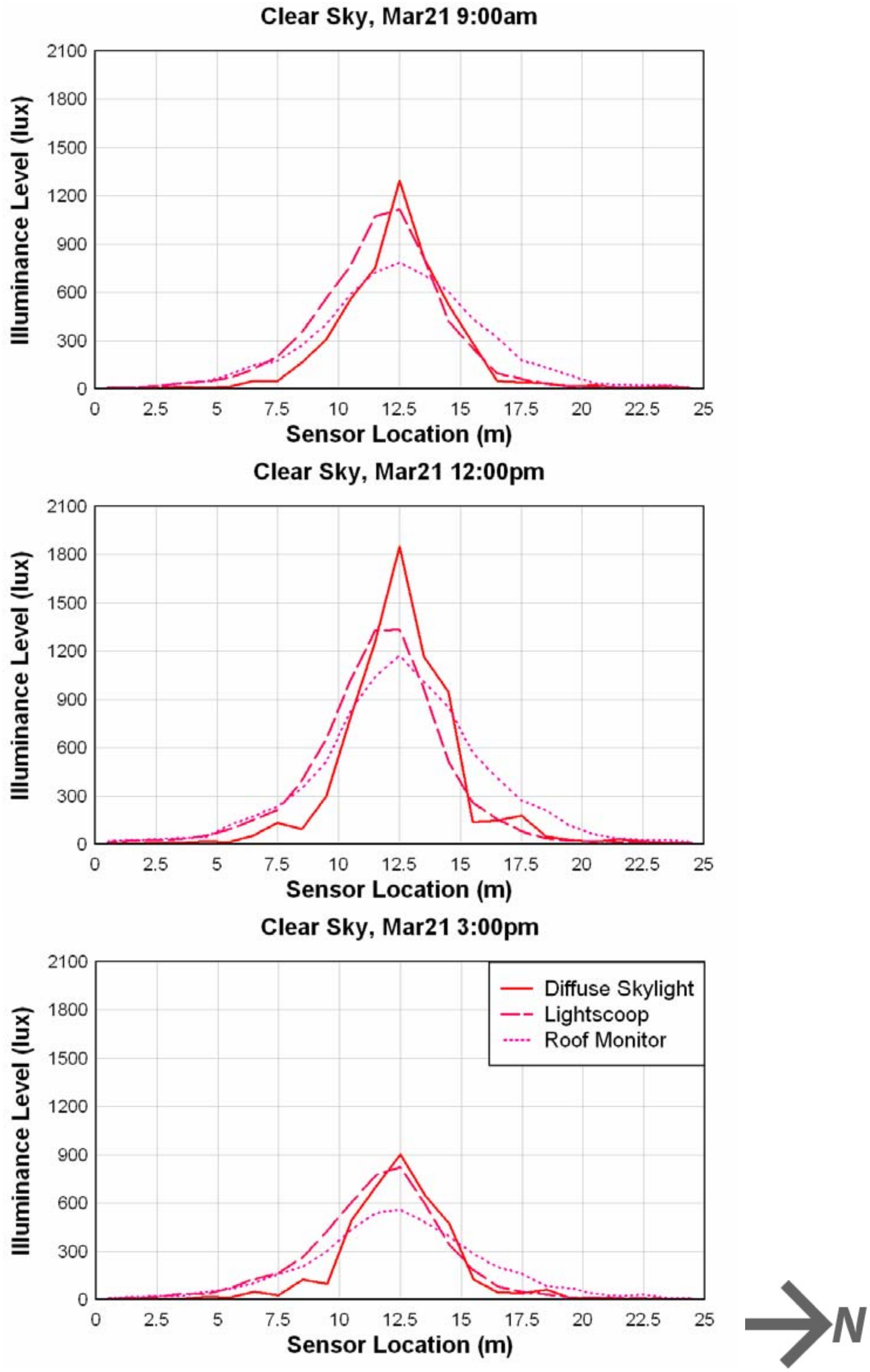

Fig. 5.3 Single unit toplighting: illuminance level comparison, clear sky, March 21

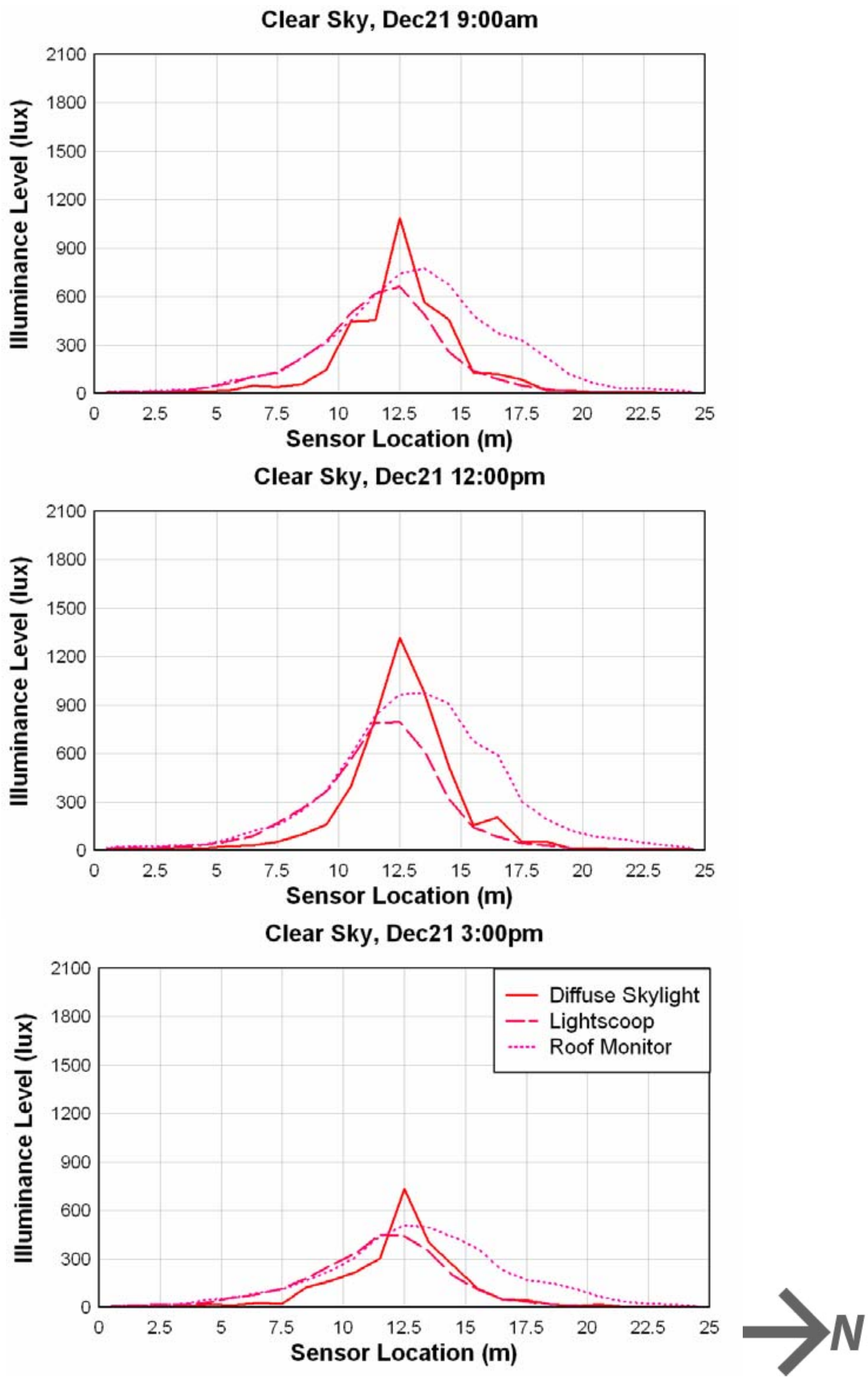

Fig. 5.4 Single unit toplighting: illuminance level comparison, clear sky, December 21

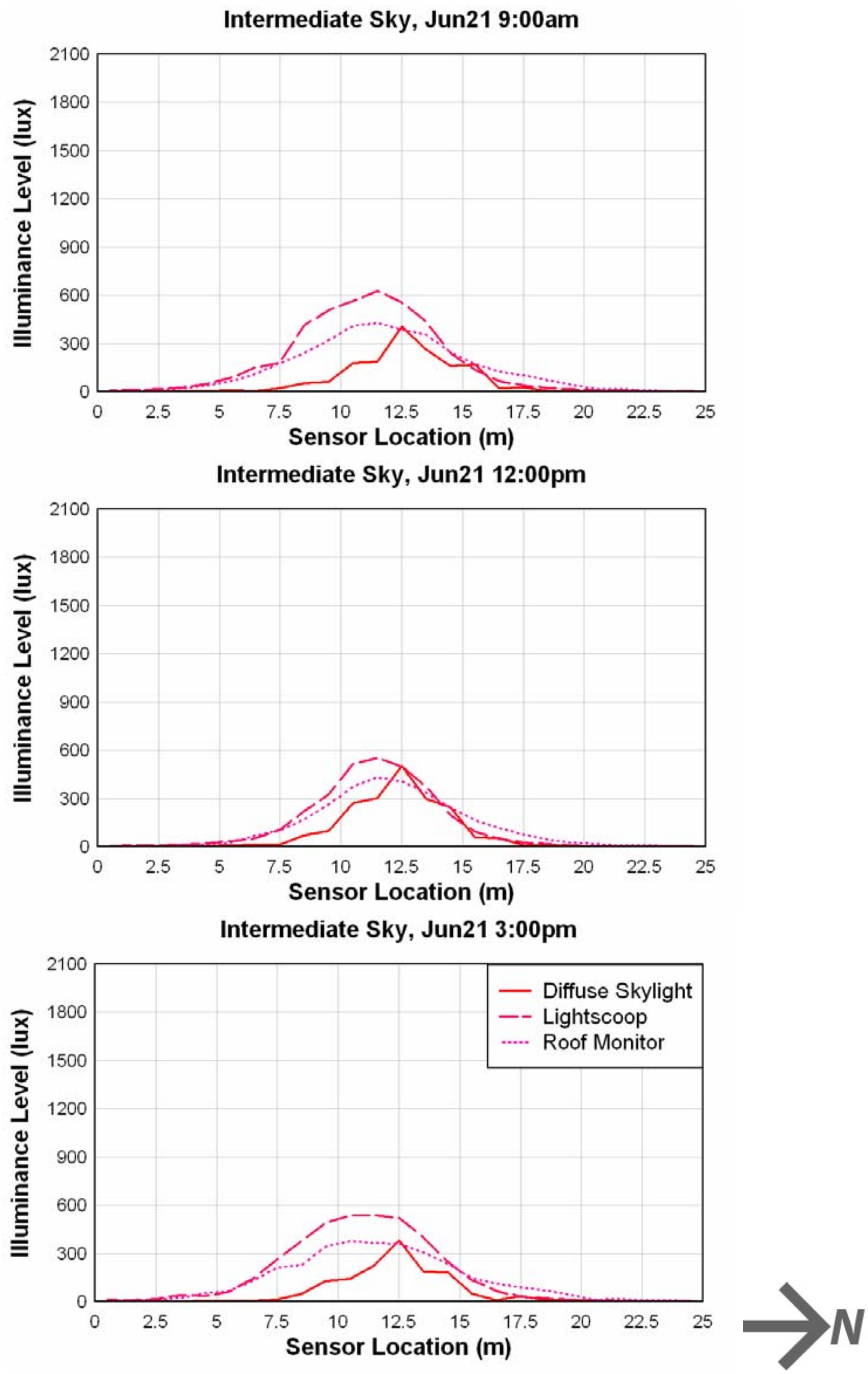

Fig. 5.5 Single unit toplighting: illuminance level comparison, intermediate sky, June 21

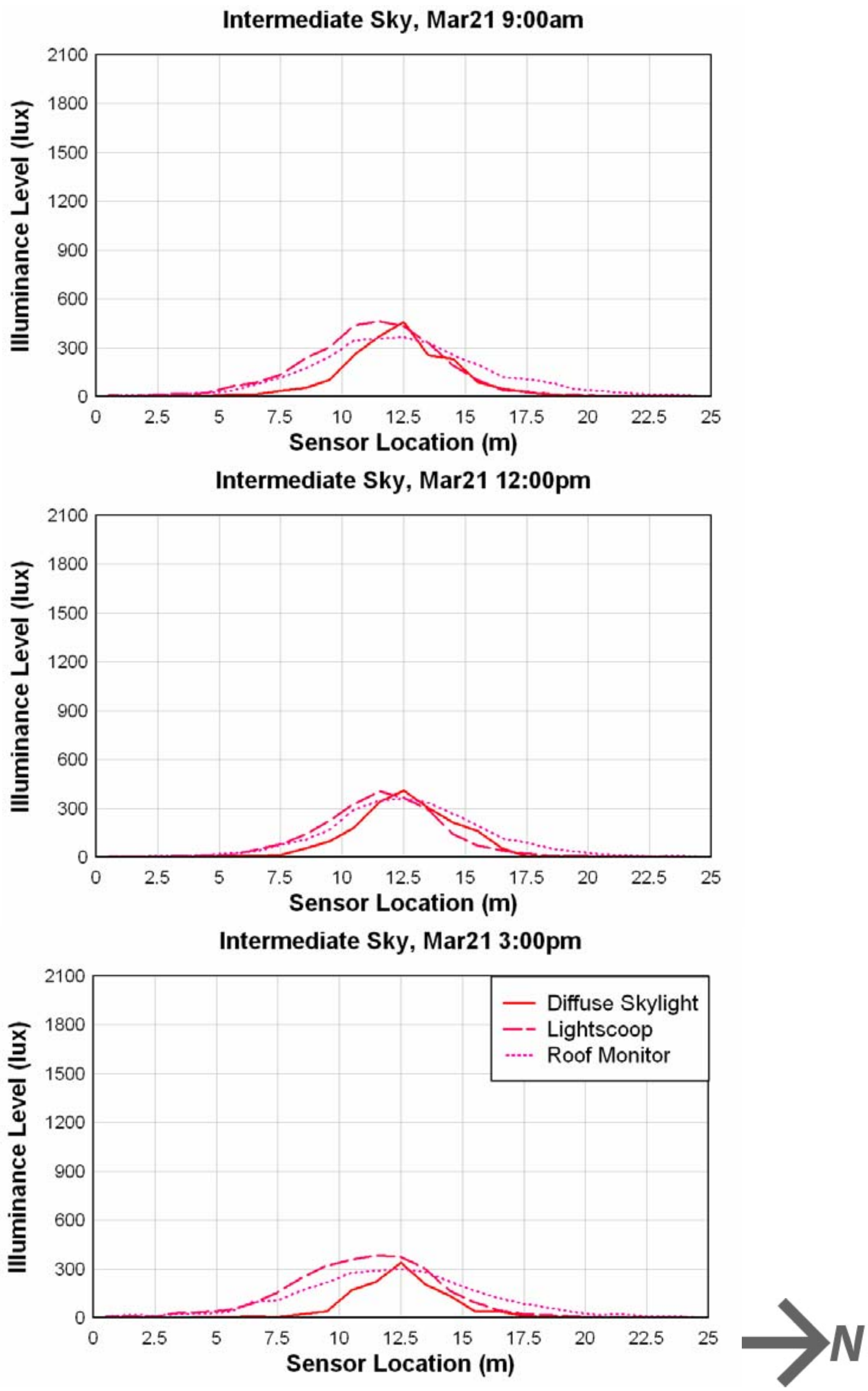

Fig. 5.6 Single unit toplighting: illuminance level comparison, intermediate sky, March 21

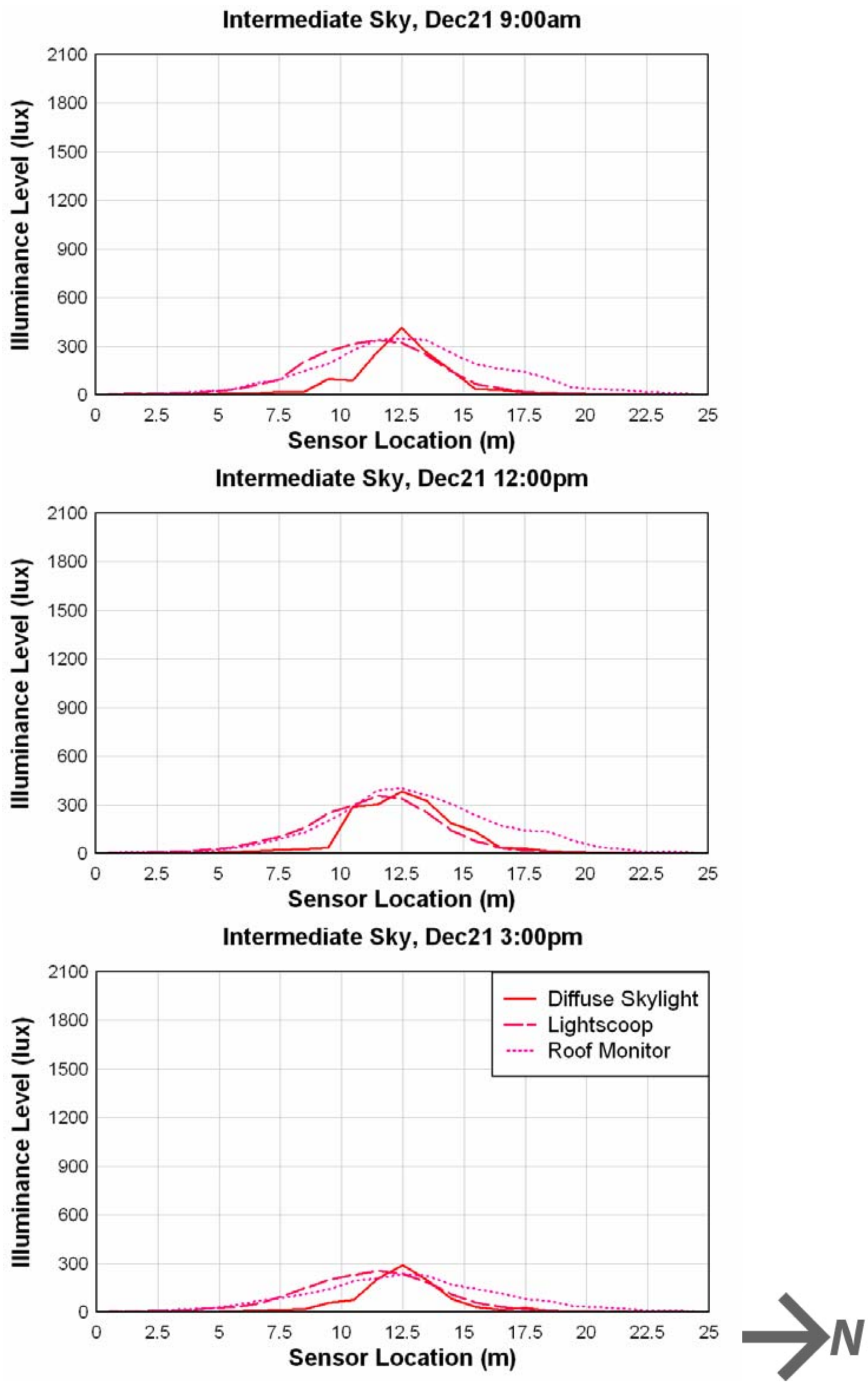

Fig. 5.7 Single unit toplighting: illuminance level comparison, intermediate sky, December 21

Overcast Sky: Daylight Factor Analysis

For the daylight factor, the lightscoop yields a higher daylight factor than the diffuse skylight or roof monitor. The lightscoop obtains a maximum daylight factor level of about 2.5%, while the diffuse skylight gives a maximum daylight factor of about 1.5%. The maximum daylight factor difference between these two systems is about 30%.

Overcast Sky: Light Distribution Analysis

From the chart, it can be seen that, for a single unit, the distribution of light is not very good. There are peaks around the center of the room and minimum points at the perimeter, resulting in uneven light distribution and possible eye fatigue.

However, no conclusions can be drawn from this chart alone, since better light distribution can be achieved through a series of units, which will be analyzed later in this chapter.

Clear Sky: Illuminance Level Analysis

For clear sky conditions, the diffuse skylight yields a higher maximum illuminance value than the lightscoop or roof monitor in most of the tested solar conditions. However, at the summer solstice, the lightscoop yields a higher illuminance level.

The diffuse skylight's illuminance levels do not vary much seasonally but change throughout the day. For example, at solar noon on the summer solstice, the maximum illuminance level ranges from 800-1,700 lux.

The lightscoop prototype yields a lower maximum illuminance value than the diffuse skylight, except at the summer solstice, when its maximum reaches 2,000 lux. For the lightscoop, the illuminance level is higher in summer and lower in winter. At the equinox, the illuminance value is higher than in the winter but not by much. Even though the lightscoop yields generally a higher illuminance level than a roof monitor, in the winter, the illuminance level of the lightscoop is generally lower than that of the roof monitor.

The single roof monitor, in general, yields lower illuminance values than the other systems. Even though it has more glazing area, the illuminance values do not vary much throughout the year compared to other systems. This could be because it has a glazing for both north and south orientations.

Clear Sky: Light Distribution Analysis

For the light distribution in clear sky conditions, the roof monitor gives a more even light distribution than the other systems during the year. The lightscoop yields a more uniformly distributed light than the diffuse skylight.

In sum, a single diffuse skylight yields a greater illuminance level in clear sky conditions. A lightscoop yields a higher daylight factor level than other systems, when the thermal performance is equal.

However, with the diffuse skylight prototype, the maximum light level occurs under the opening and is much higher here than at other points. The distribution, as analyzed from the single middle grid, is worse than a lightscoop system, which yields a lower maximum illuminance level, but whose curve is flatter, indicating better distribution. Therefore, in terms of daylight factor and illuminance levels, the performance of the single lightscoop prototype is better than the other systems.

Intermediate Sky: Illuminance Level Analysis

In general, the illuminance levels of all the prototypes are lower in intermediate sky conditions than in clear sky conditions. The levels are up to 50% less and do not vary much throughout the year. The lightscoop and roof monitor prototypes yield higher illuminance levels than the diffuse skylight prototype at summer solstice. At other times, the illuminance levels of each prototype are similar. Moreover, the difference between the illuminance level of each case is not as apparent as in clear sky conditions.

Intermediate Sky: Light Distribution Analysis

Even though no conclusion can be made at this point for the intermediate conditions, since the tested sensor locations are located in a single row along the center of the room, it can be seen that the roof monitor has a flatter curve than the other prototypes in summer. At other times, the lightscoop and roof monitor have similar distributions. The single diffuse skylight prototype has a distinguished peak in the center of the room under the opening, just as in clear sky conditions.

5.2.2. Illuminance Uniformity Analysis

The sensor locations are set in a rectangular grid of 1m x 1m (see Chapter III section 3.3.5) to allow RADIANCE to calculate the horizontal illuminance level in the building. The contour plots of horizontal illuminance levels in a reference grid of each prototype are analyzed to visualize the range and discrepancy of illuminance levels that each system yields. The parameters for analyzing the illuminance uniformity are illuminance gradient (or diversity of illuminance in CIBSE code) and uniformity of illuminance. For the illuminance gradient (the ratio of maximum to minimum illuminance), a lower value indicates better uniformity, while for uniformity of illuminance (the ratio of minimum to average illuminance), a higher value indicates better uniformity. The illuminance gradient is the primary parameter in the analysis, since it is the more relaxed parameter. Therefore, it is suitable for a space without any furniture, as in the prototype building in this study.

The illuminance gradient values are presented in Table 5.2, and uniformity of illuminance values are presented in Table 5.3.

The horizontal illuminance contours of single unit toplighting prototypes are illustrated in Fig. 5.8 for overcast sky conditions. Figs. 5.9-5.11 give the values for each case during clear sky conditions. Intermediate sky results are presented in Figs. 5.12-5.14 for each case at different solar position in all the solstices.

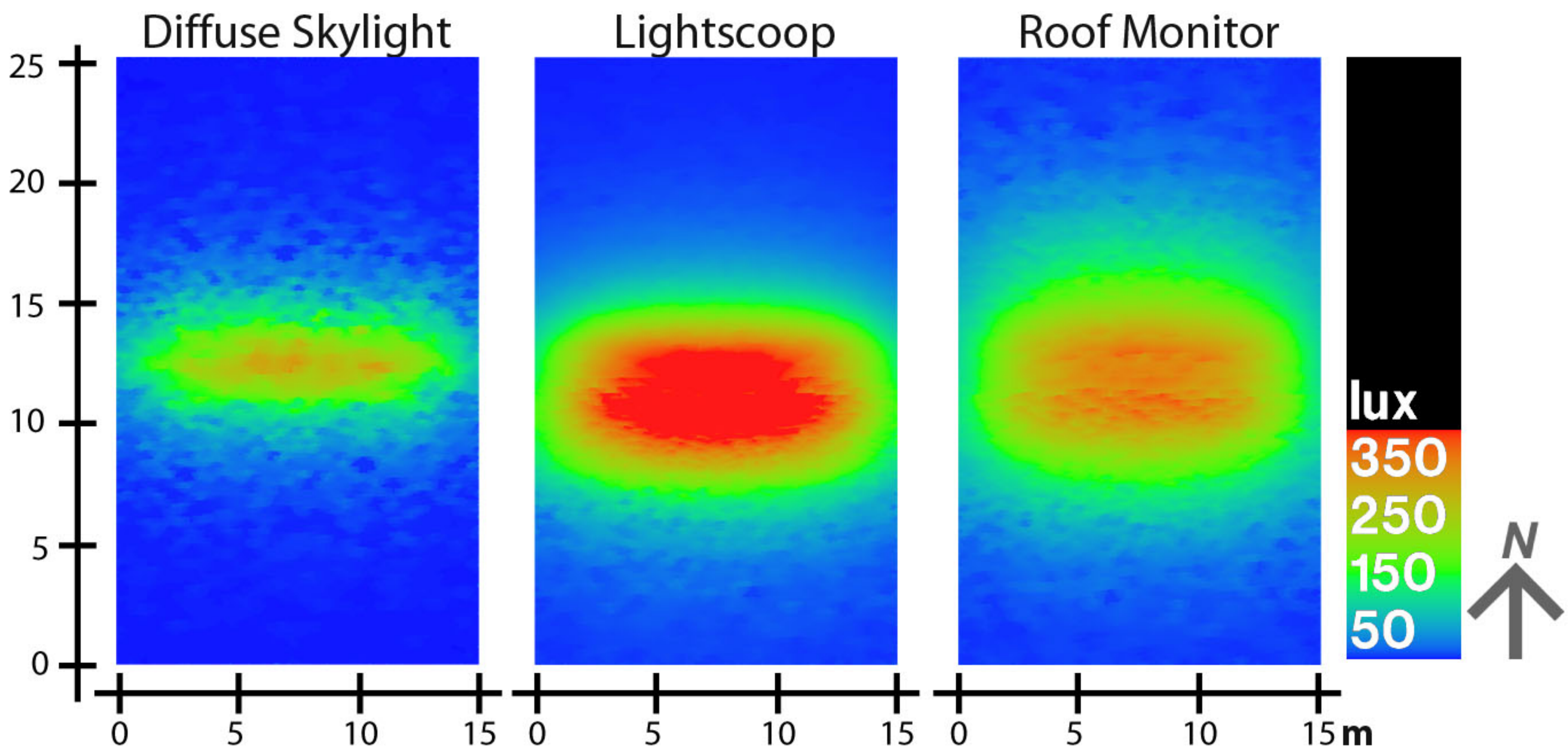

Fig. 5.8 Single unit toplighting: illuminance contour on plan, overcast sky

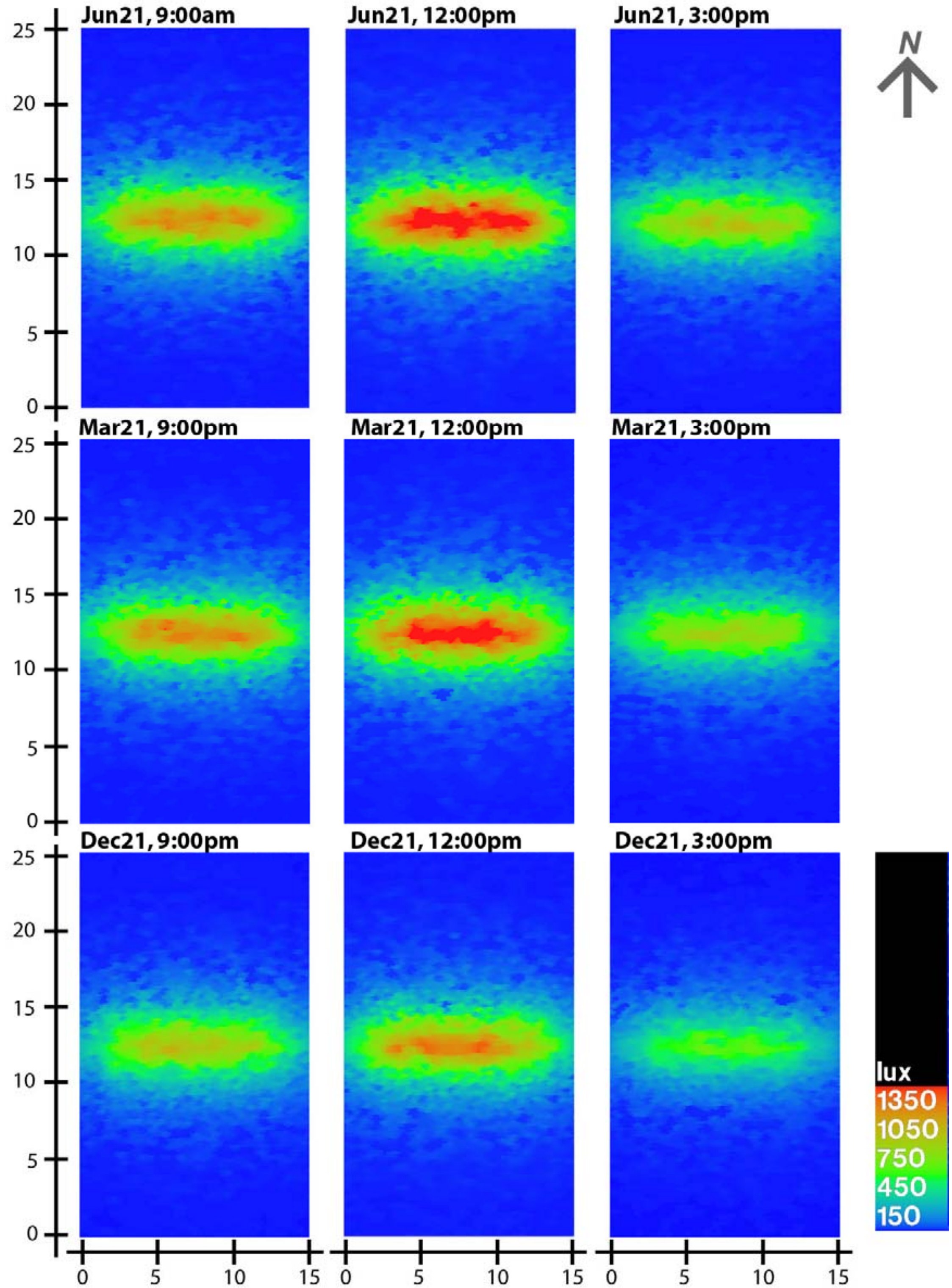

Fig. 5.9 Single diffuse skylight: illuminance contour on plan, clear sky

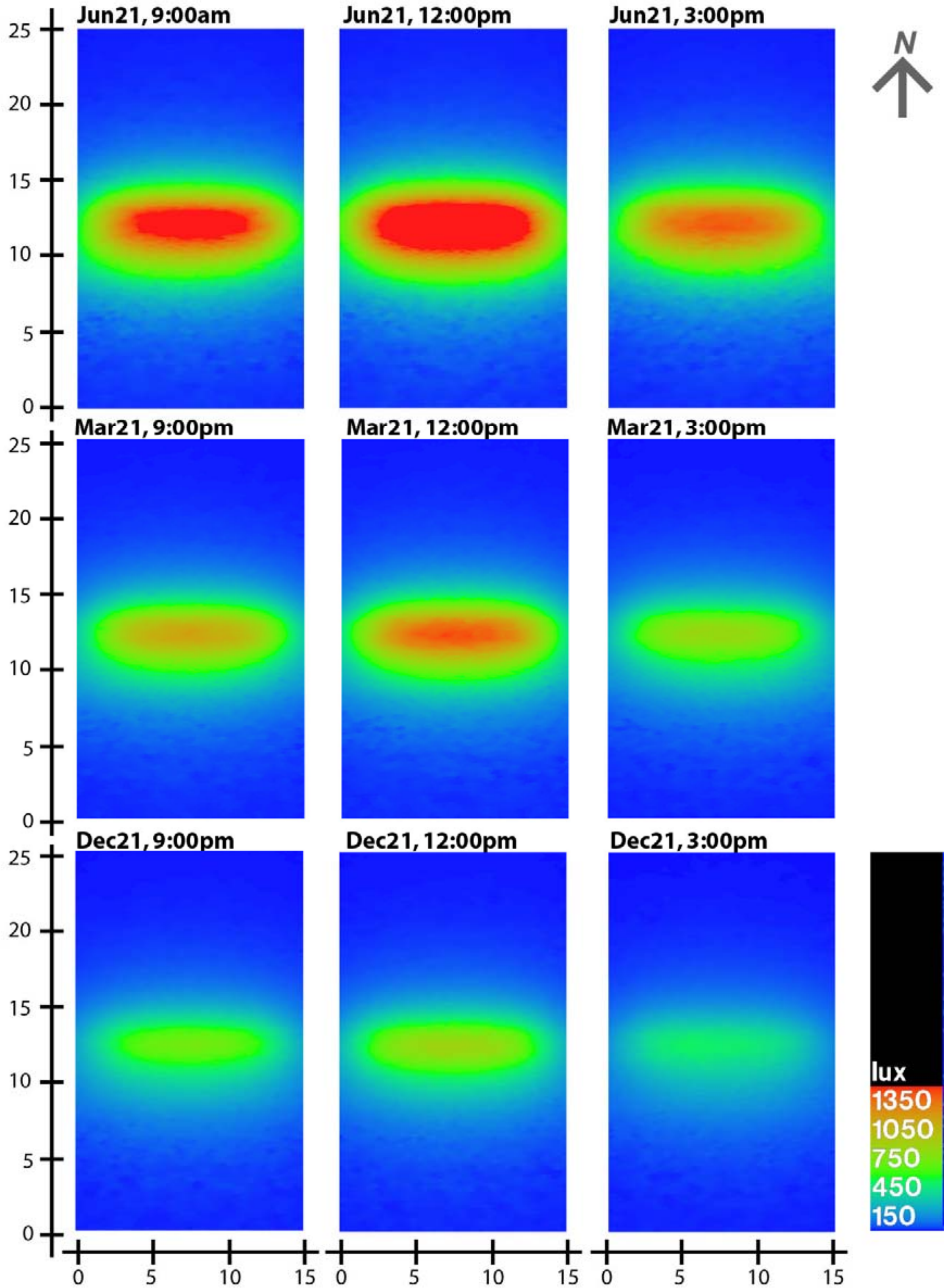

Fig. 5.10 Single lightscoop: illuminance contour on plan, clear sky

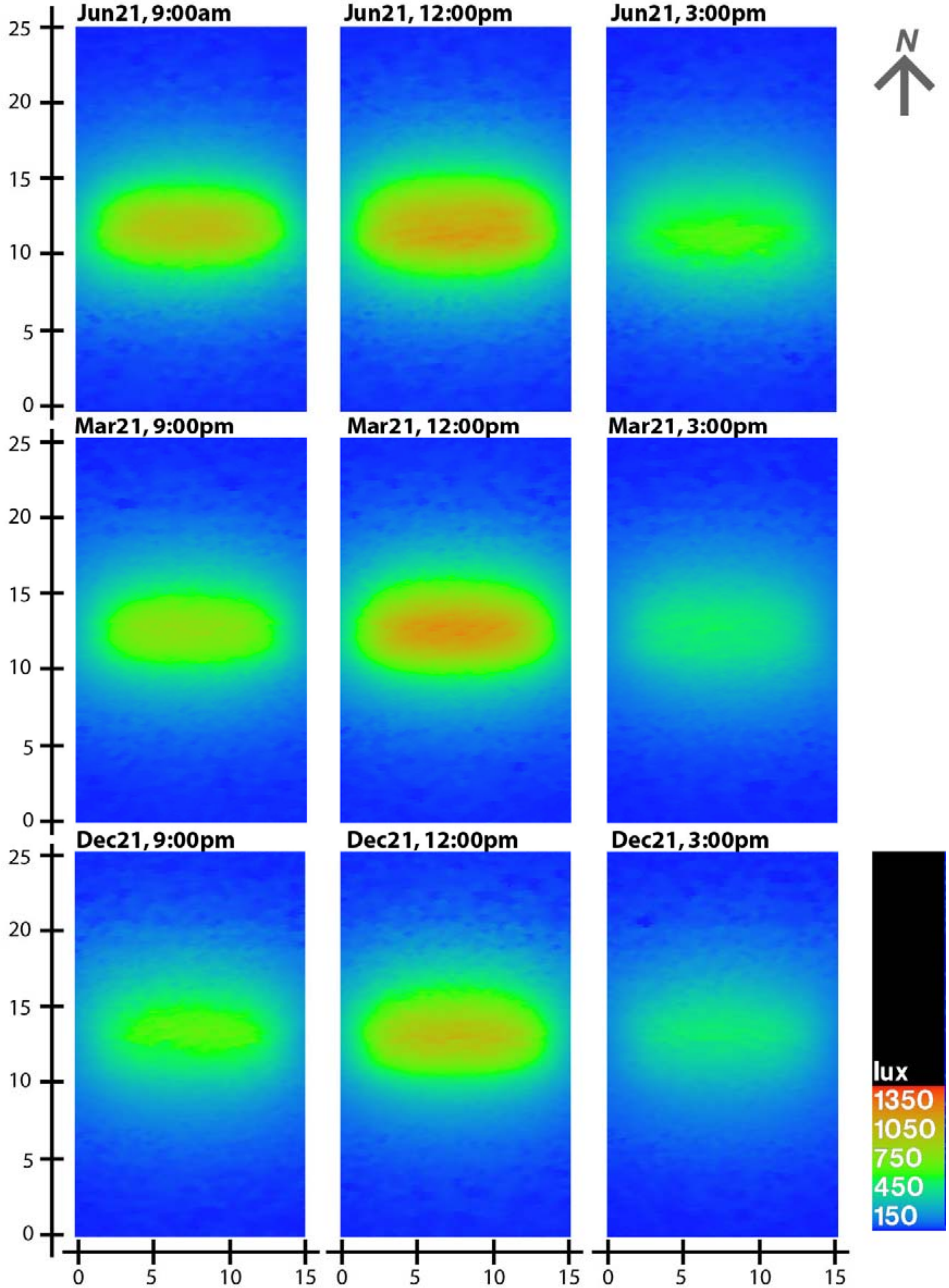

Fig. 5.11 Single roof monitor: illuminance contour on plan, clear sky

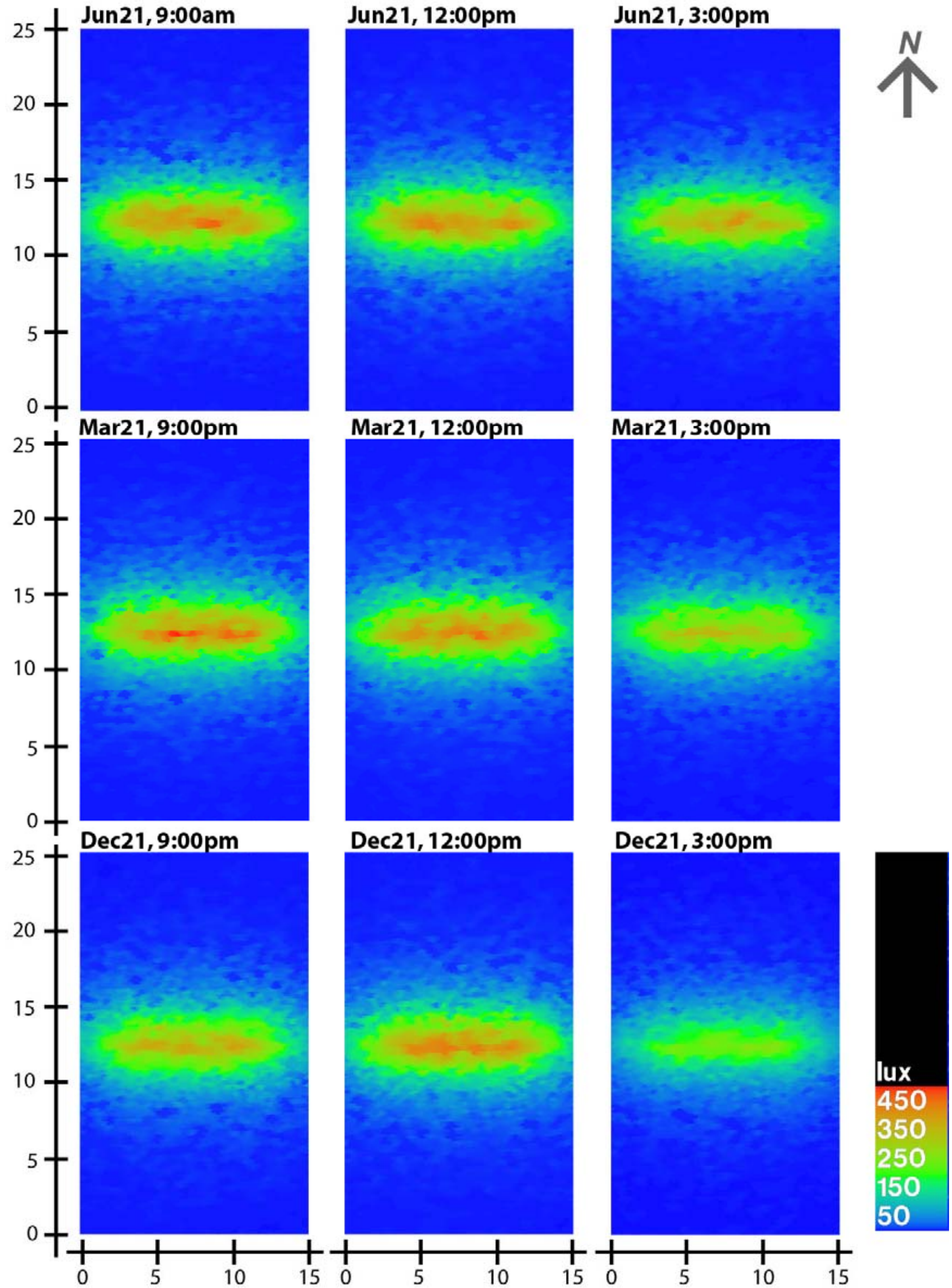

Fig. 5.12 Single diffuse skylight: illuminance contour on plan, intermediate sky

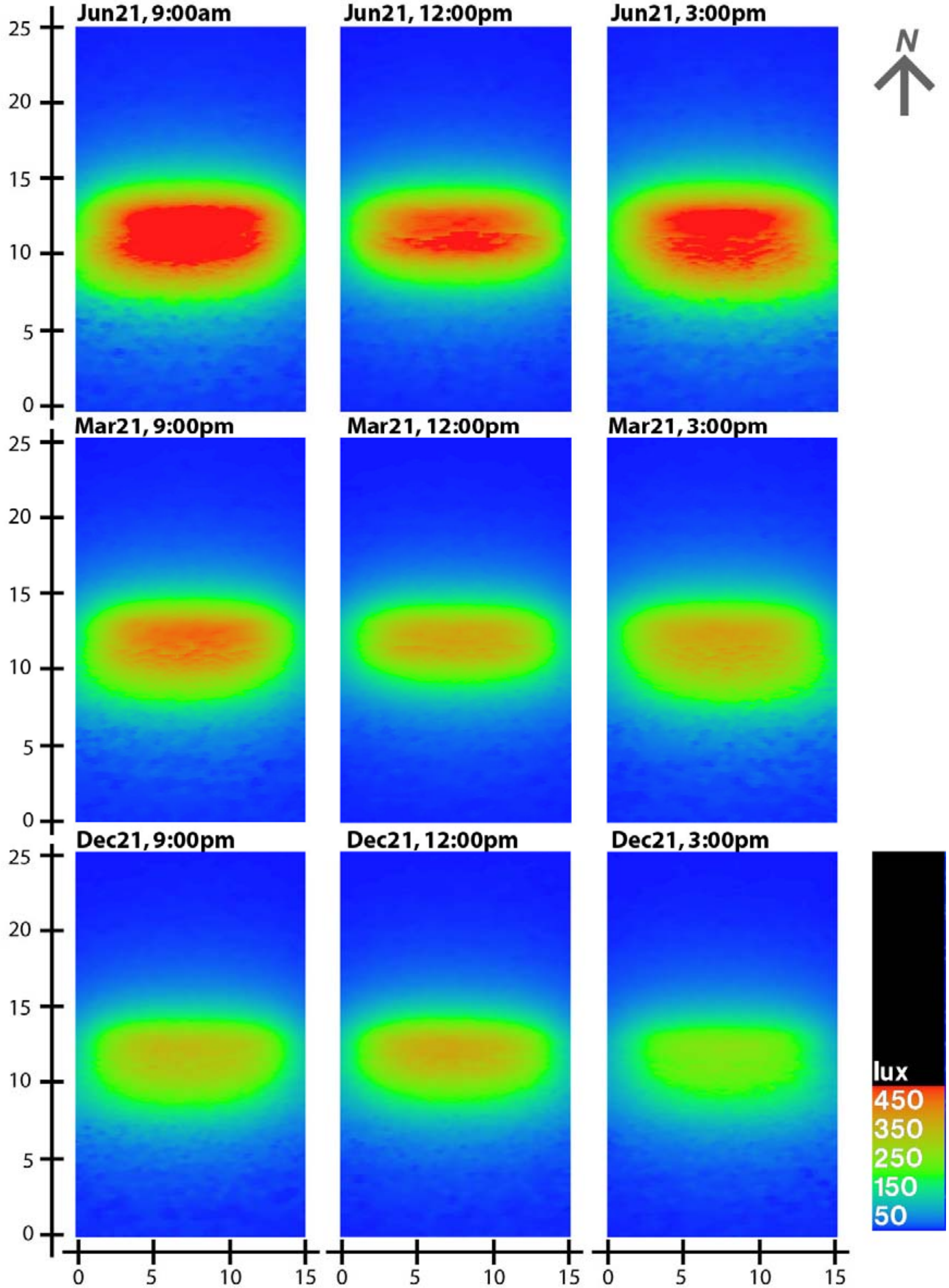

Fig. 5.13 Single lightscoop: illuminance contour on plan, intermediate sky

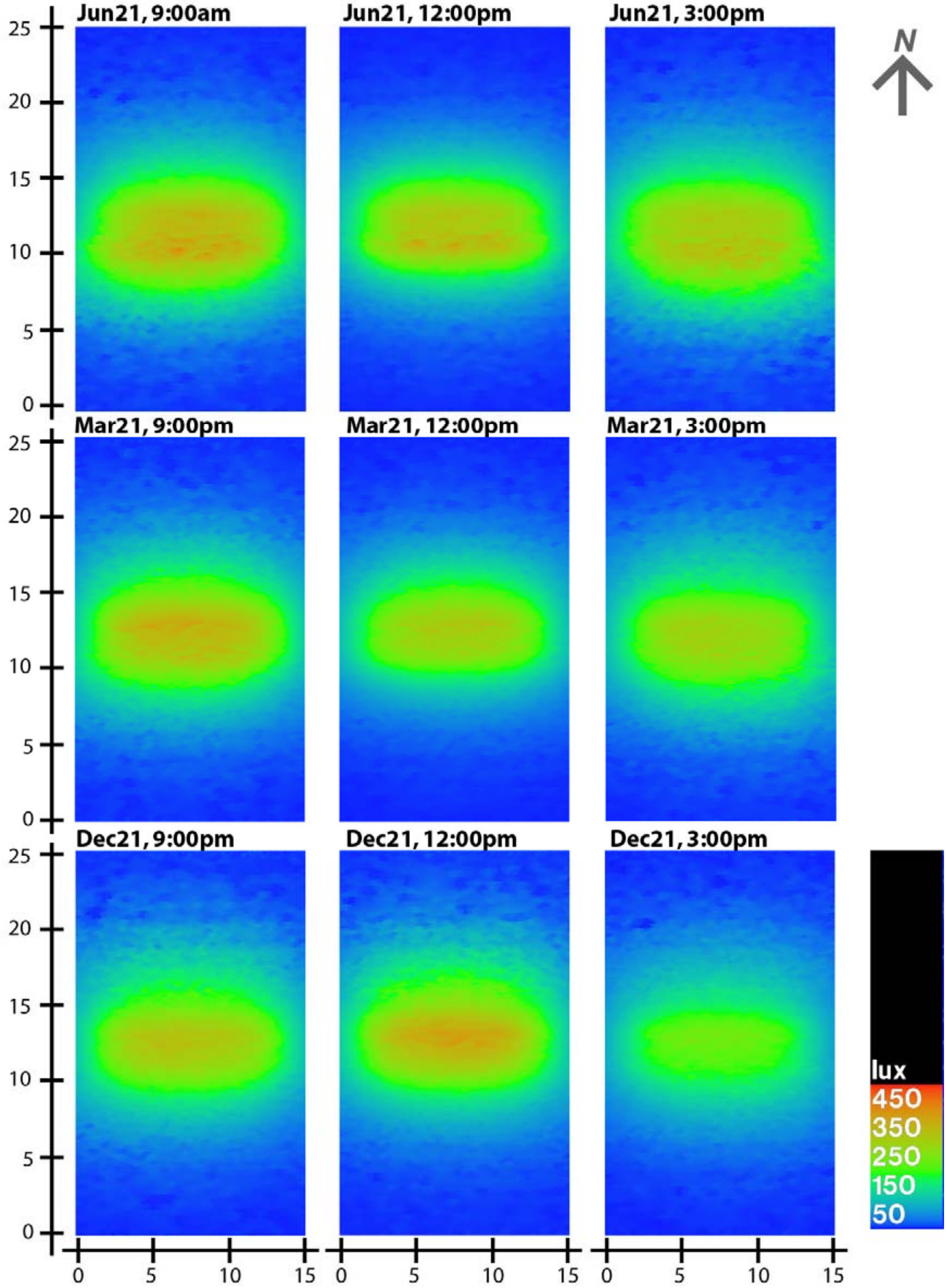

Fig. 5.14 Single roof monitor: illuminance contour on plan, intermediate sky

Table 5.2. Single unit toplighting: illuminance gradient comparison

	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast Sky	457	301	111
Clear Sky			
Jun21, 9:00am	450	358	162
Jun21, 12:00pm	408	314	159
Jun21, 3:00pm	565	299	149
Mar21, 9:00am	375	329	102
Mar21, 12:00pm	378	312	127
Mar21, 3:00pm	396	287	100
Dec21, 9:00am	339	288	95
Dec21, 12:00pm	350	316	148
Dec21, 3:00pm	398	272	96
Intermediate Sky			
Jun21, 9:00am	450	313	134
Jun21, 12:00pm	374	418	167
Jun21, 3:00pm	438	261	119
Mar21, 9:00am	451	326	127
Mar21, 12:00pm	380	399	130
Mar21, 3:00pm	438	301	116
Dec21, 9:00am	404	324	132
Dec21, 12:00pm	420	353	87
Dec21, 3:00pm	469	284	105

Illuminance gradient is the ratio of maximum to minimum illuminance of each case; lower value indicates better uniformity

Table 5.3. Single unit toplighting: uniformity of illuminance comparison

Time/Case	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast	0.02	0.02	0.04
Clear Sky			
Jun21, 9:00am	0.02	0.02	0.03
Jun21, 12:00pm	0.02	0.02	0.03
Jun21, 3:00pm	0.02	0.02	0.03
Mar21, 9:00am	0.02	0.02	0.04
Mar21, 12:00pm	0.02	0.02	0.03
Mar21, 3:00pm	0.02	0.02	0.04
Dec21, 9:00am	0.03	0.02	0.04
Dec21, 12:00pm	0.02	0.02	0.03
Dec21, 3:00pm	0.02	0.02	0.04
Intermediate Sky			
Jun21, 9:00am	0.02	0.02	0.03
Jun21, 12:00pm	0.02	0.01	0.03
Jun21, 3:00pm	0.04	0.03	0.04
Mar21, 9:00am	0.02	0.02	0.03
Mar21, 12:00pm	0.02	0.01	0.03
Mar21, 3:00pm	0.02	0.02	0.04
Dec21, 9:00am	0.02	0.02	0.03
Dec21, 12:00pm	0.02	0.01	0.05
Dec21, 3:00pm	0.02	0.02	0.03

Uniformity of illuminance ratio is the ratio of minimum to average illuminance of each case; higher value indicates better uniformity

From the illuminance contour charts and the tables presented, it can be seen that the single roof monitor yields a more uniformly distributed light in both overcast and clear sky conditions. A single roof monitor system yields the lowest values for the illuminance gradient, with less than half of other systems' values. In addition, it yields higher values for the uniformity of illuminance, even though the values are not much different.

Overcast Sky Condition: Distribution and Uniformity Analysis

In the overcast sky condition, the roof monitor provides better light distribution throughout the room, even though it yields a lower illuminance value. The lightscoop spreads more light than the skylight system but less than the roof monitor. For the diffuse skylight, the light is distributed mostly under the opening in the center of the room. With the lightscoop and roof monitor prototypes, the light concentration shifts a little from the area directly under the opening.

It can be seen from the chart that a roof monitor distributes light to up to half the area of the space. This results from the glazing, which captures light from both the north and south. The lightscoop prototype, which has only the glazing facing north, is able to distribute light to about one-third of the area of the space, while the two skylight systems can only distribute light to about a quarter of the space.

The illuminance gradient ratio of the roof monitor is the lowest, less than half the value of other prototypes. The lightscoop performs second best. As seen in Table 5.2, in overcast sky conditions, the illuminance gradient values are 457, 301, and 111, for a single diffuse skylight, lightscoop, and roof monitor, respectively.

On the uniformity of illuminance ratio, the roof monitor still outperforms the other systems. The uniformity of illuminance ratios for diffuse skylight, lightscoop, and roof monitor, are 0.02, 0.02, and 0.04, respectively. Still, the recommended value for the uniformity of illuminance is more than 0.8. Therefore, the values for all the systems are within a closed range. As a result, this parameter should not be the primary parameter to determine the best-performing system.

In conclusion, it can be said that, in the overcast sky condition, the roof monitor gives better light distribution and uniformity than other systems, with the lightscoop performing second best.

Clear Sky Condition: Distribution and Uniformity Analysis

In clear sky conditions, the single roof monitor once again performs better than the other prototypes on the tested days.

From the illuminance contour charts (Figs. 5.9-5.11), it can be seen that, for the diffuse skylight prototype in clear sky conditions, the light distribution is concentrated around the central area right under the aperture. The light does not spread to more than one-third of the space, even though it yields a higher illuminance value. The distributions of light do not vary at different times of the year, as the light level simply decreases from summer to winter. In sum, the light from the diffuse skylight is not uniformly distributed, since all the light is concentrated in the area under the opening.

For the lightscoop prototype, the distribution patterns also do not vary during the year. The lightscoop spreads light to about one-third of the space area under the aperture. Better uniformity is achieved in winter due to the lower light level. Still, the light is more uniformly distributed than in the diffuse skylight system. With the lightscoop, light spreads more to the perimeter of the room and is not concentrated directly under the aperture.

The roof monitor's light distribution patterns vary throughout the year, spreading more light to the south area of the room in summer and more to the north of the room in winter. This is because it has two sides of glazing, and, hence, it is able to capture more light in all seasons. Light is distributed more than in the case of the lightscoop, with the light spread more evenly to the room perimeter than in other the cases. The area lit by this single unit is up to half the space area.

From the horizontal illuminance contour charts, it can be seen that the prototype that performs best in terms of illuminance distribution and uniformity is the single roof monitor. The lightscoop prototype performs second best.

From the illuminance gradient ratio table (Table 5.2), the roof monitor yields half the illuminance gradient ratio of the lightscoop. The lightscoop yields higher values than the roof monitor, but lower values than the skylights prototype. These results correspond to the horizontal illuminance contour chart. For the roof monitor prototype, a lower illuminance gradient ratio is seen at the equinox and in winter. For the other cases, the gradient ratios are close throughout the year.

In the uniformity of illuminance table (Table 5.3), the roof monitor still performs better than the other systems. The diffuse skylight, normal skylight, and lightscoop have ranges of values lower than the roof monitor.

Intermediate Sky Condition: Distribution and Uniformity Analysis

For intermediate sky conditions, the roof monitor prototype still performs better than other systems across all the tested times by distributing light more evenly.

From the illuminance contour charts, it can be seen that, for the diffuse skylight prototype, the light distribution is still mostly concentrated in the central area right under the aperture. For the lightscoop and the roof monitor, the light is distributed more to the perimeter of the space. The lightscoop prototype still has a light distribution pattern similar to its performance under clear sky but with lower illuminance values. However, the difference between the clear and intermediate sky is that, in summer morning and afternoon, the light distribution is greater than at noon. This could result from light reflecting off the clouds and entering the space. For the roof monitor prototype, the light distribution is similar throughout the year under intermediate sky conditions. This is different than under clear sky conditions, where the light distribution changes throughout the year.

From the illuminance gradient ratio table (Table 5.2), it can be seen that a single roof monitor yields a lower value for the illuminance gradient in all the tested dates and times under intermediate sky conditions—usually by more than 50%. In the uniformity of illuminance table (Table 5.3), the roof monitor still yields a higher value than the other cases, just as in the clear sky condition. Still, this ratio is input only as a reference, since the simulated space does not have any interior furniture and also, all the cases yield close value of this ratio.

In conclusion, under variable sky conditions, the roof monitor performs better than the other prototypes in terms of light distribution and uniformity.

5.3. Toplighting Prototypes with a 1.5 to 1 Spacing-to-Height Ratio Analysis

5.3.1. Daylight Factor and Illuminance Level Analysis

The daylight factor comparison chart of single unit toplighting prototypes is presented in Fig. 5.15. The prototypes analyzed are the diffuse skylight, lightscoop, and roof monitor designs. The illuminance level comparison for a clear sky charts is presented from Fig. 5.16 to Fig. 5.18. Intermediate sky results are presented in Figs. 5.19-5.21.

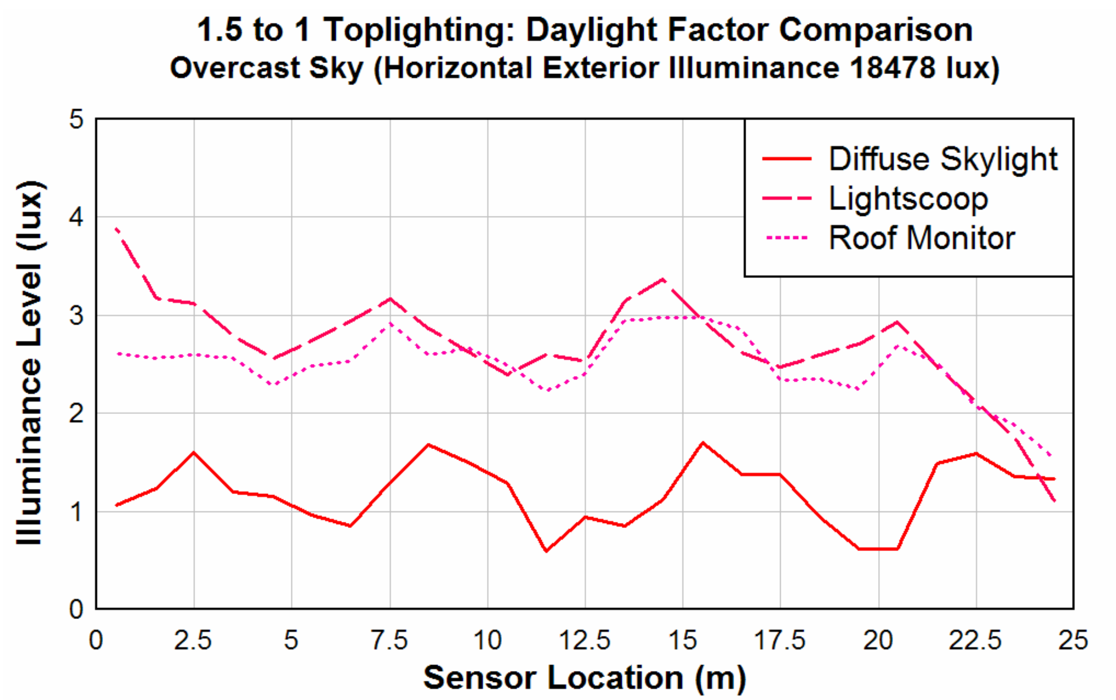

Fig. 5.15 1.5 to 1 toplighting: daylight factor comparison, overcast sky (Horizontal Exterior Illuminance from RADIANCE is 18478 lux)

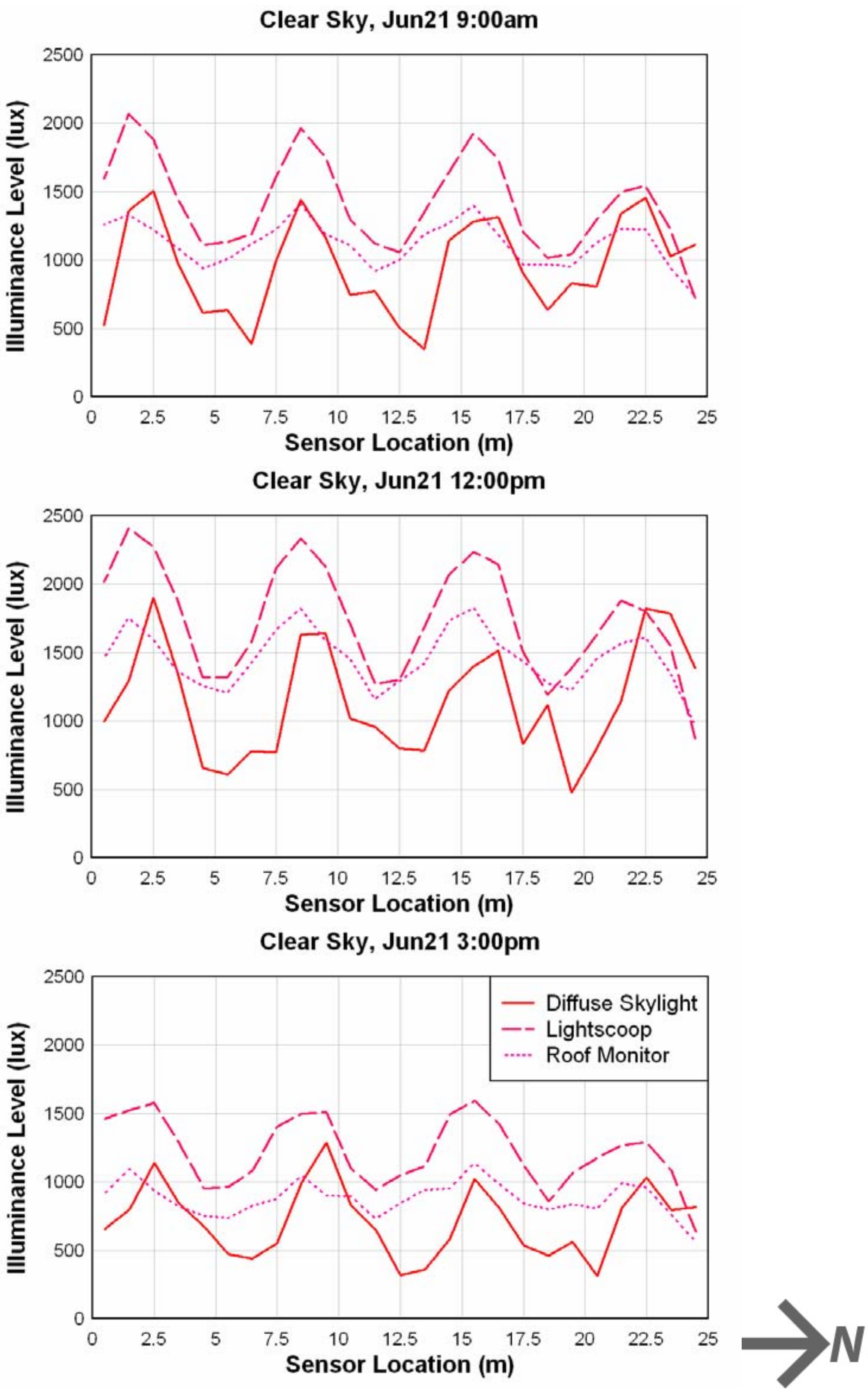

Fig. 5.16 1.5 to 1 toplighting: illuminance level comparison, clear sky, June 21

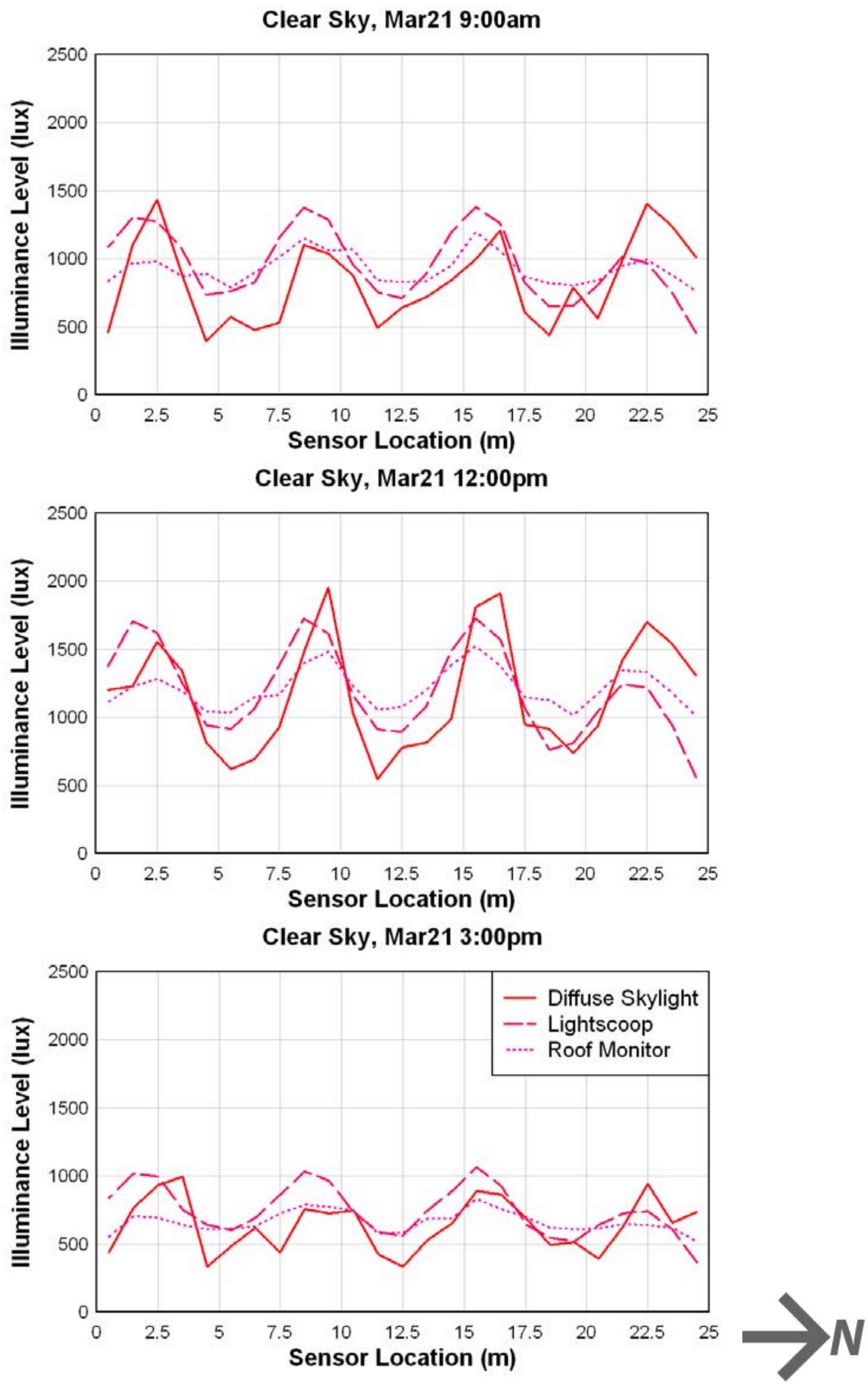

Fig. 5.17 1.5 to 1 toplighting: illuminance level comparison, clear sky, March 21

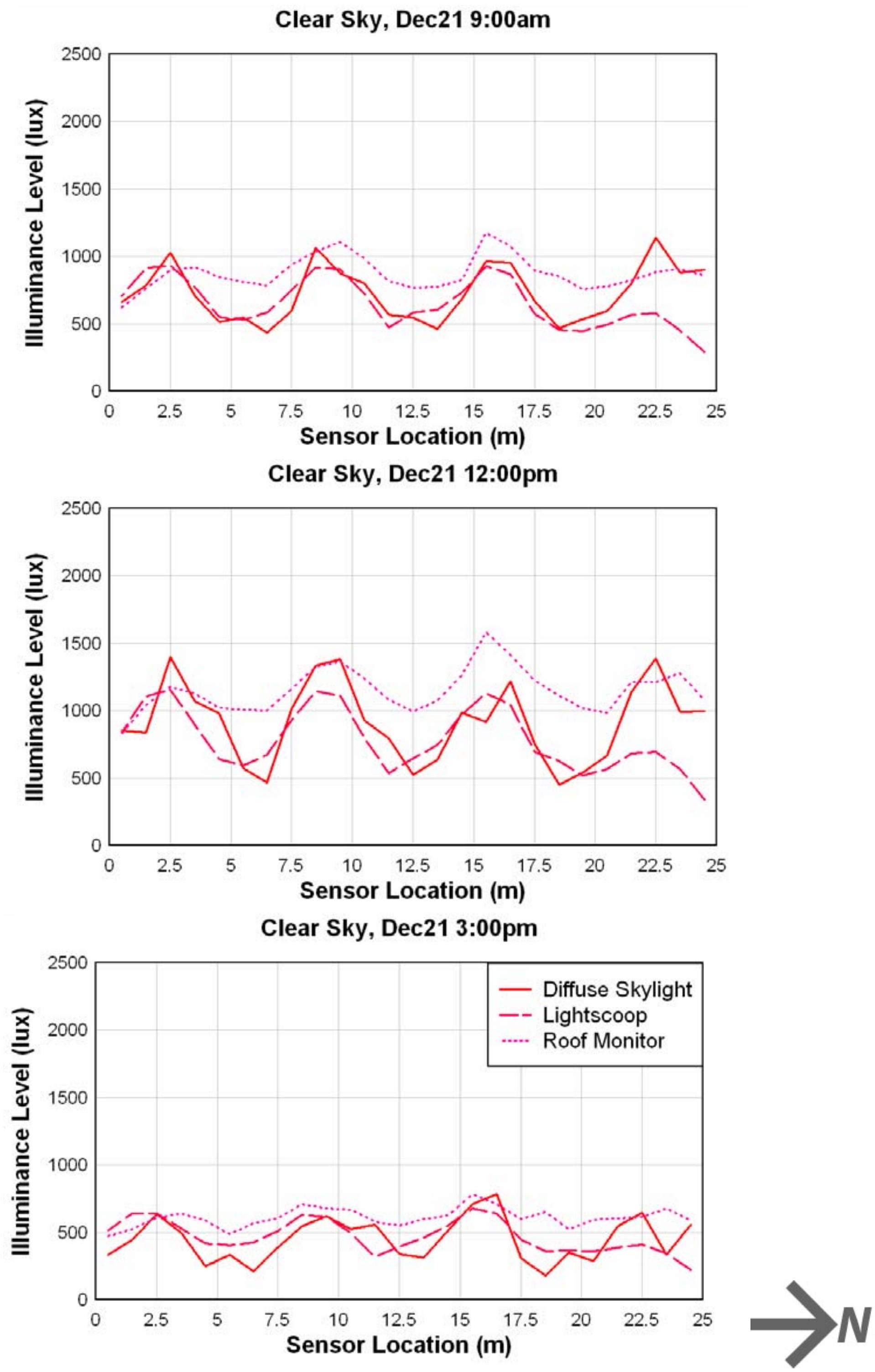

Fig. 5.18 1.5 to 1 toplighting: illuminance level comparison, clear sky, December 21

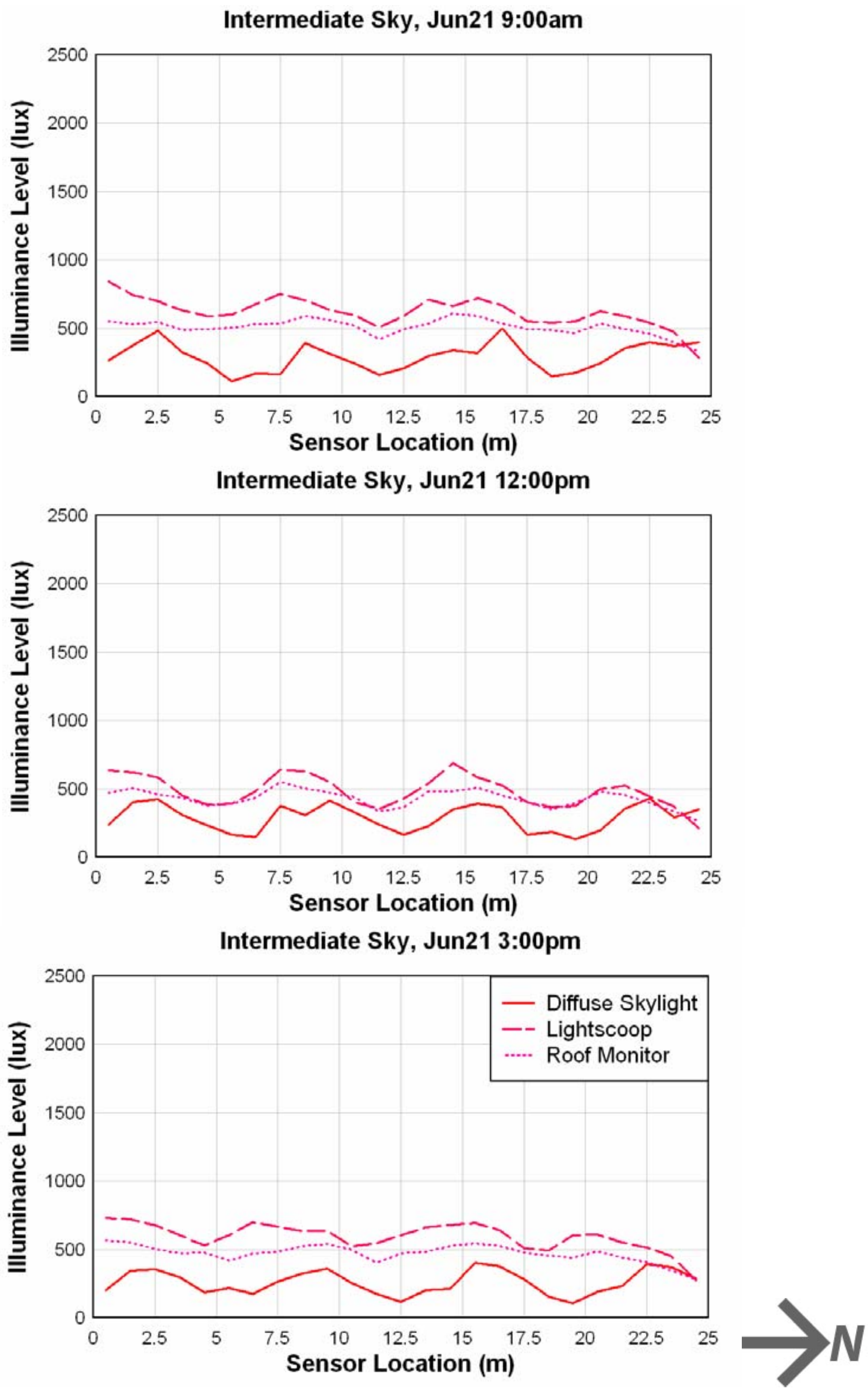

Fig. 5.19 1.5 to 1 toplighting: illuminance level comparison, intermediate sky, June 21

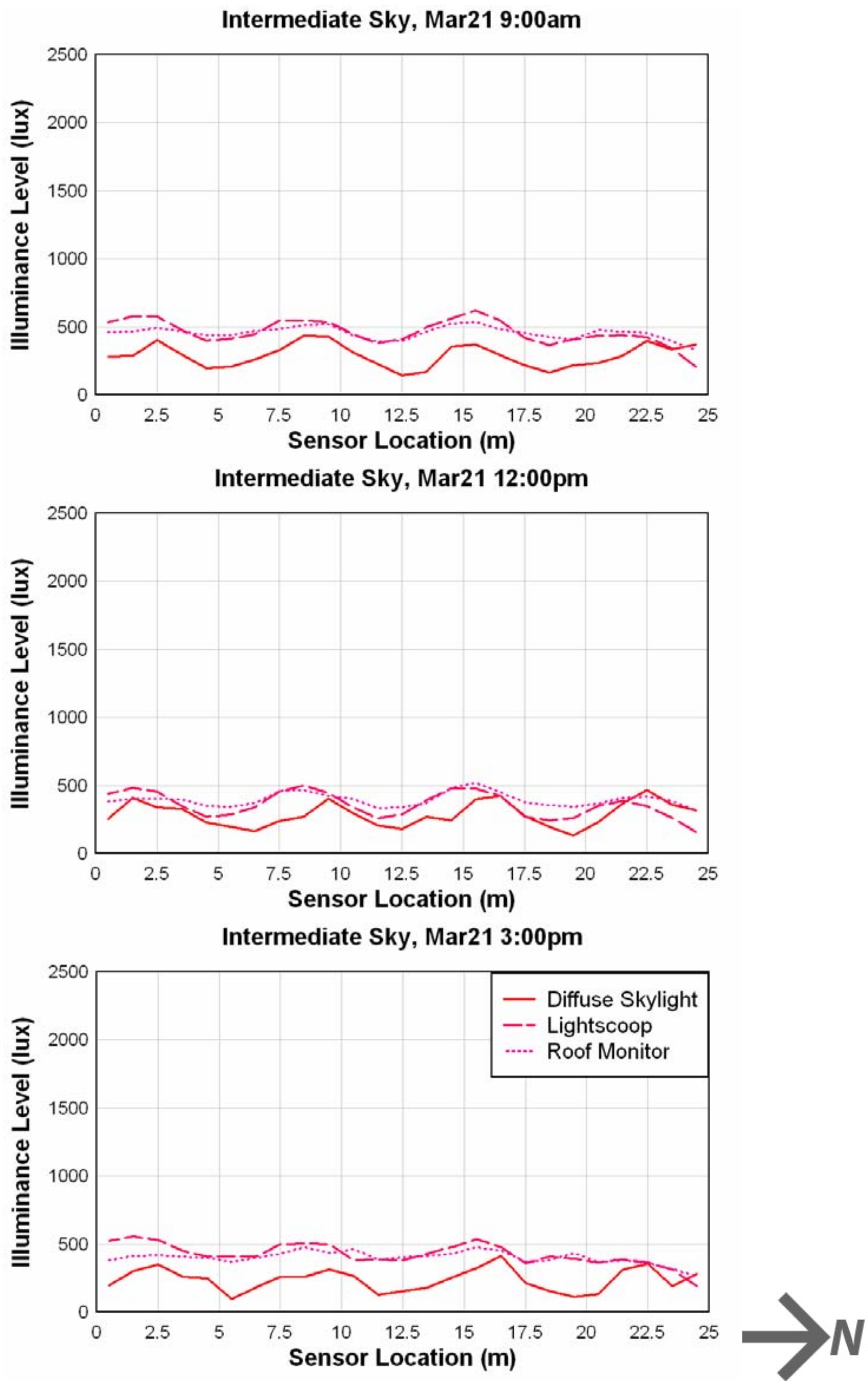

Fig. 5.20 1.5 to 1 toplighting: illuminance level comparison, intermediate sky, March 21

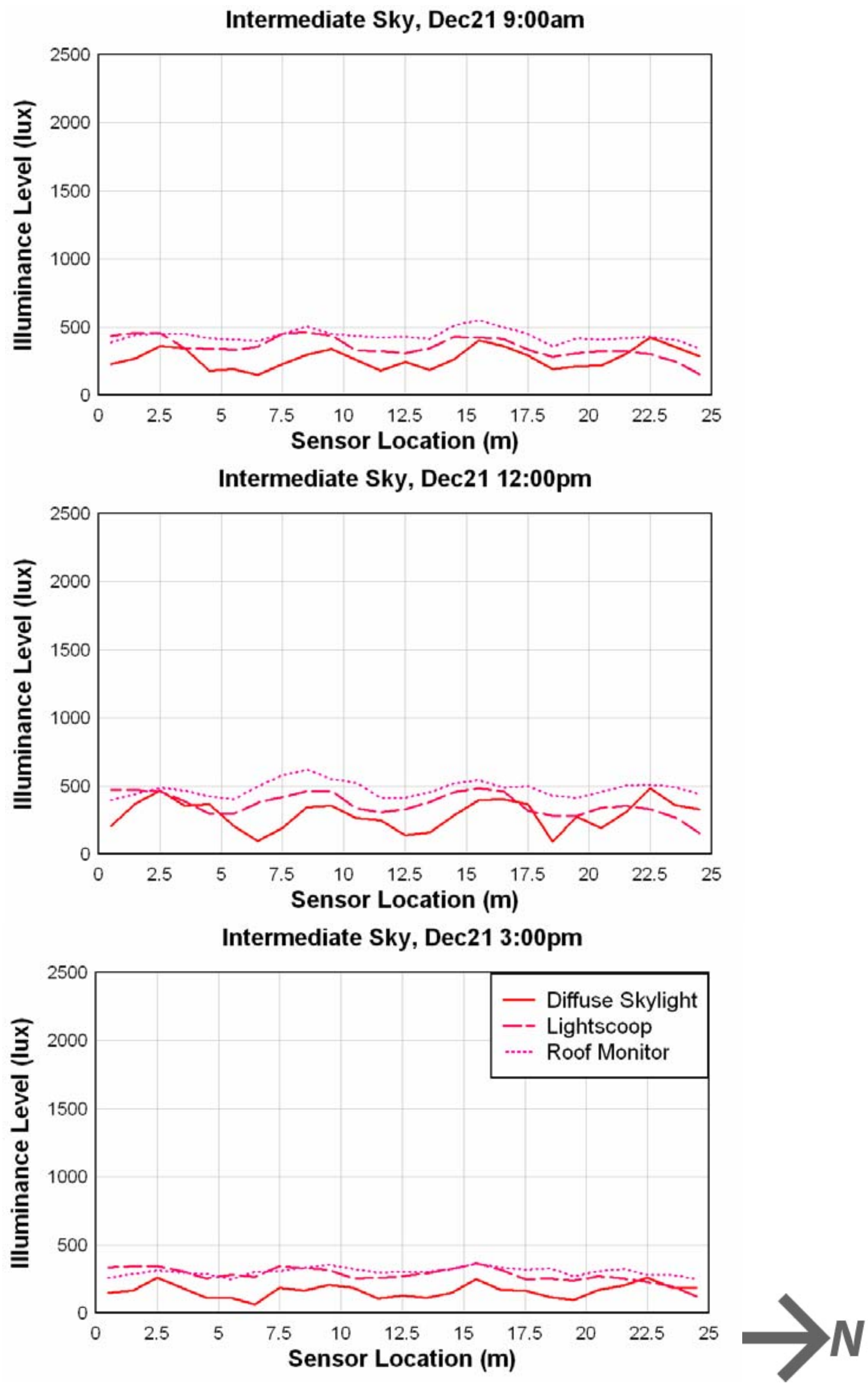

Fig. 5.21 1.5 to 1 toplighting: illuminance level comparison, intermediate sky, December 21

<u>Overcast Sky: Daylight Factor Analysis</u>

For the daylight factor level, the lightscoop yields a higher daylight factor level than other prototypes, by having roof monitor and diffuse skylight yield less maximum daylight factor, respectively. The diffuse skylight prototype has the lowest minimum points than other systems.

The 1.5 to 1 spacing-to-height lightscoop system yields maximum daylight factor level of nearly 4 % while diffuse skylight, which gives least maximum daylight factor level at 1.5 %; these two systems have a range of maximum daylight factor difference of about 40 %. The roof monitor prototype also has a maximum daylight factor less than lightscoop at a range of about 20 %.

<u>Overcast Sky: Light Distribution Analysis</u>

From the chart, it can be seen that, for the 1.5 to 1 spacing-to-height ratio, the distribution is greatly improved from a single unit, since more of daylight apertures are installed. Roof monitor and lightscoop systems seem to have a similar light distribution than diffuse skylight system, since the range between maximum and minimum points are closer than those of diffuse skylight. In the case of a diffuse skylight system, it can be seen that the system causes pools of light, by having more difference between the maximum and minimum point, which might affect the visual comfort.

<u>Clear Sky: Illuminance Level Analysis</u>

For the clear sky conditions, it can be seen that the lightscoop prototype yields higher illuminance level then other systems at most of the tested dates and times, except in winter. The diffuse skylight prototype mostly yields lower illuminance value than the lightscoop and roof monitor prototypes.

The illuminance levels of the diffuse skylight prototype vary seasonally by having higher illuminance value in summer and decreasing values in summer. The light level also changes throughout the day more than lightscoop and roof monitor.

For the lightscoop prototype, the illuminance value reaches its maximum in summer solstice at solar noon at about 2,000 lux. For lightscoop, the illuminance level is higher in summer and is lower in winter. The illuminance levels range from 500 lux in winter and up to 2,000 in summer. The overall diurnal range is at about 500 lux. Even though the lightscoop prototype yields generally higher illuminance levels than the roof monitor, in winter, the illuminance levels the lightscoop prototype are lower than the roof monitor.

The roof monitor, in general, yields lower illuminance value than other systems, still, the illuminance value do not vary much throughout the year compared to other systems; this could be because it has a glazing for both north and south orientation. In winter, the illuminance levels of the roof monitor are higher than other prototypes.

Clear Sky: Light Distribution Analysis

For the light distribution in clear sky condition, as can be visually derived from the chart, roof monitor and lightscoop prototypes seem to perform similarly by having a more even light distribution than diffuse skylight system throughout the year. More detailed analysis between these two systems on daylight distribution and uniformity will be given in the next section. The diffuse skylight prototype has a wider range of illuminance value, which could cause the light distribution to be worse than lightscoop and roof monitor.

Intermediate Sky: Illuminance Level Analysis

In general, the illuminance levels of all the prototypes are lower than those of the clear sky condition up to 50 % and do not vary much throughout the year. The lightscoop prototype yields higher illuminance values than other prototypes in summer but similar illuminance levels to the roof monitor in equinox. The illuminance levels of the roof monitor are higher than other prototypes in winter. This could be because diffuse skylight is the horizontal glazing but lightscoop and roof monitor has vertical glazing which, in partly cloudy condition, some light might bounce off the cloud and enter the vertical glazing.

There is not much difference in the illuminance value between 3 prototypes; in general, they all yield similar illuminance value at about 500 lux.

Intermediate Sky: Light Distribution Analysis

Even though no conclusion can be made at this point since the tested sensor locations are located in a single row along the center of the room, it can be seen that the roof monitor and lightscoop prototypes have flatter curves than the diffuse skylight. The single diffuse skylight prototype still has a distinguished peak in the center under the opening, same as in clear sky condition but not as evident.

In summation, for the 1.5 to 1 spacing-to-height ratio prototypes, the lightscoop prototype yields higher illuminance level in most of the tested solar conditions and the roof monitor prototype yields higher illuminance level in winter. The diffuse skylight prototype yields lower illuminance level than other prototypes. The light distribution of the lightscoop and the roof monitor prototypes are similar, with flatter curves than that of the diffuse skylight prototype.

5.3.2. Illuminance Uniformity Analysis

Horizontal illuminance contour comparison of 1.5 to 1 spacing-to-height toplighting prototypes are illustrated in Fig. 5.22 for overcast sky condition and in Figs. 5.23-5.25 for each case in the clear sky condition at different solar positions. Intermediate sky results are presented in Figs. 5.26-5.28 for each case at different solar position in all the solstices.

Table for illuminance gradient value is presented in Table 5.4 and uniformity of illuminance value is presented in Table 5.5.

Evaluation of the light distribution and uniformity of each case in different sky conditions are discussed later on in this section.

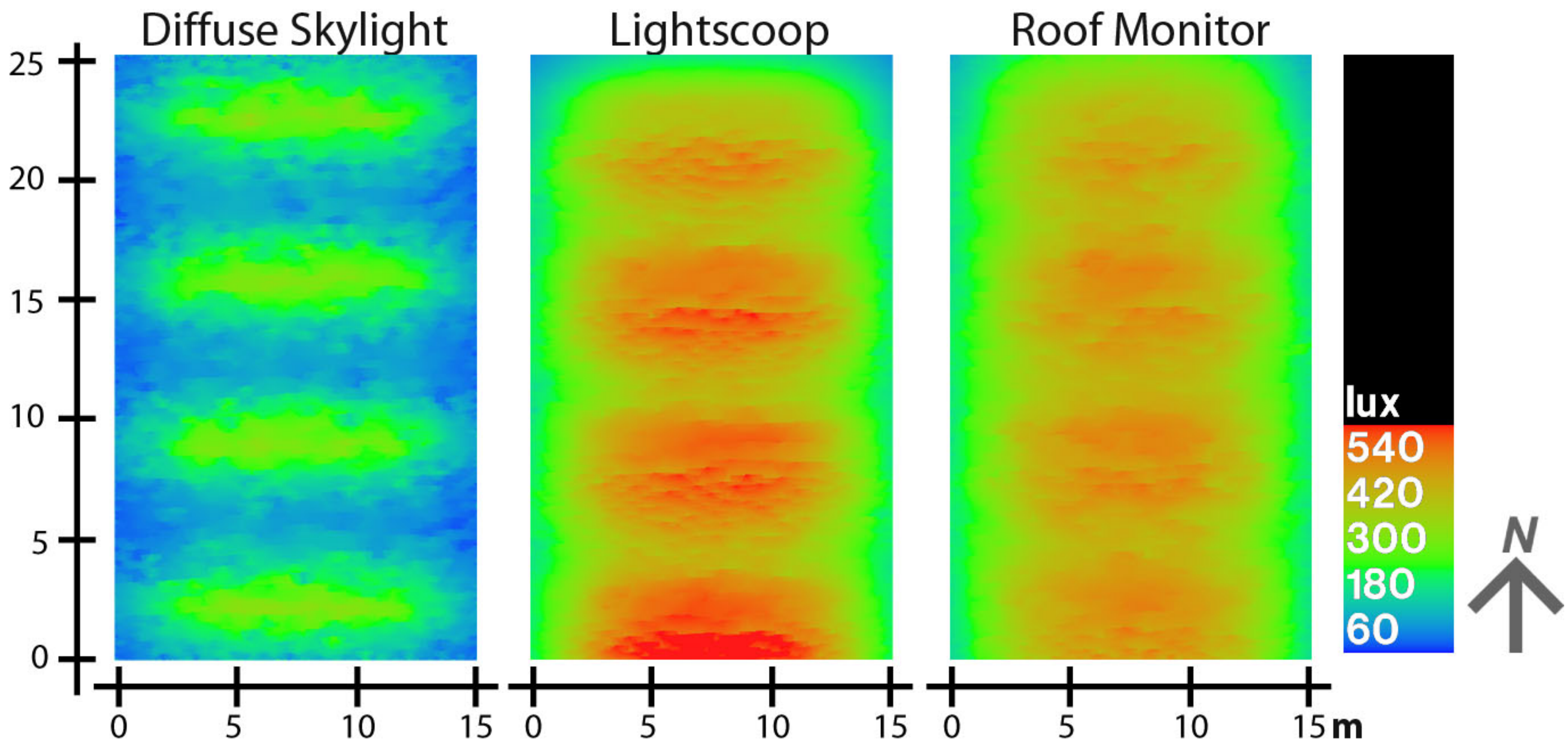

Fig. 5.22 1.5 to 1 toplighting: illuminance contour on plan, overcast sky

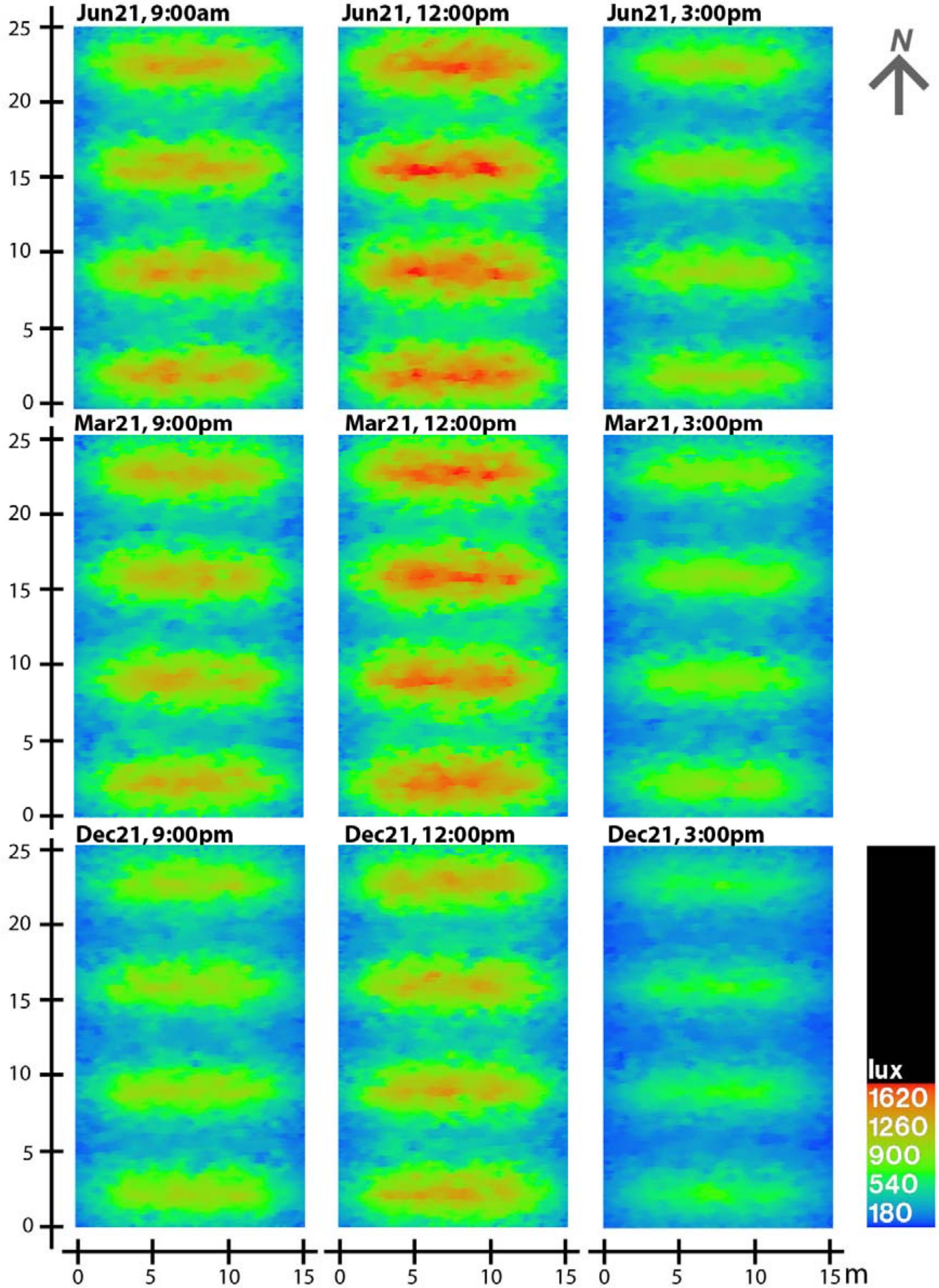

Fig. 5.23 1.5 to 1 diffuse skylight: illuminance contour on plan, clear sky

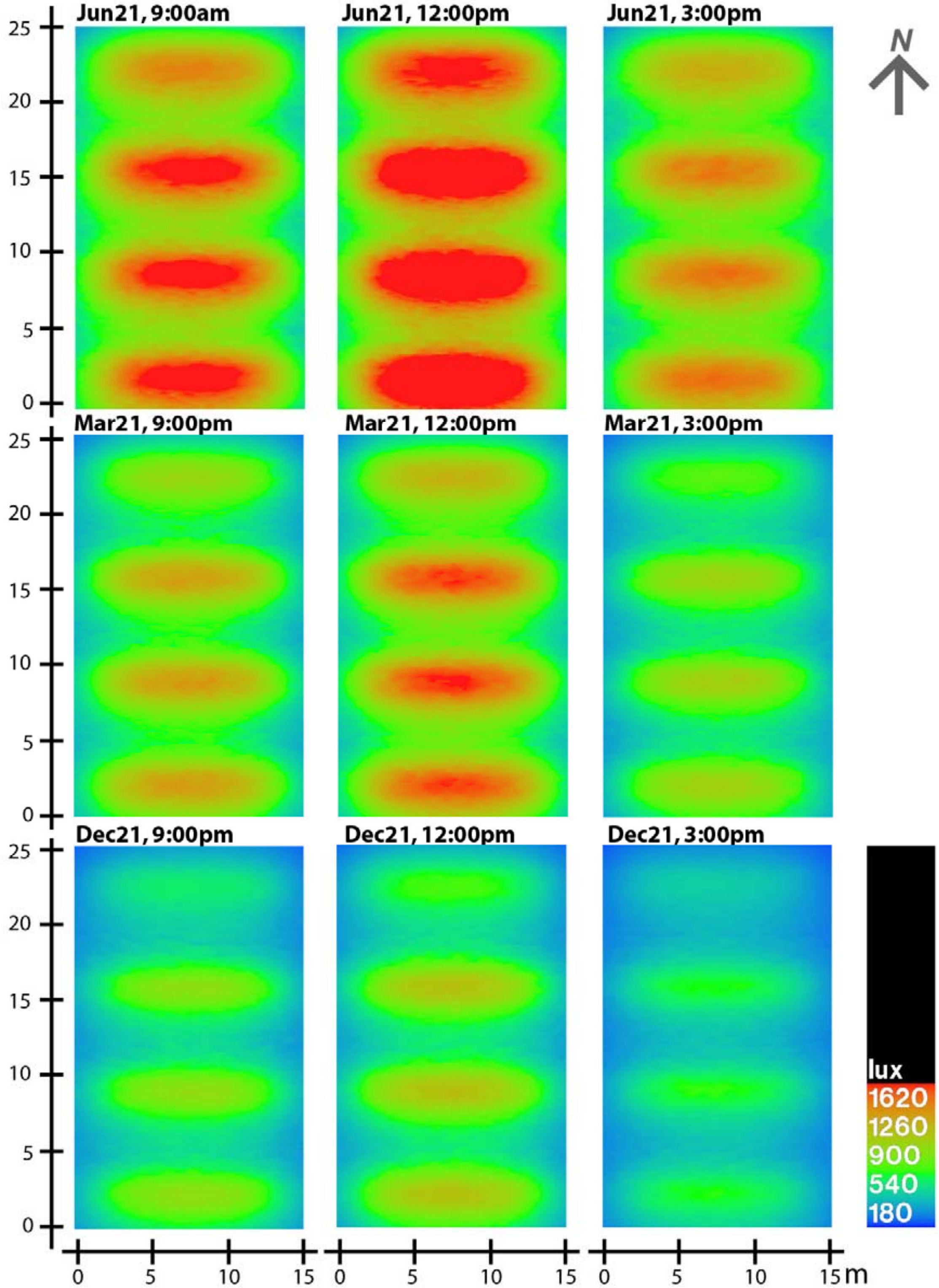

Fig. 5.24 1.5 to 1 lightscoop: illuminance contour on plan, clear sky

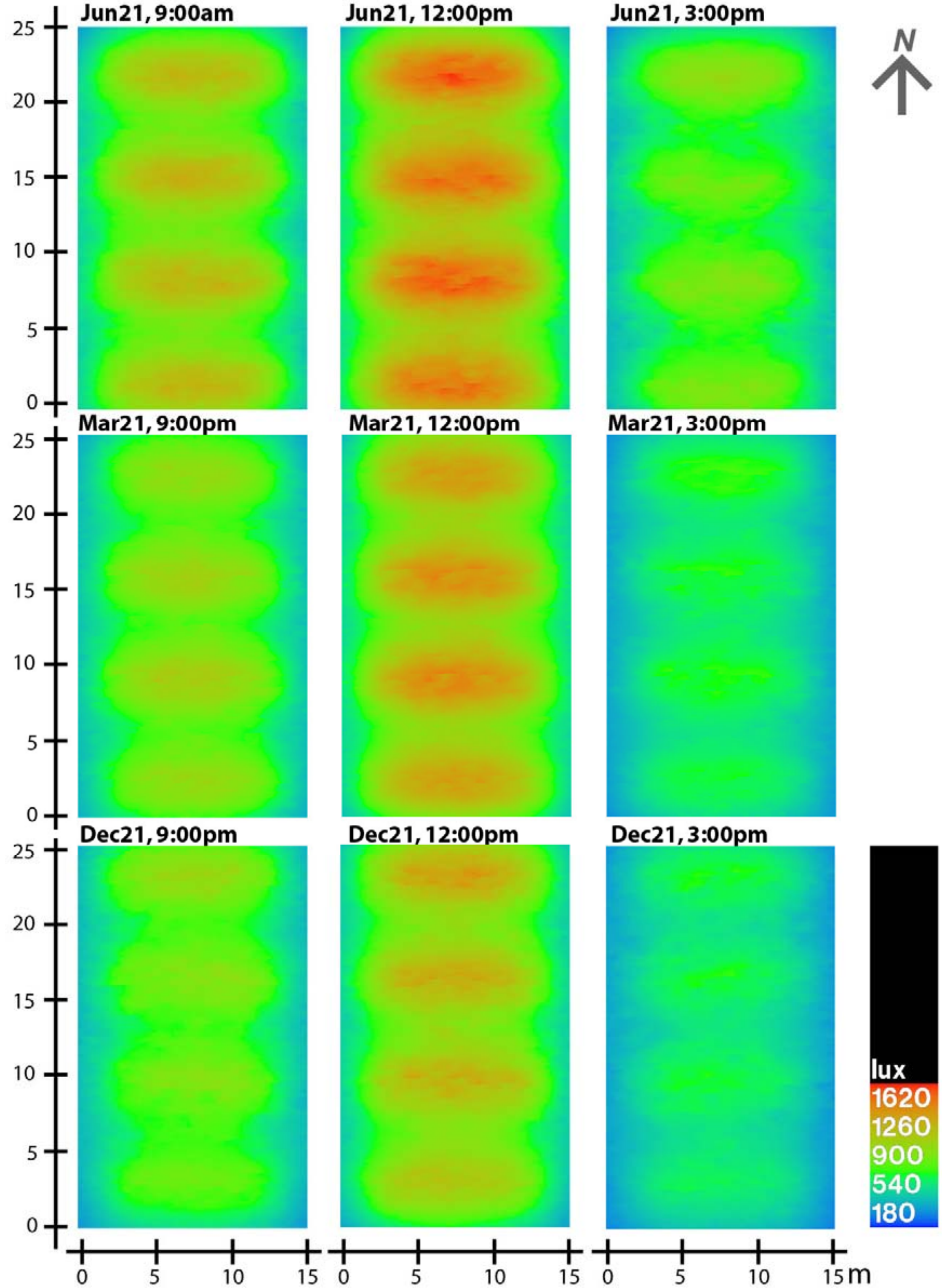

Fig. 5.25 1.5 to 1 roof monitor: illuminance contour on plan, clear sky

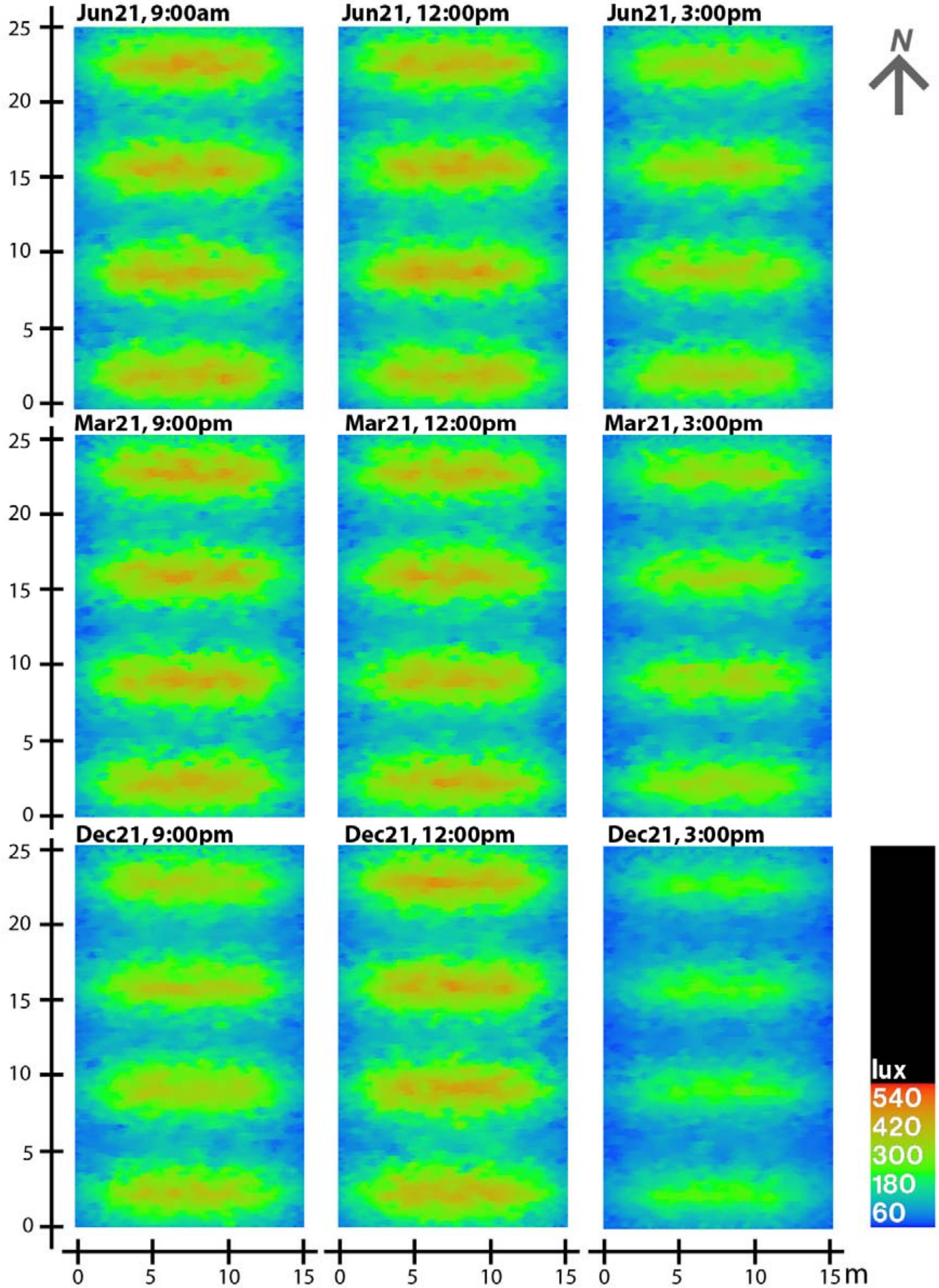

Fig. 5.26 1.5 to 1 diffuse skylight: illuminance contour on plan, intermediate sky

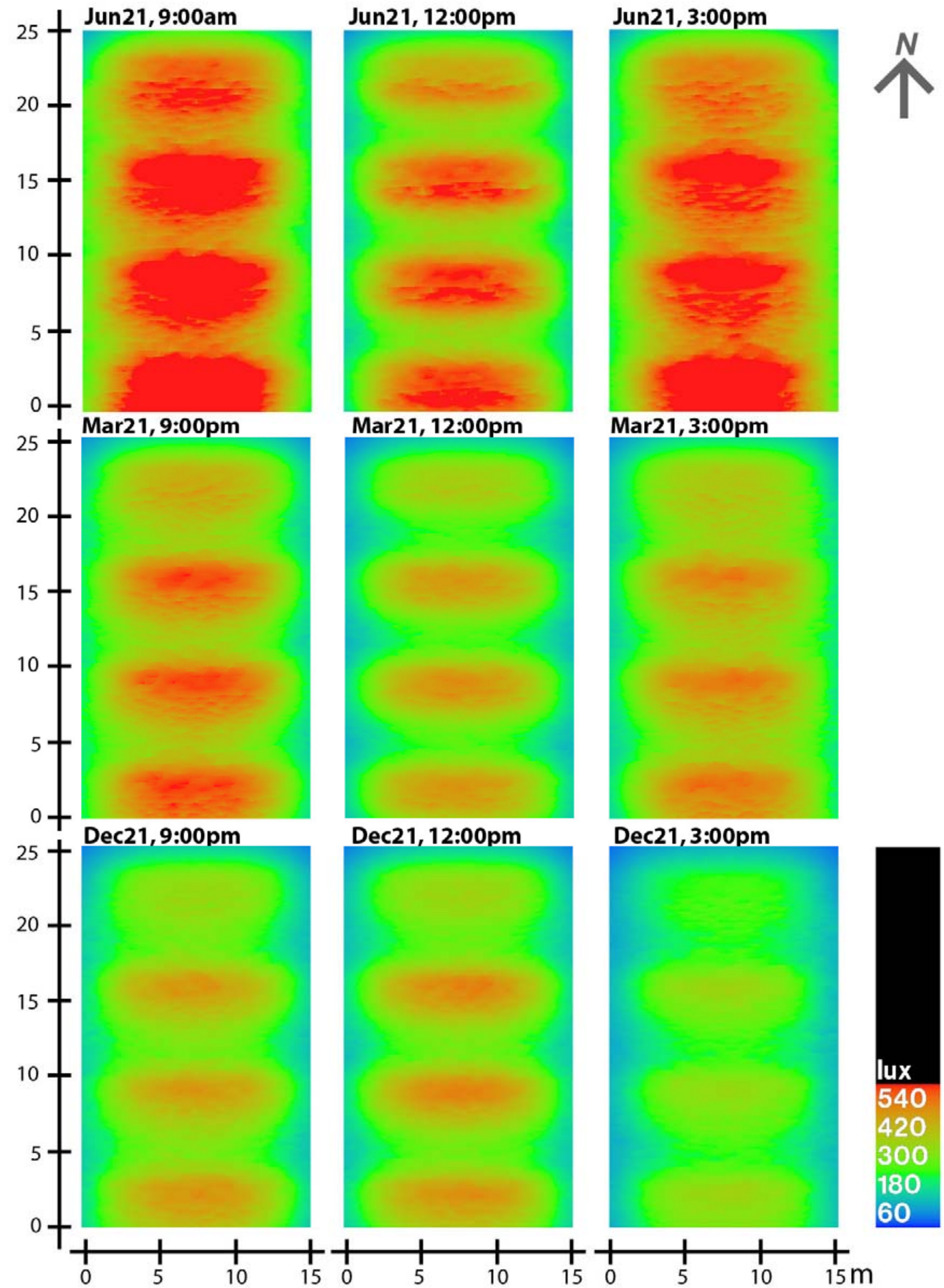

Fig. 5.27 1.5 to 1 lightscoop: illuminance contour on plan, intermediate sky

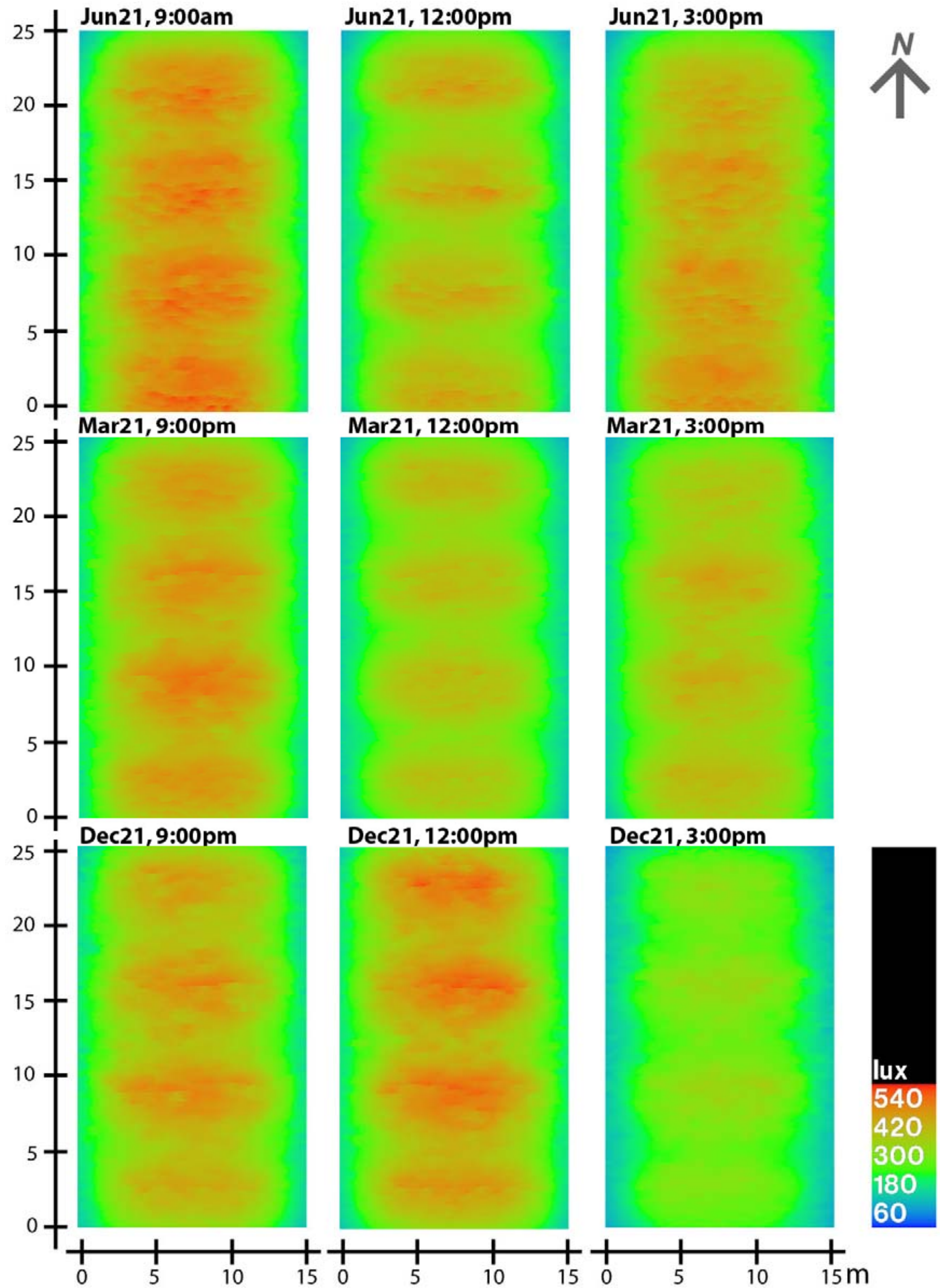

Fig. 5.28 1.5 to 1 roof monitor: illuminance contour on plan, intermediate sky

Table 5.4 1.5 to 1 spacing-to-height ratio toplighting: illuminance gradient comparison

	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast Sky	13	8	4
Clear Sky			
Jun21, 9:00am	11	6	4
Jun21, 12:00pm	15	6	5
Jun21, 3:00pm	13	6	5
Mar21, 9:00am	12	7	3
Mar21, 12:00pm	13	7	3
Mar21, 3:00pm	10	7	3
Dec21, 9:00am	12	7	3
Dec21, 12:00pm	15	8	4
Dec21, 3:00pm	13	10	3
Intermediate Sky			
Jun21, 9:00am	13	7	5
Jun21, 12:00pm	14	8	5
Jun21, 3:00pm	12	6	5
Mar21, 9:00am	10	7	4
Mar21, 12:00pm	11	7	3
Mar21, 3:00pm	10	6	4
Dec21, 9:00am	12	7	4
Dec21, 12:00pm	12	7	3
Dec21, 3:00pm	13	9	4

Illuminance gradient is the ratio of maximum to minimum illuminance of each case; lower value indicates better uniformity

Table 5.4 1.5 to 1 spacing-to-height ratio toplighting: uniformity of illuminance comparison

Time/Case	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast	0.18	0.23	0.35
Clear Sky			
Jun21, 9:00am	0.20	0.29	0.35
Jun21, 12:00pm	0.16	0.28	0.34
Jun21, 3:00pm	0.18	0.30	0.32
Mar21, 9:00am	0.16	0.26	0.44
Mar21, 12:00pm	0.18	0.26	0.46
Mar21, 3:00pm	0.22	0.26	0.44
Dec21, 9:00am	0.19	0.25	0.45
Dec21, 12:00pm	0.15	0.25	0.38
Dec21, 3:00pm	0.19	0.25	0.47
Intermediate Sky			
Jun21, 9:00am	0.17	0.25	0.31
Jun21, 12:00pm	0.16	0.24	0.34
Jun21, 3:00pm	0.19	0.26	0.33
Mar21, 9:00am	0.22	0.24	0.38
Mar21, 12:00pm	0.20	0.25	0.43
Mar21, 3:00pm	0.21	0.25	0.37
Dec21, 9:00am	0.17	0.23	0.41
Dec21, 12:00pm	0.19	0.23	0.45
Dec21, 3:00pm	0.18	0.24	0.41

Uniformity of illuminance ratio is the ratio of minimum to average illuminance of each case; higher value indicates better uniformity

Overcast Sky Condition: Distribution and Uniformity Analysis

In the overcast sky conditions, the roof monitor provides more even light distribution throughout the room even though it yields a lower illuminance value. The lightscoop distribution is close to the roof monitor prototype but the light distribution is more uneven, as can be seen from the chart. The contours are closed together than are the case with the roof monitor. For the diffuse skylight prototype, light distributes mostly under the apertures in the while for lightscoop and roof monitor, light concentration shifts a little from the area directly under the opening into the south side of the room. Also, the lights from the lightscoop and the roof monitor reach the perimeter of the room more than from a diffuse skylight prototype, indicating better light distribution.

The illuminance gradient ratio of roof monitor is the lowest, which is about half the values of other prototypes. The lightscoop performs second best. From table 5.3, in the overcast sky condition, the illuminance gradient values of each case with the spacing-to-height ratio of 1.5 to 1 are 13, 8, and 4, for the diffuse skylight, lightscoop, and roof monitor, respectively. It can also be noted that the illuminance gradient ratio of the prototypes with spacing-to-height ratio of 1.5 to 1 (or 4-unit prototypes) has decreased from the single unit value of more than 30 times. This indicates that better lighting performance can be achieved with the series of units.

For the uniformity of illuminance ratio, the roof monitor still performs better by having the highest value. The uniformity of illuminance ratios for the diffuse skylight, lightscoop, and roof monitor, are 0.18, 0.23, and 0.35, respectively. From these values, it can be analyzed that the roof monitor prototype still performs better in terms of illuminance uniformity, while the lightscoop performs second best. It can also be seen that this value have increased more than 5 times for diffuse skylight and 7 times for lightscoop and roof monitor cases, from the single unit prototypes.

To summarize, it can be said that, in the overcast sky conditions, the roof monitor prototype gives better light distribution and uniformity than other systems, with the lightscoop prototype performing second-best.

Clear Sky Condition: Distribution and Uniformity Analysis

In clear sky conditions, the single roof monitor still performs better than other prototypes in all the tested representative days.

From the illuminance contour charts (Figs. 5.23-5.25), it can be seen that, for the diffuse skylight in clear sky condition, the light distribution is concentrated around the central areas right under the apertures. The light does not spread into the room perimeter as much as other prototypes, even though it yields high illuminance value. The distribution pattern is similar all year but the light level decreases in winter time.

For the lightscoop prototype, the distribution patterns also do not vary during the year and better uniformity is achieved in winter due to less light level than in summer. The light distribution patterns of lightscoop still have some pools of light but are not as evident as in the case of diffuse skylight since light which spreads more into the room perimeter.

The light distribution patterns of a 1.5 to 1 spacing-to-height roof monitor vary a little throughout the year from spreading more light to the south area of the room in summer and more to the north of the room in winter. Light is distributed better than in the case of lightscoop because the contours are farther apart than in the case of lightscoop, even though it gives lower illuminance value. However, in general, the light distribution performance is still close to that of a 1.5 to 1 spacing-to-height lightscoop system.

From the horizontal illuminance contour charts, it can be summarized that the prototype that performs best in terms of illuminance distribution and uniformity is the roof monitor, with the lightscoop performing second-best.

From Table 5.3, the illuminance gradient ratio, the roof monitor prototype yields the lowest value than other systems in all the tested date and time, with a range from 3-5. From these results, it can be seen that the roof monitor system can meet and in some dates even exceed the standard set by CIBSE Code which is set at 5 for the maximum. Therefore, in a case of the roof monitor prototype, the spacing-to-height ratio might be increased and can still meet the standard. The values generated also correspond to the horizontal illuminance contour charts analysis. For the roof monitor prototype, the illuminance gradient ratio decreases from summer to winter. The value does not vary much throughout the day, except for winter, that the illuminance gradient value reaches 3 in equinox and winter.

From Table 5.4, the illuminance uniformity ratio, the roof monitor prototype still performs better than other prototypes, by yielding more uniformity ratio than other cases. Lightscoop gives about 0.10 less than a roof monitor. Still, all the values cannot meet the criteria set by CIBSE which is recommended at more than 0.80 yet. However, since the simulated space does not have any interior furniture, this parameter is not analyzed as a primary factor as the illuminance gradient. In general, the performance that can be analyzed from this parameter is the same as from illuminance gradient parameter as discussed earlier.

Intermediate Sky Condition: Distribution and Uniformity Analysis

For intermediate sky conditions, the roof monitor system still performs better than other prototypes in all the tested times by distributing light more evenly.

From the illuminance contour charts (Figs. 5.26-5.28), it can be seen that, for the diffuse skylight prototype, the light distribution is still mostly concentrated in the central area right under the aperture, while for lightscoop and roof monitor, the light is distributed more to the perimeter of the space. In the case of lightscoop and roof monitor, there are some parts of the room to the north side in the corner that is darker than other parts but in the case of skylight, the light distribution decreases greatly farther away from the area under the aperture. The distribution for diffuse skylight has similar pattern throughout the year, but with more illuminance level at noon time.

Lightscoop still has the light distribution pattern similar to its performance under clear sky, which the distribution pattern remains quite constant under different solstices. However, the difference is that the illuminance level at noon in general is lower than morning and afternoon under intermediate sky. This could be because of partly cloudy sky which cloud could reflect light into the interior space when the sun is not overhead like at noon.

For the roof monitor, the light distribution is similar throughout the year with the intermediate sky condition, unlike in clear sky, which the light distribution changes throughout the year. The illuminance level is higher in summer and lower in winter. Also, the illuminance value in summer and equinox, it can be seen from the chart that, the illuminance value at noon is a little lower than at 9:00am and 3:00pm, which is the same behavior as in the case of lightscoop which is discussed previously.

From the illuminance gradient ratio table (Table 5.4), it can be seen that the single roof monitor prototype still yields less value of illuminance gradient in all the tested dates and times under intermediate sky than other cases, with the values range from 3-5. The diffuse skylight prototype’s gradient ratios range from 10-13, which are of close values to its performance under clear sky conditions. The lightscoop prototype has the illuminance gradient values range from 6-9, which is higher than clear sky’s values which range from 6-8 (except in winter afternoon), pointing out worse performance under intermediate sky condition than under clear sky condition. Same conclusion can be made to the roof monitor prototype. Even the illuminance gradient values both range from 3-5 but under clear sky condition, the lower values are achieved more in clear sky.

In the uniformity of illuminance table (Table 5.5), the roof monitor prototype still yields more ratio than other cases, reaching at about 0.30-0.40 while other cases have the ratio range from 0.20-0.30. Still, this ratio is input as a reference since the simulated space does not have any interior furniture.

In summation, the light distribution pattern of each prototype is similar to those under clear sky condition by having similar ratio of illuminance gradient and uniformity, with the difference in illuminance level much lower than under clear sky condition, at more than 50 percent.

5.2.3. Glare Analysis

Glare analysis method has been discussed in Chapter III Methodology which is to use the luminance ratio to analyze the fisheye view rendering of the scene from each prototype. Renderings of the scene and the luminance of each reference points from each toplighting prototype with a 1.5 to 1 spacing-to-height ratio are presented in Figs. 5.29-5.31. The renderings are done for the day which there could be more presence of glare: June 21, at solar noon.

The fisheye view used in this analysis is when the observer is standing in the center and 4.00m from the back of the room. The position of the observer can be noticed in the offending angle picture.

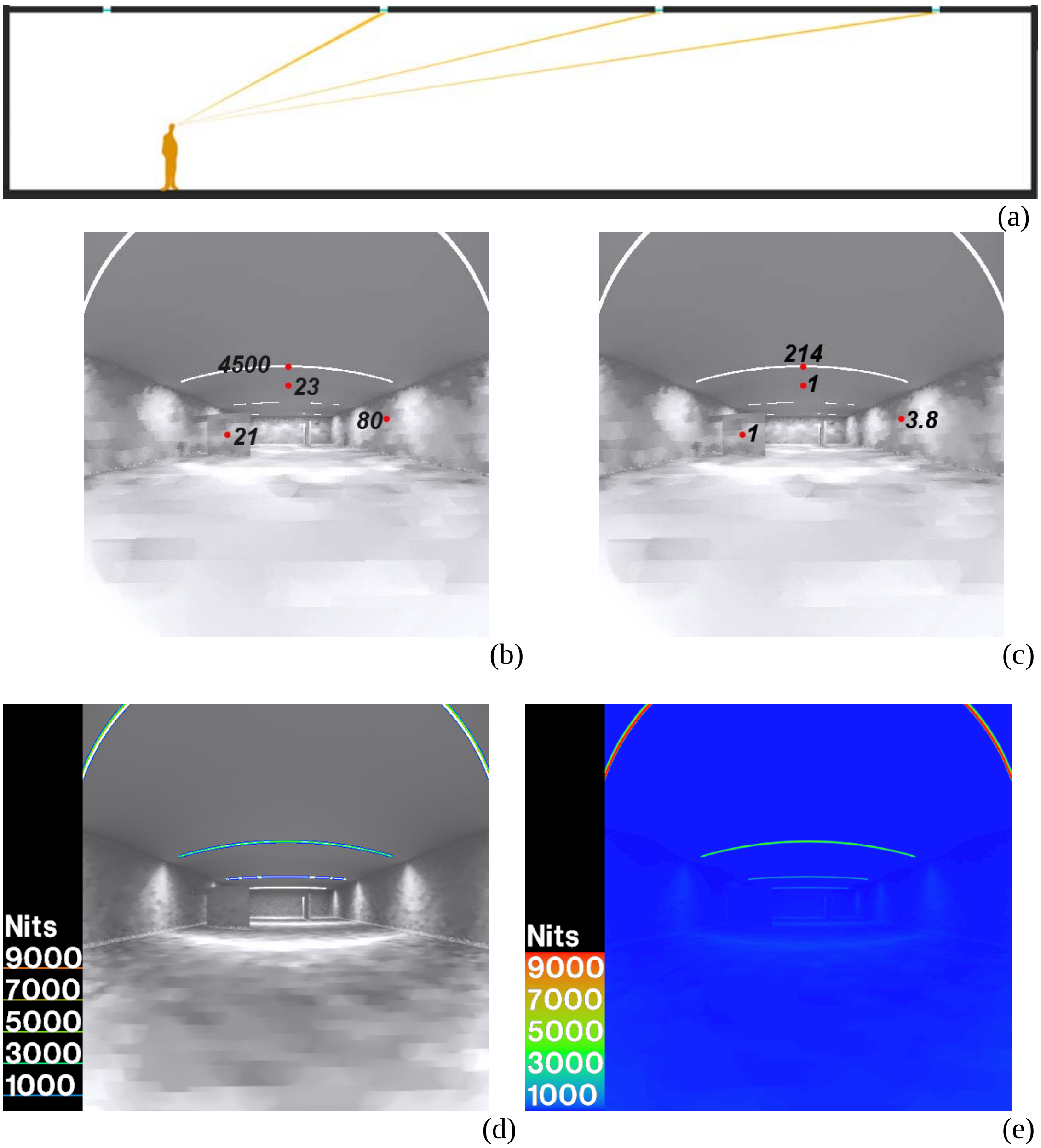

Fig. 5.29 1.5 to 1 diffuse skylight: glare analysis pictures from RADIANCE
(a) section showing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

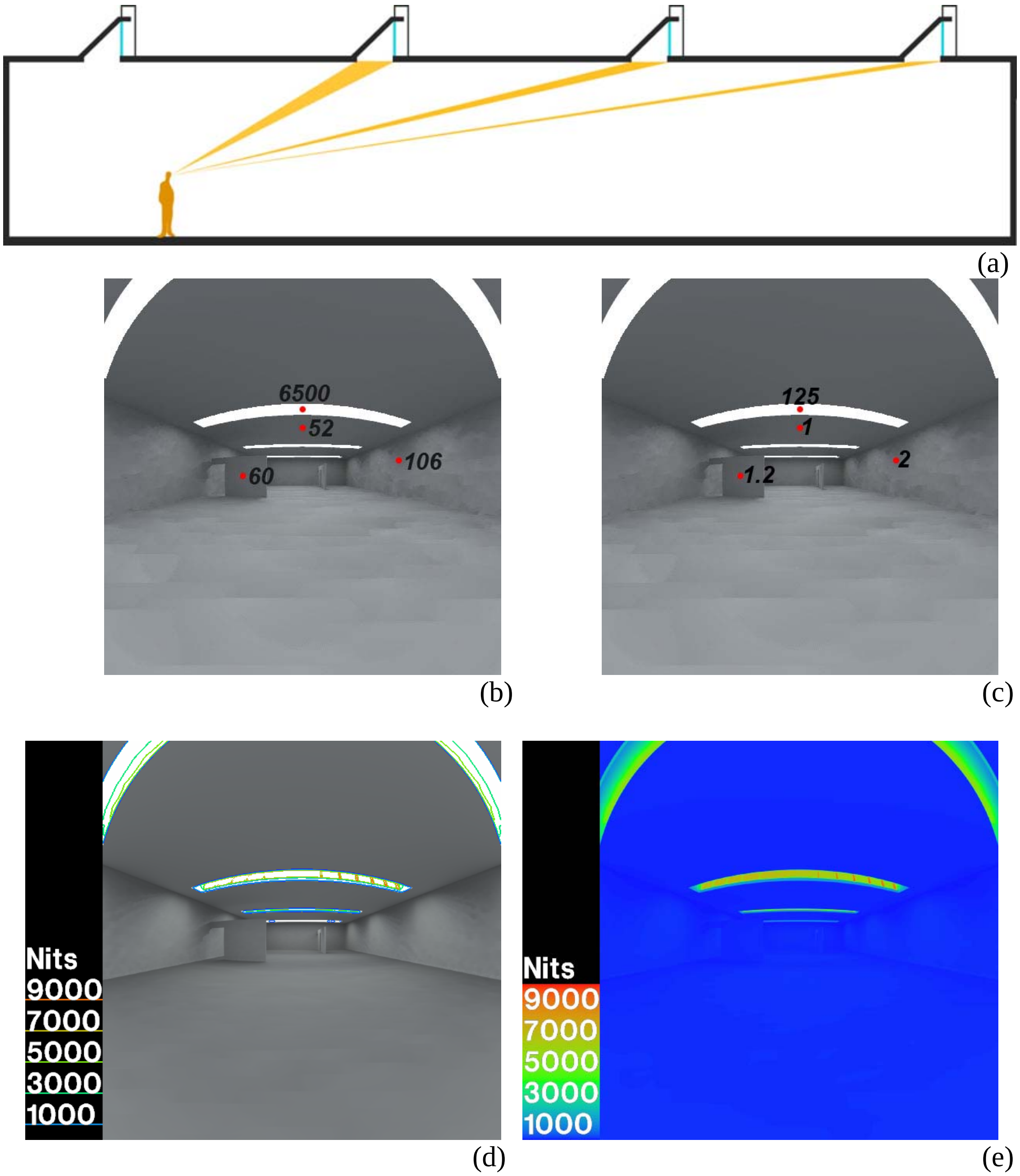

Fig. 5.30 1.5 to 1 lightscoop: glare analysis pictures from RADIANCE
(a) section showing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

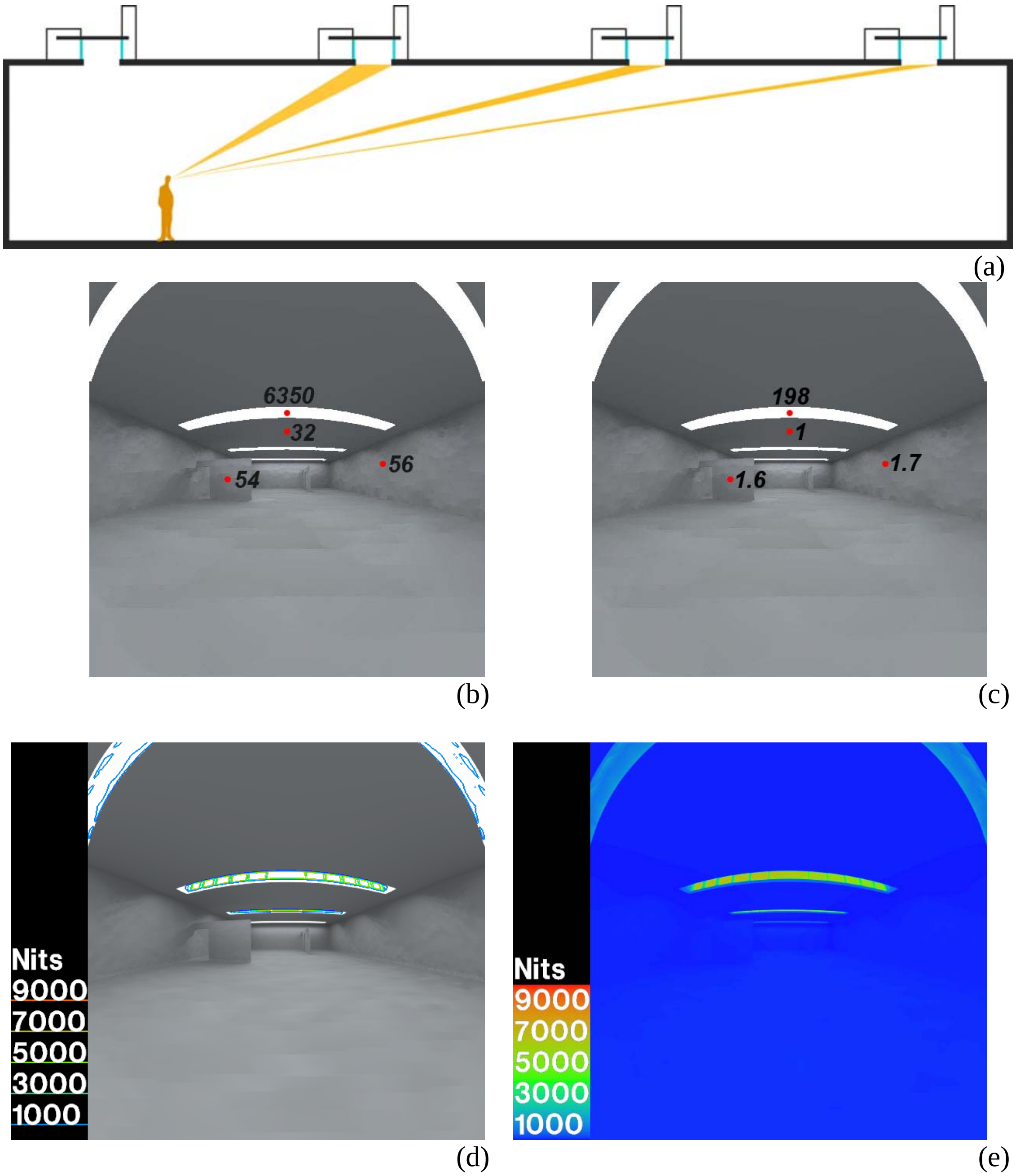

Fig. 5.31 1.5 to 1 roof monitor: glare analysis pictures from RADIANCE
(a) section showing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

From Figs. 5.29-5.31, it can be seen that, all the cases have a chance of glare on clear day of the summer solstice at noon which are caused from the glazing in the field of view of the observer.

The diffuse skylight prototype, even though it has less glazing area which makes the offending angle less than other cases, still, the luminance of the aperture is too high compared to the adjacent surfaces around it. The luminance ratio exceeds 1 to 20 and for the aperture and the adjacent surfaces and exceeds 1 to 40 in the field of view. The average luminance at the glazing in the field of view is at 4,500 cd/m^2 which is very high compared to other surfaces which the luminance levels are not higher than 100 cd/m^2. The luminance ratio between the glazing and the adjacent ceiling surface is 1:214.

For the lightscoop prototype, the luminance at the glazing is reduced from the case of diffuse skylight but is still the cause of glare under summer solstice at noon. From the section shown, it can be seen that the offending angles of lightscoop has caused more probability of glare than in the case of diffuse skylight, even though the luminance ratio in the field of view is lower. The luminance ratio, however, still exceeds 1 to 40 and 1 to 20. Although the luminance values of the surfaces range from 52-106 cd/m^2, the luminance ratio of the surface and the glazing is 1:125. Even with the shading devices, the viewer can still see the glazing, which can cause glare by the its excessive brightness.

The roof monitor prototype performs similarly to the lightscoop, having similar luminance ratio in the field of view and between the glazing and adjacent surfaces, which are still higher than the recommended; 1:198. The offending angles of the roof monitor are the same as the lightscoop since the width of the light well is the same at 1.00m. The luminance of the surfaces in the space ranges from 32-56 cd/m^2 but the luminance of the glazing in the field of view is at about 6,350 cd/m^2.

The solutions to help reduce glare problem could be to change the geometry of the toplighting systems; lift up the glazing to be out of the field of view or change the geometry of the light well to create the cut off angle, preventing the viewer from seeing the glazing.

To summarize the lighting performance of the 1.5 to 1 spacing-to-height prototypes, it can be seen that, the overall performance is superior to those of the single unit toplighting prototype. Each system yields higher illuminance value and better light distribution and uniformity. It can be seen from the illuminance gradient table that the values have decreased more than half of the values derived from the single unit toplighting prototype. Therefore, series of toplighting units are better than single toplighting unit for all the tested prototypes since it could improve the lighting performance of each toplighting prototype.

5.4. Toplighting Prototypes with a 1 to 1 Spacing-to-Height Ratio Analysis

5.4.1. Daylight Factor and Illuminance Level Analysis

The daylight factor comparison chart of single unit toplighting prototypes is presented in Fig. 5.32. The prototypes analyzed are diffuse skylight, lightscoop, and roof monitor. The illuminance level comparison for clear sky charts are presented from Fig. 5.33 to Fig. 5.35. Intermediate sky results are presented in Figs. 5.36-5.38.

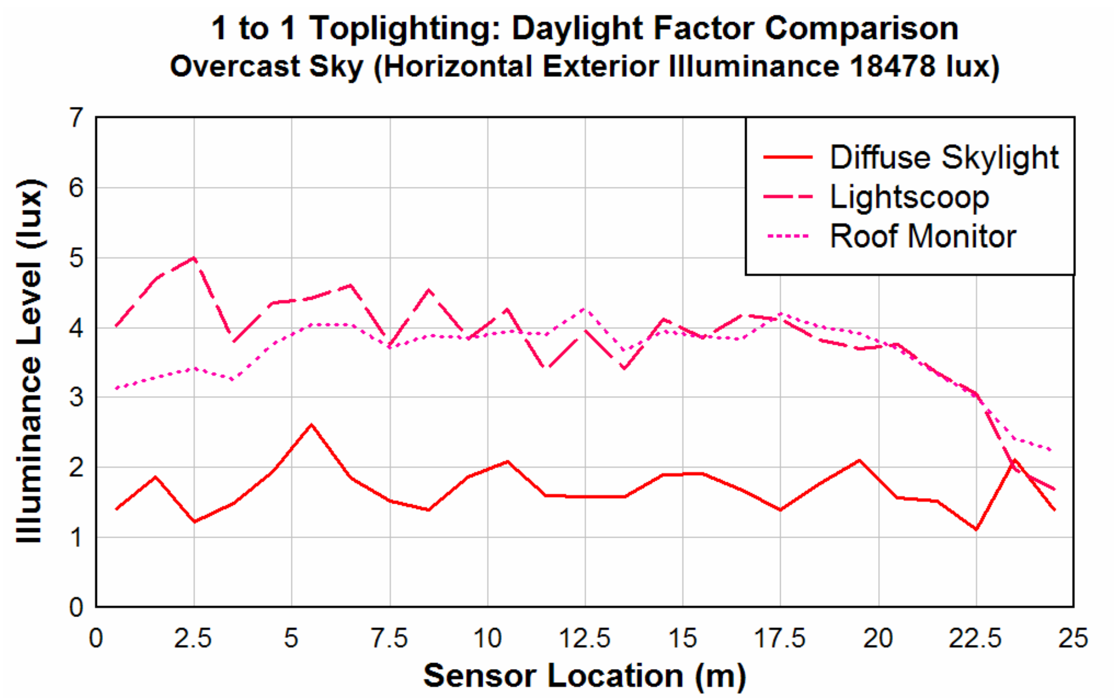

Fig. 5.32 1 to 1 toplighting: daylight factor comparison, overcast sky (Horizontal Exterior Illuminance from RADIANCE is 18478 lux)

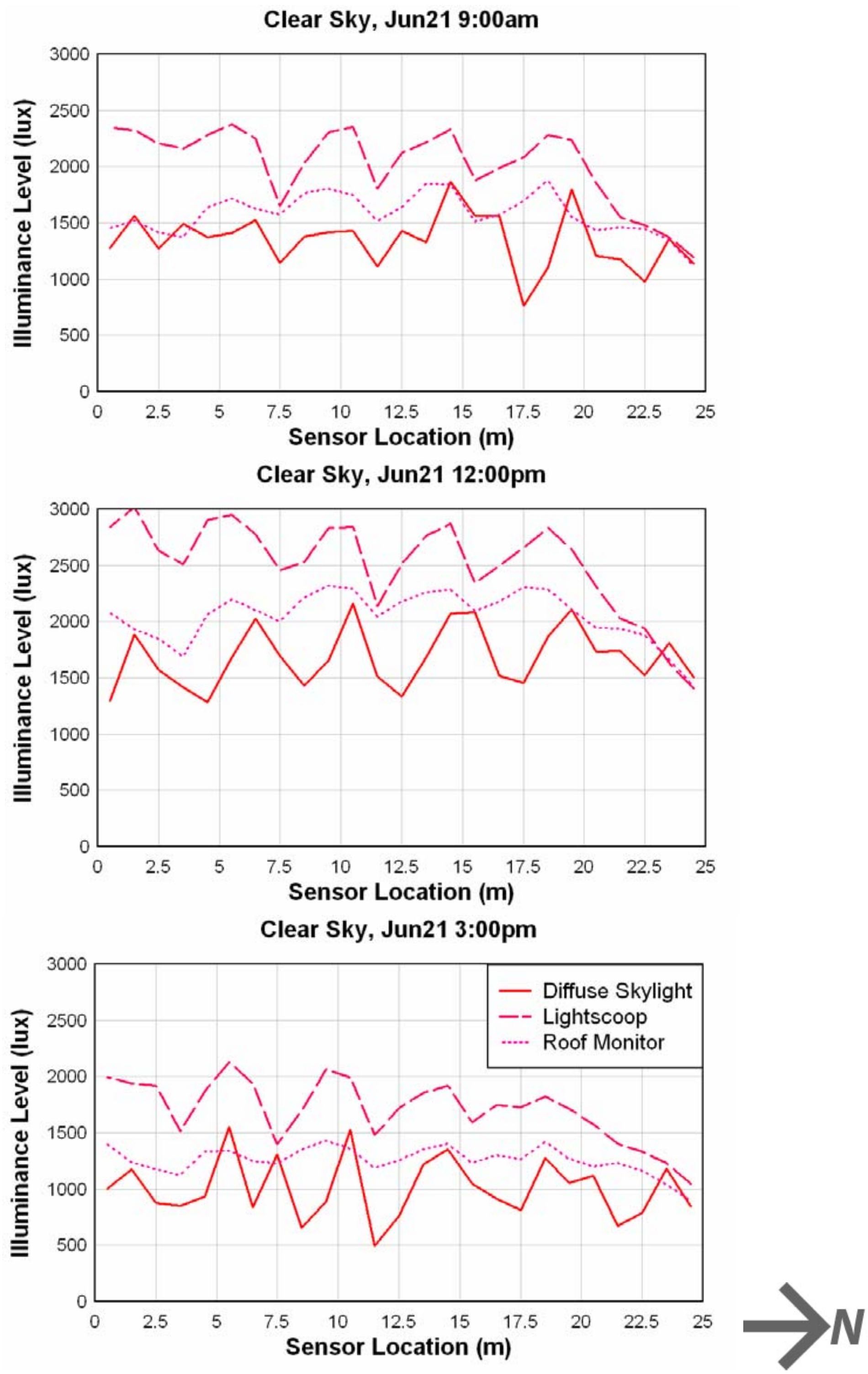

Fig. 5.33 1 to 1 toplighting: illuminance level comparison, clear sky, June 21

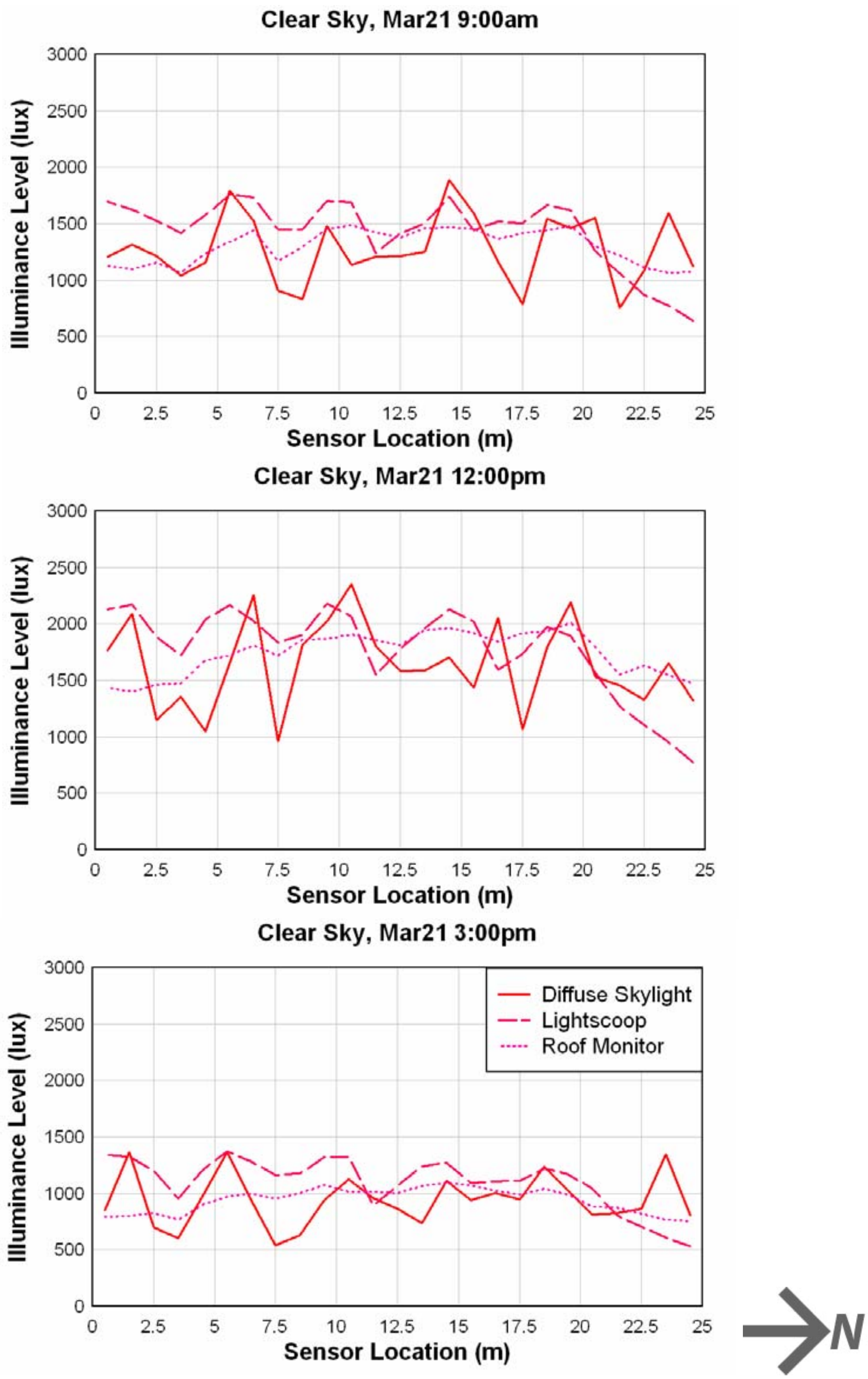

Fig. 5.34 1 to 1 toplighting: illuminance level comparison, clear sky, March 21

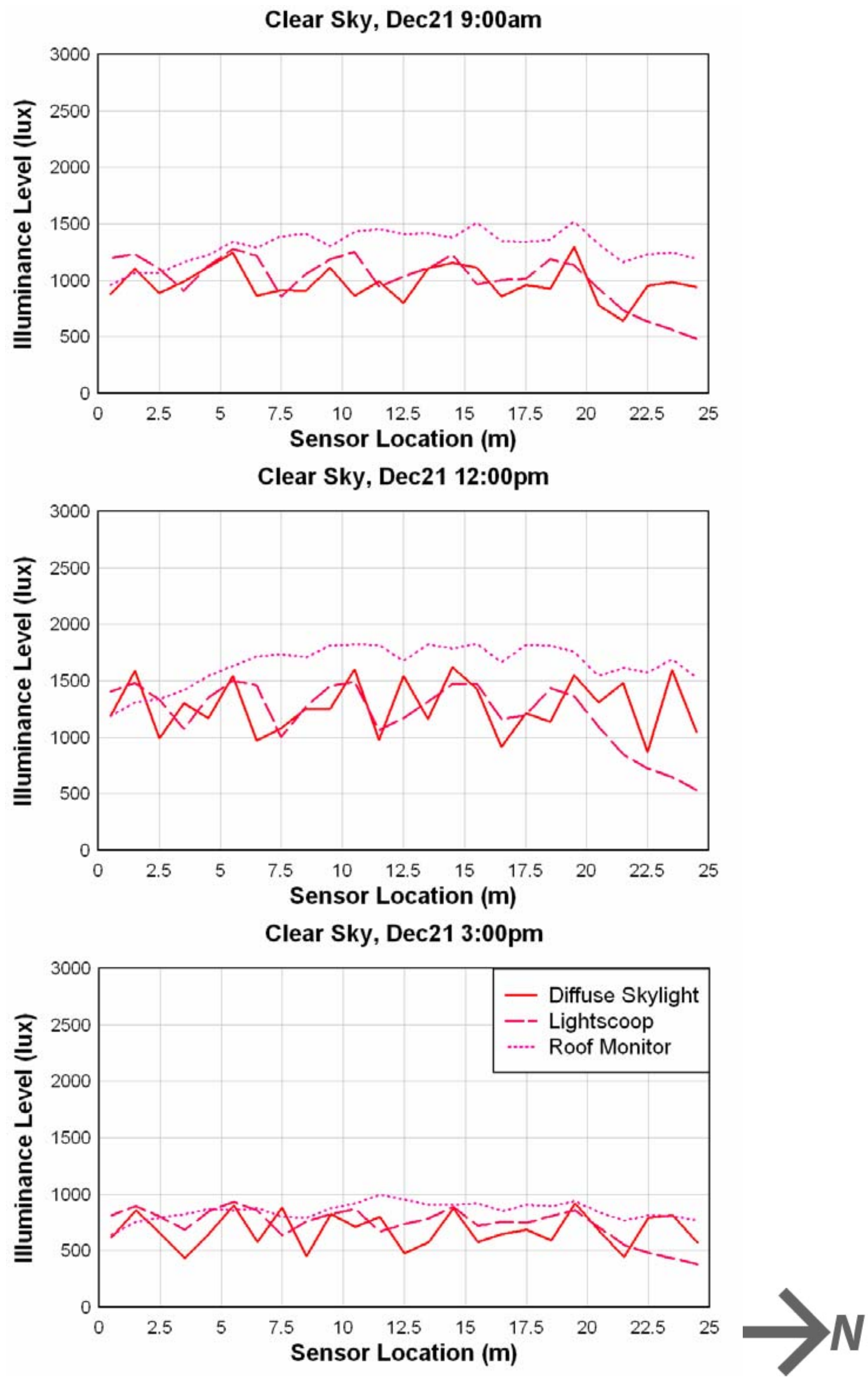

Fig. 5.35 1 to 1 toplighting: illuminance level comparison, clear sky, December 21

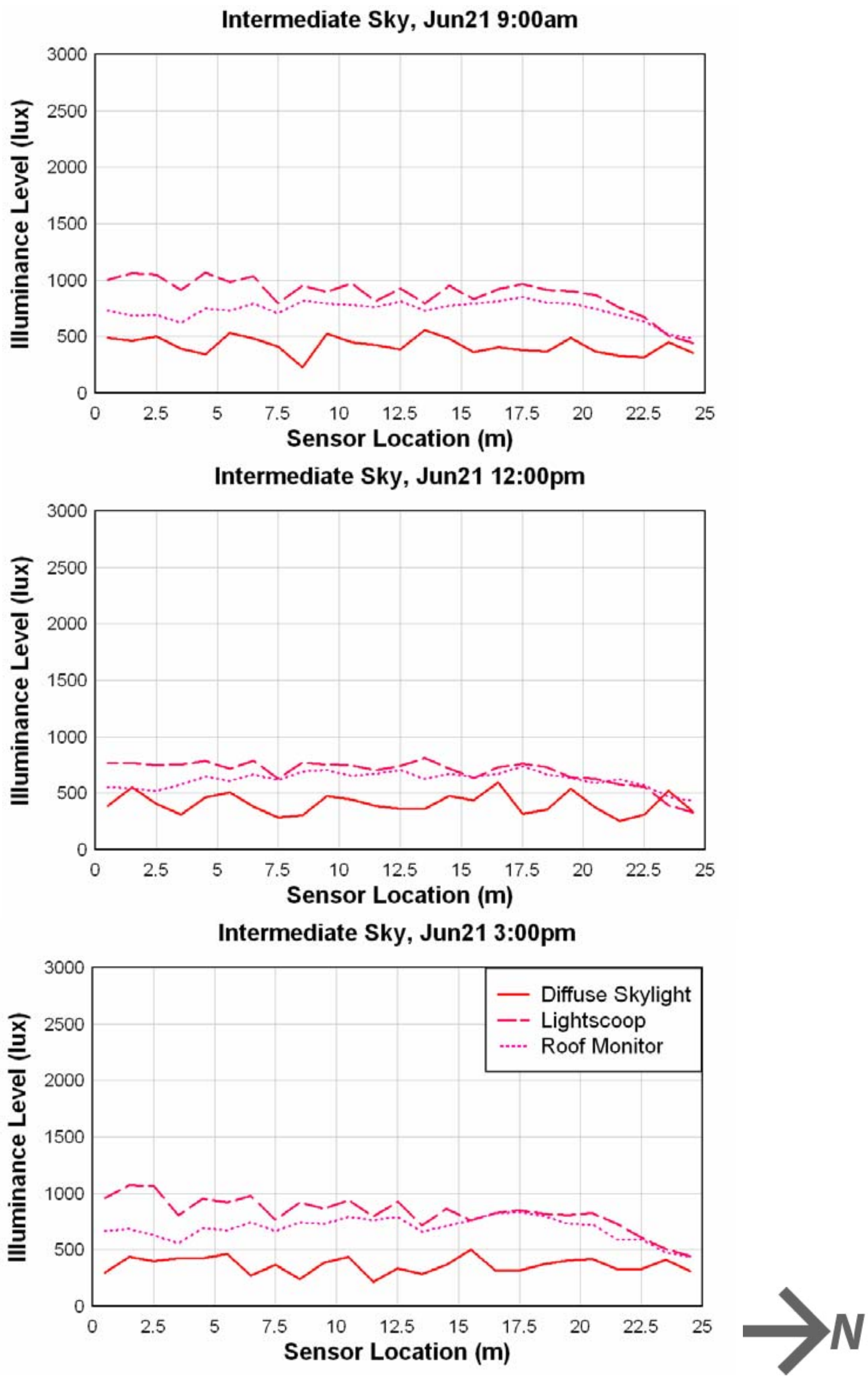

Fig. 5.36 1 to 1 toplighting: illuminance level comparison, intermediate sky, June 21

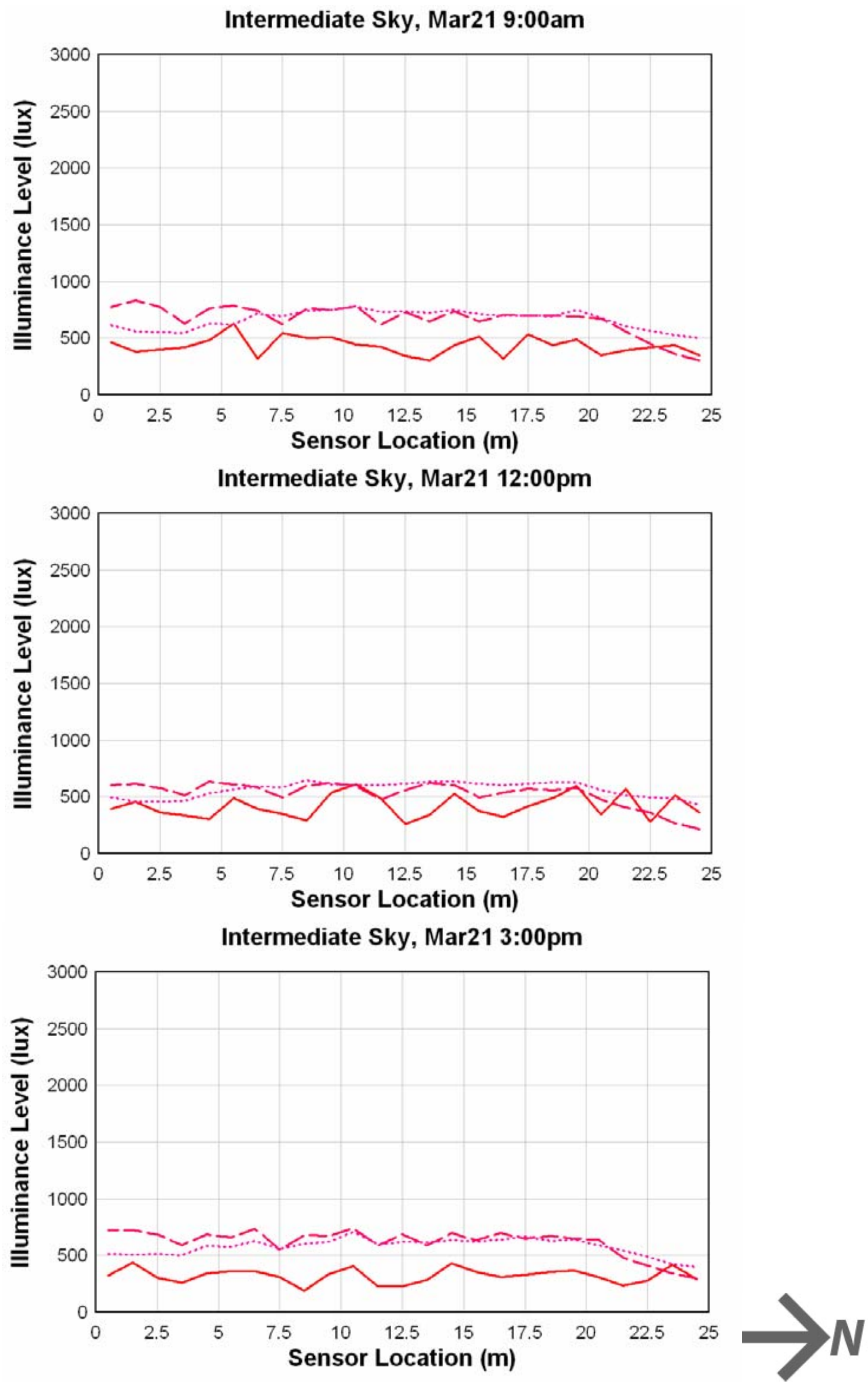

Fig. 5.37 1 to 1 toplighting: illuminance level comparison, intermediate sky, March 21

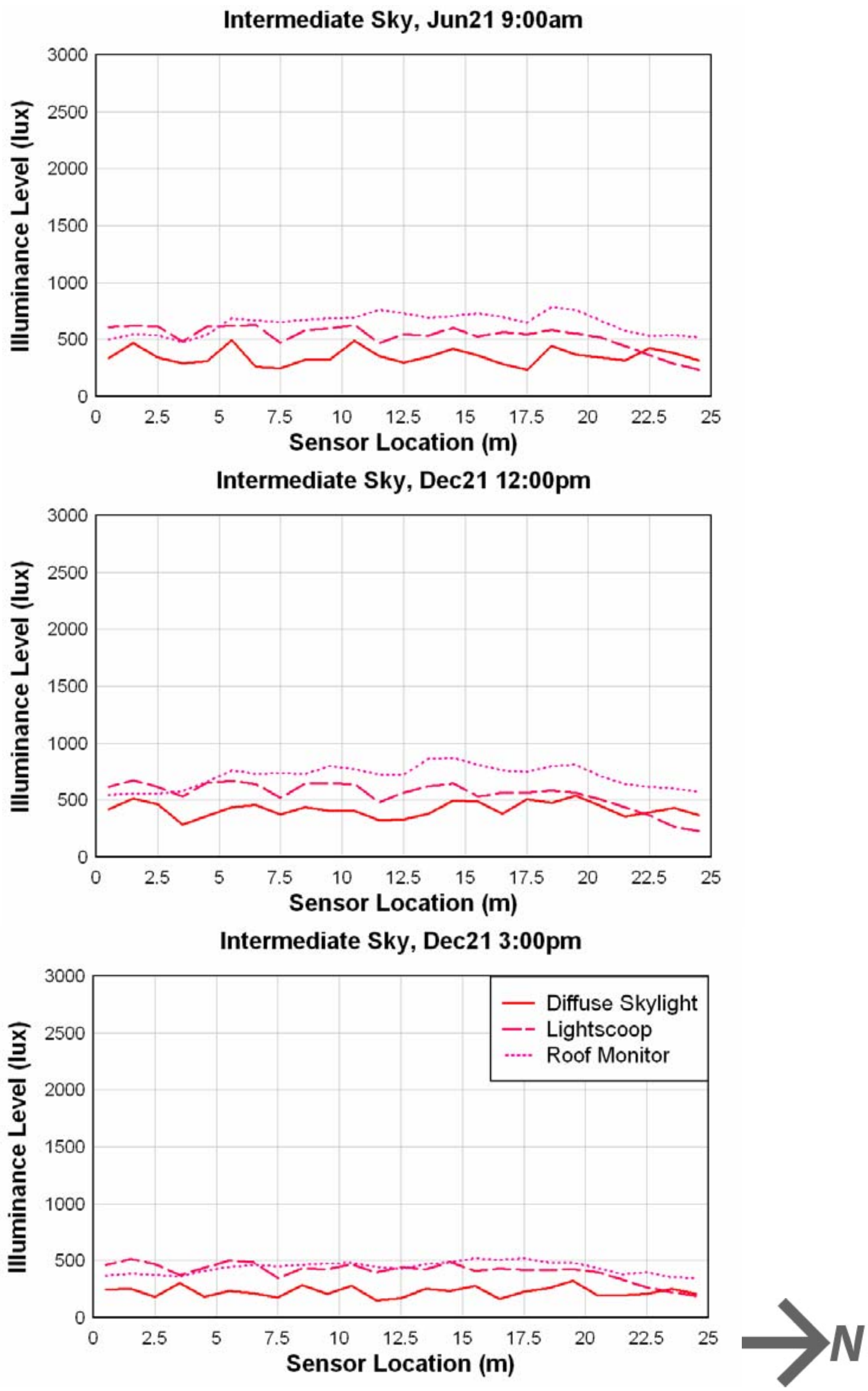

Fig. 5.38 1 to 1 toplighting: illuminance level comparison, intermediate sky, December 21

Overcast Sky: Daylight Factor Analysis

For the daylight factor level, lightscoop prototype yields a higher daylight factor level than the other prototypes. The roof monitor and diffuse skylight yield a lower maximum daylight factor, respectively. From the chart, it can be seen that, even though the lightscoop yields a higher daylight factor than the roof monitor, still, the curves are close. The diffuse skylight prototype has the lowest illuminance values.

The 1 to 1 spacing-to-height lightscoop prototype yields maximum daylight factor level of 5 % while diffuse skylight, which gives least maximum daylight factor level at 2.5 %; these two prototypes have a range of maximum daylight factor difference of 34 %. The roof monitor also has a maximum daylight factor less than lightscoop at a range of 25 %. In general, daylight factor values are more than in the 1.5 to 1 spacing-to-height prototypes at about 0.5 %.

Overcast Sky: Light Distribution Analysis

From the chart, it can be seen that, for a 1 to 1 spacing-to-height ratio, the distribution is improved from a single unit and a 1.5 to 1 spacing-to-height prototype, since more of daylight apertures are installed. Even though only 2 units are added from the 1.5 to 1 spacing-to-height prototype, the distribution is better. The roof monitor and lightscoop prototypes have similar light distribution pattern than the diffuse skylight prototype. In the case of the diffuse skylight, it can be seen that the system causes pools of light, by having more difference between the maximum and minimum point under each opening, which might affect the visual comfort.

Clear Sky: Illuminance Level Analysis

For clear sky conditions, the diffuse skylight prototype yields a higher maximum illuminance value than the lightscoop or roof monitor in all the tested solar conditions; reaching up to 3,000 lux at summer noon. The lightscoop and roof monitor yield closer illuminance value than for the diffuse skylight prototype; still, the diffuse skylight has closer illuminance level to other prototypes in equinox and winter.

The diffuse skylight's illuminance levels are mostly lower than other prototypes. The illuminance levels vary seasonally by having more illuminance value in summer and decreasing in summer. The maximum illuminance level in summer is at about 2,200 lux and in winter at about 600 lux.

The illuminance value of the lightscoop prototype reaches its maximum in summer solstice at solar noon at nearly 3,000 lux. For the lightscoop, the illuminance level is higher in summer and is lower in winter, with the difference between the maximum illuminance level of summer and winter at 1,100 lux. Even though the lightscoop prototype yields generally higher illuminance level than the roof monitor, still, in winter, the illuminance level of the lightscoop prototype is lower than the roof monitor. This is the same as in the case of a 1.5 to 1 spacing-to-height prototype.

The roof monitor prototype, in general, yields lower illuminance value than the lightscoop prototype, still, the illuminance value does not vary much throughout the year compared to other prototypes. However, the illuminance levels are higher than other prototypes in winter.

Clear Sky: Light Distribution Analysis

For the light distribution in the clear sky conditions, as can be visually derived from the charts, the roof monitor and lightscoop prototypes perform similarly by having a more even light distribution than the diffuse skylight throughout the year. More detailed analysis between these two systems on daylight distribution and uniformity will be given in the next section. The diffuse skylight prototype, has a wider range of illuminance value, which causes the light distribution to be worse than lightscoop and roof monitor.

In sum, the lightscoop prototype still yields higher illuminance level in clear sky condition and higher daylight factor in overcast condition when the thermal performance is equal. The roof monitor prototype has higher illuminance level in winter and visually better light distribution.

Intermediate Sky: Illuminance Level Analysis

In general, the illuminance levels of all the prototypes are lower than those of clear sky condition at more than 50 % and the illuminance level is quite constant throughout the year. The illuminance of lightscoop is higher than other prototypes in summer. In equinox, the lightscoop and roof monitor prototypes have similar illuminance values, which are higher than the diffuse skylight. In winter, the roof monitor yields higher illuminance level than other prototypes.

Intermediate Sky: Light Distribution Analysis

The light distributions of all the prototypes, as can be seen from the charts, are better than under clear sky conditions because the curves are flatter and more constant. Different performance between each prototype cannot be clearly distinguished using the line chart as presented since all the lines seem to have similar distribution. Therefore, the distributions have to be analyzed using the contour charts for rectangular reference grid.

5.4.2. Illuminance Uniformity Analysis

Horizontal illuminance contour comparison of 1.5 to 1 spacing-to-height toplighting prototypes are illustrated in Fig. 5.39 for the overcast sky conditions and in Figs. 5.40-5.42 for each case in clear sky condition at different solar positions.

The intermediate sky results are presented in Figs. 5.43-5.45 for each case at different solar positions in all the solstices.

The illuminance gradient values are presented in Table 5.6 and the uniformity of illuminance value is presented in Table 5.7. As described earlier in Chapter III, that the primary parameter for analyzing the uniformity of the illuminance is the illuminance gradient (or illuminance diversity as referred by CIBSE term).

Evaluation of the light distribution and uniformity of each case in different sky conditions are discussed later on in this section.

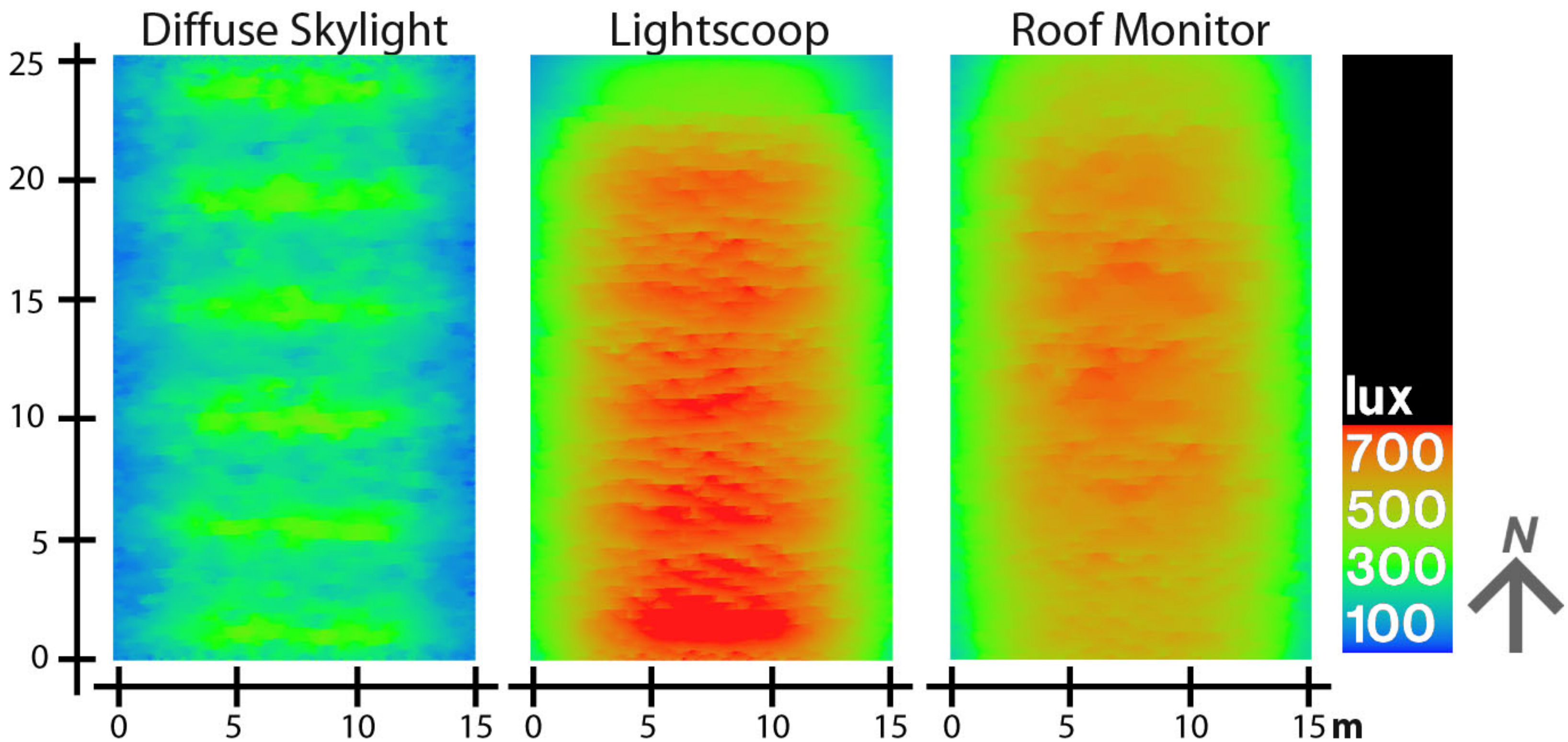

Fig. 5.39 1 to 1 toplighting: illuminance contour on plan, overcast sky

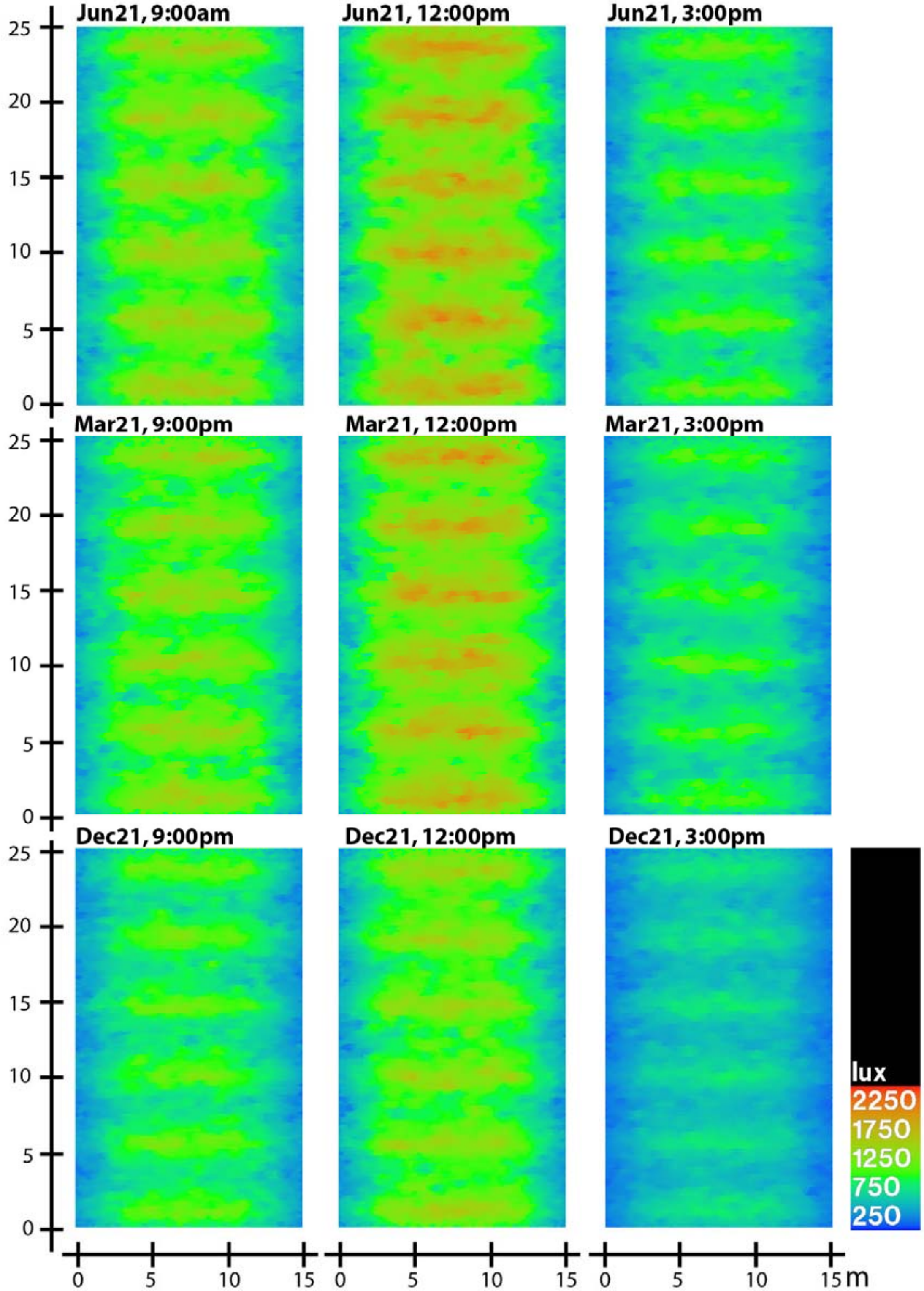

Fig. 5.40 1 to 1 diffuse skylight: illuminance contour on plan, clear sky

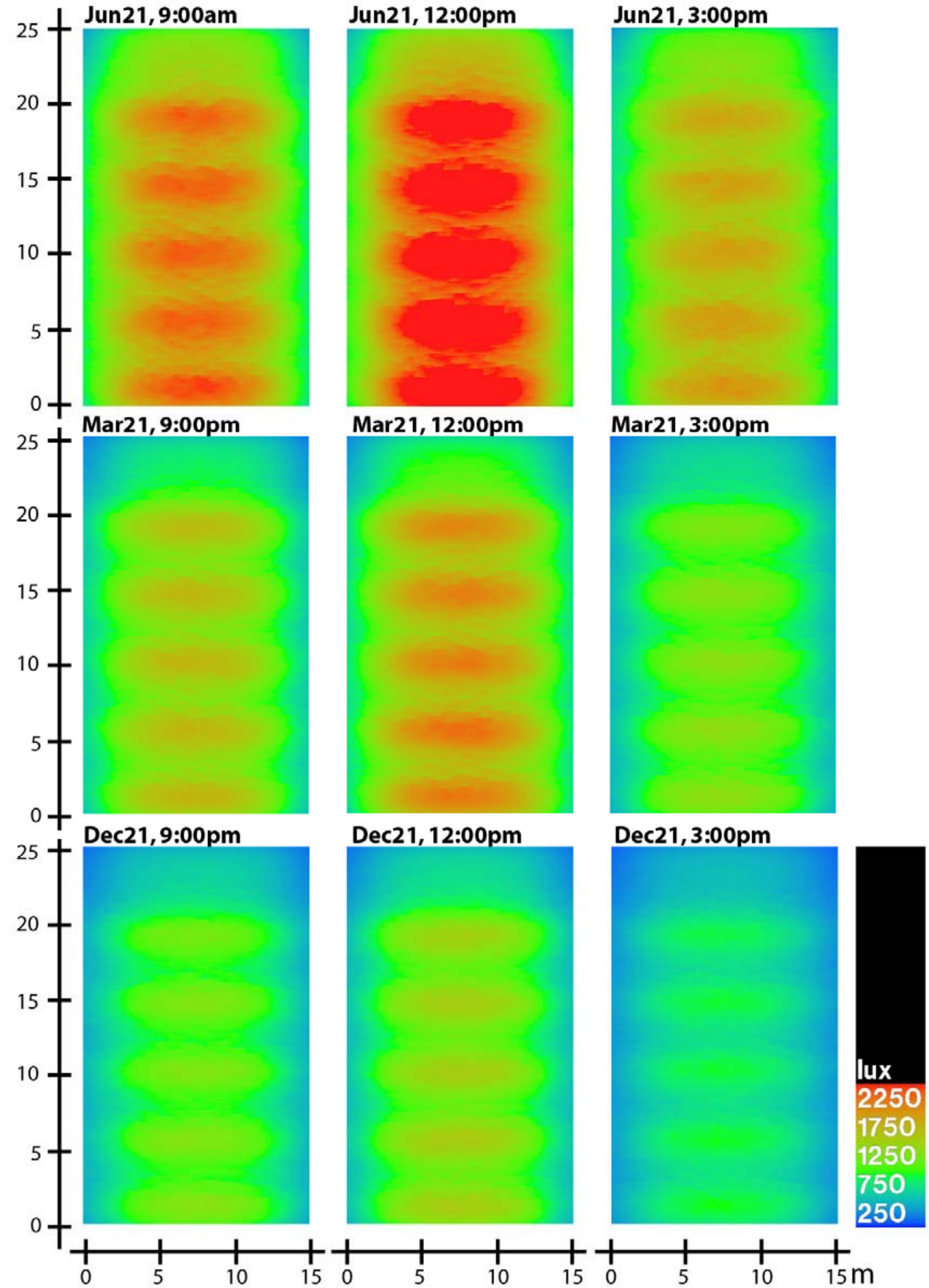

Fig. 5.41 1 to 1 lightscoop: illuminance contour on plan, clear sky

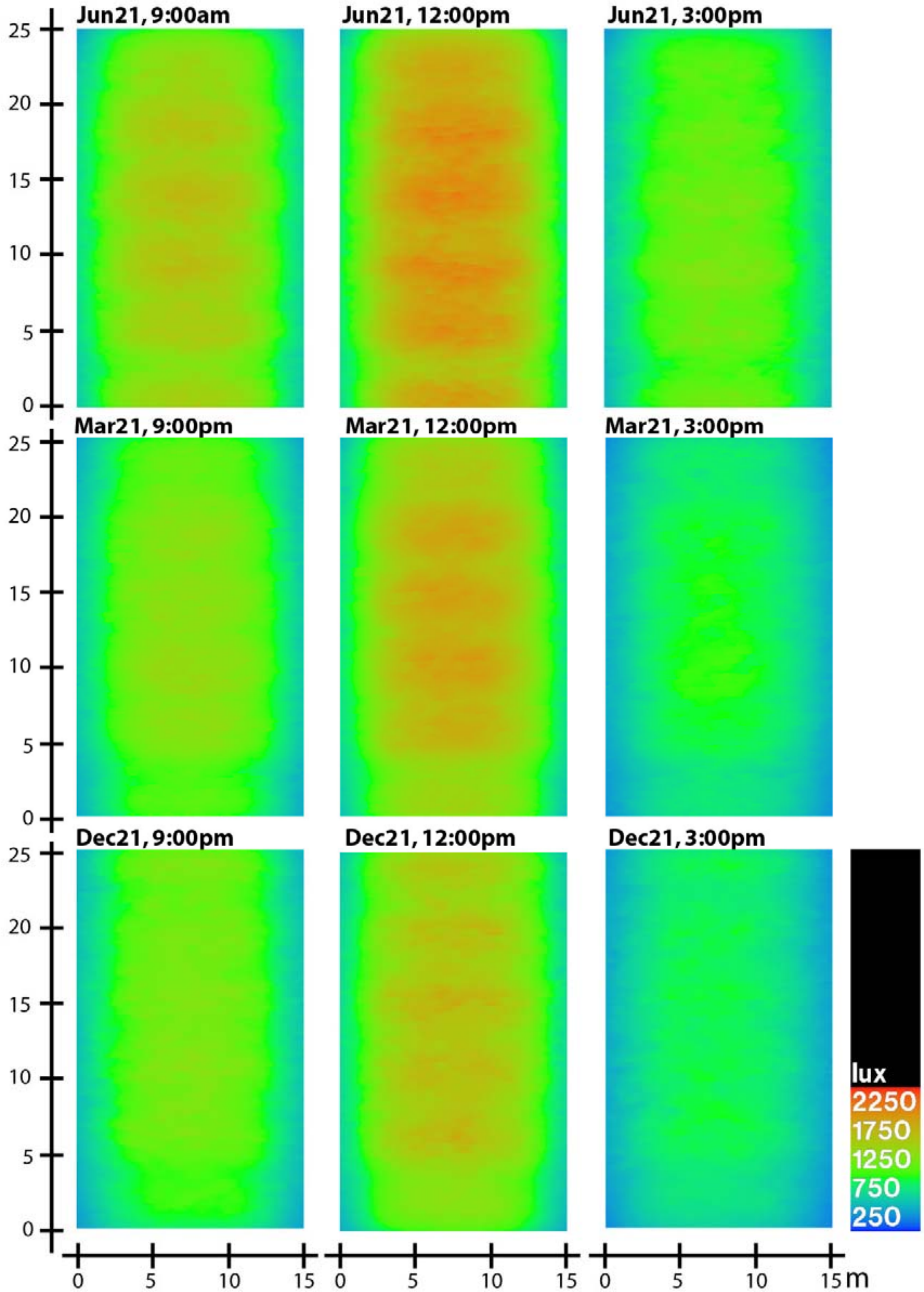

Fig. 5.42 1 to 1 roof monitor: illuminance contour on plan, clear sky

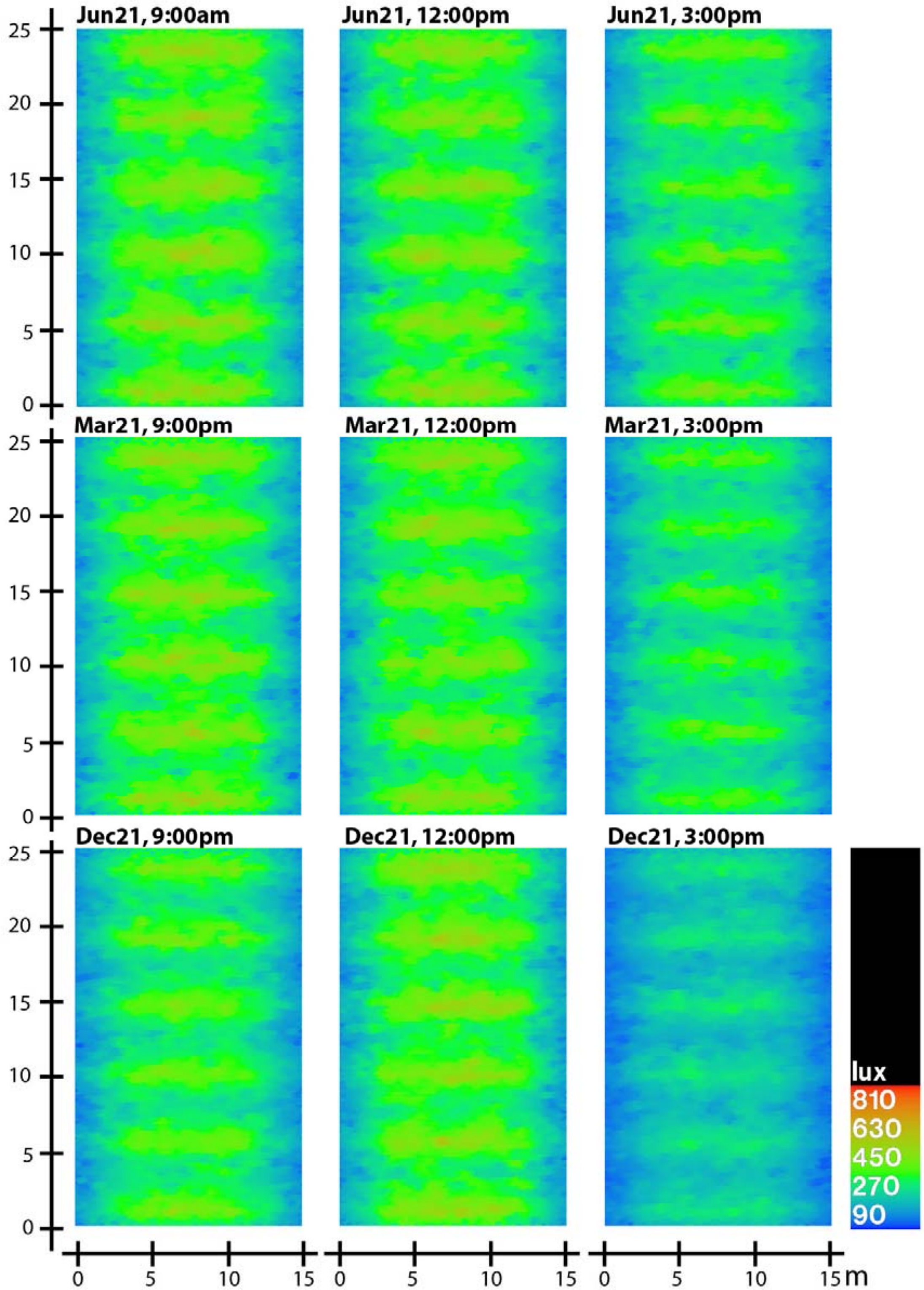

Fig. 5.43 1 to 1 diffuse skylight: illuminance contour on plan, intermediate sky

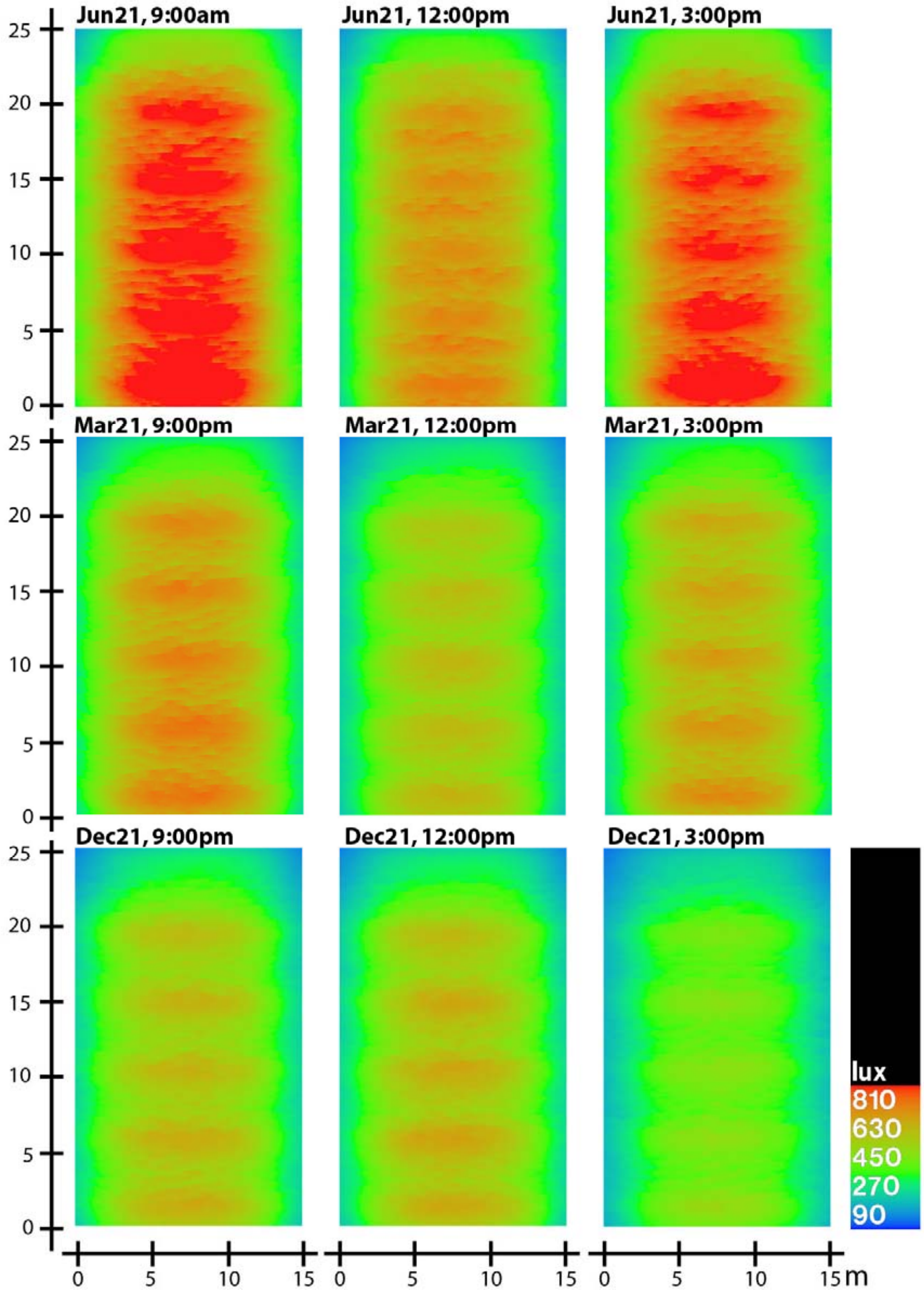

Fig. 5.44 1 to 1 lightscoop: illuminance contour on plan, intermediate sky

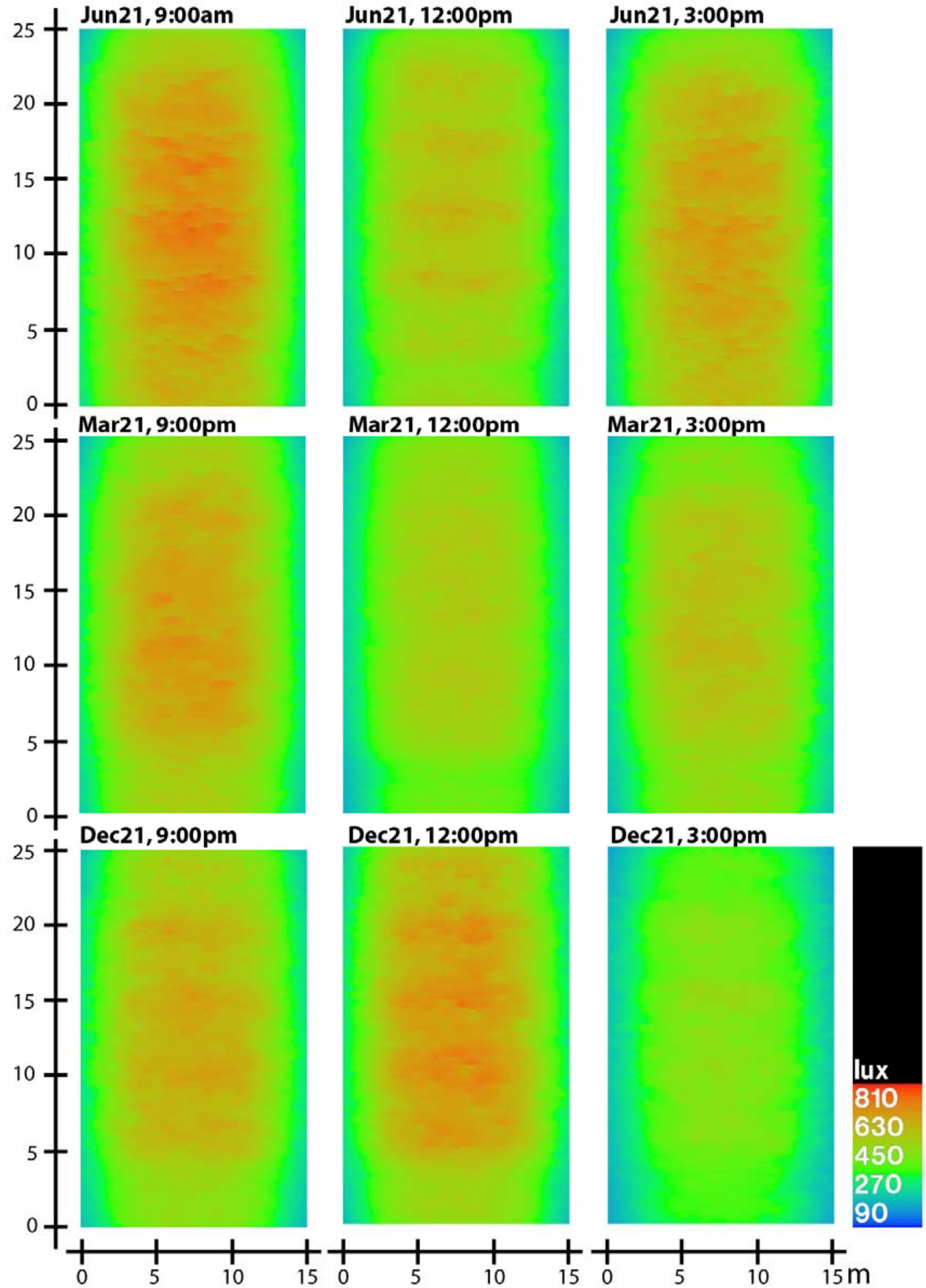

Fig. 5.45 1 to 1 roof monitor: illuminance contour on plan, intermediate sky

Table 5.6 1 to 1 spacing-to-height ratio toplighting: illuminance gradient comparison

	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast Sky	7	7	5
Clear Sky			
Jun21, 9:00am	6	5	4
Jun21, 12:00pm	8	5	4
Jun21, 3:00pm	9	5	4
Mar21, 9:00am	5	7	4
Mar21, 12:00pm	8	7	3
Mar21, 3:00pm	7	6	4
Dec21, 9:00am	8	6	3
Dec21, 12:00pm	7	7	4
Dec21, 3:00pm	8	6	3
Intermediate Sky			
Jun21, 9:00am	8	6	4
Jun21, 12:00pm	7	7	5
Jun21, 3:00pm	7	6	5
Mar21, 9:00am	7	7	4
Mar21, 12:00pm	8	7	4
Mar21, 3:00pm	5	7	5
Dec21, 9:00am	7	7	4
Dec21, 12:00pm	6	7	4
Dec21, 3:00pm	8	7	4

Illuminance gradient is the ratio of maximum to minimum illuminance of each case; lower value indicates better uniformity

Table 5.7 1 to 1 spacing-to-height ratio toplighting: uniformity of illuminance comparison

Time/Case	Diffuse Skylight	Lightscoop	Roof Monitor
Overcast	0.29	0.21	0.29
Clear Sky			
Jun21, 9:00am	0.33	0.28	0.34
Jun21, 12:00pm	0.22	0.27	0.35
Jun21, 3:00pm	0.22	0.30	0.34
Mar21, 9:00am	0.34	0.23	0.39
Mar21, 12:00pm	0.24	0.22	0.41
Mar21, 3:00pm	0.28	0.25	0.39
Dec21, 9:00am	0.23	0.24	0.42
Dec21, 12:00pm	0.28	0.22	0.41
Dec21, 3:00pm	0.23	0.26	0.44
Intermediate Sky			
Jun21, 9:00am	0.26	0.25	0.33
Jun21, 12:00pm	0.27	0.24	0.33
Jun21, 3:00pm	0.27	0.26	0.30
Mar21, 9:00am	0.25	0.22	0.36
Mar21, 12:00pm	0.24	0.20	0.40
Mar21, 3:00pm	0.33	0.23	0.34
Dec21, 9:00am	0.29	0.21	0.42
Dec21, 12:00pm	0.32	0.21	0.40
Dec21, 3:00pm	0.27	0.23	0.39

Uniformity of illuminance ratio is the ratio of minimum to average illuminance of each case; higher value indicates better uniformity

Overcast Sky Condition: Distribution and Uniformity Analysis

In the overcast sky condition, the roof monitor prototype provides better light distribution throughout the room even though it yields less illuminance value than the lightscoop. The lightscoop's distribution is close to the roof monitor prototype but the light distribution is not as even, as can be seen from the chart that the contours are closed together than with a case of the roof monitor. For the diffuse skylight, light is distributed mostly under the apertures in the while for the lightscoop or roof monitor, light concentration shifts a little from the area directly under the opening into the south side of the room. Also, light from the lightscoop and roof monitor reaches the perimeter of the room more than from the diffuse skylight prototype, indicating better light distribution.

The illuminance gradient ratio of the roof monitor is the lowest, with the lightscoop prototype performing second best. From the tables, in the overcast sky conditions, the illuminance gradient values of each case with the spacing-to-height ratio of 1 to 1 are 7, 7, and 5, for the diffuse skylight, lightscoop, and roof monitor, respectively. Compared to the illuminance gradient values of the 1.5 to 1 spacing-to-height ratio, these values are lower for all the prototypes. (The illuminance gradient value for the 1.5 to 1 spacing-to-height ratio prototypes are 13, 8, and 4, for the diffuse skylight, lightscoop, and roof monitor, respectively.)

For the uniformity of illuminance ratio, the roof monitor prototype still performs better by having the highest values. The uniformity of illuminance ratios for the diffuse skylight, lightscoop, and roof monitor, are 0.18, 0.23, and 0.35, respectively. From these values, it can be analyzed that the roof monitor prototype still performs better in terms of illuminance uniformity and the lightscoop performing second best.

To summarize, it can be said that, in overcast sky conditions, the roof monitor gives better light distribution and uniformity than other prototypes, with the lightscoop performing second-best.

Clear Sky Condition: Distribution and Uniformity Analysis

For the clear sky conditions, the single roof monitor still performs better than other prototypes in all the tested representative days by distributing light more uniformly. From the illuminance contour charts (Figs. 5.40-5.42), it can be seen that, for the diffuse skylight, in clear sky conditions, the light distribution concentrates around the areas right under the apertures and does not spread into the room perimeter as much as other prototypes. The distribution pattern is similar all year but the light level decreases in winter time.

For the lightscoop prototype, the distribution patterns also do not vary much by the time of year and better uniformity is achieved in winter due to lower light level than in summer. The light distribution patterns of the lightscoop still have some pools of light but not as evident as in the case of the diffuse skylight prototype since light spreads more into the room perimeter.

The light distribution patterns of the 1 to 1 spacing-to-height roof monitor vary a little throughout the year by spreading more light to the south area of the room in summer and more to the north of the room in winter. Light is distributed better than in the case of lightscoop because the contours are farther apart than in the case of the lightscoop prototype, even though it gives lower illuminance value most of the time. However, in general, the light distribution performance is still close to that of a 1.5 to 1 spacing-to-height lightscoop prototype.

From the horizontal illuminance contour charts, it can be summarized that the system that performs best in terms of illuminance distribution and uniformity is the roof monitor prototype, with the lightscoop performing second-best.

From the illuminance gradient ratio table (Table 5.6), the roof monitor yields the least value than other prototypes in all the tested date and time, which range from

3-5. From the results, it can be seen that the roof monitor prototype can meet and in some dates even exceed the standard set by CIBSE Code which is set at 5 at maximum. Therefore, in a case of the roof monitor, the spacing-to-height ratio might be increased and can still meet the standard. The values generated also correspond to the horizontal illuminance contour charts analysis.

For the uniformity of illuminance table (Table 5.7), the roof monitor still performs better than other prototypes, by yielding higher uniformity ratio than other cases. Lightscoop gives about 0.10 less than a roof monitor. Still, all the values cannot meet the criteria set by CIBSE which is recommended at more than 0.80 yet. However, since the simulated space does not have any interior furniture, this parameter is not analyzed as a primary factor as the illuminance gradient. In general, the performance that can be analyzed from this parameter is the same as from illuminance gradient parameter as discussed earlier.

When comparing the illuminance diversity ratio between overcast and clear sky condition, all the systems performs better in clear sky condition.

Intermediate Sky Condition: Distribution and Uniformity Analysis

For intermediate sky conditions, the roof monitor prototype still performs better than other systems in all the tested times by distributing light more evenly.

From the illuminance contour charts (Figs. 5.43-5.45) , for the diffuse skylight prototype, the light distribution is still mostly concentrated in the central area right under the aperture, while for lightscoop and roof monitor, the light are distributed more to the perimeter of the space. This is the same as in the case of 1.5 to 1 spacing-to-height ratio prototypes. The distribution for diffuse skylight has similar pattern throughout the year, but with more illuminance level at noon time.

The lightscoop prototype still has the light distribution pattern similar to its performance under clear sky, which the distribution pattern remains quite constant under different solstices but the overall illuminance values are much lower. Still, the difference is that the illuminance level at noon in general is lower than morning and afternoon under intermediate sky in summer. Also, more variability of light can be noticed if compared to the case of a 1.5 to 1 spacing-to-height ratio prototype. This could be because of higher illuminance level is achieved though more units of glazing.

The roof monitor prototype still has similar light distribution patterns throughout the year and the patterns do not vary much. Comparing to the distribution of the 1.5 to 1 spacing-to-height ratio prototypes, it can be seen that the distribution of the 1 to 1 spacing-to-height ratio prototype has more variability of light that can be noticed. This could be because the 6-unit yields more illuminance level than a 4-unit prototype. Therefore, no conclusions can be drawn from analyzing only the contour charts. The illuminance gradient has to be analyzed. Still, it can be noticed that the roof monitor still has better uniformity than other prototypes.

From the illuminance gradient ratio table (Table 5.6), it can be seen that the roof monitor prototype still yields less value of illuminance gradient in all the tested date and time under intermediate sky than other cases; with the values range from 4-5.

The diffuse skylight's gradient ratios are mostly from 5-8, which are similar to the performance under clear sky conditions. Still, for the case of the diffuse skylight, there are times of year that the illuminance gradient peaks to 14 at summer solstice at 3:00pm.

The lightscoop prototype has the illuminance gradient values range from 6-7, which are generally higher than the values under clear sky which range from 5-7, pointing out worse performance under intermediate sky condition than under clear sky condition. Still, the illuminance gradient under intermediate sky condition of a 1 to 1 spacing-to-height lightscoop is better than of a 1.5 to 1 spacing-to-height which has the illuminance gradient ranges from 6-9. The results point out that, for the lightscoop prototype, decreasing the pacing-to-height ratio to 1 to 1 can help nullify the uniformity problem that occurs with a 1.5 to 1 prototype by bringing the illuminance gradient ratio under clear sky and intermediate sky to a narrower range of 5-7 while in a 1.5 to 1 spacing-to-height ratio, this value ranges from 6-10 under both sky conditions.

For the roof monitor prototype, the illuminance gradient ratios are also higher under intermediate sky condition than under clear sky condition, which the values range from 4-5 under intermediate sky and 3-4 under clear sky condition. Comparing to the performance of a 1.5 to 1 spacing-to-height ratio prototype, the illuminance gradient ratios of a 1 to 1 spacing-to-height ratio prototype under intermediate sky are similar to a 1.5 to 1 spacing-to-height ratio prototype.

In the uniformity of illuminance table (Table 5.7), the roof monitor prototype still yields more ratio than other cases, reaching at about 0.30-0.40. In general, these values are similar to the values under the clear sky conditions for all the cases.

For the diffuse skylight prototype, the uniformity of illuminance values are higher with a 1 to 1 spacing-to-height ratio than in a 1.5 to 1 spacing-to-height ratio. For the lightscoop, the ratios are about the same as for a 1.5 to 1 spacing-to-height ratio prototype. For the roof monitor, these ratios are similar to its performance with a 1.5 to 1 spacing-to-height ratio prototype which the values range from 0.30-0.40 also.

To summarize the distribution and uniformity of all the systems, the roof monitor prototype gives better light distribution and uniformity than other systems under variable sky conditions as tested for the entire spacing-to-height ratio tested. The diffuse skylight and lightscoop prototypes perform better with decreased spacing-to-height ratio but roof monitor prototype developed has its optimum spacing-to-height ratio at 1.5 to 1. Comparing between the diffuse skylight and lightscoop prototypes, under variable sky conditions, the lightscoop performs better than diffuse skylight. Only under intermediate sky conditions that the diffuse skylight with a 1 to 1 spacing-to-height ratio performs similarly to the lightscoop in terms of light distribution and uniformity.

5.4.3. Glare Analysis

Renderings and the luminance of each reference points from each toplighting prototype with a 1.5 to 1 spacing-to-height ratio are presented in Figs. 5.46-5.48.

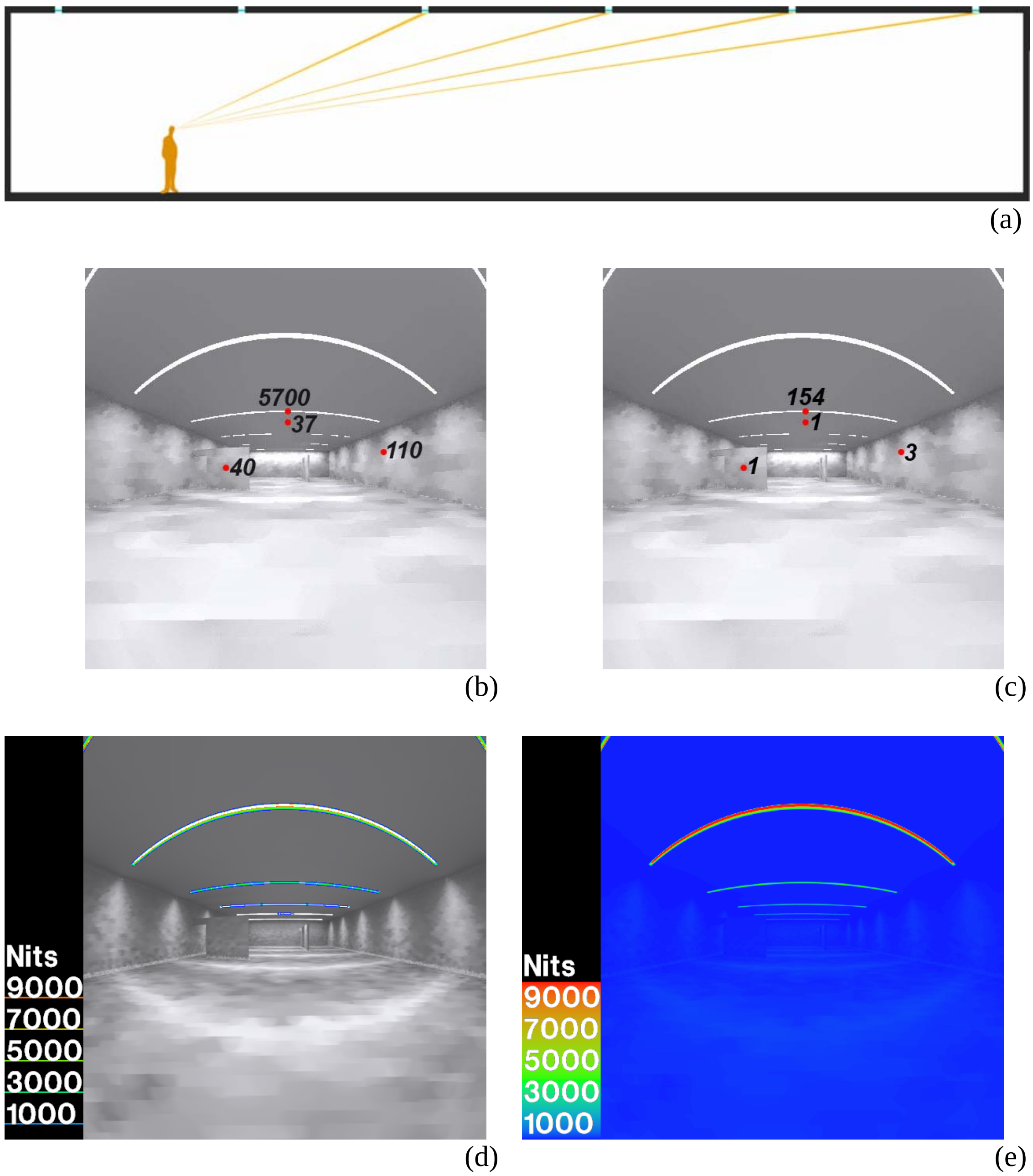

Fig. 5.46 1 to 1 diffuse skylight: glare analysis pictures from RADIANCE
(a) section showing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

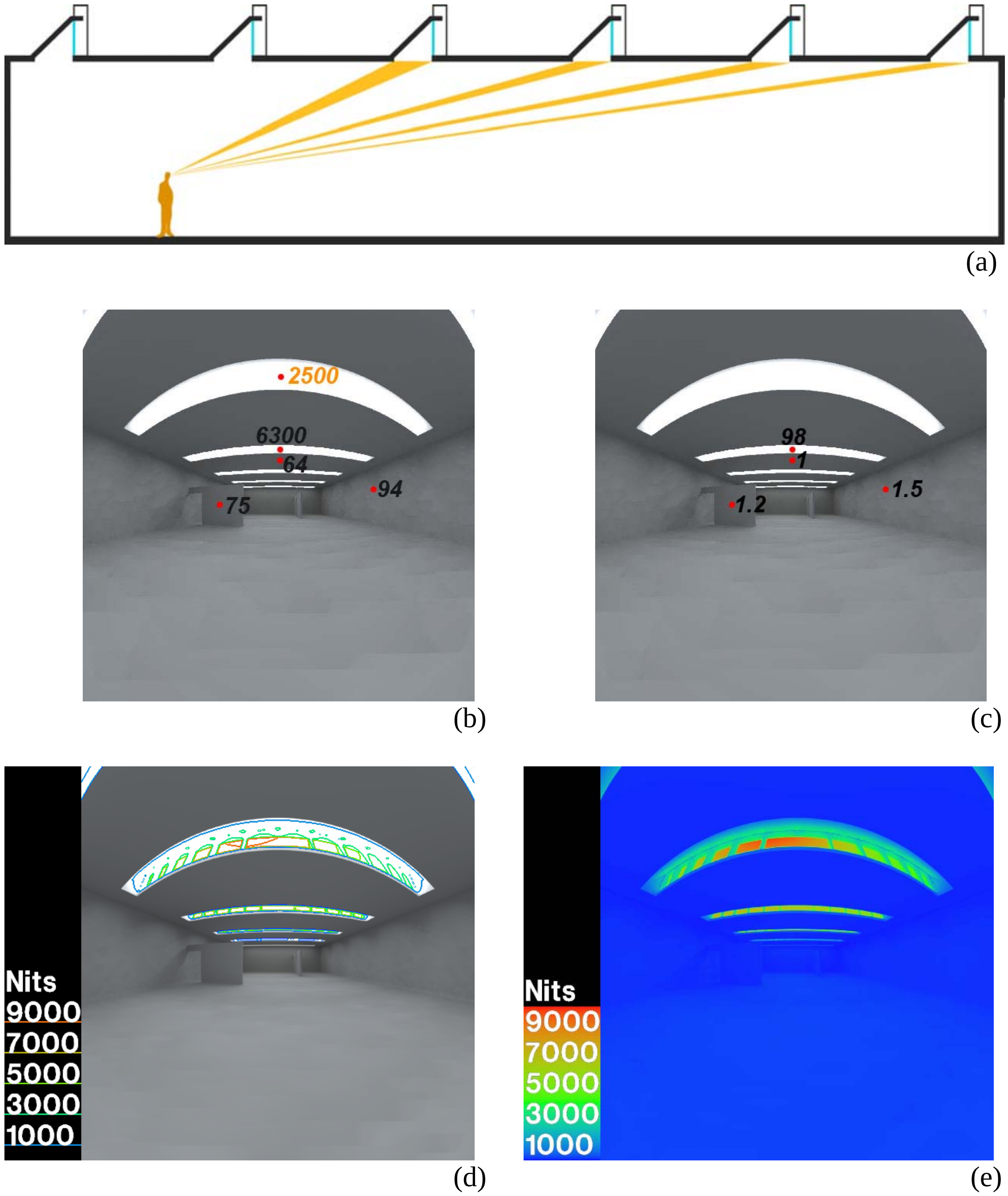

Fig. 5.47 1 to 1 lightscoop: glare analysis pictures from RADIANCE
(a) section showing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

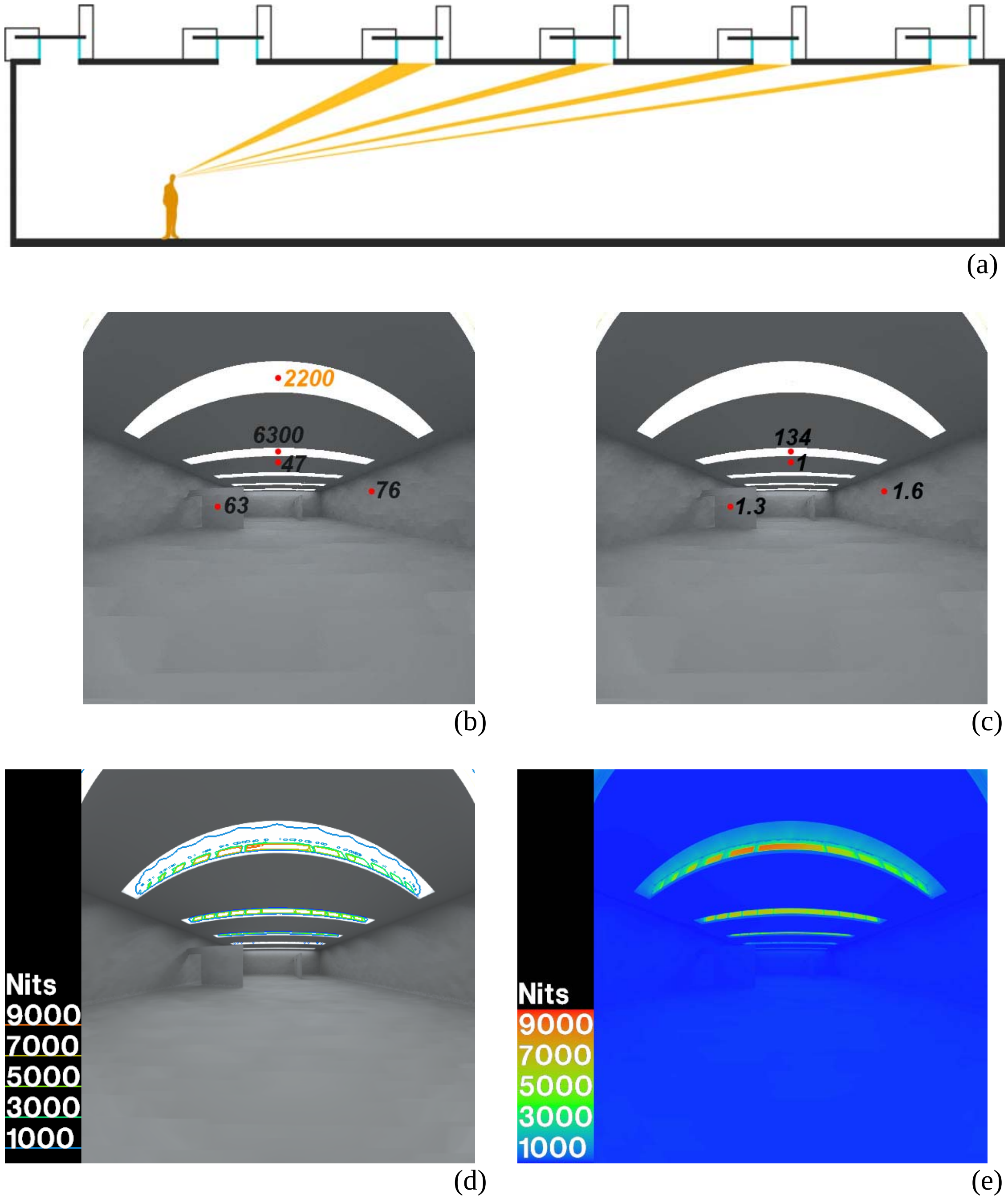

Fig. 5.48 1 to 1 roof monitor: glare analysis pictures from RADIANCE
(a) section analyzing offending angle (b) luminance at reference points in the room
(c) luminance ratio (d) iso-contour rendering (e) falsecolor rendering

The position of the observer is the same as mentioned in the previous section which is at the center and 4.00m from the back of the room.

From Figs. 5.46-5.48, it can be seen that, all the prototypes with a 1 to 1 spacing-to-height ratio have the probability of causing glare on clear summer solstice at solar noon, by having higher luminance ratio than the recommended ratio of 1 to 40 in the observer's field of view.

The diffuse skylight prototype, even with diffuse glazing, still has higher luminance ratio than other cases, same as for the 1.5 to 1 spacing-to-height ratio prototype. The offending angle section has shown that it has narrower angles than the lightscoop or roof monitor prototypes. Still, from the luminance of at 5,700 cd/m^2, the luminance ratio between the glazing and the adjacent ceiling surface is 154, which is still higher than 1:20 or 1:40.

For the lightscoop prototype, the luminance ratio is similar to the case of 1.5 to 1 spacing-to-height ratio prototype, having the luminance at the glazing in the field of view at 6,300 cd/m^2. It can be noticed that, the luminance at the toplighting system is high at the glazing but is reduced only the parts covered by the shading devices are seen (in the orange spot), which is at 2,500 cd/m^2; (but this point is present in the fisheye projection only but not in the observer's field of view). The overall luminance at the room surfaces is at about 60-90 cd/m^2 which is higher than in the case of 1.5 to 1 spacing-to-height ratio prototype. The luminance ratio of the glazing and the adjacent surface is at about 1 to 98. From the iso-contour and the falsecolor images presented (in Figs. 5.47d, 5.47e), the luminance contrast can be clearly noticed.

The roof monitor prototype with a spacing-to-height ratio of 1 to 1 performs similarly to the lightscoop in terms of glare by having close luminance ratio which is still higher than 1 to 40. However, the luminance ratio between the adjacent surface and the glazing is higher than in the case of lightscoop; at 1:134. This is because the luminance at the ceiling of the roof monitor prototype is lower than the lightscoop.

To summarize, all the prototypes with the spacing-to-height ratio of 1 to 1 have the chance of glare because the glazing is in the observer's field of view. The solution could be to lift the system off the occupant's field of view or to design the light well to make the cut off angle to block the glazing from the occupant's field of view. Also, the tested date and time is for most chance of glare; if test the different date/time and view angle, glare might be lower.

5.5. Summary on Lighting Performance Evaluation

5.5.1. Summary on Daylight Factor and Illuminance Level

- Under overcast conditions, the lightscoop prototype gives higher daylight factor values than the other systems.
- Under the clear sky and intermediate sky conditions, the lightscoop prototype has a higher illuminance level than the other prototypes in summer, while the diffuse skylight prototype has a higher illuminance level at all other times.
- Under intermediate sky conditions, all the prototypes perform similarly in terms of illuminance level. Still, the overall illuminance values of all the prototypes are less than half the values under clear sky conditions.

- In general, the roof monitor yields a lower illuminance value than the other prototypes.

5.5.2. Summary on Illuminance Distribution and Uniformity

- All the prototypes perform better in terms of light distribution and uniformity when increased from single unit to multi-unit prototypes.
- The reduction of the spacing-to-height ratio from 1.5 to 1 to 1 to 1 (or the addition of units of aperture from 4 to 6 units) increases the uniformity for all the prototypes, except for the roof monitor, which performs similarly in terms of the light distribution and uniformity for both spacing-to-height ratios.
- The roof monitor prototype performs better than the other prototypes in terms of light distribution and uniformity under all sky conditions, as a greater spacing-to-height ratio can be used to achieve the same level of illuminance gradient ratio.

5.5.3. Summary on Glare Analysis

- For all the prototypes under clear sky on the summer solstice at solar noon, there is a chance of glare because of the glazing area is exposed to the observer’s field of view.
- Chances of glare under overcast and intermediate sky conditions are not observed due to the time limits. The results might be different from under the clear sky condition.

- The luminance ratio exceeds 1 to 40, which is the recommended maximum luminance ratio. Therefore, some adjustments to the design have to be done to alleviate this problem.
- By lifting the toplighting system off the observer's field of view or creating a cut off angle, the presence of glare can be reduced.
- The tested view angle is the critical angle; therefore, for different view angles and other dates and times, the luminance ratio might be lower.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

From the results of the study, it could be concluded that, when all the developed prototypes have performed similarly in terms of the thermal performance by having similar amounts of the cooling load, the overall performance of the roof monitor prototype is the better than other prototypes. Under variable sky conditions, the roof monitor has better illuminance uniformity and distribution than other systems, with adequate illuminance level (at mostly higher than 500 lux).

6.1. Conclusions about the Thermal Performance of the Prototypes

Shading has proved to be very significant for the design of toplighting in a climate like that of Bangkok, Thailand. From the prototypes, it can be seen that the installation of shading devices has effectively helped to reduce the total cooling loads.

All the prototypes have proved to be thermally comparable by yielding similar average cooling loads during the year. When all the prototypes yield similar cooling loads, the prototype with the largest glazing area is the roof monitor, followed by the lightscoop, and then the diffuse skylight. Increasing the glazing area does not affect the total cooling load to a great extent. Moving from a single unit prototype to one of 6 units, the average total cooling load increased less than 15%, even with a cooling schedule of 24 hours.

As a result, allowing daylight into the interior spaces via toplighting should not be dismissed as a design option in this climate. However, designers should consider their design priorities regarding increased cooling loads and the reduction of electric lighting energy use.

6.2. Conclusions about the Lighting Performance of the Prototypes

The overall performance of the roof monitor prototype bests the other prototypes under variable sky conditions. Yielding better uniformity and distribution than other systems, despite a lower illuminance level, the roof monitor prototype can be considered as outperforming the other prototypes. The diffuse skylight prototype, even though it yields a higher illuminance level than the other prototypes during most of the year, has poor lighting performance in terms of light distribution and uniformity. The presence of glare is problematic in all of the toplighting prototypes.

These conclusions are made based on the performance of the developed prototypes only and can be applied only to toplighting systems with a similar geometry. Hence, these results cannot be generalized to all skylight, lightscoop, or roof monitor designs. Different designs will result in different performance.

6.3. Design Guidelines on Toplighting in Hot and Humid Climates

For hot and humid climates with variable sky conditions similar to Bangkok, Thailand, roof monitor systems are recommended, as the lighting performance of roof monitors is better than lightscoops and skylights (given similar thermal performance).

The lightscoop design could also be used as an effective strategy. However, electric lighting in dark spots or design adjustments will have to be made to improve its lighting performance in terms of distribution and uniformity. In addition, the lightscoop system, given similar thermal performance, has less glazing area than the roof monitor system, which could reduce the money spent on glazing.

The diffuse skylight is not recommended for use in hot and humid climates, because its lighting performance is worse than the lightscoop and the roof monitor. However, if a skylight is preferred for design reasons, a spacing-to-height ratio of 1 to 1 or less should be used but with the expense of additional costs for glazing, construction, and cooling loads etc.

Glare will be a concern of any toplighting system in this climate. Given the daylight availability, glare could occur even with vertical toplighting systems like the lightscoop or roof monitor. Therefore, the designer should test the geometry of the system in order to hide the glazing from the occupant's field of view and test the use of splay wells or interior louvers.

6.4 Recommendations for Future Studies

Concerning aspects of thermal performance, more studies should be done to test the effect of natural ventilation on interior temperatures. This should be undertaken, because daylighting systems can contribute, not just to lighting of a building, but to its thermal comfort as well.

Concerning aspects of lighting performance, more studies should be done to test the effects of various geometries and shapes of toplighting systems on lighting performance. For example, lightscoop geometry could have some effects on light distribution and uniformity, which could help improve its lighting performance, while maintaining the same glazing area. In addition, the integration of electric lighting into each toplighting prototype should be studied for cost benefits and energy efficiency.

Concerning glare, this study used a height of 1.50m, which is equal to the view of a standing person. More studies should be done testing the presence of glare for a sitting person. Moreover, additional glare design strategies could be tested, such as the addition of light baffles to the toplighting prototype, which could reduce the luminance of the ceiling in the field of view.

More studies of the thermal and lighting performance of toplighting systems should be conducted at latitudes other than that of Bangkok, Thailand. This will increase the amount and type of available results and allow for comparisons between locations. In addition, more studies should be done on the feasibility of implementing these prototypes in Thailand, utilizing feedback from Thai architects.

REFERENCES

[1] F. Moore, Concepts and Practice of Architectural Daylighting, Van Nostrand Reinhold, New York, 1985.

[2] C. Robbins, Daylighting: Design and Analysis, Van Nostrand Reinhold, New York, 1986.

[3] N. Lechnor, Heating, Cooling, Lighting: Design Methods for Architects, John Wiley and Sons, New York, 2001.

[4] Heschong Mahone Group, Daylight and Retail Sales, The California Energy Commission, California, 2003.

[5] Heschong Mahone Group, Windows and Offices: A Study of Office Worker Performance and the Indoor Environment, The California Energy Commission, California, 2003.

[6] Heschong Mahone Group, Windows and Classrooms: A Study of Student Performance and the Indoor Environment, The California Energy Commission, California, 2003.

[7] Pacific Gas and Electric Company, 1999 Commercial Building Survey Report, California, 1999.

[8] IESNA, IESNA Recommended Practice of Daylighting, Illuminating Engineering Society of North America, New York, 1999.

[9] J.F. Busch, P. Pont, S. Chirarattananon, Conserving Electricity for Lighting in Thai Commercial Buildings: A Review of Current Status, Potential, and Policies, in: Proceedings of Right Light 1, Stockholm, Sweden, 1991.

[10] G. D. Ander, Daylighting Performance and Design, Van Nostrand Reinhold, New York, 1995.

[11] W. Lam, Sunlighting as Formgiver for Architecture, Van Nostrand Reinhold, New York, 1986.

[12] R. Cabu’s, F. Pereira, Luminous Efficacy of Daylighting in Intertropical Region: An Analysis for Toplighting Systems, Renewable Energy, 8 (1996) 210-213.

[13] S. Treado, G. Gillette, T. Kusada, Daylighting with Windows, Skylights, and Clerestories, Energy and Buildings 6 (1984) 319-330.

[14] W. Place, M. Fontoynont, C. Conner, R. C. Kammerud, B. Anderson, F. Bauman, W. Carroll, T.C. Howard, A. Mertol, T. Webster, The Predicted Impact of Roof Aperture Design on the Energy Performance of Office Buildings, Energy and Buildings 6 (1984) 361-373.

[15] V. Garcia-Hansen, A. Esteves, A. Pattini, Passive Solar Systems for Heating, Daylighting and Ventilation for Rooms without an Equator-Facing Facade, Renewable Energy 26 (2002) 91-111.

[16] E.J. Dewey, P.J. Littlefair, Rooflight spacing and uniformity, Lighting Research and Technology 30(3) (1998) 119-125.

[17] S. Chirarattananon, P. Chaiwiwatworakul, S. Pattanasethanon, Daylight Availability and Models for Global and Diffuse Horizontal Illuminance and Irradiance for Bangkok, Renewable Energy 26 (2002) 69-89.

[18] IESNA, IESNA Lighting Handbook, 9th Edition, Illuminating Engineering Society of North America, New York, 2000.

[19] S. Chirarattananon, P. Chaiwiwatworakul, S. Pattanasethanon, Challenges of Daylighting with the Luminosity and Variability of the Tropical Sky, Lighting Research and Technology 35(1) (2003) 3-10.

[20] M. J. Witte, R. H. Henniner, J. Glazer, Testing and Validation of a New Building Energy Simulation Program, Proceedings of the Seventh International IBPSA Conference, Rio de Janeiro, Brazil, 2001, pp. 353-359.

[21] LBNL, EnergyPlus Input Output Reference: The Encyclopedic Reference to EnergyPlus Input and Output, University of Illinois and Lawrence Berkeley National Laboratory, 2004.

[22] E.S. Lee, L.O. Beltran, S.E. Selkowitz, Demonstration of a Light-Redirecting Skylight System at the Palm Springs Chamber of Commerce, LBNL, California, 1996.

[23] G. Ward Larsen, R. Shakespeare, Rendering with Radiance- The Art and Science of Lighting Visualization, Morgan Kaufmann Publishers, San Francisco, 2003.

[24] Thai Asahi Glass Company, PairTAG Cross Sections , http://www.tag.co.th/en/sales/assets/pdf/ins7.PDF, (accessed on November 20, 2004).

[25] Thai Asahi Glass Company, PairTAG Glazing Specifications, http://www.tag.co.th/en/sales/assets/pdf/ins4.PDF, (accessed on November 20, 2004).

[26] L.O. Beltran, E.S. Lee, S.E. Selkowitz, Advanced Optical Daylighting Systems: Lightshelves and Lightpipes, LBNL, Berkeley, California, 1996.

[27] CIBSE, CIBSE Code for interior lighting, Chartered Institution of Building Service Engineers, London, 1994.

[28] B. Stein, J.S. Reynolds, Mechanical and Electrical Equipment for Buildings, John Wiley and Sons, New York, 2000.

APPENDIX A

GLOSSARY

This part of the appendix gives the description of the terms used in this thesis.

Daylighting:
the use of the sky or the sun as the source of light

Toplighting:
the use of the ceiling or roof part of the building to bring daylight into the interior space

Illuminance:
the amount of light incident on a surface, measured in Lux

Luminance:
the amount of light reflected off a surface, measured in candela/m^2 (which is the same as Nits)

Cooling load:
the total energy needed to remove heat from the space

Heating Load
the total energy needed to heat the space to the temperature setpoint

Heat gains:
the amount of heat entering the space through building surfaces, equipments, or people, etc

Heat losses:
the amount of heat leaving the space through building surfaces, equipments, or people, etc

APPENDIX B

DEVELOPMENT OF PROTOTYPES

Using the solar intensity and solar heat gain factors (SHGF) data from 1989 and 1993 ASHRAE Fundamentals Handbook [20,21] of latitude 8°N and 16°N, the ratio between horizontal glazing and vertical looking north and south were generated. The 1993 ASHRAE handbook which is in SI units does not have the data for latitude 8°N, therefore, the data from the handbook in 1989 which is in IP units are converted to SI units. The data of latitude 13.7°N (use 14°N for ease of the calculation) were linearly interpolated from the 2 latitudes described previously as suggested from the handbook. The data are presented in Table B1.

Table B1
Interpolate value of solar heat gain factors for latitude 14°N

Interpolate Value of Solar Heat Gain Factors for Latitude 14°N (SI Units)			
Daily Total (W/m2)	N	S	HOR
Jan	741	4693	5523
Feb	790	3732	5976
Mar	871	2230	6458
Apr	1105	1242	6613
May	1778	1021	6504
Jun	2520	1027	6356
Jul	2561	1039	6304
Aug	1869	1058	6372
Sep	1175	1280	6424
Oct	903	2196	6282
Nov	806	3641	5883
Dec	745	4650	5498
Total	15865	27811	74190

N: north orientation; S: south orientation; HOR: horizontal orientation

This data is not the actual heat gains from the daylighting systems but could be used to help in the estimation of the glazing area of each toplighting system which leads to the creation of the prototypes. From the data, the ratio of solar heat gain factors of apertures looking to the north: south: horizontal at latitude 14N is 15865: 27811: 74190 or 1: 1.75: 4.68.

To simplify this ratio for developing the glazing area for each prototype, ratio 1: 2: 5 will first be tested and adjust until the cooling load from each prototypes is similar (within 5 percent). EnergyPlus software was used for the calculation of the average cooling load.

Initial Tests for Apertures before Shading Installation

After the test from EnergyPlus, the dimension of each prototype is presented in Figures B1 and B2 for skylight, lightscoop, and roof monitor systems which are the cases with the similar cooling loads.

The initial cooling load test result is presented in Fig. B3. The glazing area comparison for the prototypes without shading is illustrated in Figure B4. More details of EnergyPlus input files are provided in Appendix C: EnergyPlus Input.

From the data presented, the average cooling load of each case differs less than 1 percent and hence can be considered thermally comparable. The monthly average total cooling load of skylight, lightscoop, and roof monitor are 7261, 7320, and 7277 Watts, respectively, indicating less than 1 percent difference.

As presented, the ratio of the glazing area for each toplighting system, skylight performs worst since its system with a 0.25m width has the same cooling load as a lightscoop with a 0.95m height glazing, and a roof monitor with a 0.55m glazing looking north and 0.20m looking south (exclude frame height).

However, the toplighting systems designed should be able to prevent the interior spaces from direct sun, and the shading devices should be implemented. With the shading devices in use, the heat gain would be less than those presented above and same as the cooling load. Therefore, the prototypes must be simulated again after the installation of the shading devices to identify the difference in cooling load that the shading devices have.

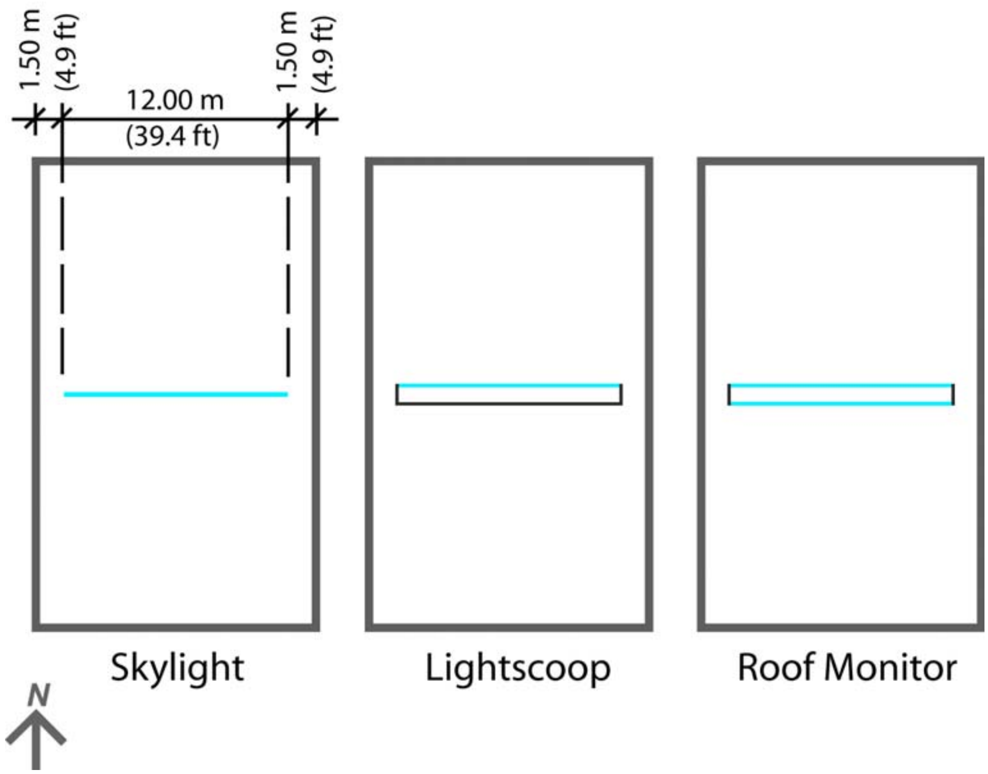

Fig. B1 Floor plan for single unit systems without shading devices

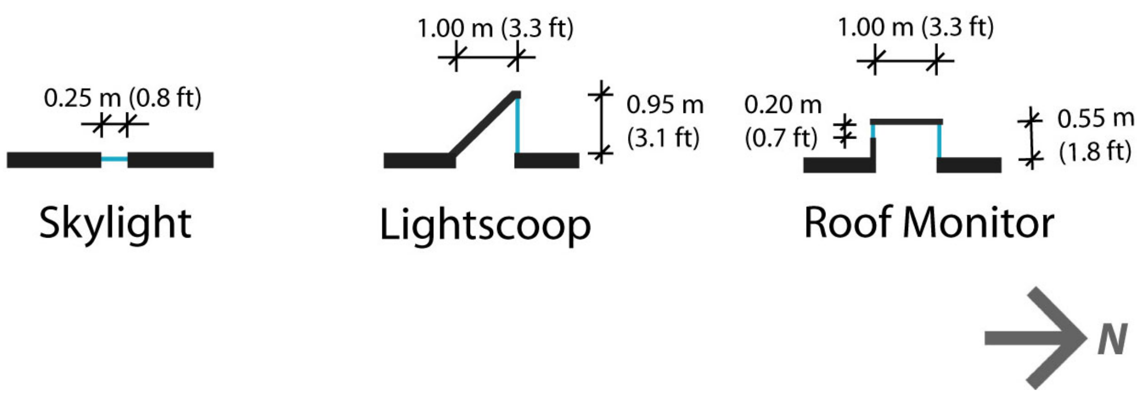

Fig. B2 Section of toplighting systems for single unit systems without shading devices

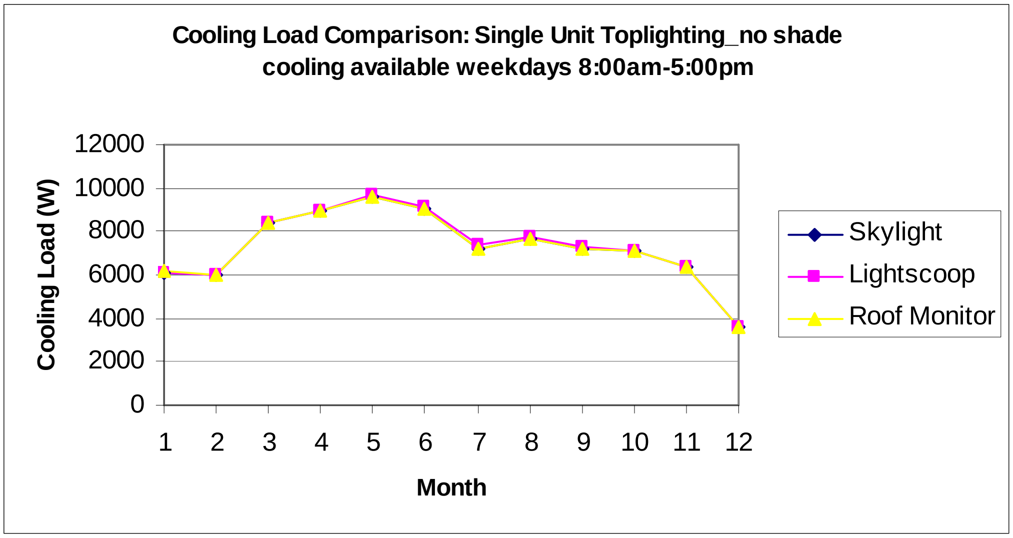

Fig. B3 Cooling load comparison of single unit toplighting prototypes without shading devices

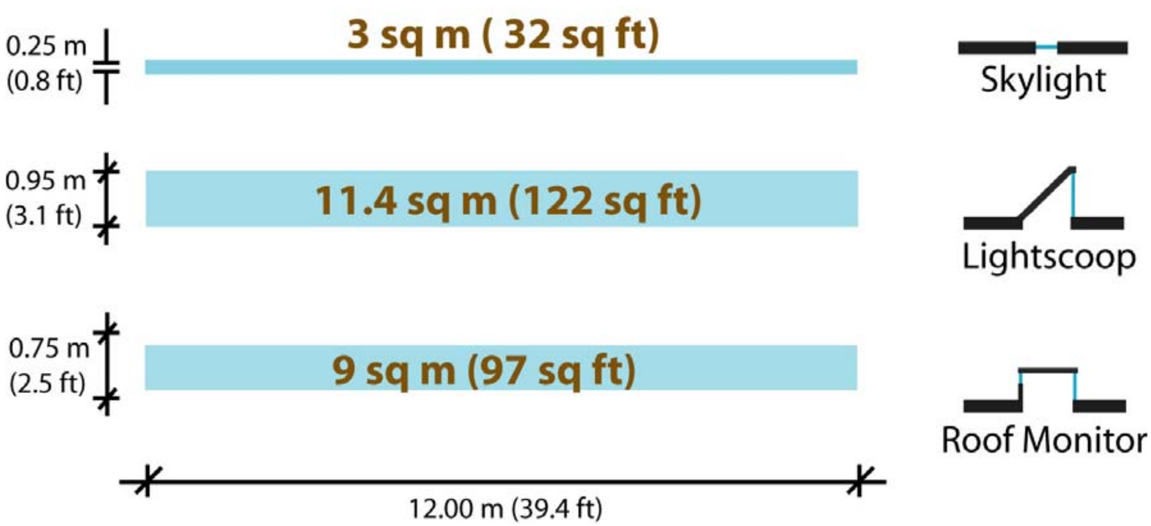

Fig. B4 Glazing area comparison for single unit systems without shading devices

The shading devices are designed for a lightscoop and a roof monitor cases to create more logical prototypes with shadings. After the proper shading devices are designed and installed, the predicted amount of cooling load is tested for each case to ensure that they are comparable. This resulted in the change of the glazing area for each toplighting prototypical case since, after the shading devices are installed, the heat gains would be reduced from the cases without shading and so is the cooling load. The results of the test are covered in Chapter III Methodology.

Shading Device Design for Lightscoop and Roof Monitor

The shading devices are designed to prevent direct sun from entering the interior spaces at average office hours which is from 9:00am – 5:00 pm.

The sun chart for latitude 13.7N is presented in Fig. B5. As seen from the sun chart, during summer, the sun will be on the north side of the building, therefore, the shading device has to be designed for both the north and the south side glazing. For skylights, the diffuse glazing could be used to prevent direct sun from coming in. In this study, for comparison, same glazing type which is low-E glazing will be use for all cases but the diffuse low-E glazing will be added only to the base case skylight to test the difference between these 2 glazing types. Ecotect is the software used in this thesis to test that no sun patches enter the interior space during the specified hours.

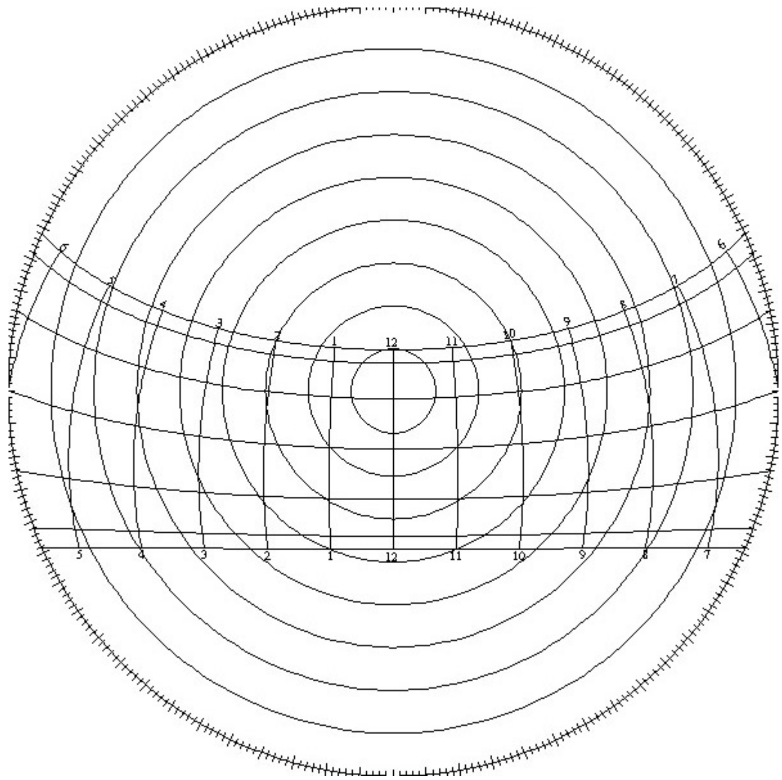

Fig. B5 Sun chart of latitude 13.7°N

<u>Lightscoop Shading Devices Design</u>

The lightscoop unit is located at the center of the prototype building with a ceiling void width of 1.00m (Fig. 3.9). For the aperture looking north, the overhang width is 0.28m and the vertical fin's dimension is 0.37m in depth and 1.43 in height. The vertical fins are spaced 1.00m apart. The shading devices dimension and the shading mask overlay on the sun chart pictures for a lightscoop unit are in Figs. B6-B7.

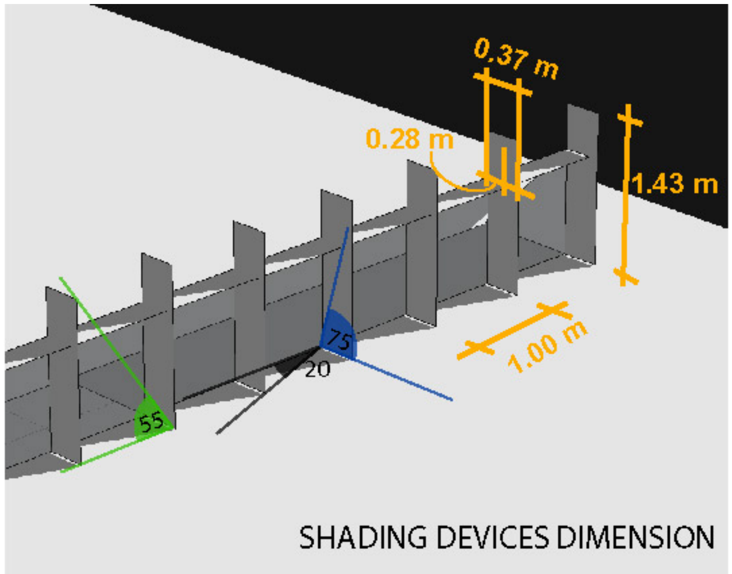

Fig. B6 Lightscoop: shading devices dimension

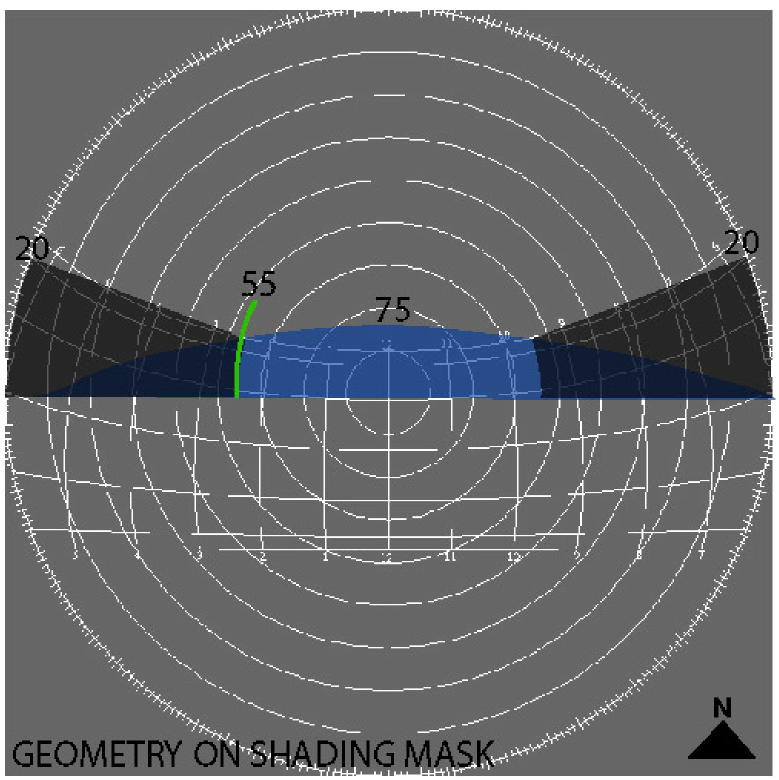

Fig. B7 Lightscoop: shading mask overlay

Roof Monitor Shading Devices Design

The roof monitor unit is located at the center of the prototype building with a ceiling void width of 1.00m. For the aperture looking north, the overhang width is 0.17m and the vertical fin's dimension is 0.37m in depth and 1.43 in height. The vertical fins are spaced 1.00m apart. For the aperture looking south, the overhang width is 0.72m and the vertical fin's dimension is 0.72m in depth and 0.95m in height. The vertical fins are spaced 1.00m apart. The shading mask overlay on the sun chart and the shading devices dimension for a roof monitor are in Figs. B8-B11.

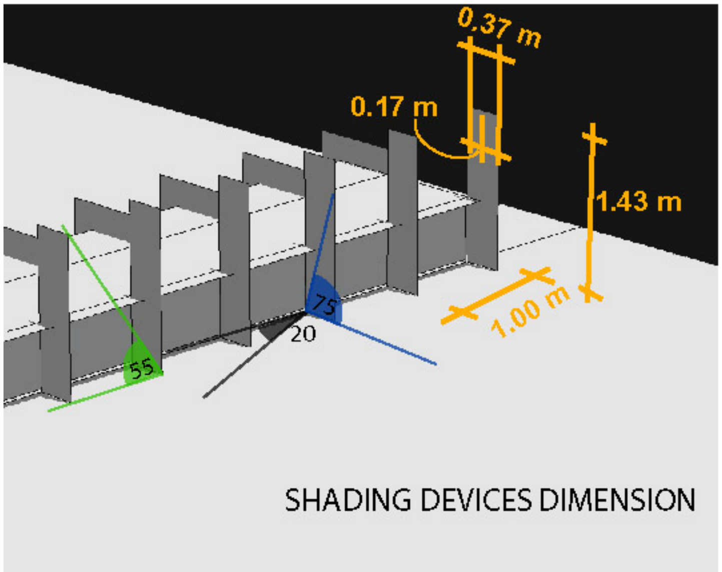

Fig. B8 Roof Monitor: north shading devices dimension

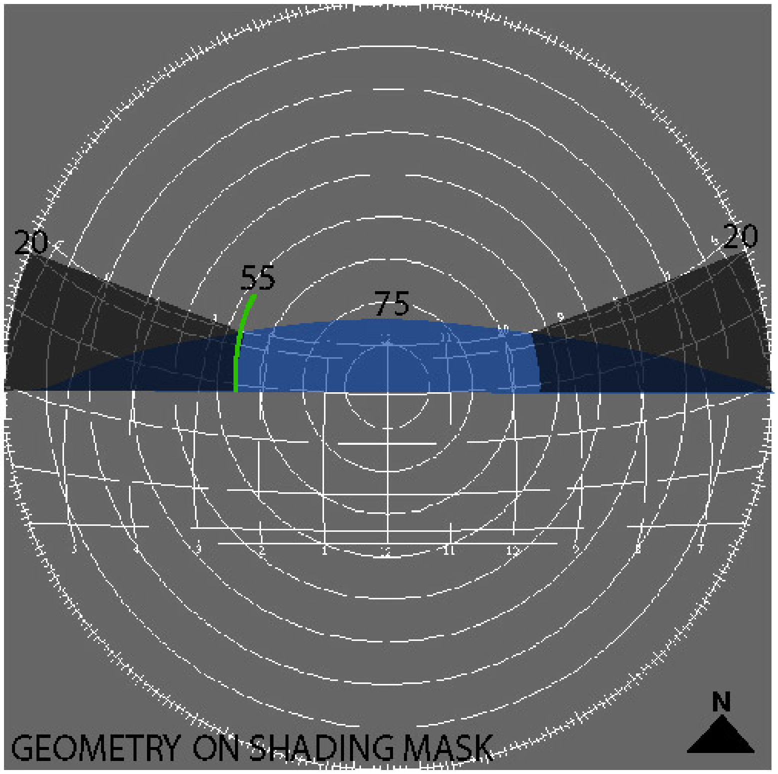

Fig. B9 Roof monitor: north shading devices shading mask overlay

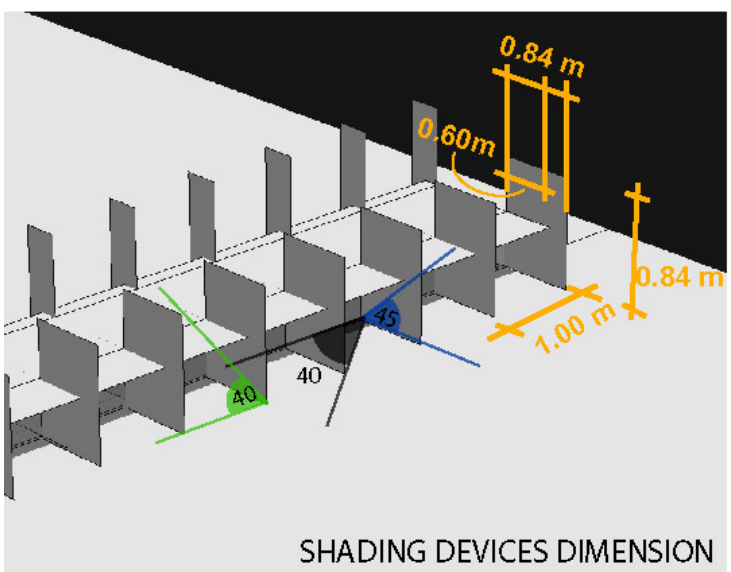

Fig. B10 Roof monitor: south shading devices dimension

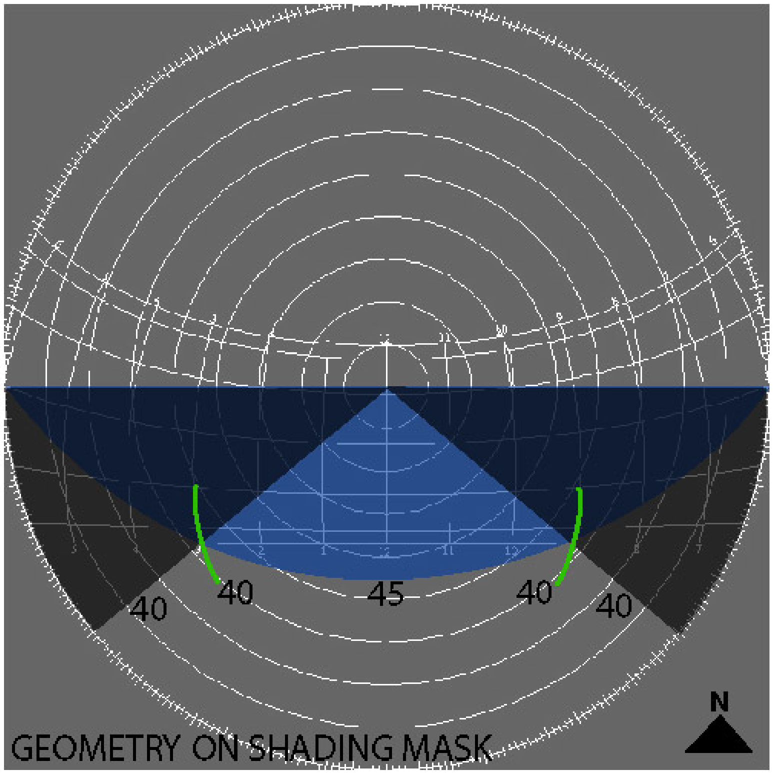

Fig. B11 Roof monitor: south shading mask overlay

From the results of the cooling load tests, it can be seen that, after the shading devices are installed, the cooling loads from each toplighting system have reduced significantly, about 40 percent for lightscoop cases with the same glazing area, thus emphasizing the importance of the shading devices for the hot and humid climates where heat gains are critical design issues.

As can be seen from the data presented, the comparable size of skylight to other systems is very small; in this case, the glazing width is only 0.15m. The skylight unit width of 0.15m is very low and not a reasonable size for construction, therefore, skylight will be evaluated only as a base case test and not aiming for real construction.

APPENDIX C

ENERGYPLUS INPUT FILES

The selected input file for simulating the thermal performance in EnergyPlus is provided in the following. The prototype selected is single lightscoop prototype. The input file is created manually and edited with IDF Editor.

The first file is without the system to get the interior temperature and the second input file is the same as the first except for the system part which purchased air has been added to get the total cooling load.

EnergyPlus Input File without the System

```
!-Generator IDFEditor 1.13

!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-      Use '!' comments if they need to be retained when using the IDFEditor.

!-   ===========  ALL OBJECTS IN CLASS: VERSION ===========
! DATE: Jan 26 13:10:17 2005
! SYSTEM: NO
! INTERNAL GAINS: YES
! TEST FOR HOURLY HEAT GAINS/LOSSES AND INT TEMPERATURE
VERSION,
    1.2;                     !- Version Identifier
!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========
BUILDING,
    [NoName],                !- Building Name
    0.00000,                 !- North Axis {deg}
    City,                    !- Terrain
    0.05000,                 !- Loads Convergence Tolerance Value {W}
    0.50000,                 !- Temperature Convergence Tolerance Value {deltaC}
    FullExterior,            !- Solar Distribution
    25;                      !- Maximum Number of Warmup Days
!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP IN HOUR ===========
TIMESTEP IN HOUR,
    1;                       !- Time Step in Hour
!-   ===========  ALL OBJECTS IN CLASS: INSIDE CONVECTION ALGORITHM
INSIDE CONVECTION ALGORITHM,
    Detailed;                !- InsideConvectionValue
!-   ===========  ALL OBJECTS IN CLASS: OUTSIDE CONVECTION ALGORITHM
OUTSIDE CONVECTION ALGORITHM,
    Simple;                  !- OutsideConvectionValue
!-   ===========  ALL OBJECTS IN CLASS: SOLUTION ALGORITHM ===========
SOLUTION ALGORITHM,
    CTF;                     !- SolutionAlgo
!-   ===========  ALL OBJECTS IN CLASS: SHADOWING CALCULATIONS
```

```
SHADOWING CALCULATIONS,
    14;                     !- Period_for_calculations
!-   ===========  ALL OBJECTS IN CLASS: AIRFLOW MODEL ===========
Airflow Model,
    Simple;                 !- AirFlowModelValue
!-   ===========  ALL OBJECTS IN CLASS: RUN CONTROL ===========
RUN CONTROL,
    No,                     !- Do the zone sizing calculation
    No,                     !- Do the system sizing calculation
    No,                     !- Do the plant sizing calculation
    No,                     !- Do the design day simulations
    Yes;                    !- Do the weather file simulation
!-   ===========  ALL OBJECTS IN CLASS: RUNPERIOD ===========
RunPeriod,
    1,                      !- Begin Month
    1,                      !- Begin Day Of Month
    12,                     !- End Month
    31,                     !- End Day Of Month
    UseWeatherFile,         !- Day Of Week For Start Day
    Yes,                    !- Use WeatherFile Holidays/Special Days
    Yes,                    !- Use WeatherFile DaylightSavingPeriod
    Yes,                    !- Apply Weekend Holiday Rule
    Yes,                    !- Use WeatherFile Rain Indicators
    Yes;                    !- Use WeatherFile Snow Indicators
!-   ===========  ALL OBJECTS IN CLASS: LOCATION ===========
Location,
    BANGhourt.dat ,         !- LocationName
    13.7,                   !- Latitude {deg}
    100.5,                  !- Longitude {deg}
    7.00000,                !- TimeZone {hr}
    10.00000;               !- Elevation {m}
!-   ===========  ALL OBJECTS IN CLASS: GROUNDTEMPERATURES ===========
GroundTemperatures,
    24.27,                  !- January Ground Temperature {C}
    24.23,                  !- February Ground Temperature {C}
    24.22,                  !- March Ground Temperature {C}
    24.18,                  !- April Ground Temperature {C}
    24.17,                  !- May Ground Temperature {C}
    24.23,                  !- June Ground Temperature {C}
    24.26,                  !- July Ground Temperature {C}
    24.27,                  !- August Ground Temperature {C}
    24.32,                  !- September Ground Temperature {C}
    24.38,                  !- October Ground Temperature {C}
    24.36,                  !- November Ground Temperature {C}
    24.26;                  !- December Ground Temperature {C}
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:REGULAR ===========
! WALL
! FINISH
MATERIAL:REGULAR,
    HF-A6,                  !- Name
    MediumSmooth,           !- Roughness
    1.2700000E-02,          !- Thickness {m}
    0.4151000    ,          !- Conductivity {W/m-K}
```

```
    1249.000    ,           !- Density {kg/m3}
    1088.000    ,           !- Specific Heat {J/kg-K}
    0.9000000    ,          !- Absorptance:Thermal
    0.5000000    ,          !- Absorptance:Solar
    0.5000000    ;          !- Absorptance:Visible
! INSULATION 1IN
MATERIAL:REGULAR,
    HF-B2,                  !- Name
    VeryRough,              !- Roughness
    2.5300000E-02,          !- Thickness {m}
    4.3200001E-02,          !- Conductivity {W/m-K}
    32.00000    ,           !- Density {kg/m3}
    837.0000    ,           !- Specific Heat {J/kg-K}
    0.9000000    ,          !- Absorptance:Thermal
    0.5000000    ,          !- Absorptance:Solar
    0.5000000    ;          !- Absorptance:Visible
! COMMON BRICK 4IN
MATERIAL:REGULAR,
    HF-C4,                  !- Name
    Rough,                  !- Roughness
    0.1016000    ,          !- Thickness {m}
    0.7264000    ,          !- Conductivity {W/m-K}
    1922.000    ,           !- Density {kg/m3}
    837.0000    ,           !- Specific Heat {J/kg-K}
    0.9000000    ,          !- Absorptance:Thermal
    0.7600000    ,          !- Absorptance:Solar
    0.7600000    ;          !- Absorptance:Visible
! 3/4IN PLAS-3/4IN GYPS
MATERIAL:REGULAR,
    HF-E1,                  !- Name
    Smooth,                 !- Roughness
    1.9099999E-02,          !- Thickness {m}
    0.7264000    ,          !- Conductivity {W/m-K}
    1602.000    ,           !- Density {kg/m3}
    837.0000    ,           !- Specific Heat {J/kg-K}
    0.9000000    ,          !- Absorptance:Thermal
    0.9200000    ,          !- Absorptance:Solar
    0.9200000    ;          !- Absorptance:Visible
! CEILING AND ROOF
! CONCRETE HW 8IN
MATERIAL:REGULAR,
    HF-C10,                 !- Name
MediumRough,                !- Roughness
    0.2033000    ,          !- Thickness {m}
    1.729600    ,           !- Conductivity {W/m-K}
    2243.000    ,           !- Density {kg/m3}
    837.0000    ,           !- Specific Heat {J/kg-K}
    0.9000000    ,          !- Absorptance:Thermal
    0.6500000    ,          !- Absorptance:Solar
    0.6500000    ;          !- Absorptance:Visible
! ACOUSTIC TILE
MATERIAL:REGULAR,
    HF-E5,                  !- Name
```

```
    MediumSmooth,            !- Roughness
    1.9099999E-02,           !- Thickness {m}
    6.0500000E-02,           !- Conductivity {W/m-K}
    481.0000    ,            !- Density {kg/m3}
    837.0000    ,            !- Specific Heat {J/kg-K}
    0.9000000    ,           !- Absorptance:Thermal
    0.3200000    ,           !- Absorptance:Solar
    0.3200000    ;           !- Absorptance:Visible
! CONC SLAB ON GROUND (AS FROM ECOTECT)
MATERIAL:REGULAR,
    ConcSlab_OnGround-0,     !- Name
    Rough,                   !- Roughness
    1.50000,                 !- Thickness {m}
    0.83680,                 !- Conductivity {W/m-K}
    1300.00000,              !- Density {kg/m3}
    1046.00000,              !- Specific Heat {J/kg-K}
    0.90000,                 !- Absorptance:Thermal
    0.93000,                 !- Absorptance:Solar
    0.93000;                 !- Absorptance:Visible
MATERIAL:REGULAR,
    ConcSlab_OnGround-1,     !- Name
    Rough,                   !- Roughness
    0.10000,                 !- Thickness {m}
    0.75300,                 !- Conductivity {W/m-K}
    3800.00000,              !- Density {kg/m3}
    656.90002,               !- Specific Heat {J/kg-K}
    0.90000,                 !- Absorptance:Thermal
    0.93000,                 !- Absorptance:Solar
    0.93000;                 !- Absorptance:Visible
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:AIR ===========
! Air Layer 3/4 in to 4 ines Vertical Walls
MATERIAL:AIR,
    AL21,                    !- Name
    0.1570000    ;           !- Thermal Resistance {m2-K/W}
! CEILING AIR SPACE
MATERIAL:AIR,
    HF-E4,                   !- Name
   0.1762000    ;            !- Thermal Resistance {m2-K/W}
!-   ==========  ALL OBJECTS IN CLASS: MATERIAL:WINDOWGLASS
! GLAZING (LOW-E) Data from Window5 program in glazing system library named Ngao_try1
!  Name           Th   Ts   Rfs  Rbs  Tv   Rfv  Rbv Tir Ef  Eb Con
! ID 2007
MATERIAL:WINDOWGLASS,
    E178-4.CIG,              !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Name of Window Glass Spectral Data Set
    .0041,                   !- Thickness {m}
    .607,                    !- Solar Transmittance at Normal Incidence
    .194,                    !- Solar Reflectance at Normal Incidence: Front Side
    .253,                    !- Solar Reflectance at Normal Incidence: Back Side
    .860,                    !- Visible Transmittance at Normal Incidence
    .054,                    !- Visible Reflectance at Normal Incidence: Front Side
    .048,                    !- Visible Reflectance at Normal Incidence: Back Side
```

```
   .0,                   !- IR Transmittance at Normal Incidence
   .840,                 !- IR Hemispherical Emissivity: Front Side
   .083,                 !- IR Hemispherical Emissivity: Back Side
   1;                    !- Conductivity {W/m-K}
! ID 103
MATERIAL:WINDOWGLASS,
   CLEAR_6.DAT,          !- Name
   SpectralAverage,      !- Optical Data Type
   ,                     !- Name of Window Glass Spectral Data Set
   .0057,                !- Thickness {m}
   .771,                 !- Solar Transmittance at Normal Incidence
   .070,                 !- Solar Reflectance at Normal Incidence: Front Side
   .070,                 !- Solar Reflectance at Normal Incidence: Back Side
   .884,                 !- Visible Transmittance at Normal Incidence
   .080,                 !- Visible Reflectance at Normal Incidence: Front Side
   .080,                 !- Visible Reflectance at Normal Incidence: Back Side
   .0,                   !- IR Transmittance at Normal Incidence
   .84,                  !- IR Hemispherical Emissivity: Front Side
   .84,                  !- IR Hemispherical Emissivity: Back Side
   1;                    !- Conductivity {W/m-K}
!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:WINDOWGAS ===========
MATERIAL:WINDOWGAS,
   AIR 12.7MM,           !- Name
   Air    ,              !- Gas Type
   .0127  ;              !- Thickness {m}
!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========
CONSTRUCTION,
   BRICK_TH,             !- Name
! FINISH
   HF-A6,                !- Outside Layer
! INSULATION 1IN
   HF-B2,                !- Layer #2
! COMMON BRICK 4IN
   HF-C4,                !- Layer #3
! Air Layer 3/4 in to 4 ines Vertical Walls
   AL21,                 !- Layer #4
! COMMON BRICK 4IN
   HF-C4,                !- Layer #5
! 3/4IN PLAS-3/4IN GYPS
   HF-E1;                !- Layer #6
CONSTRUCTION,
   ASHI-38,              !- Name
! CONCRETE HW 8IN
   HF-C10,               !- Outside Layer
! CEILING AIR SPACE
   HF-E4,                !- Layer #2
! ACOUSTIC TILE
   HF-E5;                !- Layer #3
CONSTRUCTION,
   ConcSlab_OnGround,    !- Name
   ConcSlab_OnGround-0,  !- Outside Layer
   ConcSlab_OnGround-1;  !- Layer #2
! 2634  U=1.751 SC= .654  SHGC=.568  Rel. Ht. gain=426 w/m2 TVIS=.763 Keff=.0328w/m-K
```

```
CONSTRUCTION,
    Asahi_Low-E,             !- Name
    E178-4.CIG,              !- Outside Layer
    AIR 12.7MM,              !- Layer #2
    CLEAR_6.DAT;             !- Layer #3
!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========
ZONE,
    Zone_1,                  !- Zone Name
    0.00000,                 !- Relative North (to building) {deg}
    0.0,                     !- X Origin {m}
    0.0,                     !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    1,                       !- Type
    1.0,                     !- Multiplier
    4.50000,                 !- Ceiling Height {m}
    1687.50000;              !- Volume {m3}
!-   ===========  ALL OBJECTS IN CLASS: SURFACEGEOMETRY ===========
SurfaceGeometry,
    UpperLeftCorner,         !- SurfaceStartingPosition
    CounterClockWise,        !- VertexEntry
    WorldCoordinateSystem;   !- SurfaceGeometryKey
!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER ===========
Surface:HeatTransfer,
    Obj:0000,                !- User Supplied Surface Name
    FLOOR,                   !- Surface Type
    ConcSlab_OnGround,       !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    Ground,                  !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    1.00000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    0.00000,                 !- Vertex 1 X-coordinate {m}
    0.00000,                 !- Vertex 1 Y-coordinate {m}
    0.00000,                 !- Vertex 1 Z-coordinate {m}
    0.00000,                 !- Vertex 2 X-coordinate {m}
    25.00000,                !- Vertex 2 Y-coordinate {m}
    0.00000,                 !- Vertex 2 Z-coordinate {m}
    15.00000,                !- Vertex 3 X-coordinate {m}
    25.00000,                !- Vertex 3 Y-coordinate {m}
    0.00000,                 !- Vertex 3 Z-coordinate {m}
    15.00000,                !- Vertex 4 X-coordinate {m}
    0.00000,                 !- Vertex 4 Y-coordinate {m}
    0.00000;                 !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0001,                !- User Supplied Surface Name
    WALL,                    !- Surface Type
    BRICK_TH,                !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
```

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   WindExposed,            !- Wind Exposure
   0.50000,                !- View Factor to Ground
   4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
   0.00000,                !- Vertex 1 X-coordinate {m}
   25.00000,               !- Vertex 1 Y-coordinate {m}

   4.50000,                !- Vertex 1 Z-coordinate {m}
   0.00000,                !- Vertex 2 X-coordinate {m}
   25.00000,               !- Vertex 2 Y-coordinate {m}
   0.00000,                !- Vertex 2 Z-coordinate {m}
   0.00000,                !- Vertex 3 X-coordinate {m}
   0.00000,                !- Vertex 3 Y-coordinate {m}
   0.00000,                !- Vertex 3 Z-coordinate {m}
   0.00000,                !- Vertex 4 X-coordinate {m}
   0.00000,                !- Vertex 4 Y-coordinate {m}
   4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
   Obj:0002,               !- User Supplied Surface Name
   WALL,                   !- Surface Type
   BRICK_TH,               !- Construction Name of the Surface
   Zone_1,                 !- InsideFaceEnvironment
   ExteriorEnvironment,    !- OutsideFaceEnvironment
   ,                       !- OutsideFaceEnvironment Object
   SunExposed,             !- Sun Exposure
   WindExposed,            !- Wind Exposure
   0.50000,                !- View Factor to Ground
   4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
   15.00000,               !- Vertex 1 X-coordinate {m}
   25.00000,               !- Vertex 1 Y-coordinate {m}
   4.50000,                !- Vertex 1 Z-coordinate {m}
   15.00000,               !- Vertex 2 X-coordinate {m}
   25.00000,               !- Vertex 2 Y-coordinate {m}
   0.00000,                !- Vertex 2 Z-coordinate {m}
   0.00000,                !- Vertex 3 X-coordinate {m}
   25.00000,               !- Vertex 3 Y-coordinate {m}
   0.00000,                !- Vertex 3 Z-coordinate {m}
   0.00000,                !- Vertex 4 X-coordinate {m}
   25.00000,               !- Vertex 4 Y-coordinate {m}
   4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
   Obj:0003,               !- User Supplied Surface Name
   WALL,                   !- Surface Type
   BRICK_TH,               !- Construction Name of the Surface
   Zone_1,                 !- InsideFaceEnvironment
   ExteriorEnvironment,    !- OutsideFaceEnvironment
   ,                       !- OutsideFaceEnvironment Object
   SunExposed,             !- Sun Exposure
   WindExposed,            !- Wind Exposure
   0.50000,                !- View Factor to Ground
   4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
   15.00000,               !- Vertex 1 X-coordinate {m}
   0.00000,                !- Vertex 1 Y-coordinate {m}
   4.50000,                !- Vertex 1 Z-coordinate {m}
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    15.00000,              !- Vertex 2 X-coordinate {m}
    0.00000,               !- Vertex 2 Y-coordinate {m}
    0.00000,               !- Vertex 2 Z-coordinate {m}
    15.00000,              !- Vertex 3 X-coordinate {m}
    25.00000,              !- Vertex 3 Y-coordinate {m}
    0.00000,               !- Vertex 3 Z-coordinate {m}
    15.00000,              !- Vertex 4 X-coordinate {m}
    25.00000,              !- Vertex 4 Y-coordinate {m}
    4.50000;               !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0004,              !- User Supplied Surface Name
    WALL,                  !- Surface Type
    BRICK_TH,              !- Construction Name of the Surface
    Zone_1,                !- InsideFaceEnvironment
    ExteriorEnvironment,   !- OutsideFaceEnvironment
    ,                      !- OutsideFaceEnvironment Object
    SunExposed,            !- Sun Exposure
    WindExposed,           !- Wind Exposure
    0.50000,               !- View Factor to Ground
    4,                     !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    0.00000,               !- Vertex 1 X-coordinate {m}
    0.00000,               !- Vertex 1 Y-coordinate {m}
    4.50000,               !- Vertex 1 Z-coordinate {m}
    0.00000,               !- Vertex 2 X-coordinate {m}
    0.00000,               !- Vertex 2 Y-coordinate {m}
    0.00000,               !- Vertex 2 Z-coordinate {m}
    15.00000,              !- Vertex 3 X-coordinate {m}
    0.00000,               !- Vertex 3 Y-coordinate {m}
    0.00000,               !- Vertex 3 Z-coordinate {m}
    15.00000,              !- Vertex 4 X-coordinate {m}
    0.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;               !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0005,              !- User Supplied Surface Name
    WALL,                  !- Surface Type
    ASHI-38,               !- Construction Name of the Surface
    Zone_1,                !- InsideFaceEnvironment
    ExteriorEnvironment,   !- OutsideFaceEnvironment
    ,                      !- OutsideFaceEnvironment Object
    SunExposed,            !- Sun Exposure
    WindExposed,           !- Wind Exposure
    0.50000,               !- View Factor to Ground
    4,                     !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.5,                  !- Vertex 1 X-coordinate {m}
    13.0,                  !- Vertex 1 Y-coordinate {m}
    5.5,                   !- Vertex 1 Z-coordinate {m}
    13.5,                  !- Vertex 2 X-coordinate {m}
    13.0,                  !- Vertex 2 Y-coordinate {m}
    4.5,                   !- Vertex 2 Z-coordinate {m}
    1.5,                   !- Vertex 3 X-coordinate {m}
    13.0,                  !- Vertex 3 Y-coordinate {m}
    4.5,                   !- Vertex 3 Z-coordinate {m}
    1.5,                   !- Vertex 4 X-coordinate {m}
```

```
    13.0,                    !- Vertex 4 Y-coordinate {m}
    5.5;                     !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0006,                !- User Supplied Surface Name
    CEILING,                 !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.75000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    1.5,                     !- Vertex 1 X-coordinate {m}
    13.0,                    !- Vertex 1 Y-coordinate {m}
    5.5,                     !- Vertex 1 Z-coordinate {m}
    1.5,                     !- Vertex 2 X-coordinate {m}
    12.0,                    !- Vertex 2 Y-coordinate {m}
    4.5,                     !- Vertex 2 Z-coordinate {m}
    13.5,                    !- Vertex 3 X-coordinate {m}
    12.0,                    !- Vertex 3 Y-coordinate {m}
    4.5,                     !- Vertex 3 Z-coordinate {m}
    13.5,                    !- Vertex 4 X-coordinate {m}
    13.0,                    !- Vertex 4 Y-coordinate {m}
    5.5;                     !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0007,                !- User Supplied Surface Name
    WALL,                    !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.50000,                 !- View Factor to Ground
    3,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    1.5,                     !- Vertex 1 X-coordinate {m}
    13.0,                    !- Vertex 1 Y-coordinate {m}
    5.5,                     !- Vertex 1 Z-coordinate {m}
    1.5,                     !- Vertex 2 X-coordinate {m}
    13.0,                    !- Vertex 2 Y-coordinate {m}
    4.5,                     !- Vertex 2 Z-coordinate {m}
    1.5,                     !- Vertex 3 X-coordinate {m}
    12.0,                    !- Vertex 3 Y-coordinate {m}
    4.5;                     !- Vertex 3 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0008,                !- User Supplied Surface Name
    WALL,                    !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
```

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    WindExposed,             !- Wind Exposure
    0.50000,                 !- View Factor to Ground
    3,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.5,                    !- Vertex 1 X-coordinate {m}
    13.0,                    !- Vertex 1 Y-coordinate {m}
    5.5,                     !- Vertex 1 Z-coordinate {m}
    13.5,                    !- Vertex 2 X-coordinate {m}
    12.0,                    !- Vertex 2 Y-coordinate {m}
    4.5,                     !- Vertex 2 Z-coordinate {m}
    13.5,                    !- Vertex 3 X-coordinate {m}
    13.0,                    !- Vertex 3 Y-coordinate {m}
    4.5;                     !- Vertex 3 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0010,                !- User Supplied Surface Name
    CEILING,                 !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.00000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    0.00000,                 !- Vertex 1 X-coordinate {m}
    25.00000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    0.00000,                 !- Vertex 2 X-coordinate {m}
    13.00000,                !- Vertex 2 Y-coordinate {m}
    4.50000,                 !- Vertex 2 Z-coordinate {m}
    15.00000,                !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    4.50000,                 !- Vertex 3 Z-coordinate {m}
    15.00000,                !- Vertex 4 X-coordinate {m}
    25.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0011,                !- User Supplied Surface Name
    CEILING,                 !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.00000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    0.00000,                 !- Vertex 1 X-coordinate {m}
    12.00000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    0.00000,                 !- Vertex 2 X-coordinate {m}
    0.00000,                 !- Vertex 2 Y-coordinate {m}
    4.50000,                 !- Vertex 2 Z-coordinate {m}
    15.00000,                !- Vertex 3 X-coordinate {m}
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```
    0.00000,                 !- Vertex 3 Y-coordinate {m}
    4.50000,                 !- Vertex 3 Z-coordinate {m}
    15.00000,                !- Vertex 4 X-coordinate {m}
    12.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0012,                !- User Supplied Surface Name
    CEILING,                 !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.00000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    0.00000,                 !- Vertex 1 X-coordinate {m}
    13.00000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    0.00000,                 !- Vertex 2 X-coordinate {m}
    12.00000,                !- Vertex 2 Y-coordinate {m}
    4.50000,                 !- Vertex 2 Z-coordinate {m}
    1.50000,                 !- Vertex 3 X-coordinate {m}
    12.00000,                !- Vertex 3 Y-coordinate {m}
    4.50000,                 !- Vertex 3 Z-coordinate {m}
    1.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:HeatTransfer,
    Obj:0013,                !- User Supplied Surface Name
    CEILING,                 !- Surface Type
    ASHI-38,                 !- Construction Name of the Surface
    Zone_1,                  !- InsideFaceEnvironment
    ExteriorEnvironment,     !- OutsideFaceEnvironment
    ,                        !- OutsideFaceEnvironment Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.00000,                 !- View Factor to Ground
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.50000,                !- Vertex 1 X-coordinate {m}
    13.00000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    13.50000,                !- Vertex 2 X-coordinate {m}
    12.00000,                !- Vertex 2 Y-coordinate {m}
    4.50000,                 !- Vertex 2 Z-coordinate {m}
    15.00000,                !- Vertex 3 X-coordinate {m}
    12.00000,                !- Vertex 3 Y-coordinate {m}
    4.50000,                 !- Vertex 3 Z-coordinate {m}
    15.00000,                !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
!-   ===========  ALL OBJECTS IN CLASS: SURFACE:HEATTRANSFER:SUB
Surface:HeatTransfer:Sub,
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    WIN_1,                  !- User Supplied Surface Name
    WINDOW,                 !- Surface Type
    Asahi_Low-E,            !- Construction Name of the Surface
    Obj:0005,               !- Base Surface Name
    ,                       !- OutsideFaceEnvironment Object
    0.50000,                !- View Factor to Ground
    ,                       !- Name of shading control
    ,                       !- WindowFrameAndDivider Name
    1.00000,                !- Multiplier
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.47500,               !- Vertex 1 X-coordinate {m}
    13.00000,               !- Vertex 1 Y-coordinate {m}
    5.47500,                !- Vertex 1 Z-coordinate {m}
    13.47500,               !- Vertex 2 X-coordinate {m}
    13.00000,               !- Vertex 2 Y-coordinate {m}
    4.52500,                !- Vertex 2 Z-coordinate {m}
    1.52500,                !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    4.52500,                !- Vertex 3 Z-coordinate {m}
    1.52500,                !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    5.47500;                !- Vertex 4 Z-coordinate {m}
!-   ===========  ALL OBJECTS IN CLASS: SURFACE:SHADING:ATTACHED
Surface:Shading:Attached,
    Overhang1,              !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.5,                   !- Vertex 1 X-coordinate {m}
    13.0,                   !- Vertex 1 Y-coordinate {m}
    5.5,                    !- Vertex 1 Z-coordinate {m}
    1.5,                    !- Vertex 2 X-coordinate {m}
    13.0,                   !- Vertex 2 Y-coordinate {m}
    5.5,                    !- Vertex 2 Z-coordinate {m}
    1.5,                    !- Vertex 3 X-coordinate {m}
    13.28,                  !- Vertex 3 Y-coordinate {m}
    5.5,                    !- Vertex 3 Z-coordinate {m}
    13.5,                   !- Vertex 4 X-coordinate {m}
    13.28,                  !- Vertex 4 Y-coordinate {m}
    5.5;                    !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_1,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    13.50000,               !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    13.50000,               !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    13.50000,               !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
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    5.93000,                !- Vertex 3 Z-coordinate {m}
    13.50000,               !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_2,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    12.50000,               !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    12.50000,               !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    12.50000,               !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
    12.50000,               !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}

Surface:Shading:Attached,
    FIN_3,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    11.50000,               !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    11.50000,               !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    11.50000,               !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
    11.50000,               !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_4,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    10.50000,               !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    10.50000,               !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    10.50000,               !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
```

```
    10.50000,                !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_5,                   !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    9.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    9.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    9.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    9.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_6,                   !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    8.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    8.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    8.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    8.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_7,                   !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    7.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    7.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    7.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    7.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
```

```
    4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_8,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    6.50000,                !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    6.50000,                !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    6.50000,                !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
    6.50000,                !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_9,                  !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    5.50000,                !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    5.50000,                !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    5.50000,                !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
    5.50000,                !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_10,                 !- User Supplied Surface Name
    Obj:0005,               !- Base Surface Name
    SHADE-1,                !- TransSchedShadowSurf
    4,                      !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    4.50000,                !- Vertex 1 X-coordinate {m}
    13.37000,               !- Vertex 1 Y-coordinate {m}
    4.50000,                !- Vertex 1 Z-coordinate {m}
    4.50000,                !- Vertex 2 X-coordinate {m}
    13.37000,               !- Vertex 2 Y-coordinate {m}
    5.93000,                !- Vertex 2 Z-coordinate {m}
    4.50000,                !- Vertex 3 X-coordinate {m}
    13.00000,               !- Vertex 3 Y-coordinate {m}
    5.93000,                !- Vertex 3 Z-coordinate {m}
    4.50000,                !- Vertex 4 X-coordinate {m}
    13.00000,               !- Vertex 4 Y-coordinate {m}
    4.50000;                !- Vertex 4 Z-coordinate {m}
```

```
Surface:Shading:Attached,
    FIN_11,                  !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    3.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    3.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    3.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    3.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_12,                  !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    2.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    2.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    2.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    2.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
Surface:Shading:Attached,
    FIN_13,                  !- User Supplied Surface Name
    Obj:0005,                !- Base Surface Name
    SHADE-1,                 !- TransSchedShadowSurf
    4,                       !- Number of Surface Vertex Groups -- Number of (X,Y,Z) groups in this surface
    1.50000,                 !- Vertex 1 X-coordinate {m}
    13.37000,                !- Vertex 1 Y-coordinate {m}
    4.50000,                 !- Vertex 1 Z-coordinate {m}
    1.50000,                 !- Vertex 2 X-coordinate {m}
    13.37000,                !- Vertex 2 Y-coordinate {m}
    5.93000,                 !- Vertex 2 Z-coordinate {m}
    1.50000,                 !- Vertex 3 X-coordinate {m}
    13.00000,                !- Vertex 3 Y-coordinate {m}
    5.93000,                 !- Vertex 3 Z-coordinate {m}
    1.50000,                 !- Vertex 4 X-coordinate {m}
    13.00000,                !- Vertex 4 Y-coordinate {m}
    4.50000;                 !- Vertex 4 Z-coordinate {m}
!-   ===========  ALL OBJECTS IN CLASS: SCHEDULETYPE ===========
ScheduleType,
```

```
    Fraction,               !- ScheduleType Name
    0.0:1.0,                !- range
    Continuous;             !- Numeric Type
ScheduleType,
    Real,                   !- ScheduleType Name
    0:500,                  !- range
    DISCRETE;               !- Numeric Type
ScheduleType,
    shading,                !- ScheduleType Name
    0.0:1.0,                !- range
    Continuous;             !- Numeric Type
!-   ===========  ALL OBJECTS IN CLASS: DAYSCHEDULE ===========
DAYSCHEDULE,
    OC-1,                   !- Name
    Fraction,               !- ScheduleType
    0.0,                    !- Hour 1
    0.0,                    !- Hour 2
    0.0,                    !- Hour 3
    0.0,                    !- Hour 4
    0.0,                    !- Hour 5
    0.0,                    !- Hour 6
    0.0,                    !- Hour 7
    0.0,                    !- Hour 8
    1.0,                    !- Hour 9
    1.0,                    !- Hour 10
    1.0,                    !- Hour 11
    0.8,                    !- Hour 12
    0.4,                    !- Hour 13
    0.8,                    !- Hour 14
    1.0,                    !- Hour 15
    1.0,                    !- Hour 16
    1.0,                    !- Hour 17
    1.0,                    !- Hour 18
    0.5,                    !- Hour 19
    0.1,                    !- Hour 20
    0.1,                    !- Hour 21
    0.0,                    !- Hour 22
    0.0,                    !- Hour 23
    0.0;                    !- Hour 24
DAYSCHEDULE,
    OC-2,                   !- Name
    Fraction,               !- ScheduleType
    0.0,                    !- Hour 1
    0.0,                    !- Hour 2
    0.0,                    !- Hour 3
    0.0,                    !- Hour 4
    0.0,                    !- Hour 5
    0.0,                    !- Hour 6
    0.0,                    !- Hour 7
    0.0,                    !- Hour 8
    0.0,                    !- Hour 9
    0.0,                    !- Hour 10
    0.0,                    !- Hour 11
```

```
    0.0,                  !- Hour 12
    0.0,                  !- Hour 13
    0.0,                  !- Hour 14
    0.0,                  !- Hour 15
    0.0,                  !- Hour 16
    0.0,                  !- Hour 17
    0.0,                  !- Hour 18
    0.0,                  !- Hour 19
    0.0,                  !- Hour 20
    0.0,                  !- Hour 21
    0.0,                  !- Hour 22
    0.0,                  !- Hour 23
    0.0;                  !- Hour 24
DAYSCHEDULE,
    SHADE,                   !- Name
    Fraction,              !- ScheduleType
    0.0,                  !- Hour 1
    0.0,                  !- Hour 2
    0.0,                  !- Hour 3
    0.0,                  !- Hour 4
    0.0,                  !- Hour 5
    0.0,                  !- Hour 6
    0.0,                  !- Hour 7
    0.0,                  !- Hour 8
    0.0,                  !- Hour 9
    0.0,                  !- Hour 10
    0.0,                  !- Hour 11
    0.0,                  !- Hour 12
    0.0,                  !- Hour 13
    0.0,                  !- Hour 14
    0.0,                  !- Hour 15
    0.0,                  !- Hour 16
    0.0,                  !- Hour 17
    0.0,                  !- Hour 18
    0.0,                  !- Hour 19
    0.0,                  !- Hour 20
    0.0,                  !- Hour 21
    0.0,                  !- Hour 22
    0.0,                  !- Hour 23
    0.0;                  !- Hour 24
DAYSCHEDULE,
    ACT,                   !- Name
    Real,                  !- ScheduleType
    100,                  !- Hour 1
    100,                  !- Hour 2
    100,                  !- Hour 3
    100,                  !- Hour 4
    100,                  !- Hour 5
    100,                  !- Hour 6
    100,                  !- Hour 7
    100,                  !- Hour 8
    100,                  !- Hour 9
    100,                  !- Hour 10
```

```
    100,                    !- Hour 11
    100,                    !- Hour 12
    100,                    !- Hour 13
    100,                    !- Hour 14
    100,                    !- Hour 15
    100,                    !- Hour 16
    100,                    !- Hour 17
    100,                    !- Hour 18
    100,                    !- Hour 19
    100,                    !- Hour 20
    100,                    !- Hour 21
    100,                    !- Hour 22
    100,                    !- Hour 23
    100;                    !- Hour 24
!-   ===========  ALL OBJECTS IN CLASS: WEEKSCHEDULE ===========
WEEKSCHEDULE,
    OC-WEEK,                !- Name
    OC-2,                   !- Sunday DAYSCHEDULE Name
    OC-1,                   !- Monday DAYSCHEDULE Name
    OC-1,                   !- Tuesday DAYSCHEDULE Name
    OC-1,                   !- Wednesday DAYSCHEDULE Name
    OC-1,                   !- Thursday DAYSCHEDULE Name
    OC-1,                   !- Friday DAYSCHEDULE Name
    OC-2,                   !- Saturday DAYSCHEDULE Name
    OC-2,                   !- Holiday DAYSCHEDULE Name
    OC-1,                   !- SummerDesignDay DAYSCHEDULE Name
    OC-2,                   !- WinterDesignDay DAYSCHEDULE Name
    OC-1,                   !- CustomDay1 DAYSCHEDULE Name
    OC-1;                   !- CustomDay2 DAYSCHEDULE Name
WEEKSCHEDULE,
    SHADE-WEEK,             !- Name
    SHADE,                  !- Sunday DAYSCHEDULE Name
    SHADE,                  !- Monday DAYSCHEDULE Name
    SHADE,                  !- Tuesday DAYSCHEDULE Name
    SHADE,                  !- Wednesday DAYSCHEDULE Name
    SHADE,                  !- Thursday DAYSCHEDULE Name
    SHADE,                  !- Friday DAYSCHEDULE Name
    SHADE,                  !- Saturday DAYSCHEDULE Name
    SHADE,                  !- Holiday DAYSCHEDULE Name
    SHADE,                  !- SummerDesignDay DAYSCHEDULE Name
    SHADE,                  !- WinterDesignDay DAYSCHEDULE Name
    SHADE,                  !- CustomDay1 DAYSCHEDULE Name
    SHADE;                  !- CustomDay2 DAYSCHEDULE Name
WEEKSCHEDULE,
    ACT-WEEK,               !- Name
    ACT,                    !- Sunday DAYSCHEDULE Name
    ACT,                    !- Monday DAYSCHEDULE Name
    ACT,                    !- Tuesday DAYSCHEDULE Name
    ACT,                    !- Wednesday DAYSCHEDULE Name
    ACT,                    !- Thursday DAYSCHEDULE Name
    ACT,                    !- Friday DAYSCHEDULE Name
    ACT,                    !- Saturday DAYSCHEDULE Name
    ACT,                    !- Holiday DAYSCHEDULE Name
```

```
   ACT,                    !- SummerDesignDay DAYSCHEDULE Name
   ACT,                    !- WinterDesignDay DAYSCHEDULE Name
   ACT,                    !- CustomDay1 DAYSCHEDULE Name
   ACT;                    !- CustomDay2 DAYSCHEDULE Name
!-   ===========  ALL OBJECTS IN CLASS: SCHEDULE ===========
SCHEDULE,
   OCCUPY-1,               !- Name
   Fraction,               !- ScheduleType
   OC-WEEK,                !- Name of WEEKSCHEDULE 1
   1,                      !- Start Month 1
   1,                      !- Start Day 1
   12,                     !- End Month 1
   31;                     !- End Day 1
SCHEDULE,
   SHADE-1,                !- Name
   Fraction,               !- ScheduleType
   SHADE-WEEK,             !- Name of WEEKSCHEDULE 1
   1,                      !- Start Month 1
   1,                      !- Start Day 1
   12,                     !- End Month 1
   31;                     !- End Day 1
SCHEDULE,
   ACT1,                   !- Name
   Real,                   !- ScheduleType
   ACT-WEEK,               !- Name of WEEKSCHEDULE 1
   1,                      !- Start Month 1
   1,                      !- Start Day 1
   12,                     !- End Month 1
   31;                     !- End Day 1
!-   ===========  ALL OBJECTS IN CLASS: PEOPLE ===========
PEOPLE,
   Zone_1,                 !- Zone Name
   30,                     !- Number of People
   OCCUPY-1,               !- Number of People SCHEDULE Name (real--fraction)
   .2,                     !- Fraction Radiant
   ACT1;                   !- Activity level SCHEDULE Name (units W/person, real)
!-   ===========  ALL OBJECTS IN CLASS: ELECTRIC EQUIPMENT ===========
ELECTRIC EQUIPMENT,
   Zone_1,                 !- Zone Name
   OCCUPY-1,               !- SCHEDULE Name
   12.00000,               !- Design Level {W}
   0.58333,                !- Fraction Latent
   0.30000,                !- Fraction Radiant
   0.00000,                !- Fraction Lost
   ;                       !- End-Use Category
!-   ===========  ALL OBJECTS IN CLASS: INFILTRATION ===========
INFILTRATION,
   Zone_1,                 !- Zone Name
   OCCUPY-1,               !- SCHEDULE Name
   0.23438,                !- Design Volume Flow Rate {m3/s}
   0.6060000,              !- Constant Term Coefficient
   0.0363599,              !- Temperature Term Coefficient
   0.1177165,              !- Velocity Term Coefficient
```

```
   0.0000000;              !- Velocity Squared Term Coefficient
!-   ===========  ALL OBJECTS IN CLASS: REPORT VARIABLE ===========
Report Variable,
   *,                      !- Key_Value
   outdoor dry bulb,       !- Variable_Name
   hourly;                 !- Reporting_Frequency
Report Variable,
   *,                      !- Key_Value
   mean air temperature,   !- Variable_Name
   hourly;                 !- Reporting_Frequency
Report Variable,
   *,                      !- Key_Value
   Zone Window Heat Gain,  !- Variable_Name
   hourly;                 !- Reporting_Frequency
Report Variable,
   *,                      !- Key_Value
   Zone Window Heat Loss,  !- Variable_Name
   hourly;                 !- Reporting_Frequency
!-   ===========  ALL OBJECTS IN CLASS: REPORT ===========
Report,
   variable dictionary;    !- Type_of_Report
Report,
   surfaces,               !- Type_of_Report
   details;                !- Name_of_Report
```

EnergyPlus Input File with Purchased Air

```
!-   ===========  ALL OBJECTS IN CLASS: SIZING PARAMETERS ===========
SIZING PARAMETERS,
   1.0,                    !- sizing factor
   2;                      !- time steps in averaging window
!-   ===========  ALL OBJECTS IN CLASS: ZONE SIZING ===========
ZONE SIZING,
   Zone_1,                 !- Name of a zone
   13.,                    !- Zone cooling design supply air temperature {C}
   50.,                    !- Zone heating design supply air temperature {C}
   0.008,                  !- Zone cooling design supply air humidity ratio {kg-H2O/kg-air}
   0.008,                  !- Zone heating design supply air humidity ratio {kg-H2O/kg-air}
   flow/person,            !- outside air method
   0.00944,                !- outside air flow per person {m3/s}
   0.0,                    !- outside air flow {m3/s}
   0.0,                    !- zone sizing factor
   design day,             !- cooling design air flow method
   0,                      !- cooling design air flow rate {m3/s}
   design day,             !- heating design air flow method
   0;                      !- heating design air flow rate {m3/s}
!-   ===========  ALL OBJECTS IN CLASS: NODE LIST ===========
NODE LIST,
   Zone1Inlets,            !- Node List Name
   NODE_1;                 !- Node_ID_1
!-   ===========  ALL OBJECTS IN CLASS: CONTROLLED ZONE EQUIP CONFIGURATION
CONTROLLED ZONE EQUIP CONFIGURATION,
```

```
    Zone_1,                  !- Zone Name
    Zone1Equipment,          !- List Name: Zone Equipment
    Zone1Inlets,             !- Node List or Node Name: Zone Air Inlet Node(s)
    ,                        !- Node List or Node Name: Zone Air Exhaust Node(s)
    NODE_2,                  !- Zone Air Node Name
    NODE_3;                  !- Zone Return Air Node Name
!-   ===========  ALL OBJECTS IN CLASS: ZONE EQUIPMENT LIST ===========
ZONE EQUIPMENT LIST,
    Zone1Equipment,          !- Name
    PURCHASED AIR,           !- KEY--Zone Equipment Type 1
    Zone1Air,                !- Type Name 1
    1,                       !- Cooling Priority
    1;                       !- Heating Priority
!-   ===========  ALL OBJECTS IN CLASS: PURCHASED AIR ===========
PURCHASED AIR,
    Zone1Air,                !- Purchased Air Name
    NODE_1,                  !- Zone Supply Air Node Name
    50,                      !- Heating Supply Air Temp {C}
    13,                      !- Cooling Supply Air Temp {C}
    0.009,                   !- Heating Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.009,                   !- Cooling Supply Air Humidity Ratio {kg-H2O/kg-air}
    NO LIMIT,                !- heating limit
    autosize,                !- Maximum heating air flow rate {m3/s}
    NO LIMIT,                !- cooling limit
    autosize,                !- Maximum cooling air flow rate {m3/s}
    NO OUTSIDE AIR,          !- outside air
    autosize,                !- Outside air flow rate {m3/s}
    HeatingAvailSched,       !- heating availability schedule
    CoolingAvailSched;       !- cooling availability schedule
!-   ===========  ALL OBJECTS IN CLASS: ZONE CONTROL:THERMOSTATIC ===========

ZONE CONTROL:THERMOSTATIC,
    Zone 1 Thermostat,       !- Thermostat Name
    Zone_1,                  !- Zone Name
    Zone Control Type Sched, !- Control Type SCHEDULE Name
    SINGLE COOLING SETPOINT, !- Control Type #1
    Cooling Setpoint with SB;!- Control Type Name #1
!-   ===========  ALL OBJECTS IN CLASS: SINGLE COOLING SETPOINT ===========

SINGLE COOLING SETPOINT,
    Cooling Setpoint with SB,!- Name
    Cooling Setpoints;       !- Setpoint Temperature SCHEDULE Name
```

APPENDIX D

LIGHTING PERFORMANCE METHODOLOGY DETAILS

Illuminance Test Results Comparison between Desktop Radiance and UNIX Version

The following test was performed to ensure that Desktop Radiance and the UNIX version yield same results using identical calculation parameters. The details are as follows.

The input files are generated and run within Desktop Radiance and run in there compared to the same octree files which run in the UNIX version of RADIANCE. Some rtrace parameters have to be modified in order to compare between these 2 versions since Desktop Radiance has set different rtrace parameters than in UNIX version.

The file for lightscoop single unit is generated to compare the results between the two programs. The adjusted parameter in Desktop Radiance is the ambient bounces; 5 is used as suggested from Rendering with Radiance book for accurate numerical results test. Other parameters are adjusted to follow Desktop Radiance settings. The test results are presented in Table D1. The results are very similar between these two programs and are considered equal.

Table D1
Illuminance level comparison between Desktop Radiance and UNIX version

X	Y	Z	DR	UNIX
7.5	24.5	0.80	3.05	3.05
7.5	22.5	0.80	4.55	4.55
7.5	20.5	0.80	6.41	6.41
7.5	18.5	0.80	12.77	12.77
7.5	16.5	0.80	41.22	41.23
7.5	14.5	0.80	106.77	106.77
7.5	12.5	0.80	210.33	210.33
7.5	10.5	0.80	292.11	292.12
7.5	8.5	0.80	362.64	362.65
7.5	6.5	0.80	142.79	142.80
7.5	4.5	0.80	53.00	53.00
7.5	2.5	0.80	22.67	22.67
7.5	0.5	0.80	11.70	11.70

Desktop Radiance Daylight Factor Test Results

Daylight factor calculation within Desktop Radiance is problematic since it seems to give a lower value than it should be.

In an effort to identify the problems or discrepancies which result in those values, the test is done by the method in the following. For Desktop Radiance, the daylight factor values can be obtained from the program directly but in UNIX, the equation for calculating it has to be specified and the global illuminance value has to be known before specifying the equation. This value (global illuminance value used for a specific sky that the user input in the program) can be obtained when Desktop Radiance is running in a DOS window. For the test case, the parameters used to generate a sky in Desktop Radiance are as follows:

Latitude: 13.7 N

Longitude: 100.5

Turbidity: 4.5

Standard Meridian: 105

The global illuminance value employed by Desktop Radiance for its daylight factor calculation as seen in DOS window is 39,000 lux. However, when using the same sky description file (rad file) and ask for the global illuminance value in UNIX version, the value is different. The rtrace command used to calculate the global illuminance value is:

```
$ rtrace –w –h –I+ -ab 1 (octree file of sky description file) < \
(reference point location file) | \
rcalc –e '$1=($1*0.265+$2*0.670+$3*0.065)*179'
```

The calculation returns the value 18478 lux which is nearly half of that produced by Desktop Radiance. If this number is to be used when specifying the equation for calculating the daylight factor, the results would turn out to be more reasonable than the output directly calculated from Desktop Radiance even though the sky rad file is the same. The results are presented in Table D2.

Table D2
Daylight factor comparison between Desktop Radiance and UNIX version when using default global horizontal illuminance value

DF directly from DR	DF from UNIX
0.00	0.02
0.00	0.02
0.00	0.03
0.00	0.07
0.00	0.22
0.00	0.58
0.00	1.14
0.01	1.58
0.01	1.96
0.00	0.77
0.00	0.29
0.00	0.12
0.00	0.06

Another solution is to set a sensor outside of the model and ask for illuminance level which, the value that Desktop Radiance gives is the exterior illuminance level. Then, the user could manually calculate the daylight factor level by dividing the interior illuminance value by this number.

From this solution, when the outside sensor is located up over the roof at height 7.00m, the illuminance value that the program returns is 18496 lux, which is close to the number from UNIX which is 18478 lux. This exterior illuminance value generated by Desktop Radiance varies from locations and heights of the sensor but is still very close to the number generated by UNIX.

Therefore, if daylight factor simulation is needed, two options are avaialble to resolve the problem.

If Desktop Radiance is still a preferred method of creating the input files; the first option is that the input file can still be generated within Desktop Radiance but the daylight factor calculation has to be done within UNIX environment or the global horizontal illuminance value has to be calculated by setting another sensor outside the modeled space and manually calculate the daylight factor.

The second option is that one could use Desktop Radiance to calculate the interior illuminance value at reference point locations but then get the exterior illuminance value calculated from UNIX version by using the sky description file generated from Desktop Radiance and let UNIX run the calculation of daylight factor.

Scale Model Material Reflectance Measurements

For the crescent board that has not been measured in terms of the reflectance value, the luminance meter is used along with a gray card to get the reflectance value. A Kodak gray card has the known reflectance of 0.18 and a white card 0.90. The equations used for calculating the reflectance is:

$$R^1_s = R_g L_s / L_g \quad (1)$$

$$R^2_s = R_w L_s / L_w \quad (2)$$

where R^1_s and R^2_s are the reflectance value of sample as calculated from the equations; R_g the reflectance of gray card; L_s the luminance of sample; L_g the luminance of gray card; R_w the reflectance of white card; L_w the luminance of white card. Then, the average of R^1_s and R^2_s is used as the material reflectance.

The crescent board that was tested is color Light Gray 916. The measurements and calculation is provided in Table D3.

Table D3
Reflectance measurement of Crescent Board Light Gray 916

Sample: Light Gray 916	Lg	Lw	Ls	R from grey card	R from white card	Average R	Rs
1st measurement	73.08	348.3	177.7	0.44	0.46	0.45	
2nd measurement	82.05	346.9	177.6	0.39	0.46	0.43	0.44

Lg: Luminance value of gray card; Lw: Luminance value of white card; Ls: Luminance value of sample; R: reflectance value; Rs: reflectance of sample.

APPENDIX E

GLAZING PROPERTIES

Glazing Thermal and Optical Properties from WINDOW5

Details of glazing system as modeled in this thesis are presented in Table E1-E5.

Table E1

ID	1
Name	Ngao_try1
Tilt	90
Glazings	2
KEFF	0.0328
Uvalue	1.75
SHGCc	0.57
SCc	0.65
Vtc	0.76
RHG	426.04

Table E2
Environmental Conditions: 1 NFRC 100-2001

	Tout (C)	Tin (C)	WndSpd (m/s)	Wnd Dir	Solar (W/m2)	Tsky (C)	Esky
Uvalue	-18	21	5.5	Windward	0	-18	1
Solar	32	24	2.8	Windward	783	32	1

Table E3
Temperature Distribution (degrees C)

Glass	Winter		Summer	
	out	in	out	in
Layer1	-15.7	-15.4	39.1	39.3
Layer2	11.1	11.5	34	33.8

Table E4
Glass and gas data for glazing system Ngao_try1

ID	Name	D(mm)	Tsol	Rsol1	Rsol2	Tvis1	Rvis1	Rvis2	Tir	Emis1	Emis2	Keff
Outside												
2007	E178-4.CIG	4.1	0.607	0.194	0.253	0.86	0.054	0.048	0	0.84	0.083	1
	1 Air	12.7										0.033
103	CLEAR_6.DAT	5.7	0.771	0.07	0.07	0.884	0.08	0.08	0	0.84	0.84	1
Inside												

Table E5

Optical Properties for Glazing System '1 Ngao_try1'

Angle	0	10	20	30	40	50	60	70	80	90	Hemis
Vtc	0.763	0.767	0.757	0.743	0.723	0.684	0.597	0.433	0.2	0	0.636
Rf	0.113	0.106	0.103	0.106	0.119	0.144	0.194	0.302	0.534	0.999	0.174
Rb	0.118	0.112	0.111	0.115	0.129	0.158	0.222	0.366	0.633	1	0.198
Tsol	0.489	0.492	0.484	0.473	0.459	0.432	0.376	0.271	0.123	0	0.403
Rf	0.226	0.22	0.217	0.22	0.23	0.25	0.287	0.375	0.577	0.999	0.273
Rb	0.208	0.203	0.201	0.202	0.208	0.225	0.266	0.366	0.576	1	0.255
Abs1	0.206	0.208	0.218	0.225	0.228	0.234	0.256	0.284	0.252	0.001	0.236
Abs2	0.08	0.08	0.081	0.082	0.083	0.084	0.081	0.07	0.048	0	0.078
SHGCc	0.568	0.572	0.565	0.556	0.543	0.517	0.461	0.35	0.182	0	0.484
Tdw-K	0	382									
Tdw-ISO	0	601									
Tuv	0	208									

Radiance Input (rad File) of Glazing Material Created by Optics5

```
#
# FileName= Ngao_try1.usr
# Product Name=
# NFRC ID= 30000
# Manufacturer Name= User
# Glazing Type= Glazing system
# Coated Side= Neither
# Transmittance= 0.761
# Front Reflectance= 0.114
# Back Reflectance= 0.118
# Thickness(mm)= 21.775
# Appearance=
#

void  glass      Ngao_try1_glass
0
0
3    0.796    0.846    0.799
void  BRTDfunc    Ngao_try1_front
10
     0.100    0.117    0.134
     0.731    0.776    0.733
     0 0 0
     .
0
9 0 0 0 0 0 0 0 0 0

void  BRTDfunc    Ngao_try1_back
10
     0.110    0.120    0.126
     0.731    0.776    0.733
     0 0 0
     .
0
9 0 0 0 0 0 0 0 0 0
```

APPENDIX F

SCALE MODEL AND RADIANCE COMPARISON

Overcast Sky Test Results

Overcast test result for single unit prototypes is presented in Fig. F1. For the results of a 1.5 to 1 spacing-to-height and a 1 to 1 spacing-to-height, the results are presented in Figs. F2-F3, respectively.

Clear Sky Test Results

Single Unit Prototype Results

Single Unit Skylight

The results from the scale model measurement and from RADIANCE are similar and are following the same trend. Single unit skylight illuminance comparison results are presented in Fig. F4. There are more discrepancies in Dec 21, at 12:00pm and 3:00pm. The average discrepancy is at 16.7 percent. All of the horizontal exterior illuminance as measured from the tilted model is higher than the value calculated from RADIANCE. This might be the cause of the discrepancy since the illuminance distribution between the scale model and RADIANCE are similar.

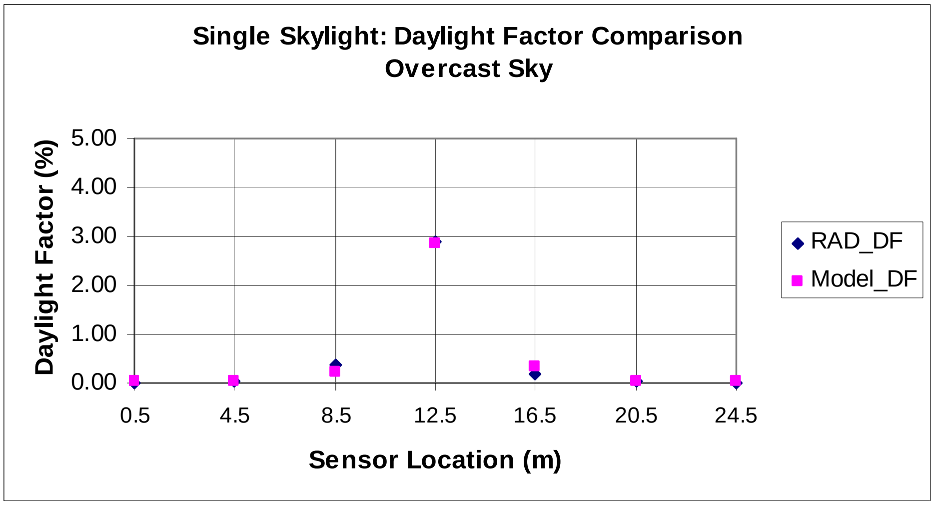
Single Unit Lightscoop

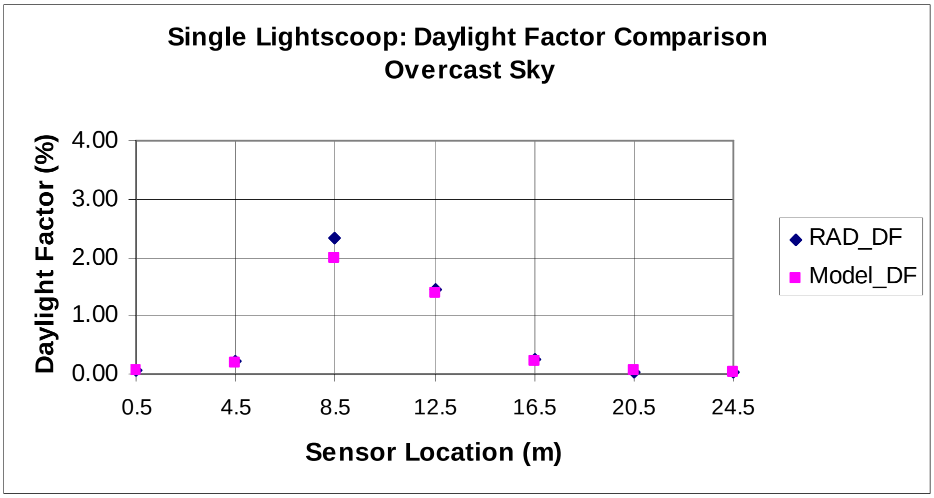
The illuminance distribution of lightscoop under clear sky condition between a scale model measurement and RADIANCE is very similar in pattern for all the tested date and time, while having some discrepancy with mostly the scale model yields higher illuminance value. Single unit lightscoop illuminance comparison results are presented in Fig. F5. From the chart, it can be seen that the trends in two lines of illuminance value under clear sky condition of the single unit lightscoop are very close to each other with the average discrepancy of 21.2 percent. Maximum discrepancy is seen in winter solstice (Dec 21) at 3:00pm at 32 percent, which could be the result of the model tilt. The horizontal exterior illuminance as measured from the tilted model is higher than the calculated value from RADIANCE in all the tested dates and times.

Single Unit Roof Monitor

The illuminance distribution of the single roof monitor under clear sky condition between a scale model and RADIANCE has shown similar results in the illuminance level and the light distribution, with the average range of 20.6 percent. Single unit roof monitor illuminance comparison results are presented in Fig. F6. The illuminance value discrepancy ranges from 2-25 percent, with more discrepancy at 3:00pm at all the dates tested which is at about 20 percent.

In sum, for single unit toplighting prototypes, the average discrepancy for all the cases is at 19 percent.





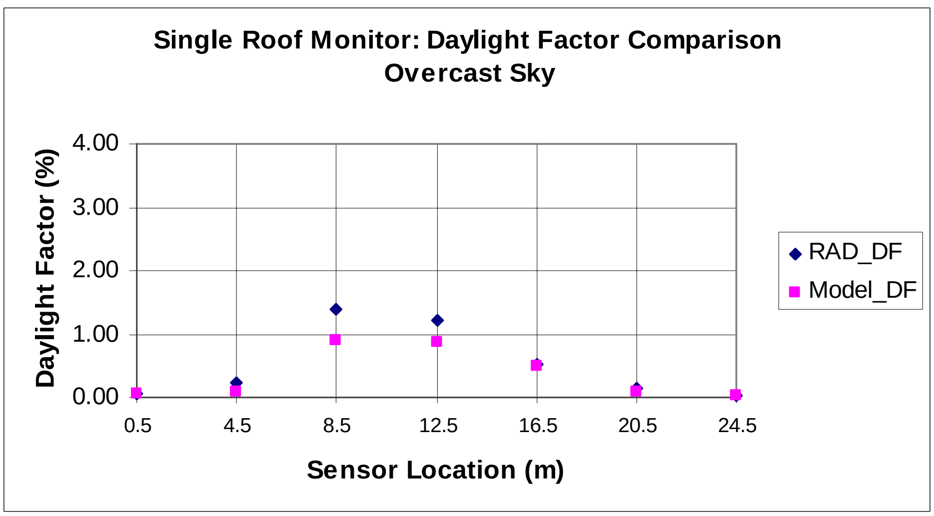


Fig. F1 Single unit prototype: DF comparison of model and RADIANCE, overcast sky

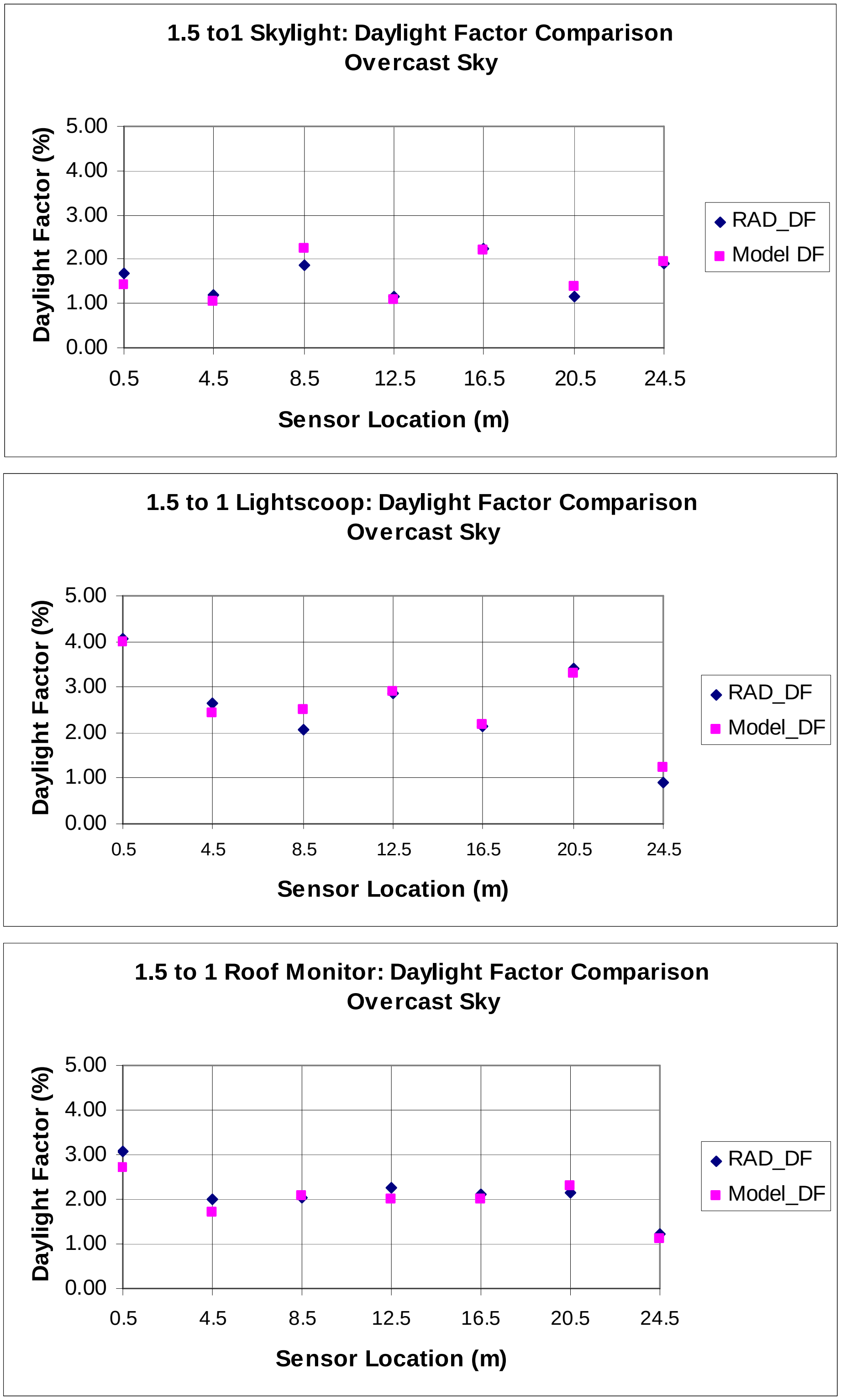
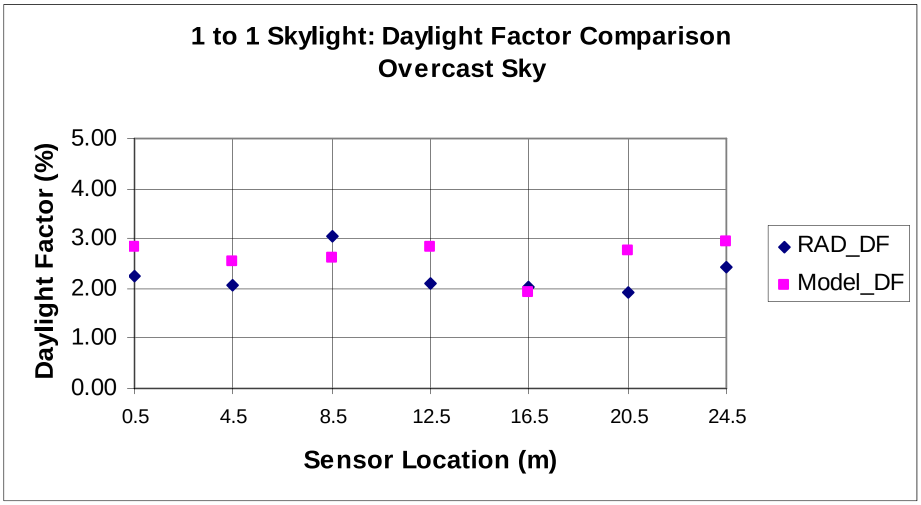
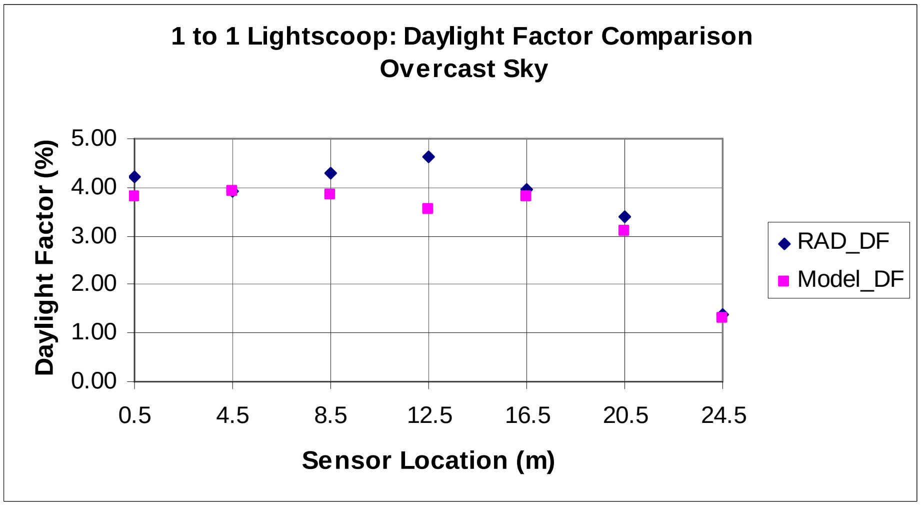


Fig. F2 1.5 to 1 Prototype: DF comparison of model and RADIANCE, overcast sky





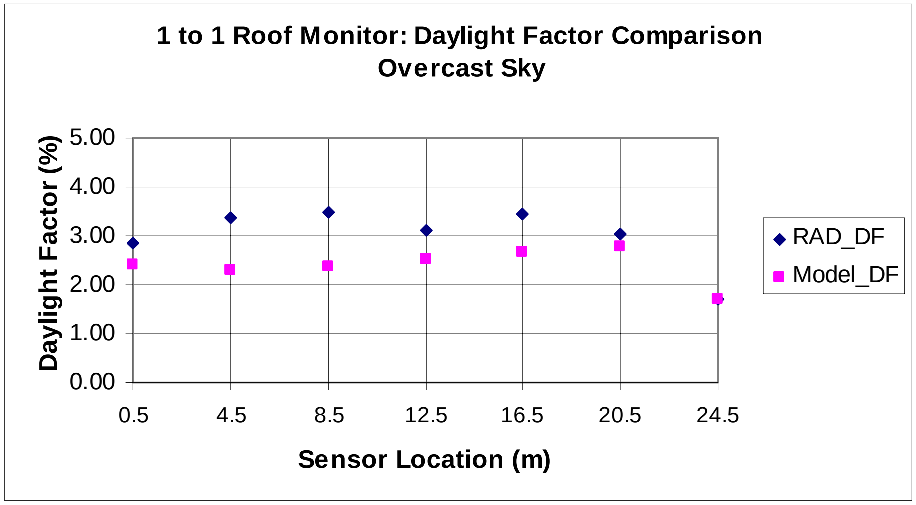


Fig. F3 1 to 1 Prototype: DF comparison of model and RADIANCE, overcast sky

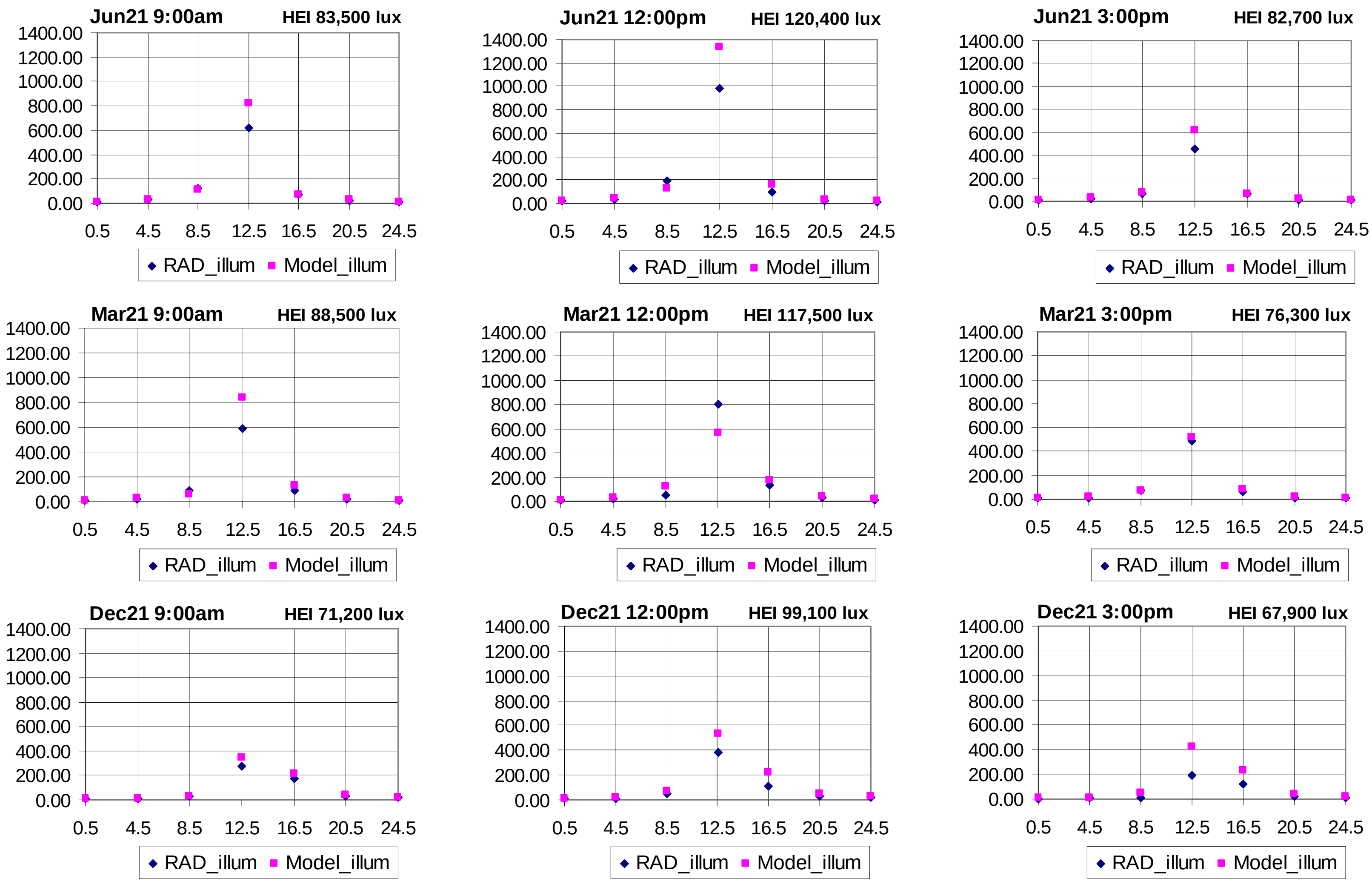


Fig. F4 Single unit skylight: illuminance comparison of scale model and RADIANCE, clear sky condition

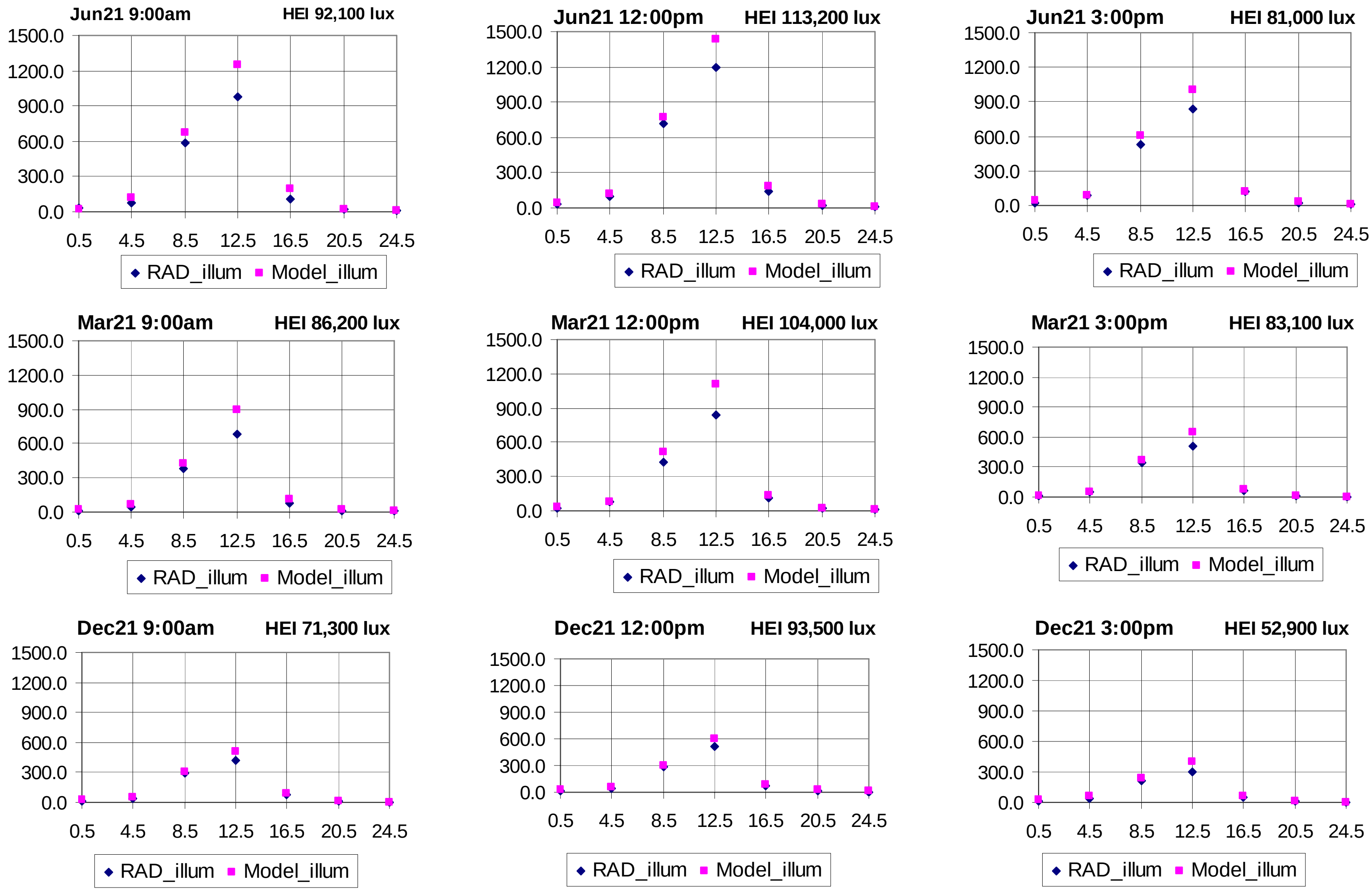


Fig. F5 Single unit lightscoop: illuminance comparison of scale model and RADIANCE, clear sky condition

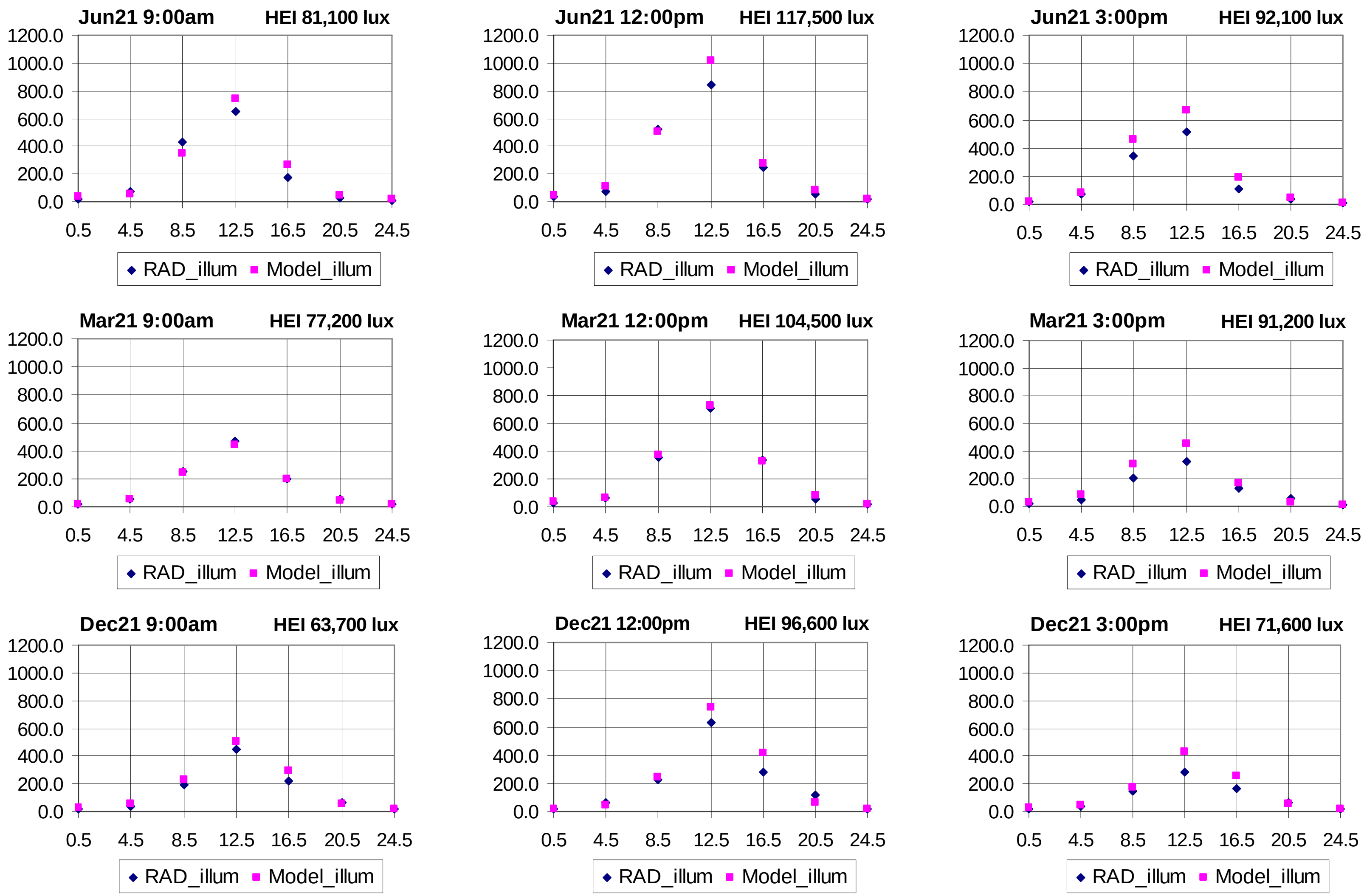


Fig. F6 Single unit roof monitor: illuminance comparison of scale model and RADIANCE, clear sky condition

5.1.2.2. Prototype with a 1.5 to 1 Spacing-to-Height Results

<u>1.5 to 1 Skylight</u>

The illuminance comparison between a scale model measurement and RADIANCE results under clear sky for a 1.5 to 1 skylight is similar, with the average discrepancy of 20.9 percent. The result is shown in Fig. F7. The time at the largest discrepancy is at the summer solstice at 3:00pm with an average discrepancy of 43 percent. For other times in summer solstice and equinox, RADIANCE results represent similar values to those measured from the scale model.

<u>1.5 to 1 Lightscoop</u>

The illuminance results between a scale model and RADIANCE are close to one another with an average of 12.4 percent discrepancy. The result of a 1.5 to 1 lightscoop illuminance comparison is shown in Fig. F8. Most of the discrepancy ranges within 10 percent except in equinox and winter solstice at 3:00pm which has the average discrepancy at about 20 percent.

<u>1.5 to 1 Roof Monitor</u>

From the illuminance comparison between a scale model and RADIANCE for a 1.5 to 1 roof monitor, the results of the distribution are similar, within the average range of 15 percent. The result of a 1.5 to 1 roof monitor illuminance comparison is shown in Fig. F9. The date with most discrepancy is in winter solstice at 3:00pm with the discrepancy of 33 percent. Other times have less discrepancy of less than 20 percent except on equinox at 3:00pm which has 24 percent discrepancy. Still, the overall results are close.

5.1.2.3. Prototype with a 1 to 1 Spacing-to-Height Results

1 to 1 Skylight

The overall discrepancy of skylight illuminance value from a scale model and RADIANCE are close, with an average discrepancy of 20.6 percent. From the results shown in Fig. F10, it can be seen that the trend in the illuminance distribution is very similar for the scale model measurement and RADIANCE. The discrepancy percentages of most of the date and time tested are less than 20 percent, except at the summer solstice, equinox, and winter solstice at 3:00pm.

1 to 1 Lightscoop

The illuminance level between a scale model measurements and RADIANCE results are similar, having an average discrepancy of 16.7 percent. The illuminance chart comparison is shown in Fig. F11. It can be seen from the chart that, the overall illuminance level between the two are very close to each other and the distribution is very similar. The average maximum discrepancy occurs in equinox at 3:00pm which is 31 percent. Most of the time, the illuminance discrepancies between the scale model and RADIANCE are less than 20 percent. The scale model results are mostly higher than RADIANCE.

1 to 1 Roof Monitor

The illuminance level between a scale model measurements and RADIANCE results are similar, having an average discrepancy of 17.3 percent. The illuminance chart comparison for a 1 to 1 roof monitor is shown in Fig. F12. Overall values and distribution between a scale model and RADIANCE are similar.

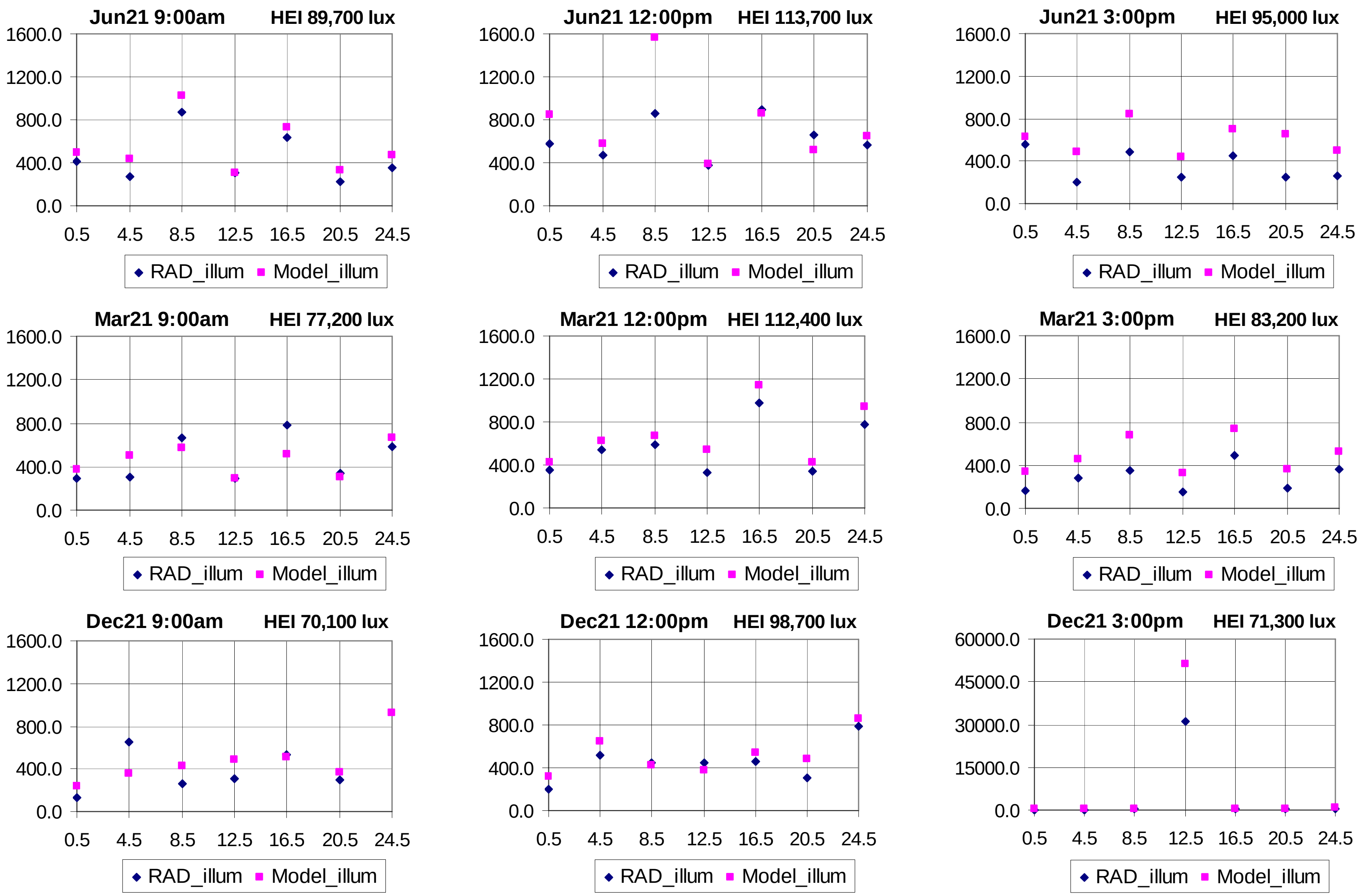


Fig. F7 1.5 to 1 skylight: illuminance comparison of scale model and RADIANCE, clear sky condition

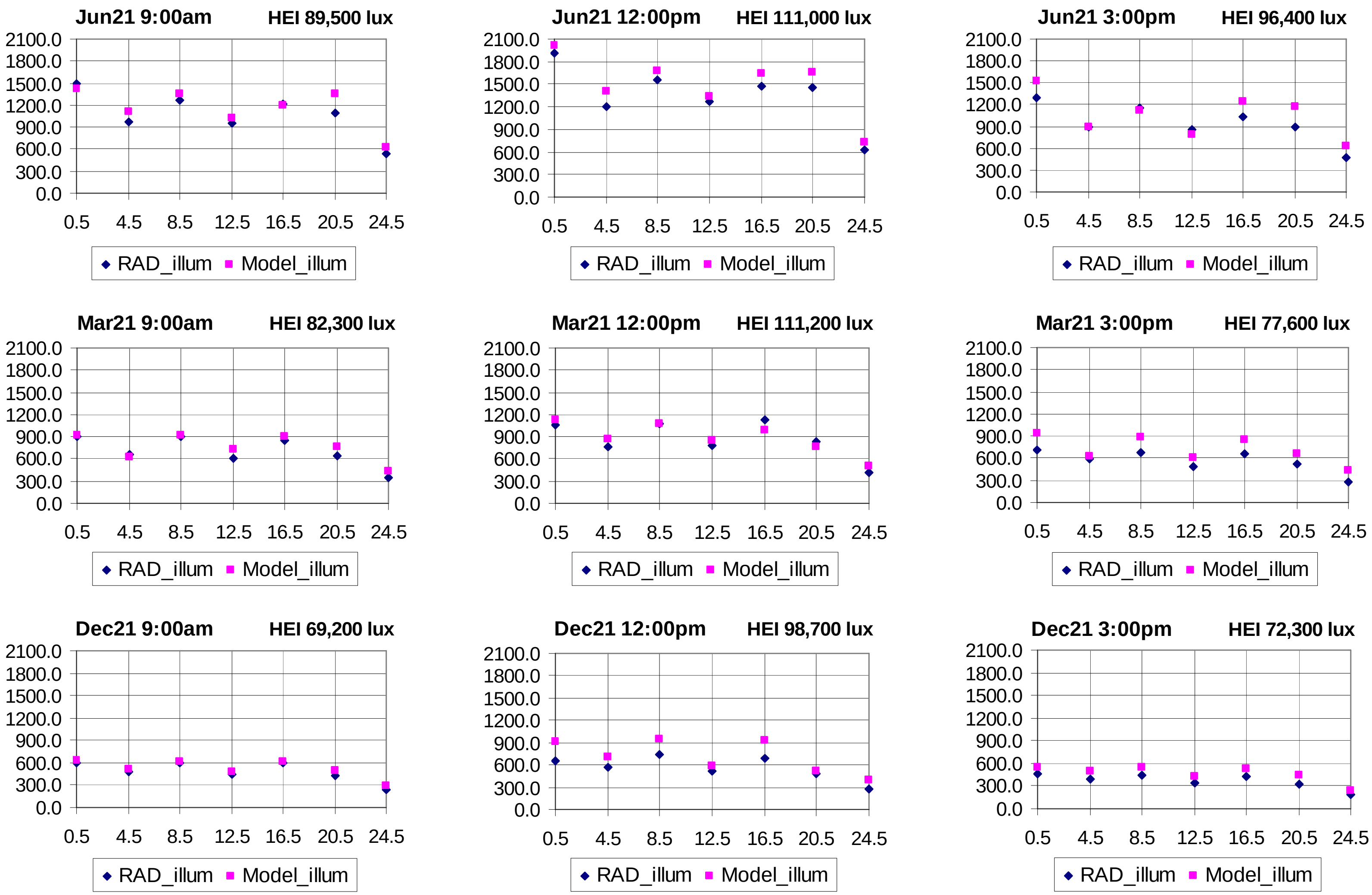


Fig. F8 1.5 to 1 lightscoop: illuminance comparison of scale model and RADIANCE, clear sky condition

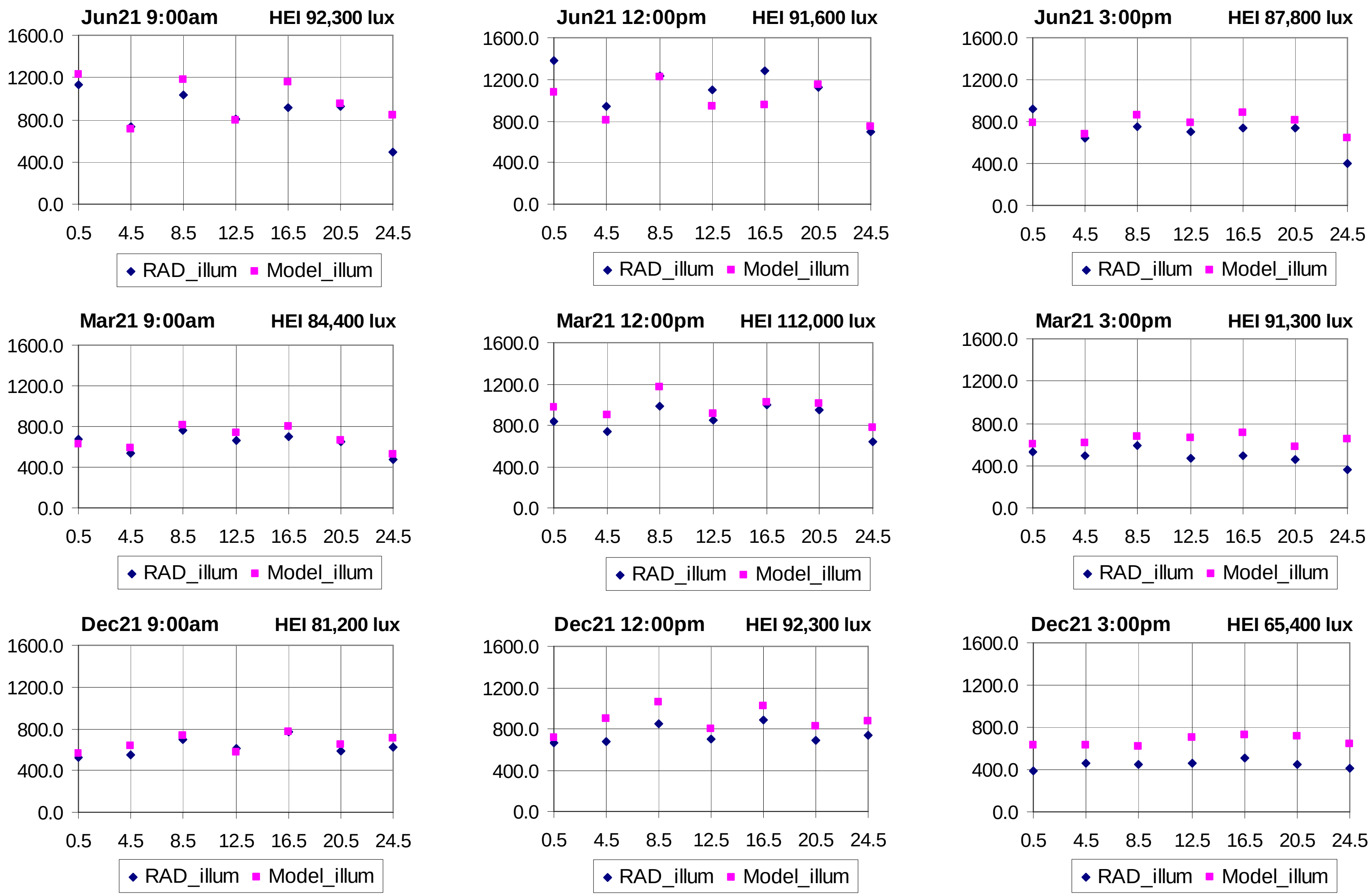


Fig. F9 1.5 to 1 roof monitor: illuminance comparison of scale model and RADIANCE, clear sky condition

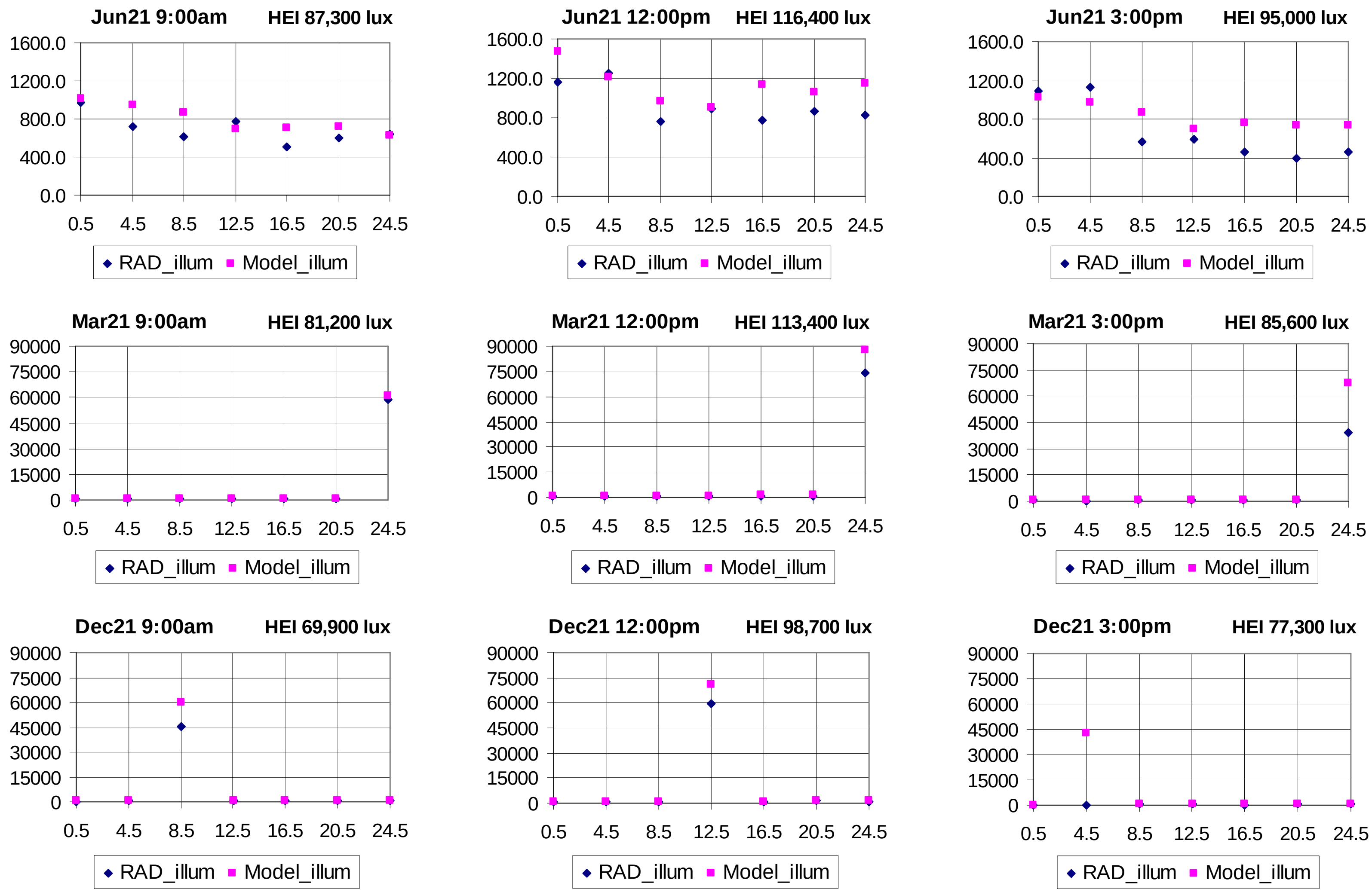


Fig. F10 1 to 1 skylight: illuminance comparison of scale model and RADIANCE, clear sky condition

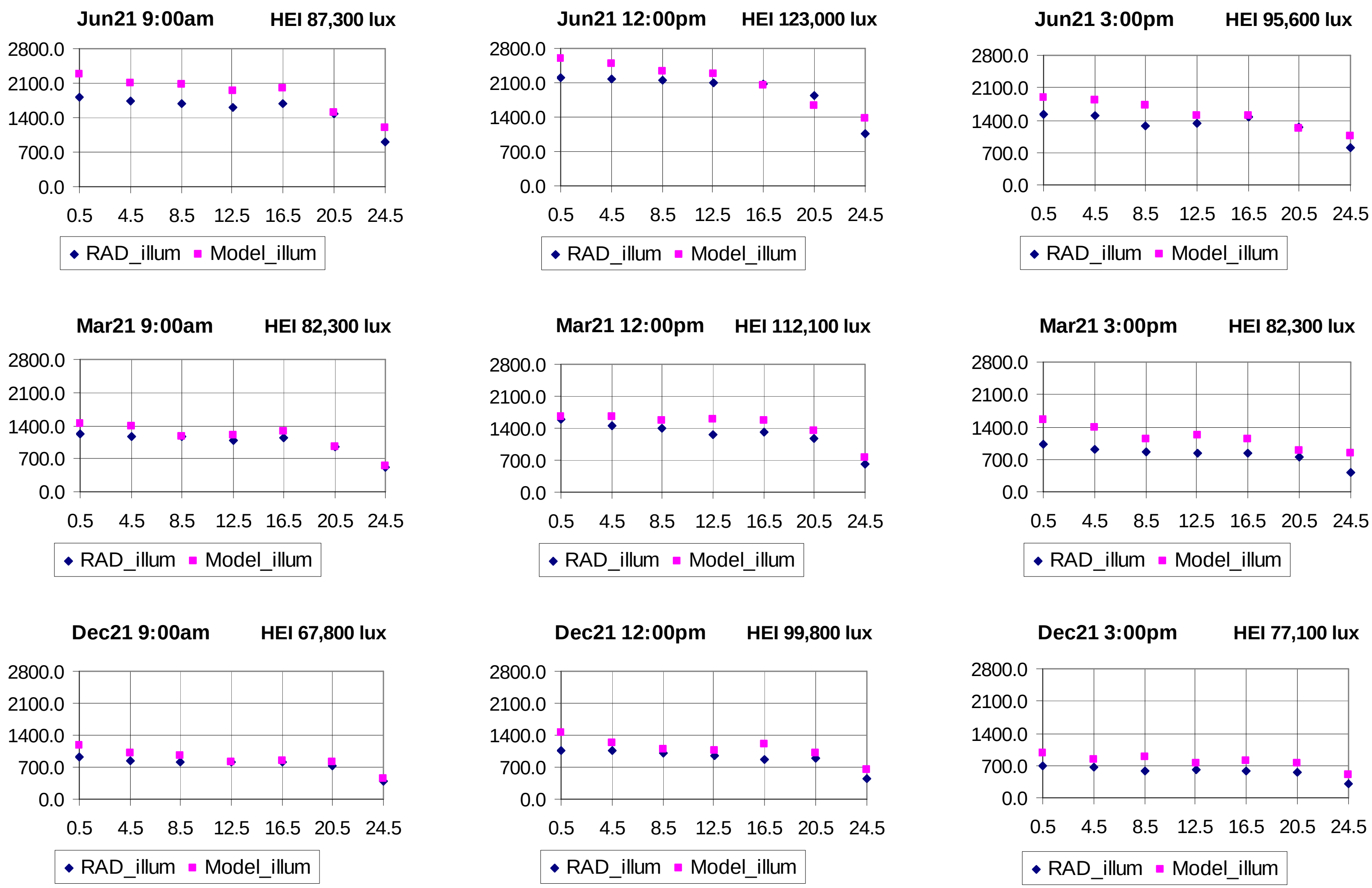


Fig. F11 1 to 1 lightscoop: illuminance comparison of scale model and RADIANCE, clear sky condition

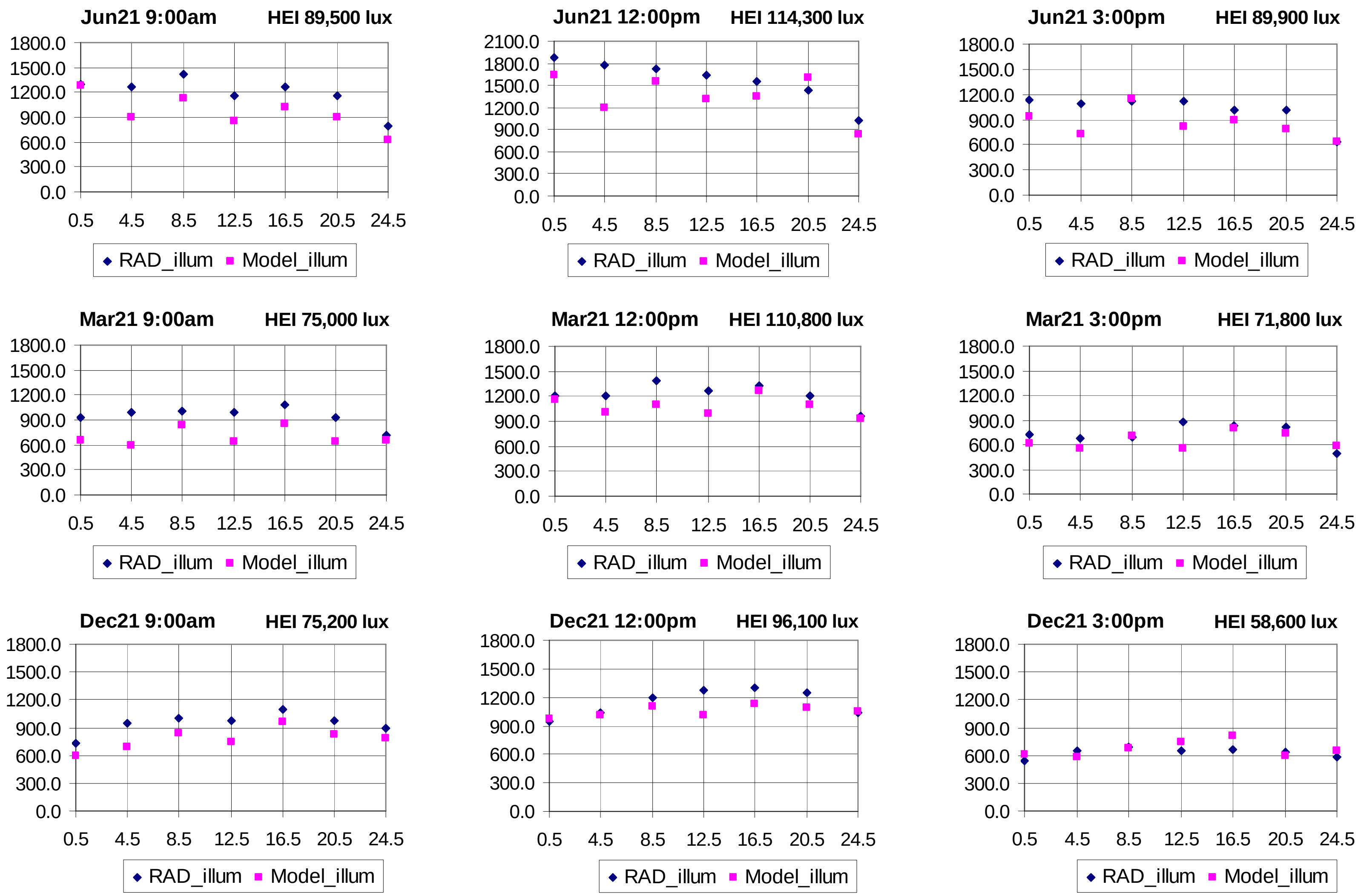


Fig. F12 1 to 1 roof monitor: illuminance comparison of scale model and RADIANCE, clear sky condition

APPENDIX G

RADIANCE SCRIPTS

Example of RADIANCE Script File and Commands Used in this Thesis

Rtrace Script to Calculate the Horizontal Illuminance Level

```
#! /bin/bash
rtrace -w -h -I+ -ab 5 -aa 0.2 -ad 1024 -as 64 -ar 128 \
oc_illum.oct < recgrid_150_1x1.pts | rcalc -e '$1=179*(.265*$1+.670*$2+.065*$3)' \
> oc_150_1x1.dat
```

For Rendering Falsecolor Images over Floor Plan

```
#! /bin/bash

# all commands (after running oconv) for render of illuminance and luminance
# contour lines pict file and convert to tif files

# script file for rpict to render scene file: luminance

rpict -vf planview.vf -ab 5 -aa 0.2 -ad 1024 -ds 0.2 -as 512 -ar 128 -x 1200 -y 1600
octree/oc.oct  \
> pic/oc_plan.pic

# script file for rpict to render scene file: illuminance

rpict -vf planview.vf -ab 5 -aa 0.2 -ad 1024 -ds 0.2 -as 512 -ar 128 -x 1200 -y 1600 -i
octree/oc.oct  \
> pic/oc_plani.pic

# falsecolor: contour line on floor plan script

falsecolor -i pic/oc_plani.pic -p pic/oc_plan.pic -cl -n 5 -s 1500 -l lux > pic/oc_ct.pic

# falsecolor: falsecolor on floor plan script

falsecolor -i pic/oc_plani.pic -p pic/oc_plan.pic  -n 5 -s 1500 -l lux > pic/oc_fls.pic

# ra_tiff for all the pict file
```

ra_tiff pic/oc_ct.pic pic/oc_ct.tif

ra_tiff pic/oc_fls.pic pic/oc_fls.tif

Commands for Rendering Perspective Views

rad jun12.rif

Rif File Example (jun12.rif)

OCTREE= octree/jun12_p.oct

PICTURE= pic/jun12_p

view= fisheye3 -vf fisheye3.vf

ZONE=

UP= Z

RESOLUTION= 1200 1200

QUALITY= H

PENUMBRAS= T

INDIRECT= 5

DETAIL= M

VARIABILITY= H

render= -av 0 0 0

Fisheye View File (fisheye3.vf)

rview -vta -vp 7.5 4 1.5 -vd 0 1 0 -vu 0 0 1 -vh 180 -vv 180 -vo 0 -va 0 -vs 0 -vl 0

APPENDIX H

BANGKOK WEATHER SUMMARY

Bangkok Weather Chart

As discussed in Chapter I, Bangkok, Thailand is located in a hot and humid climate location at latitude 13.7N.

Fig. H1 represents average Bangkok weather as generated from the Weather Tool from the EPW weather file of Bangkok available from EnergyPlus website. The pink straight band represents the thermal temperature comfort zone which is at about 25-28C. The light blue band is the maximum, minimum, and average temperature range of each month. The blue line is direct solar and the blue dotted line is diffuse solar average of each month.

Bangkok Sky Type

As in Chapter II, from the study by S. Chirarattananon et al., the sky types of Bangkok [17], Thailand are overcast, clear, and intermediate conditions. Fig. H2 graphically summarizes these sky types.

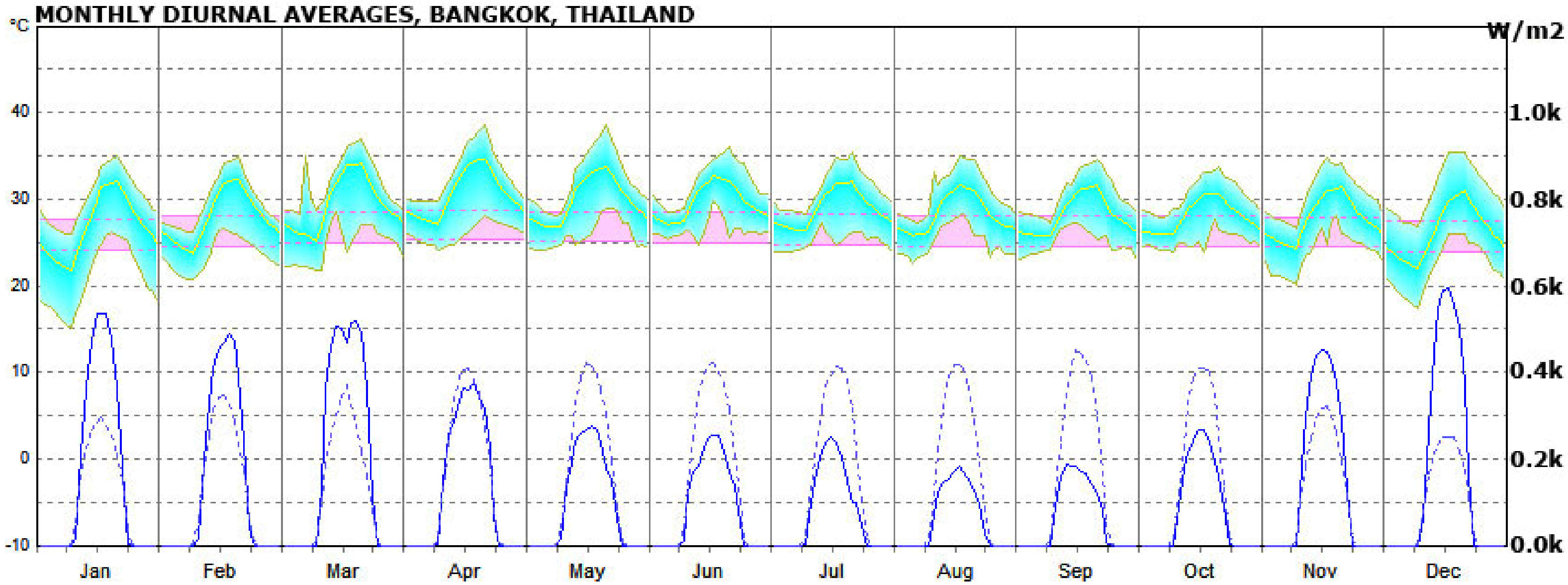


Fig. H1 Monthly diurnal averages of Bangkok, Thailand

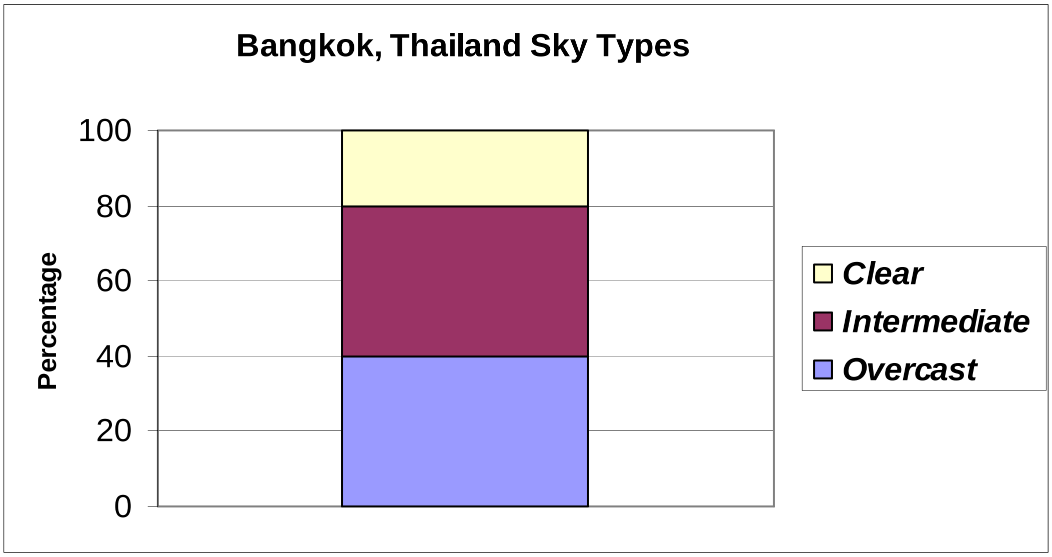


Fig. H2 Bangkok sky types

VITA

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Organization:

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Board member of the TAMU Student Chapter of the IESNA (Illuminating Engineering Society of North America) 2003-2004

Student member of IESNA and ASHRAE 2003-2005

Awards:

IESNA San Jacinto Section / Tim Carnes Memorial Scholarship recipient, May 2005

Selected to participate in the ASES student poster competition, Portland, Oregon, July 2004