Climate-Based Modelling and Daylight Coefficients

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Part 1: Introduction to Climate-Based Modelling

Climate-based daylight modelling is the prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standard meteorological datasets (e.g. TMY2 or CIBSE design years).

Climate-based daylight modelling does not yet have any kind of widely-accepted formal definition.

A proposal for a definition

An analysis that is founded on the totality of contiguous meteorological data for the evaluation period in question.

The evaluation period should be of sufficient duration so that the analysis can be truly said to capture or represent the prevailing conditions for that interval, rather than be simply a “snapshot” of specific conditions at a particular instant, e.g. summer solstice.

A period of an entire year is needed to capture the full range in climatic conditions.

The three principal modes of climate-based evaluation

- **Cumulative annual:** the aggregated luminance (or radiance) effect of all the unique hourly sky and the sun conditions for a full year.
- **Cumulative monthly:** as annual, but for each month.
- **Time-series:** predict hourly (or sub-hourly) values for a full year.

Why Climate-Based?

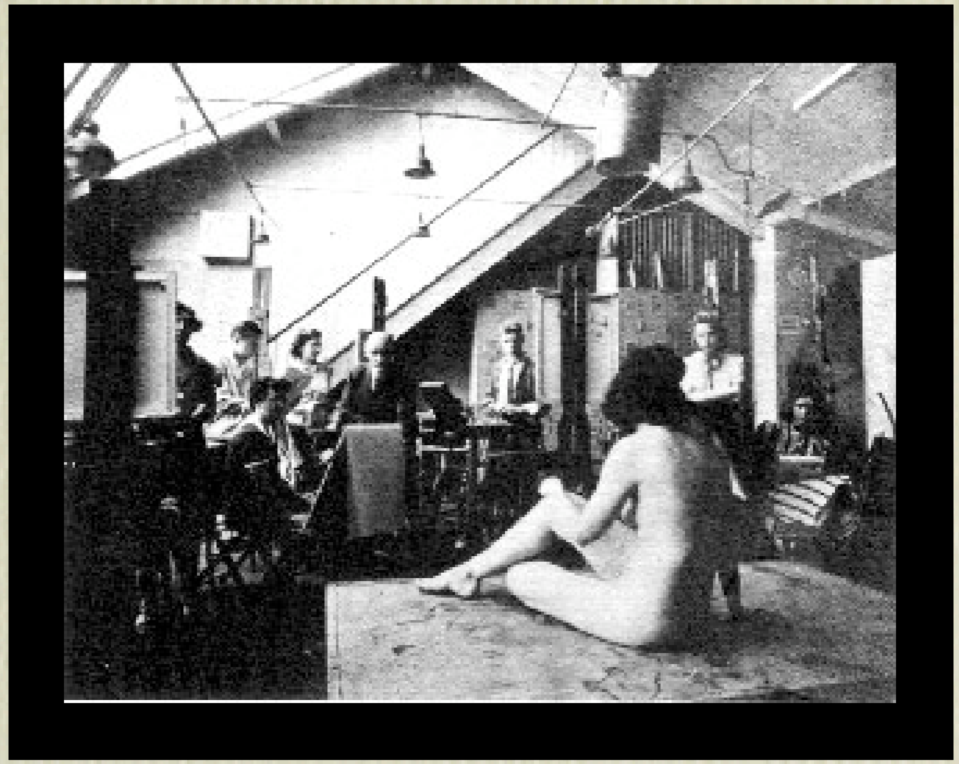
- Climate-based daylight modelling predicts absolute measures of illumination etc. using realistic descriptions for the sky and sun conditions.
- The evaluation period is usually for a full year to capture all of the naturally occurring variation in meteorological conditions.
- Sun and (variable) sky conditions are evaluated together.

Example I: The Arts Students League (New York)

Founded in 1875, the ASL boasts an alumni list that is a veritable Who's Who in American art, from Winslow Homer and Georgia O'Keeffe to Mark Rothko, Jackson Pollock and Louise Nevelson.

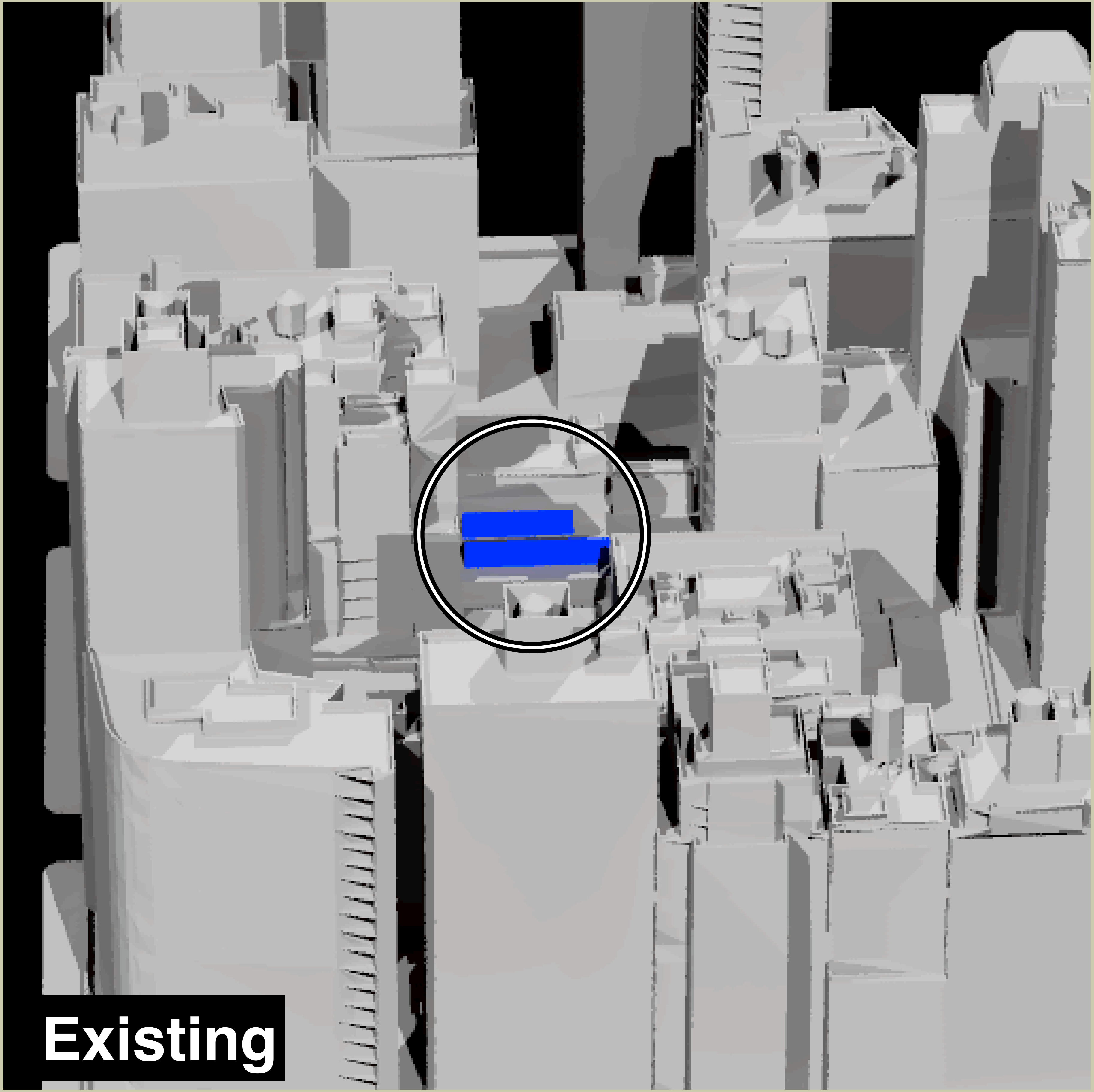
Natural Light

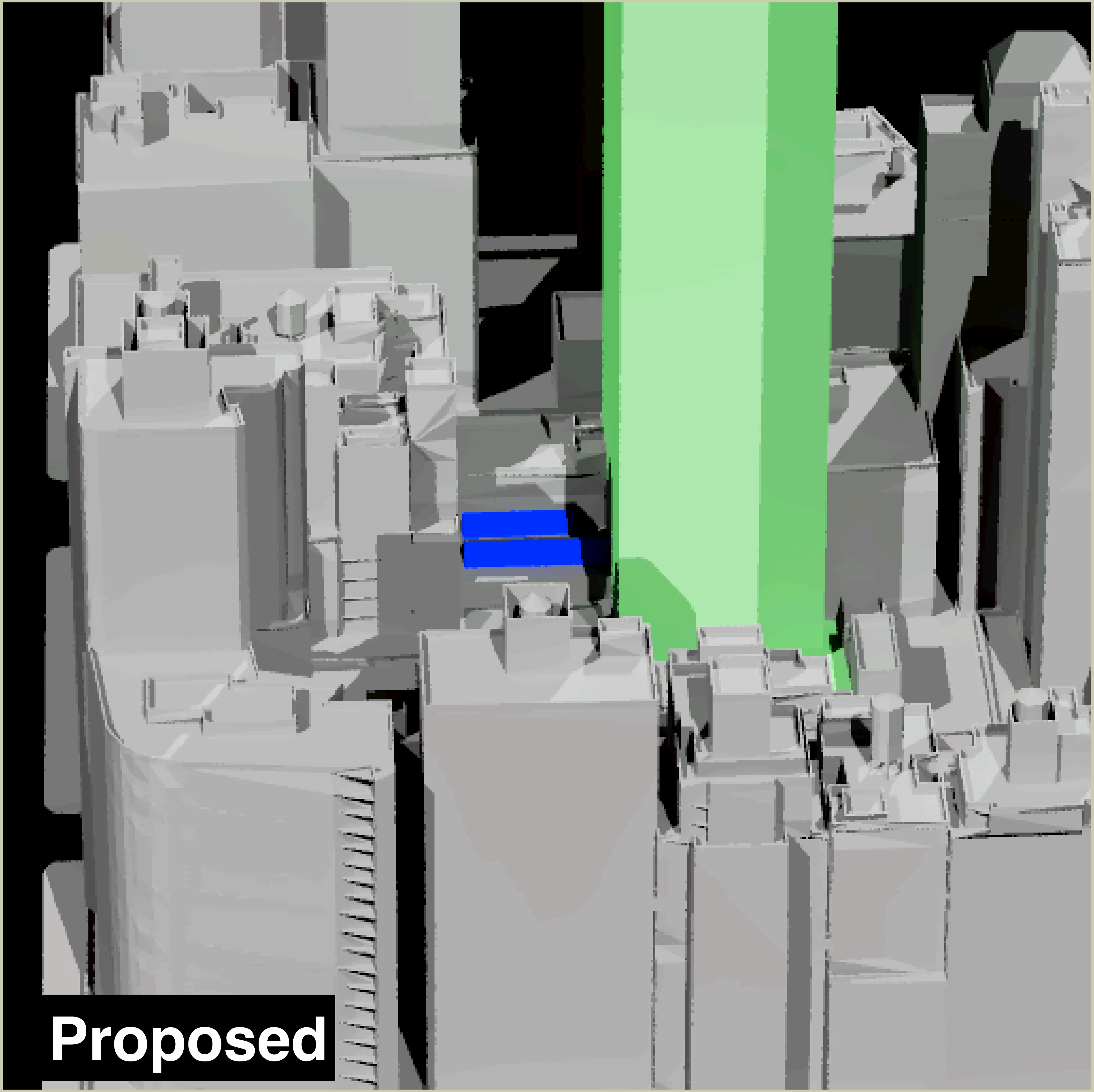
The ASL artists, teachers and students, both past and present, have all placed great value in the daylight afforded by the skylights.



Scenario: A development is proposed for the through lot immediately west of the ASL.

Design issue: The proposed tower has the potential to reduce the daylighting of the two studios on the top floor of the ASL.


Existing



Proposed

Traditional Methods Could Not Address Client Concerns

- **Shadow pattern study:** The North facing skylights rarely receive direct sun light.

- **Overcast sky approach:** The client was aware how the character of illumination in the ASL studios depends on the various sky conditions, including the potential for redirected sunlight.

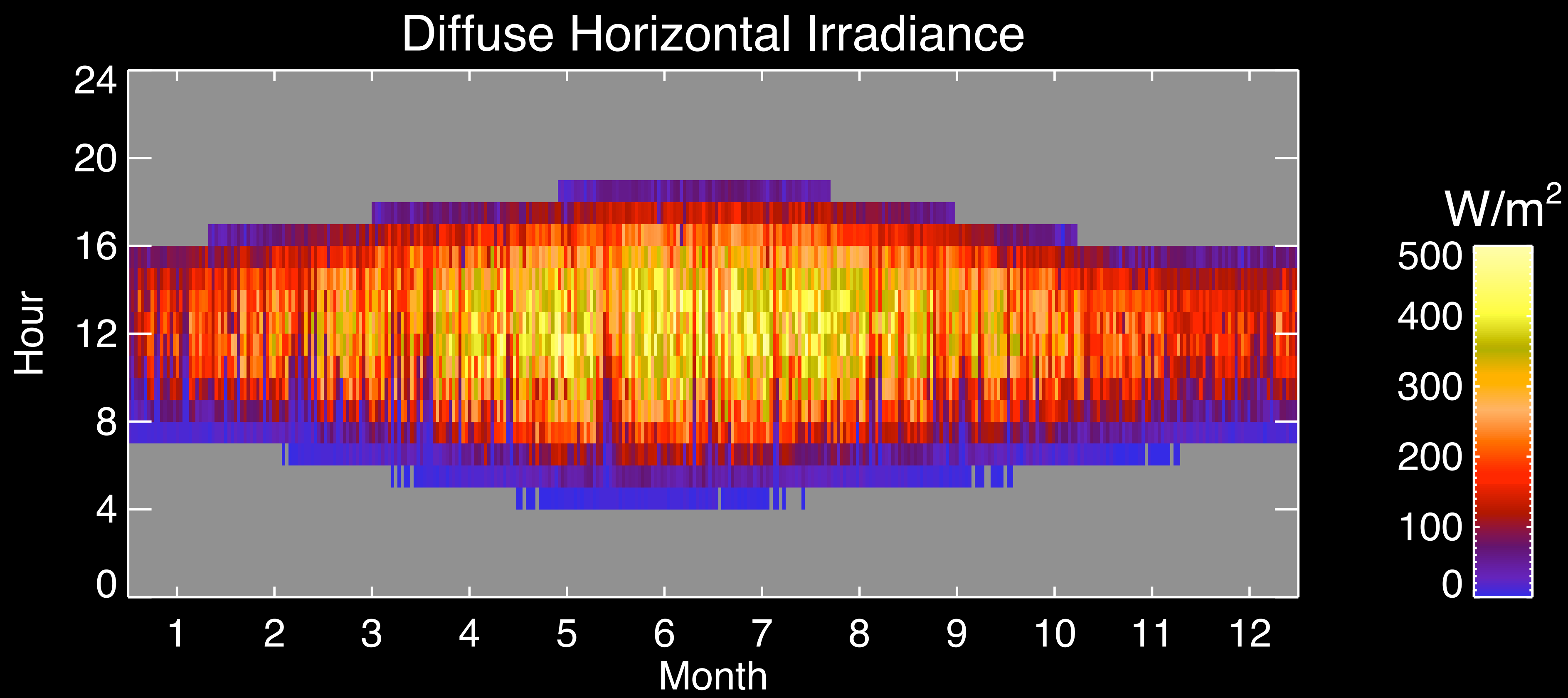
Neither the shadow pattern nor the single sky condition were considered adequate

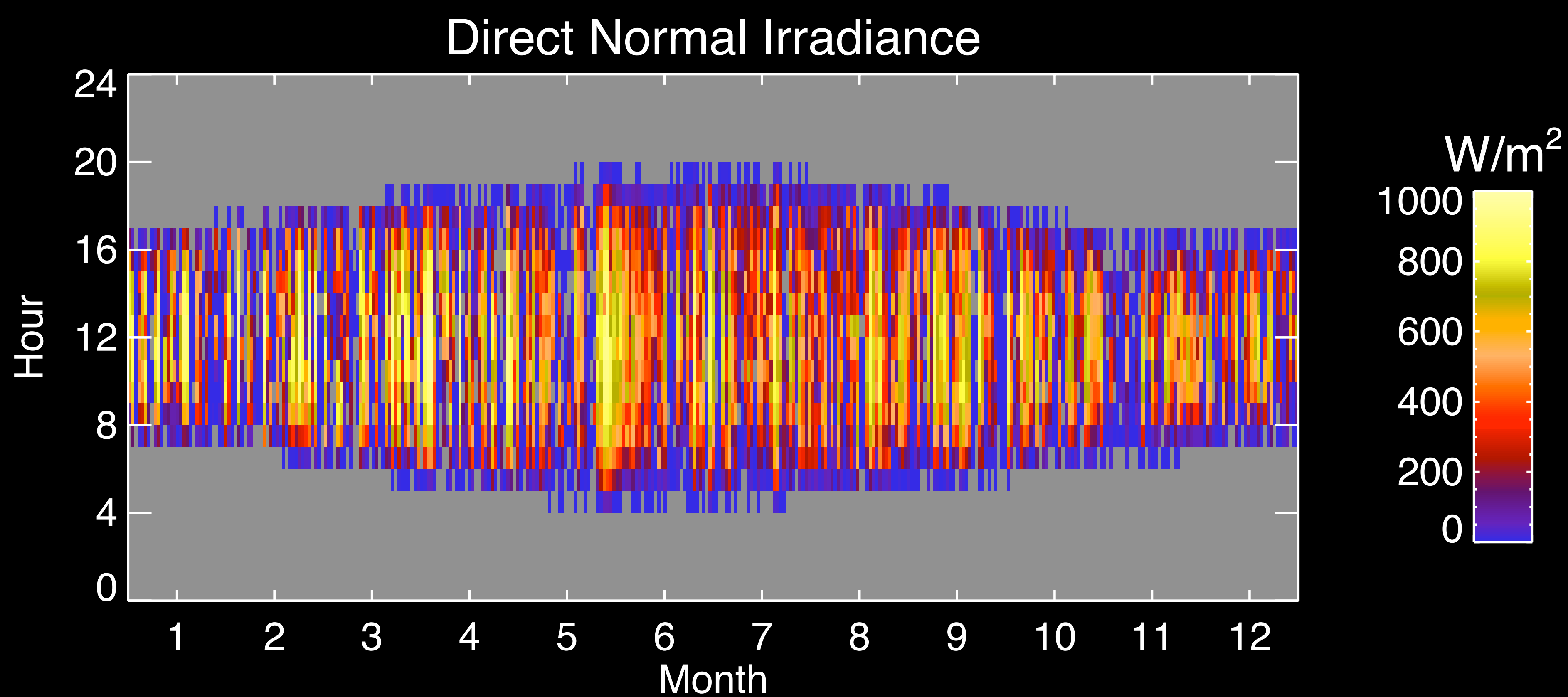
Solution: Assess Daylight in Terms of Real Illumination

Total annual illumination (TAI) is a measure of all the visible daylight energy incident on a surface.

The prediction of TAI is founded on standard climate data recorded at/near the site (NYC).

The simulation accounts for overcast and clear sky conditions, the sun and inter-reflection.





Climate Data for New York City

TMY 94728

Predict Total Annual Illumination for:

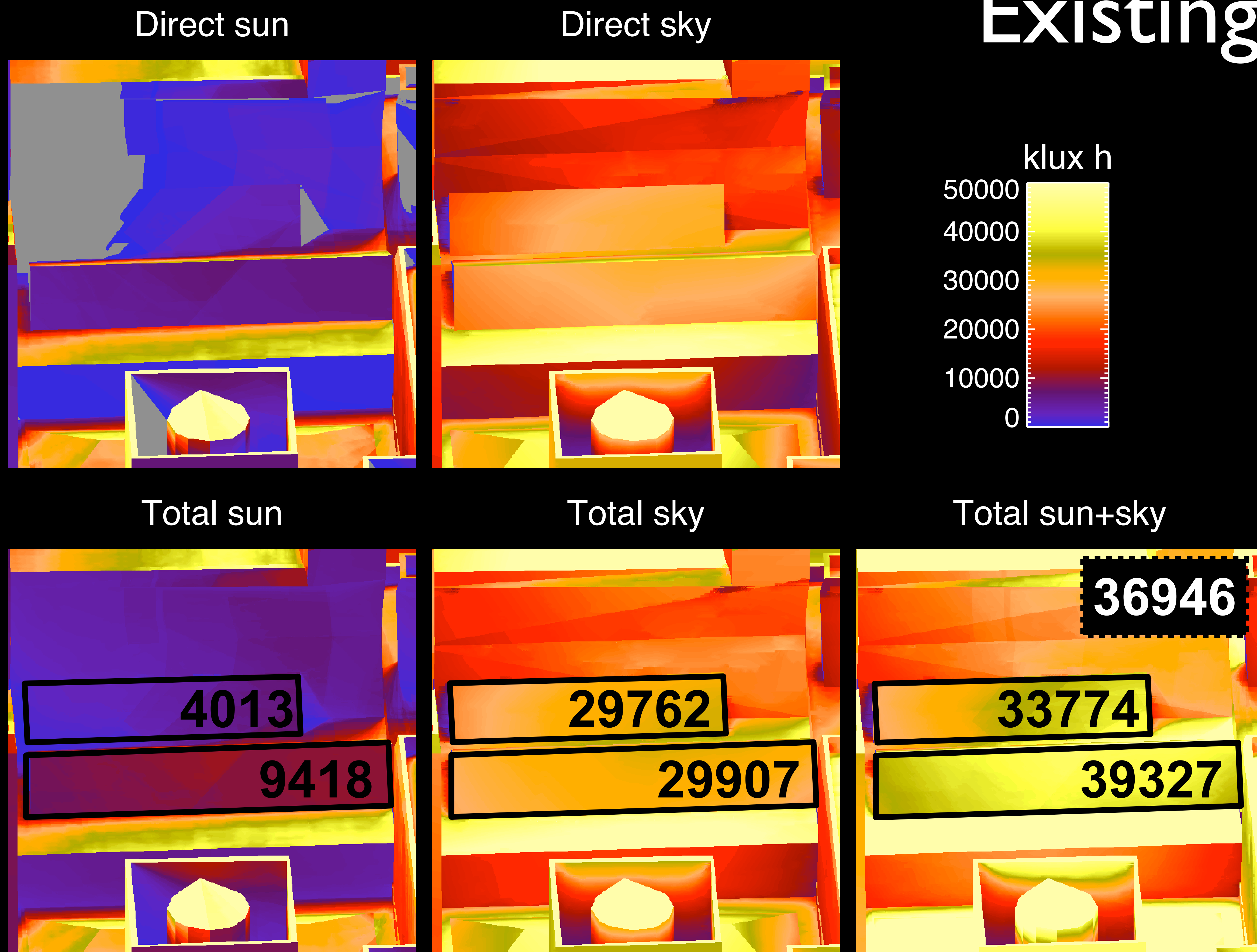
(a) Existing situation.

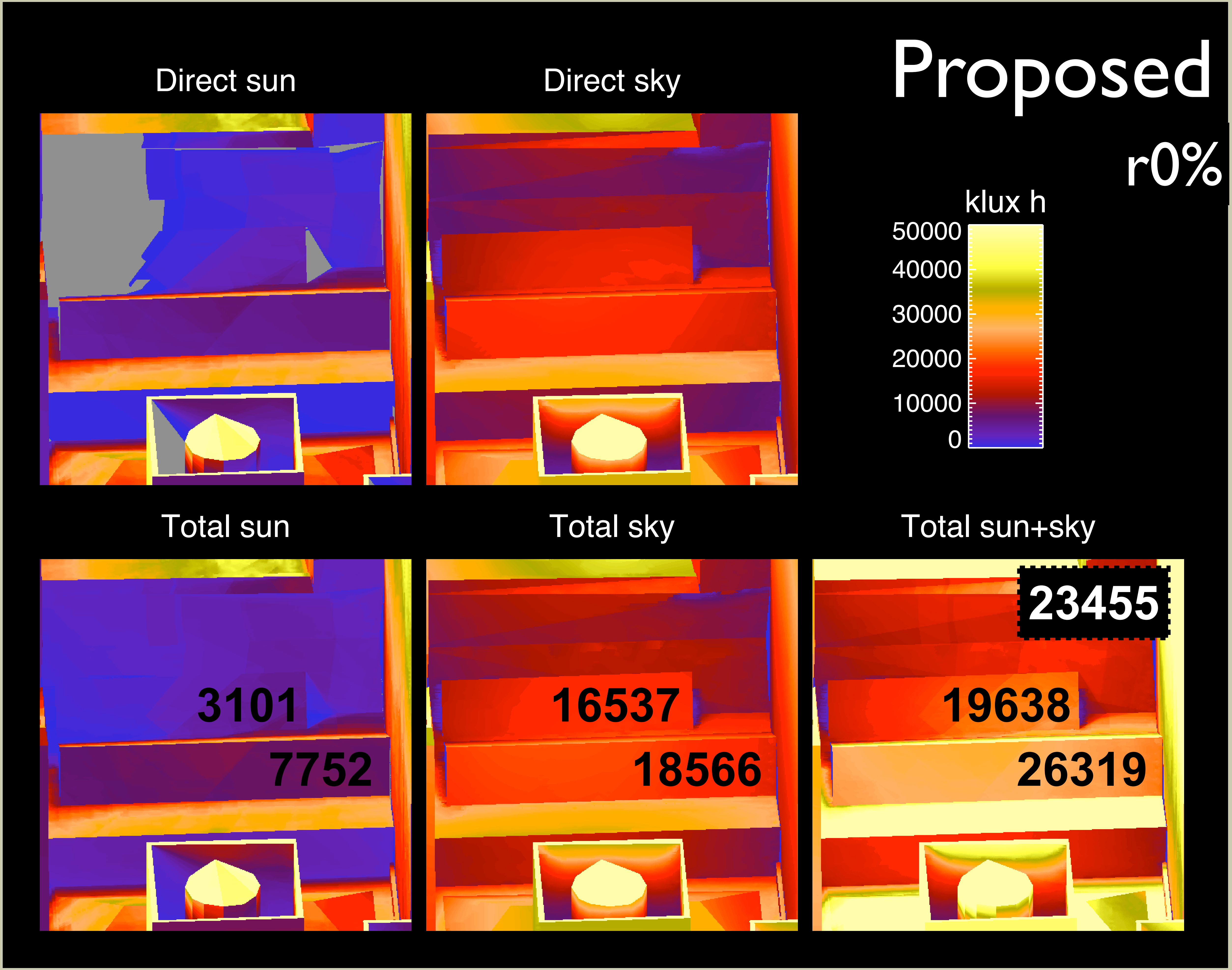
(b) With proposed tower reflectance = 0%.

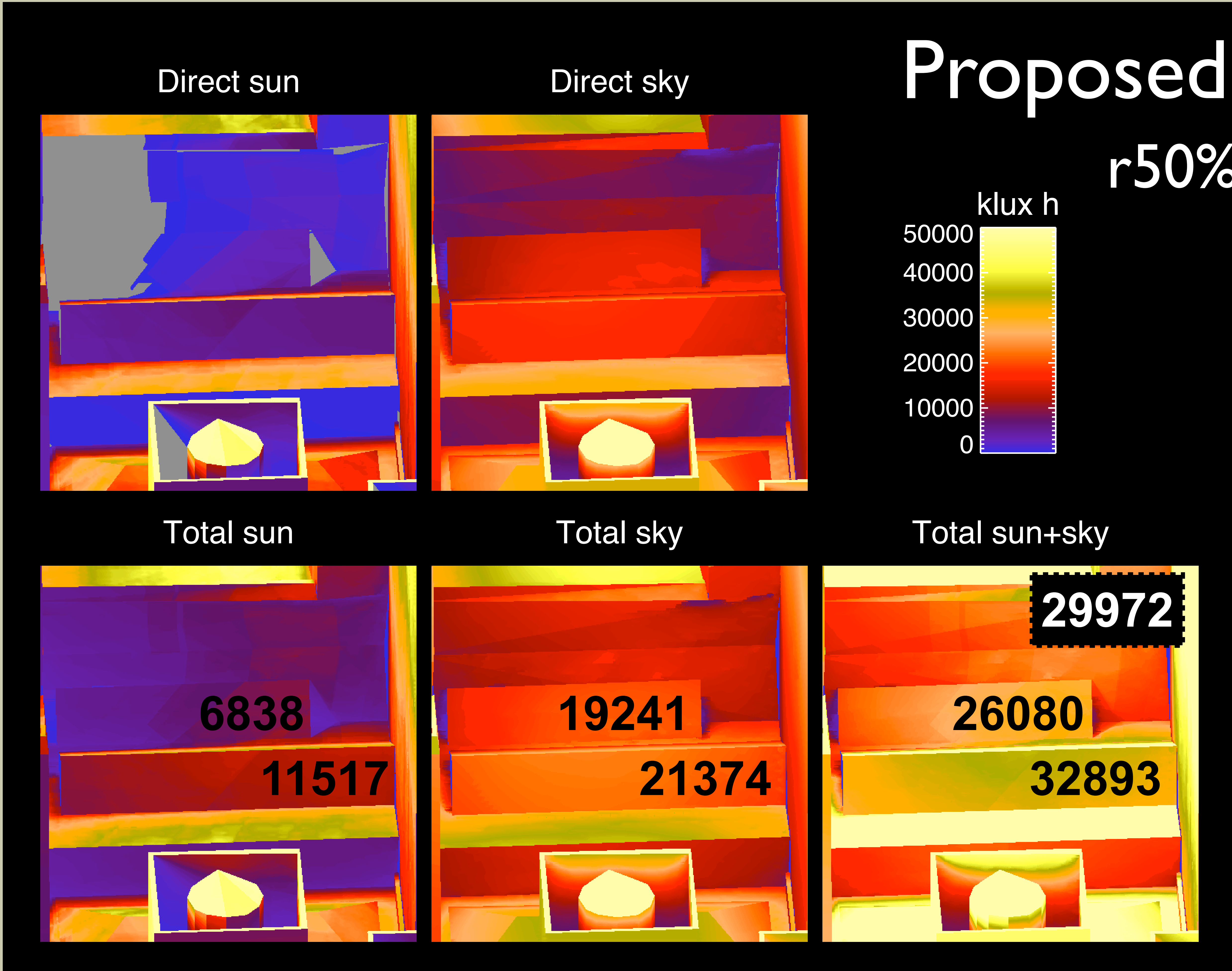
(c) With proposed tower reflectance = 50%.

Highly detailed 3D model for the area around the ASL was used.
Reflectivity of neighbouring buildings was set to 20%.

Existing


Direct sun
Direct sky
klux h
50000
40000
30000
20000
10000
0
Total sun
4013
9418
Total sky
29762
29907
Total sun+sky
36946
33774
39327


Proposed
r0%
Direct sun
Direct sky
klux h
50000
40000
30000
20000
10000
0
Total sun
Total sky
Total sun+sky
3101
7752
16537
18566
23455
19638
26319


Proposed
r50%
klux h
50000
40000
30000
20000
10000
0
Direct sun
Direct sky
Total sun
Total sky
Total sun+sky
6838
11517
19241
21374
26080
32893
29972

Results

Case	*TAI*	*Change*
Existing	36,946	-
Prop. (0% refl)	23,455	-36.5%
Prop. (50% refl)	29,972	-18.9%

Summary

Differences in the predicted levels of total annual illumination gave a realistic evaluation of the daylight injury from the proposed tower.

The mitigation effect of a reflecting* facade for the proposed tower was quantified.

**The effect of intermediate reflectivity values can be determined from linear interpolation of the existing results.*

Example II: The Hermitage Museum St. Petersburg

Climate-based lighting simulation was used to predict the distribution of mean illuminance for each month, and the total annual exposure to daylight in rooms of the General Staff Building.

Method

Hourly climate data for St. Petersburg was processed to faithfully represent local time including summer daylight savings.

Twelve cumulative monthly climate files were created using only the period of visiting hours which is 10h00 to 18h00.

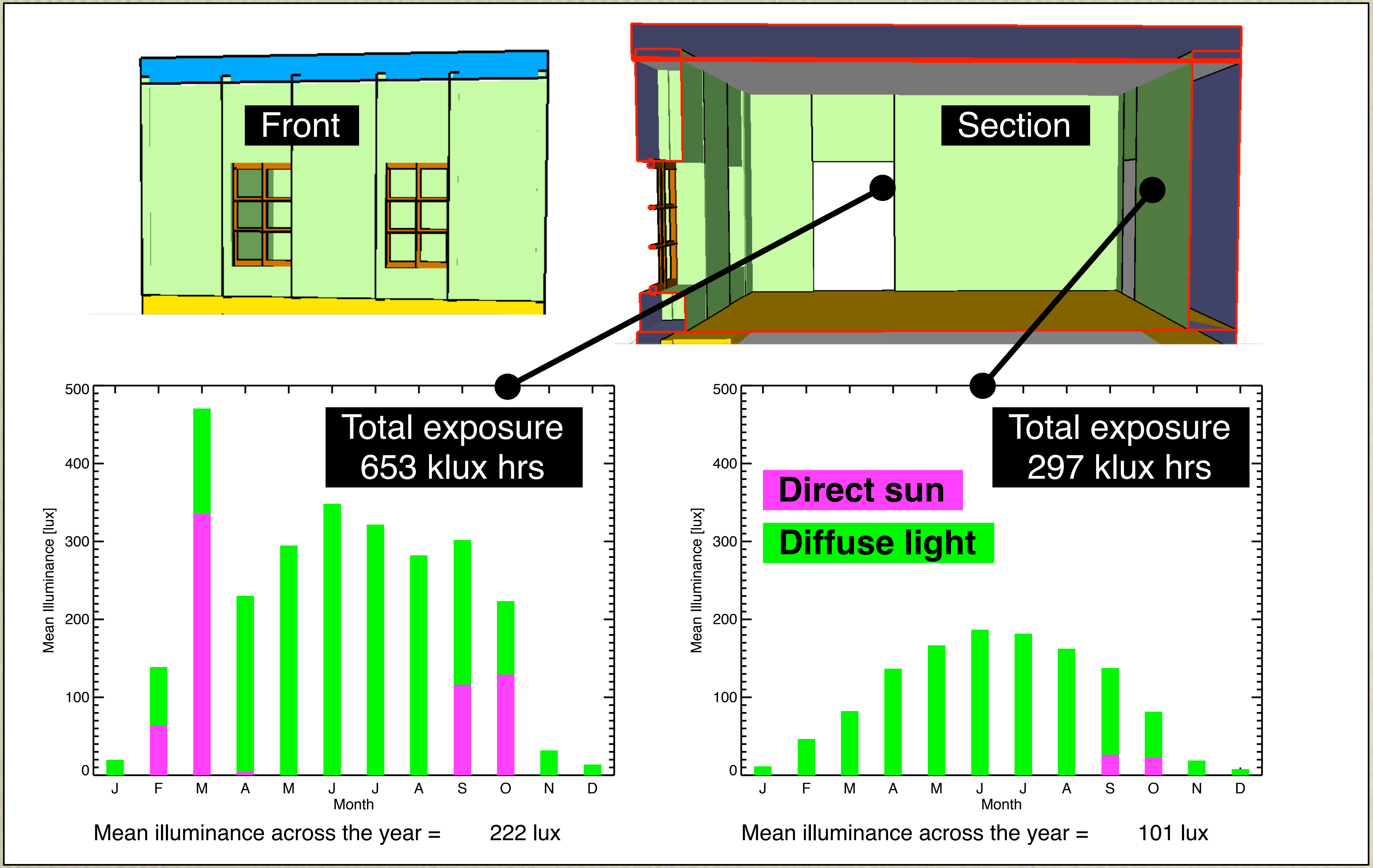
Separate climate files were created for the sun and the sky components of illumination.

Method (cont.)

Simulations showing a hemispherical view of the illuminance inside of the rooms were generated for each of the 24 climate files i.e. 12 cumulative sky files and 12 cumulative sun files.

The total annual exposure is simply the sum of the 24 monthly sun and sky illuminance images. The mean illuminance for each month was the sum of the cumulative sun and sky illuminances for that month divided by the number of hours.

Results - West facing room



Example III: Useful daylight illuminance

UDI is a scheme to reduce and interpret the voluminous data from a time-varying illuminance calculation where the daylight levels are predicted at an hourly (or sub-hourly) time-step for a full year.

Put simply, achieved UDI is defined as the annual occurrence of illuminances across the work plane that are within a range considered "useful" by the occupants.

What's "useful" daylight?

The range considered "useful" is based on a survey of reports of occupant preferences and behaviour in daylit offices with user operated shading devices.

Daylight illuminances in the range 100 to 500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting. Daylight illuminances in the range 500 to 2000 lux are often perceived either as desirable or at least tolerable.

Three (maybe four) categories

Achieved UDI is defined as the annual occurrence of daylight illuminances that are between 100 and 2000 lux.

Occurrences less than 100 lux is UDI fell-short.

Occurrences greater than 2000 lux is UDI exceeded.

Perhaps divide achieved UDI into occurrence of:
(a) 100-500 lux (UDI-supplementary); and,
(b) 500-2000 lux (UDI-autonomous).

UDI is simple

Only three (or four) metrics are needed to provide a compact representation of the hourly-varying daylight illuminances for an entire year at each of the calculation points.

The 2000 lux upper limit was based on the reported behaviour of occupants in daylit buildings. It was around the 2000 lux mark that blinds were drawn and/or dissatisfaction was noted.

Further, the occurrence of UDI exceeded (i.e. >2000 lux) is related to the building’s propensity for excessive solar gain and daylight glare.

Example application of UDI

Building with a central light-well and standard clear double glazing.

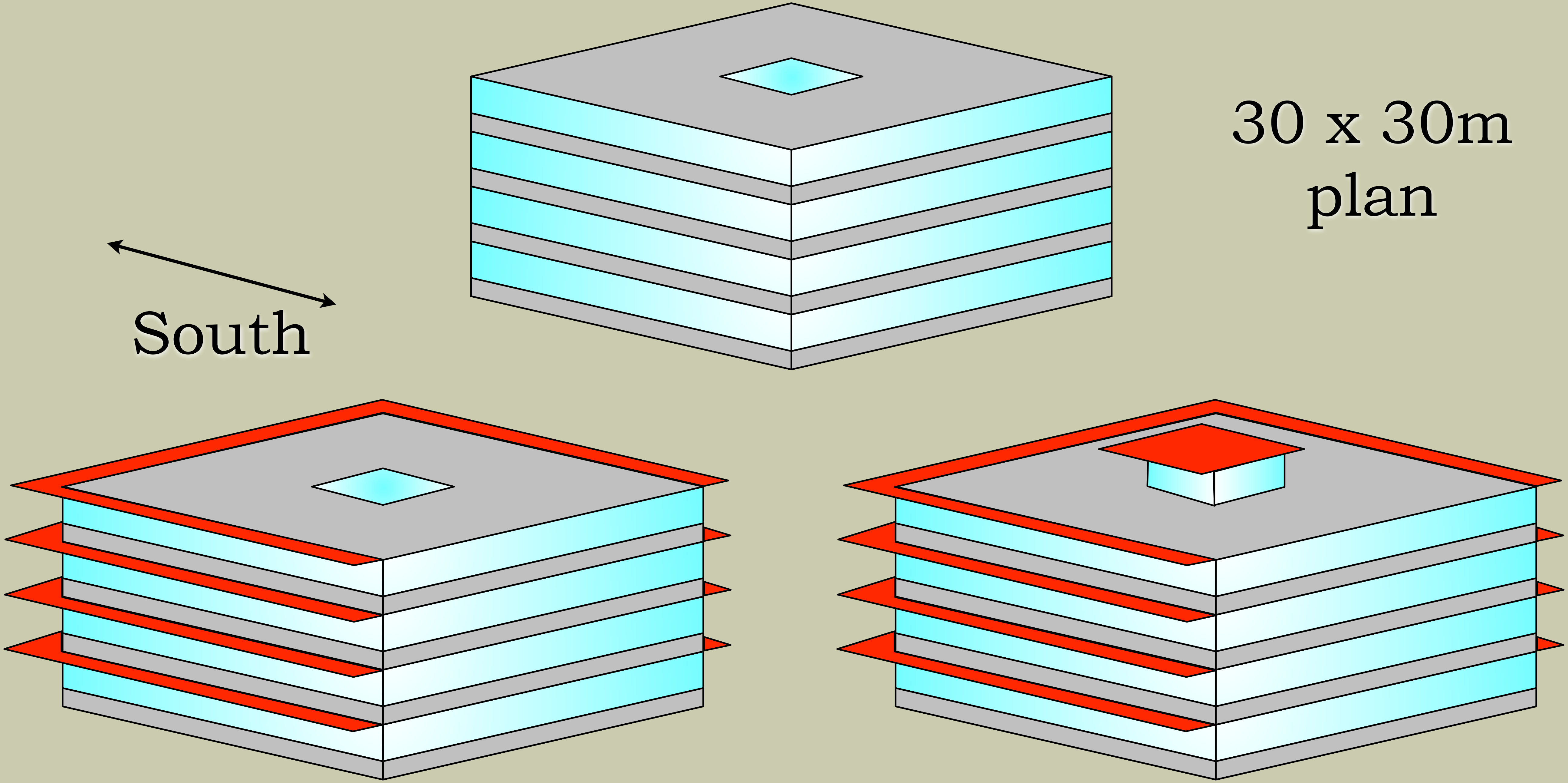
- Basecase version is totally unshaded.
- Variant 1 has a shading overhang on the East, South and West facades.
- Variant 2 additionally has a lantern with shaded top over the light well.

Internal floor, wall and ceiling reflectances were set to typical values.

Basecase - no shading

30 x 30m plan

South



Variant 1
1m overhang shading on
E, S & W facades

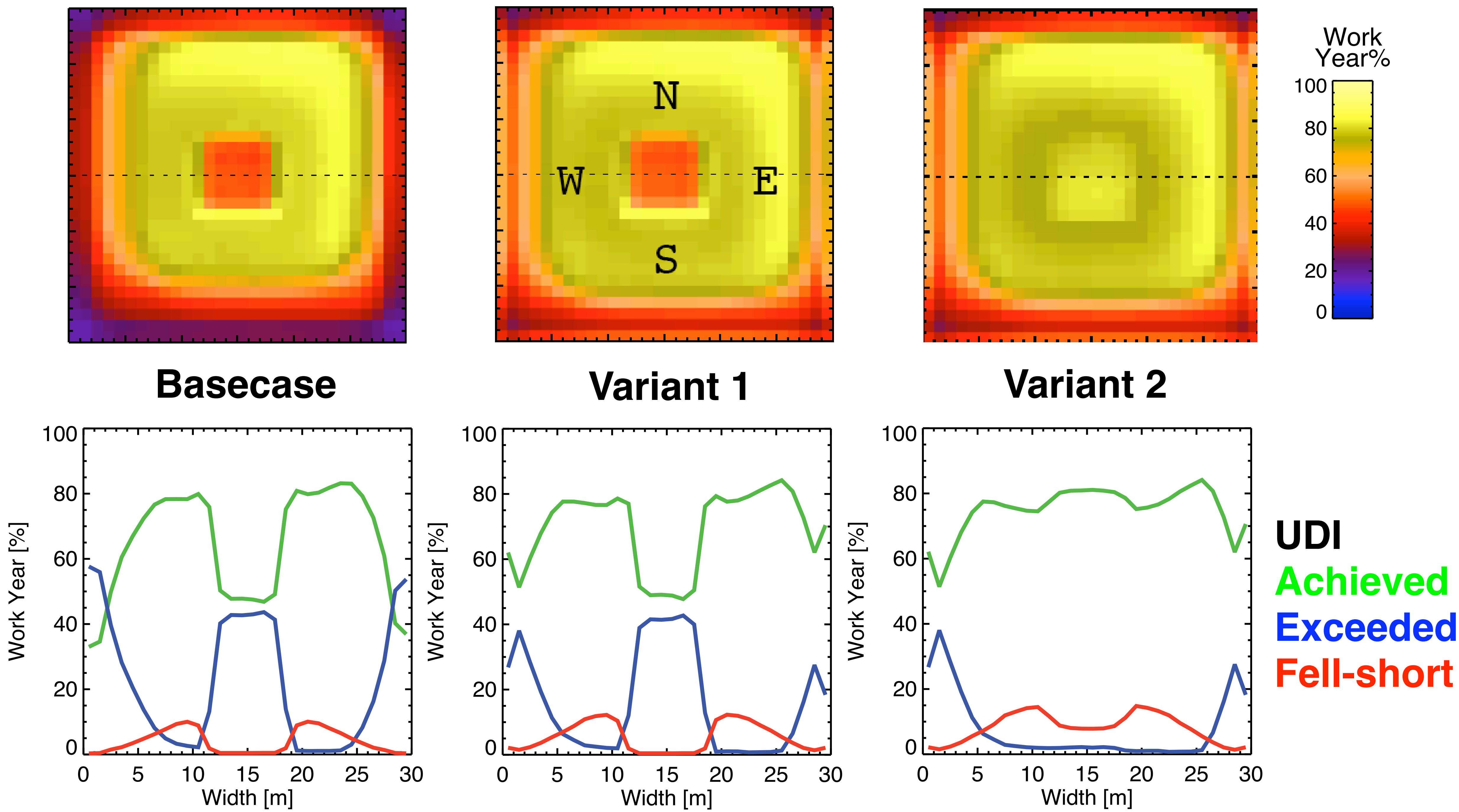
Variant 2
Addition of lantern
with shading

Illuminance modelling

Hourly daylight illuminances at work plane height across the ground floor were predicted for the Basecase and both shading variants using the **daylight coefficient** technique (900 points x ~4000 daylight hours).

London (UK) climate data was used to generate the hourly-varying sky and sun conditions.

The hourly simulation data were processed to show measures of UDI.



Work Year%
100
80
60
40
20
0
N
W
E
S
Basecase
Variant 1
Variant 2
Work Year [%]
Width [m]
UDI
Achieved
Exceeded
Fell-short

Climate-based modelling of cumulative skies in *Radiance*

Cumulative climate metrics (annual or monthly) can be determined in a straightforward manner using specially prepared *Radiance* sky description files. These contain the aggregated radiance from all the individual sky and sun configurations.

The main technical issue that needs to be nailed is the selection of sky model type from the hourly integrated values in the climate file. [CIE TC 3.37 is working on this.]

Prediction of time-varying quantities using *Radiance*

To generate an annual time-series of hourly (or sub-hourly) values for illuminance, luminance etc. requires an accelerated method such as daylight coefficients because a “brute-force” computation would take too long, i.e. ~4000 individual simulations for all the daylight hours.

The issue regarding the selection of sky model types applies also.

Daylight Coefficients

The daylight coefficient approach requires that the sky be broken into many patches.

The internal illuminance at a point that results from a patch of unit-luminance sky is computed and cached. This is done for each patch of sky.

It is then possible, in principle, to determine the internal illuminance for any arbitrary sky luminance pattern.

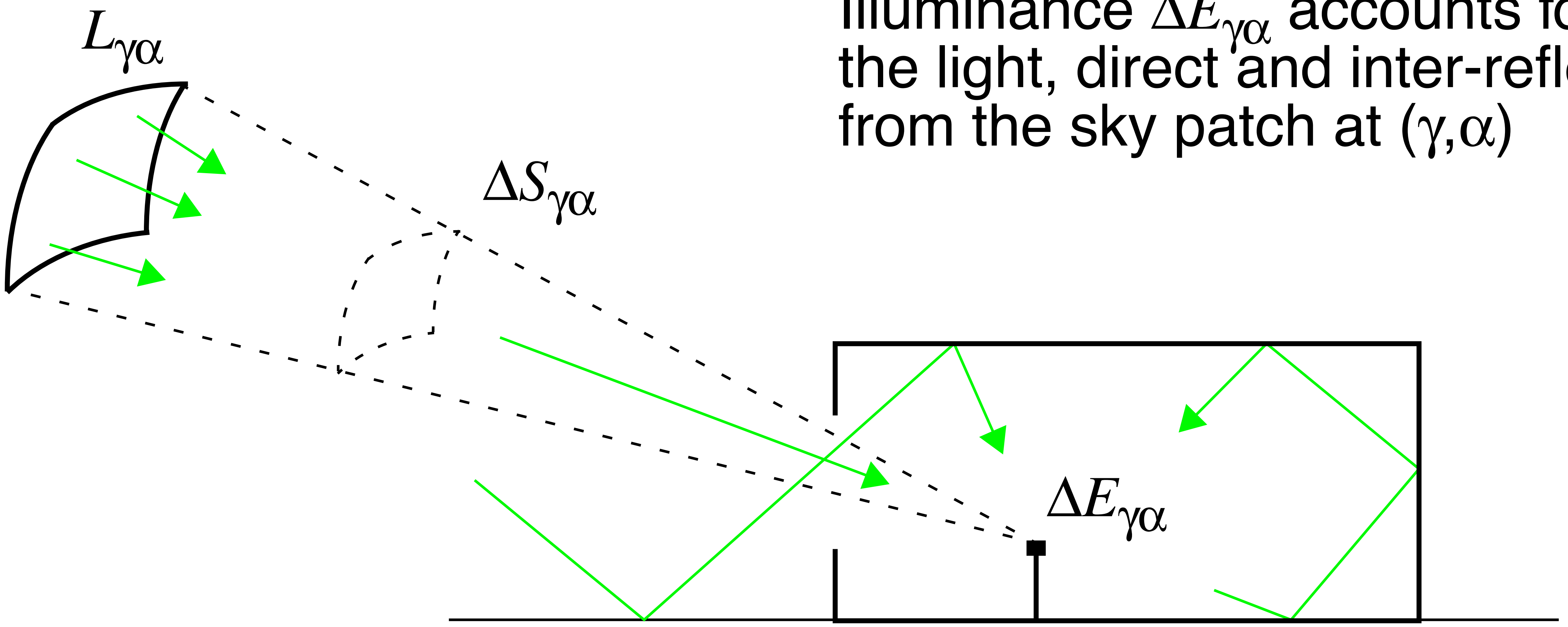
Definition

If $\Delta E_{\gamma\alpha}$ is the total illuminance produced at a point in a room by a small element of sky at altitude γ and azimuth α, then the daylight coefficient is defined as:

$$D_{\gamma\alpha} = \frac{\Delta E_{\gamma\alpha}}{L_{\gamma\alpha}\Delta S_{\gamma\alpha}}$$

where $L_{\gamma\alpha}$ is the luminance of the element of sky and $\Delta S_{\gamma\alpha}$ is the solid angle of the patch of sky [Tregenza 1983]. Note also that $D_{\gamma\alpha}$ is independent of the distribution of luminance across the sky vault, since $\Delta E_{\gamma\alpha}$ varies in proportion to $L_{\gamma\alpha}$.

Illuminance $\Delta E_{\gamma\alpha}$ accounts for all the light, direct and inter-reflected, from the sky patch at (γ,α)



The magnitude of the daylight coefficient $D_{\gamma\alpha}$ will depend on the physical characteristics of the room and the external environment, e.g. room geometry, surface reflectances, glazing transmissivity, outside obstructions and reflections etc.

The total illuminance E produced at the point in the room is then calculated from:

$$E = \int_0^{2\pi} \int_0^{\pi/2} D_{\gamma\alpha} L_{\gamma\alpha} \cos\gamma d\gamma d\alpha$$

If the sky were divided into n angular zones, then for numerical evaluation the integral is solved using:

$$E = \sum_{p=1}^{n} D_p S_p L_p$$

This gives the illuminance as the sum of n products of D, S and L, for each patch of sky p. The n values of D, S and L can therefore be treated as vectors.

In short...

Once a set of DCs have been determined, it is possible to derive internal illuminances for arbitrary sky conditions very rapidly by re-using pre-computed values - no need to do any more simulations.

However, the the building model (geometry and reflectances etc.) must not change. If they do, then a new set of DCs must be computed.

Typical procedure

- Obtain basic climate data from a weather tape, usually global and diffuse irradiance. Convert the irradiance data to external horizontal illuminances using a luminous efficacy model.
- Generate a sky luminance distribution using a sky model.
- Derive internal illuminances from pre-computed DCs.
- Determine the artificial lighting requirements using a lighting control algorithm.

How can we do this with *Radiance*?

First DC implementation 1997 [Mardaljevic]. Research tool for in-house use (XDAPS*). Based on the standard *Radiance* release and still in use. An end-user version called the DLS [Cropper] appeared briefly but is no longer supported.

End-user DC implementation called DAYSIM released in 2000 [Reinhart]. Required modified version of *Radiance* - still supported and undergoing development.

***XDAPS** = e**X**tensible **DA**ylight **P**rediction **S**ystem

XDAPS and DAYSIM...

...both work well in their respective ways, but neither approach possesses the level of **generality** that is a hallmark of the *Radiance* 'design philosophy'.

For example, XDAPS and DAYSIM are both geared to computing point values (e.g. illuminances) and are not ideal for the generation of images (e.g. a time-of-day movie sequence).

The **rtcontrib** program

This new addition to the *Radiance* suite of programs was designed to address the lack of generality in the existing daylight coefficient formulations.

And, in doing so, to extend the range of application to include image generation and the efficient modelling of varying artificial light levels as well as varying daylight conditions.

Over to Greg…