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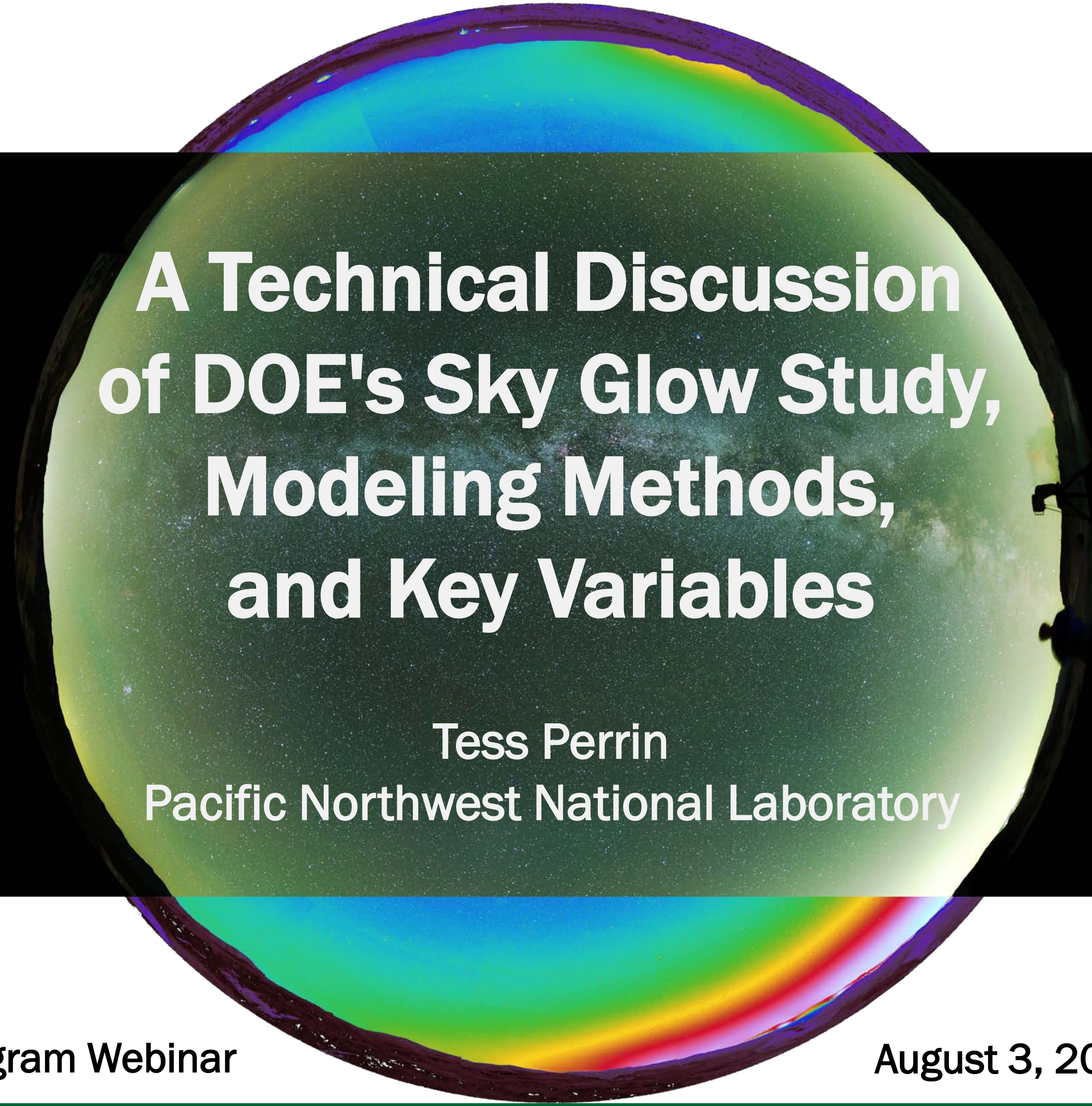

A Technical Discussion of DOE's Sky Glow Study, Modeling Methods, and Key Variables

Tess Perrin
Pacific Northwest National Laboratory

Solid-State Lighting Program Webinar

August 3, 2017

Recap: The Impact of LED Street Lighting on Sky Glow

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AMA Adopts Guidance to Reduce Harm from High Intensity Street Lights

For immediate release: Jun 14, 2016

CHICAGO - Strong arguments exist for overhauling the lighting systems on U.S. roadways with light emitting diodes (LED), but conversions to improper LED technology can have adverse consequences. In response, physicians at the Annual Meeting of the American Medical Association (AMA) today adopted guidance for communities on selecting among LED lighting options to minimize potential harmful human and environmental effects.

Photo Credit: Dan Duriscoe, NPS

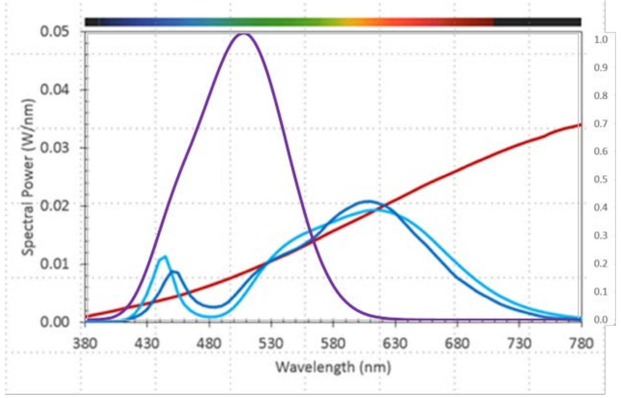
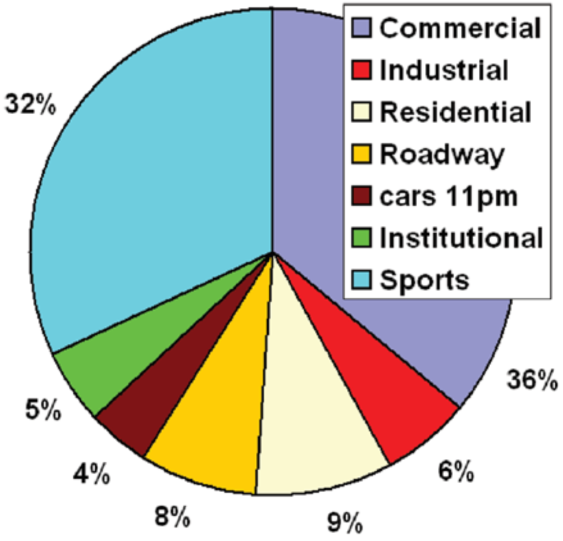


Photo Credit: Acuity

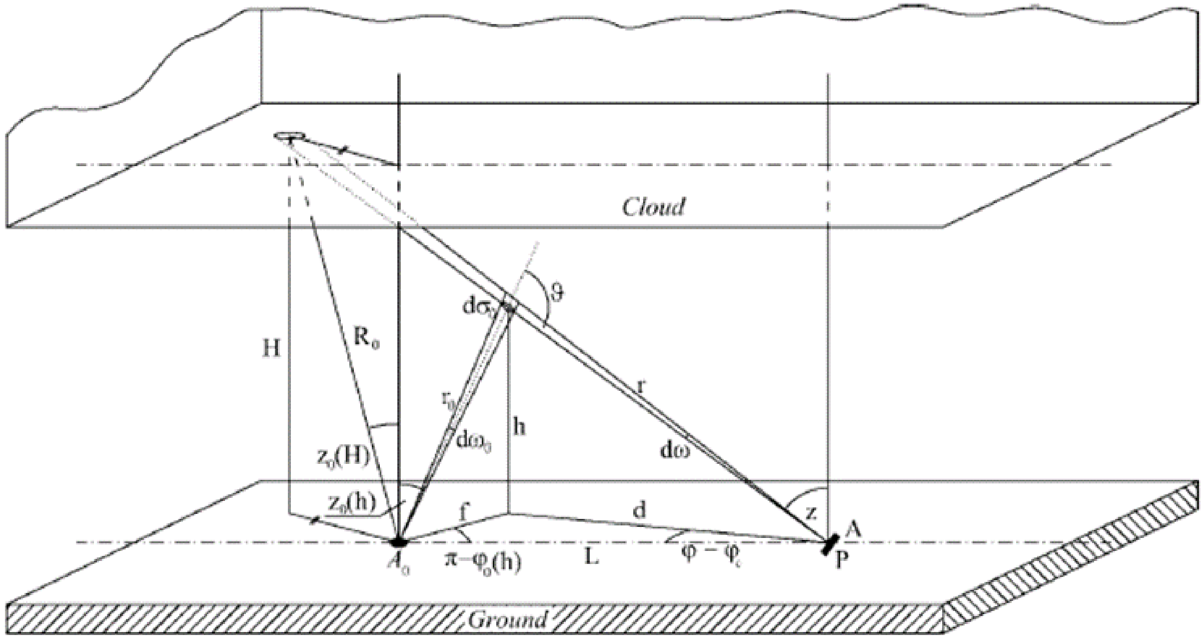


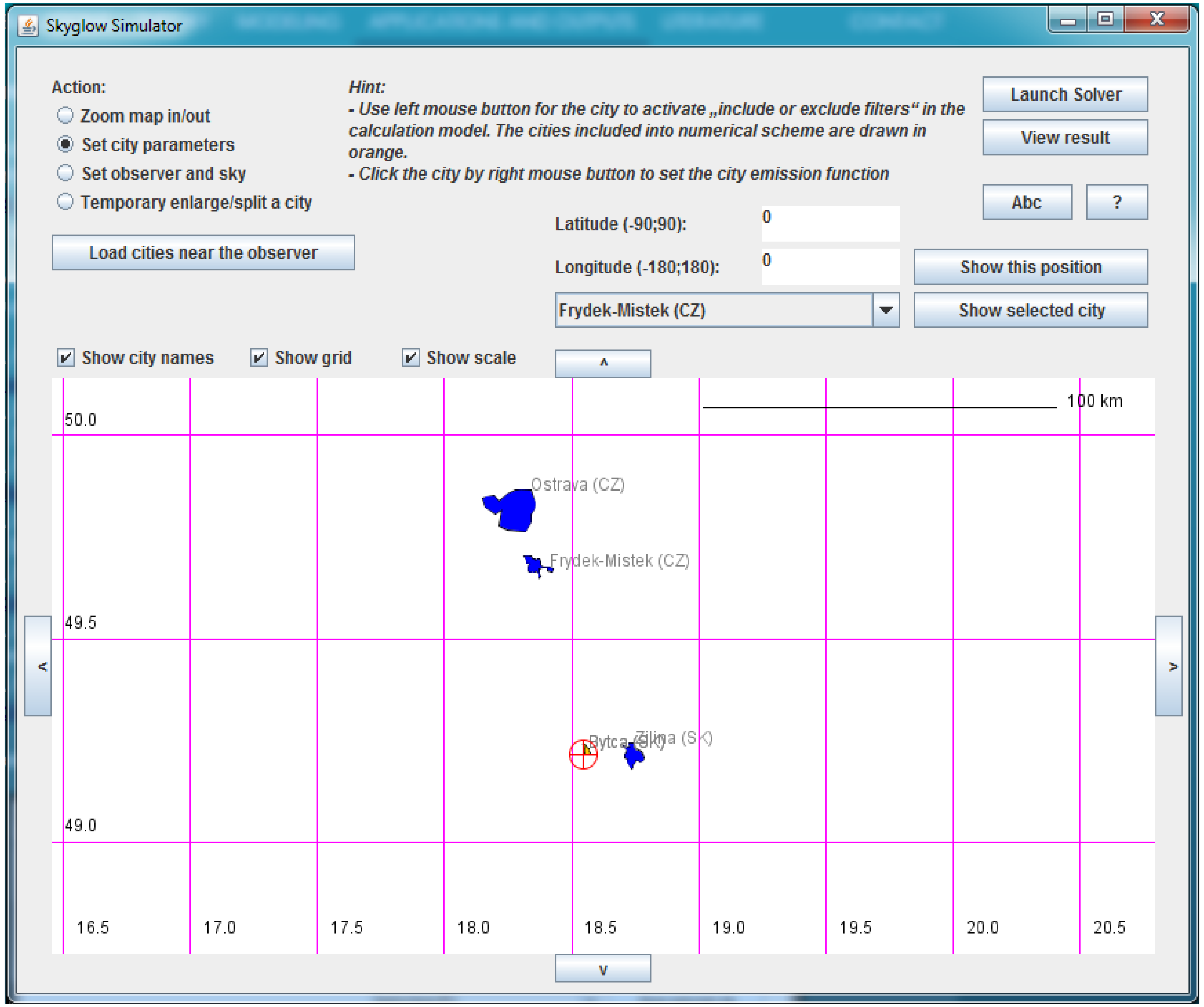
Luginbuhl et al 2009

SkyGlow Simulator

Miroslav Kocifaj, PhD

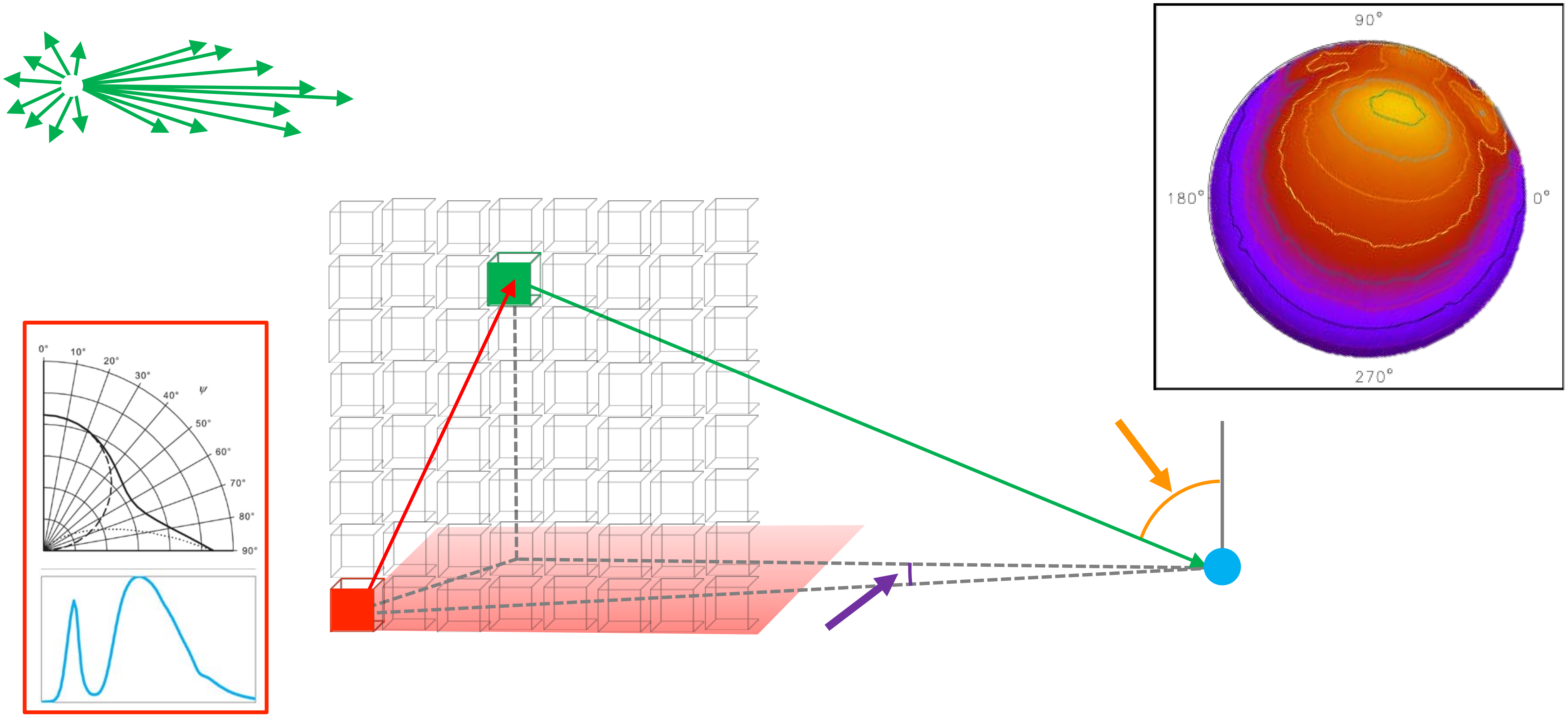
Institute of Construction and Architecture,
Slovak Academy of Sciences





http://unisky.sav.sk/?lang=en&page=aplikacia&subpage=glow

SkyGlow Simulator: An Illustration



SkyGlow Simulator

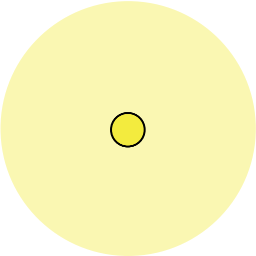
Distribution of Radiance/Luminance Values

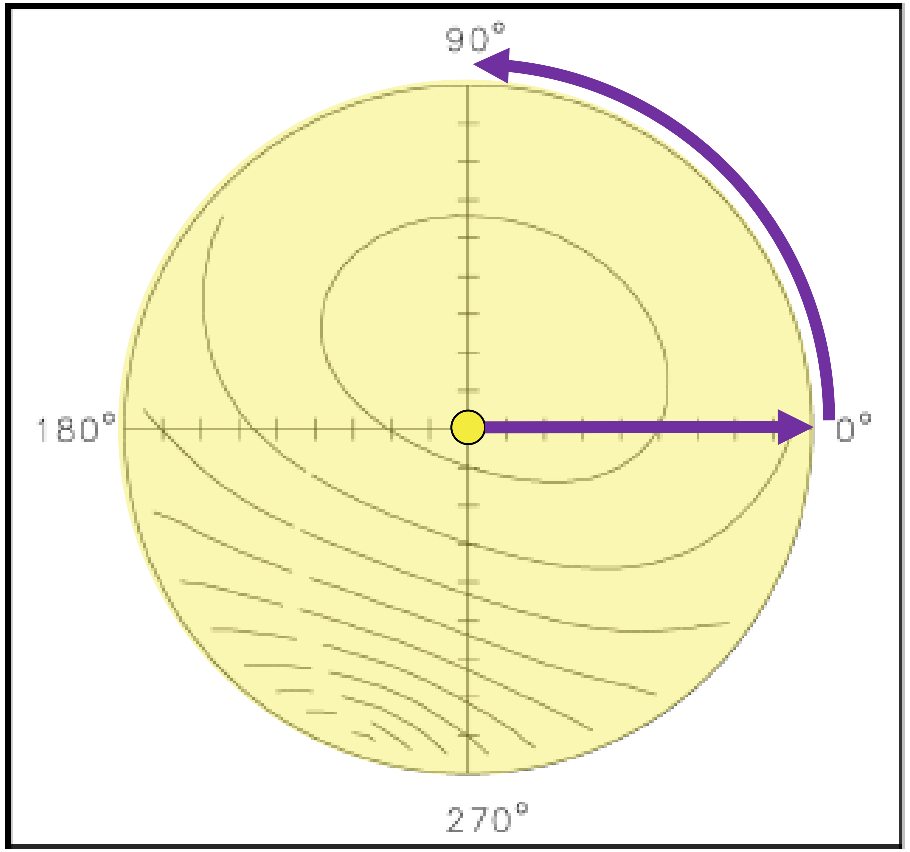
azimuth (angle along circle)

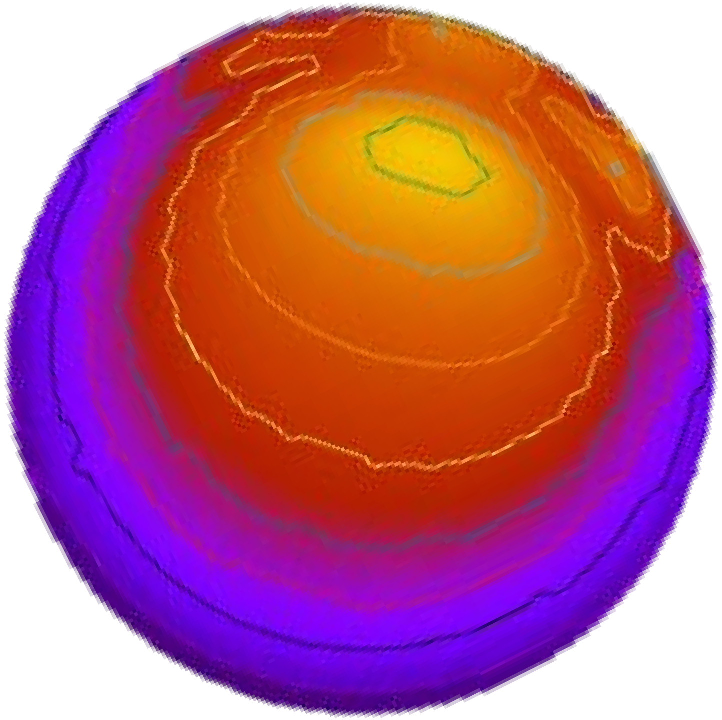
zenith (angle measured from center to margin of polar plot)

Diffuse irradiance or scotopic illuminance on horizontal surface

Ratio of zenith radiance/luminance to diffuse horizontal irradiance/illuminance



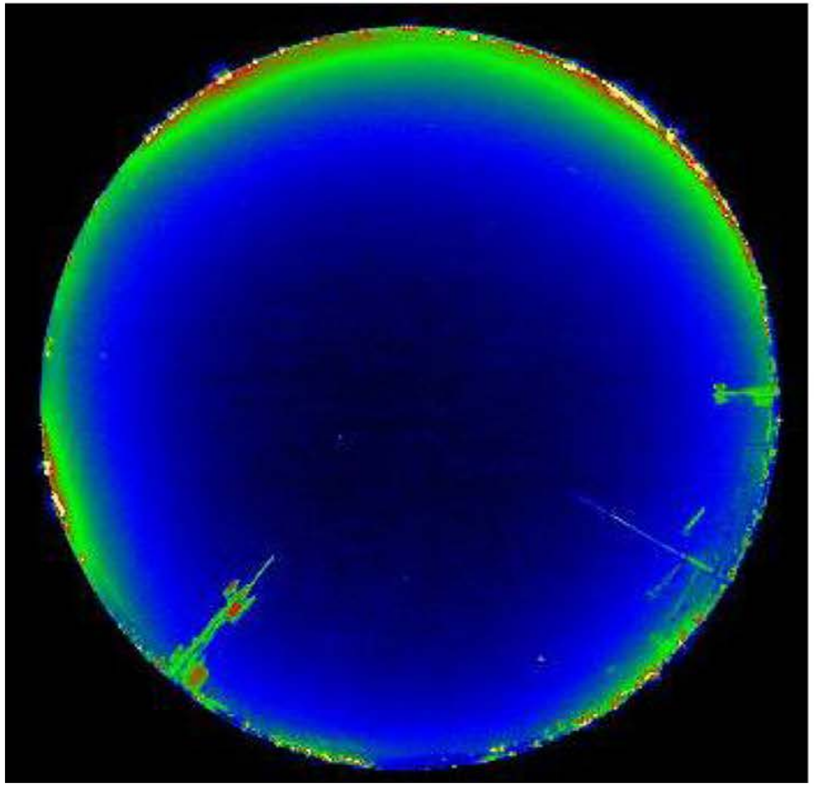




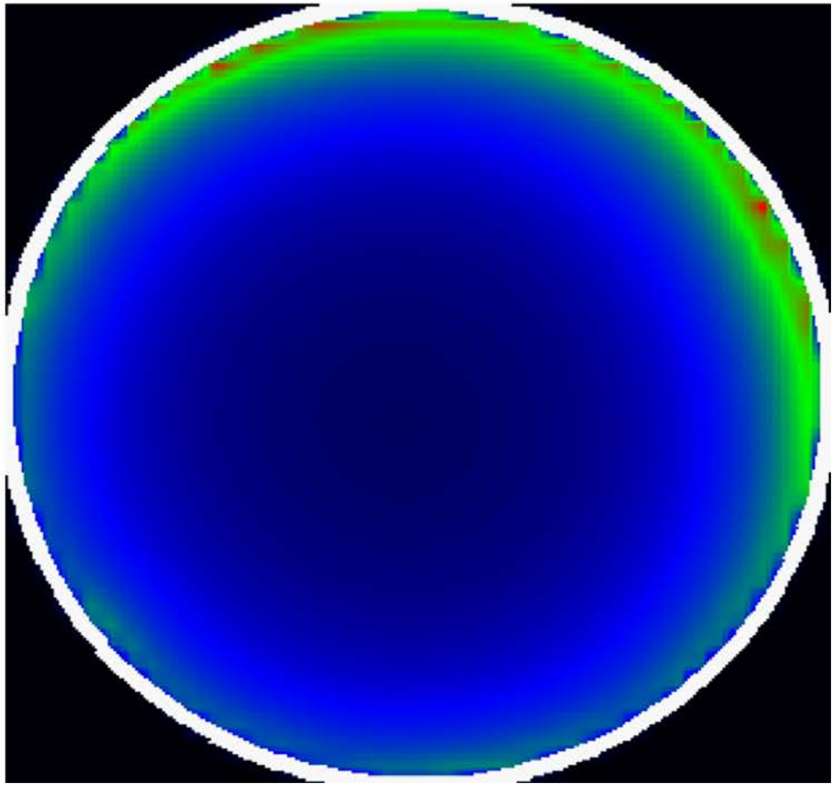
SkyGlow Simulator

Verification

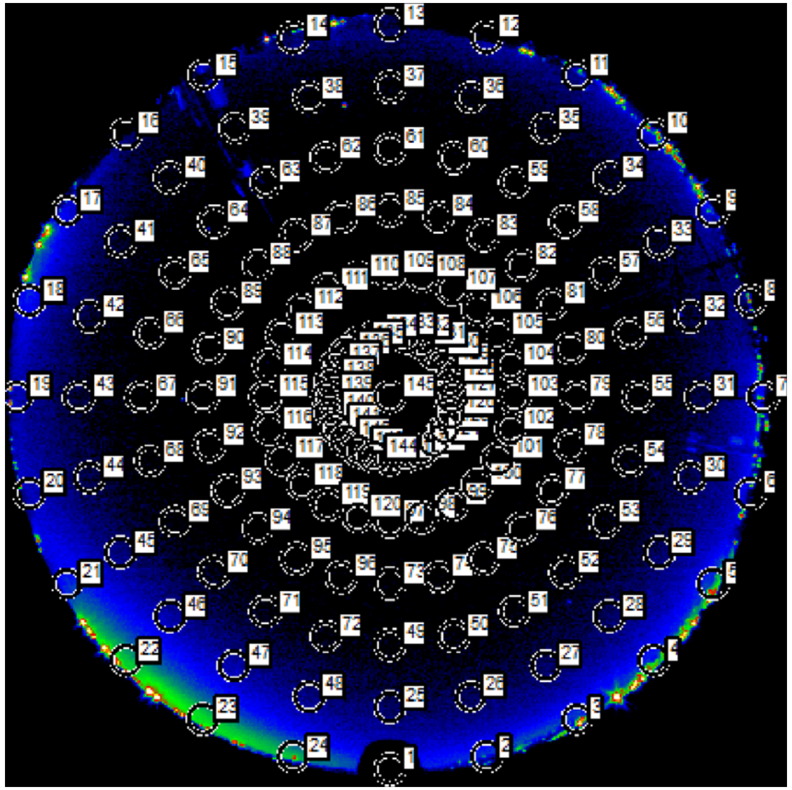
Measurements
(zenith-normalized luminance)



Reconstructed data
(zenith-normalized luminance)

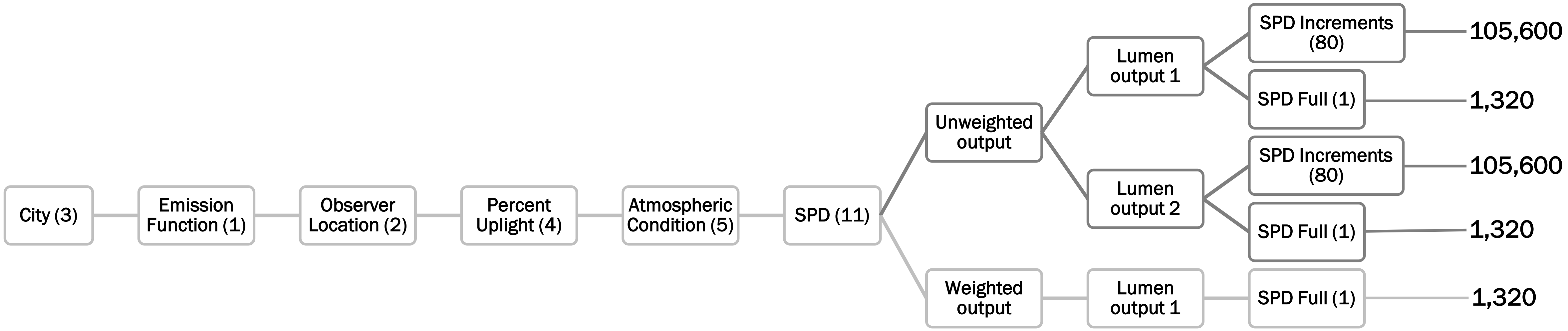


Indices and positions of
measurements



Night sky luminance under clear sky conditions: Theory vs. experiment (Journal of Quantitative Spectroscopy & Radiative Transfer, 139, 43-51, 2014)

Experimental Design



Based on predominant contribution factors to sky glow

215,160 runs total

City and Observer

City size and lighting density

	Radius (km)	City Area (km^2)	No. Fixtures	Lighting Density (fixtures per km^2)
City1	1.4	7	342	52
City2	7.2	164	3,500	21
City3	8.6	232	39,884	172

Observer's location relative to city center:

'Near' – at perimeter

'Distant' – 40 km (~25 mi) from center

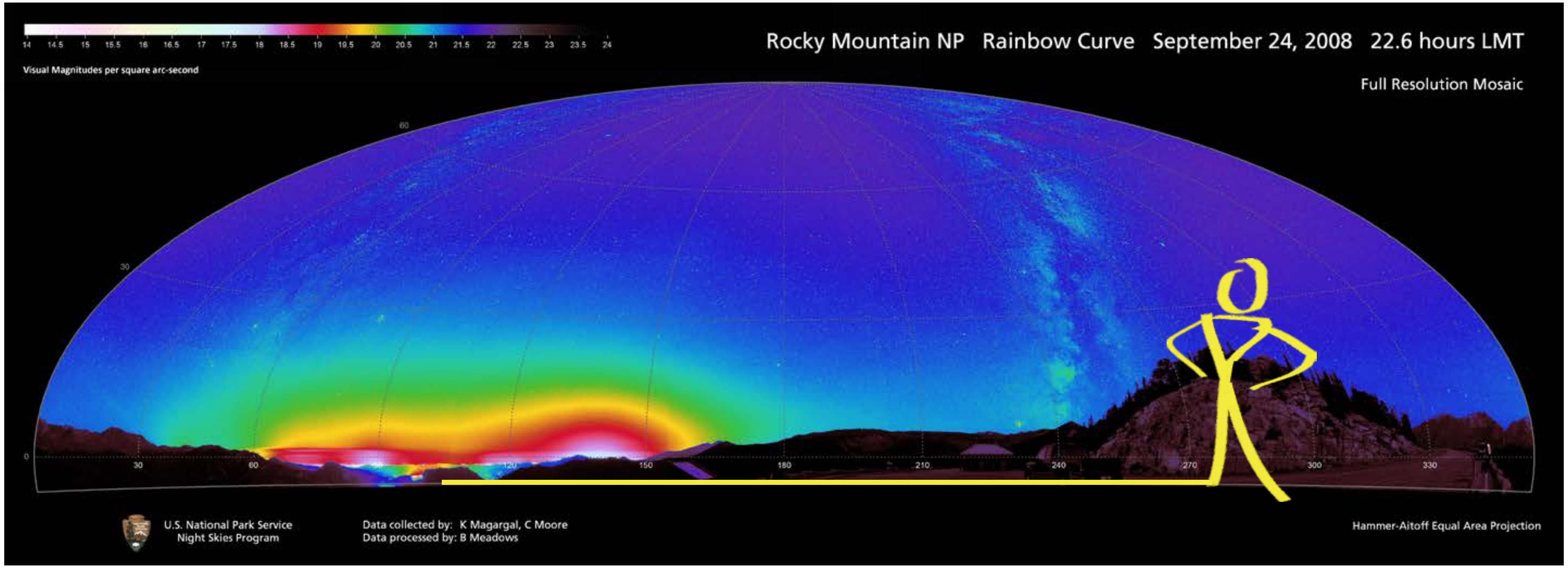


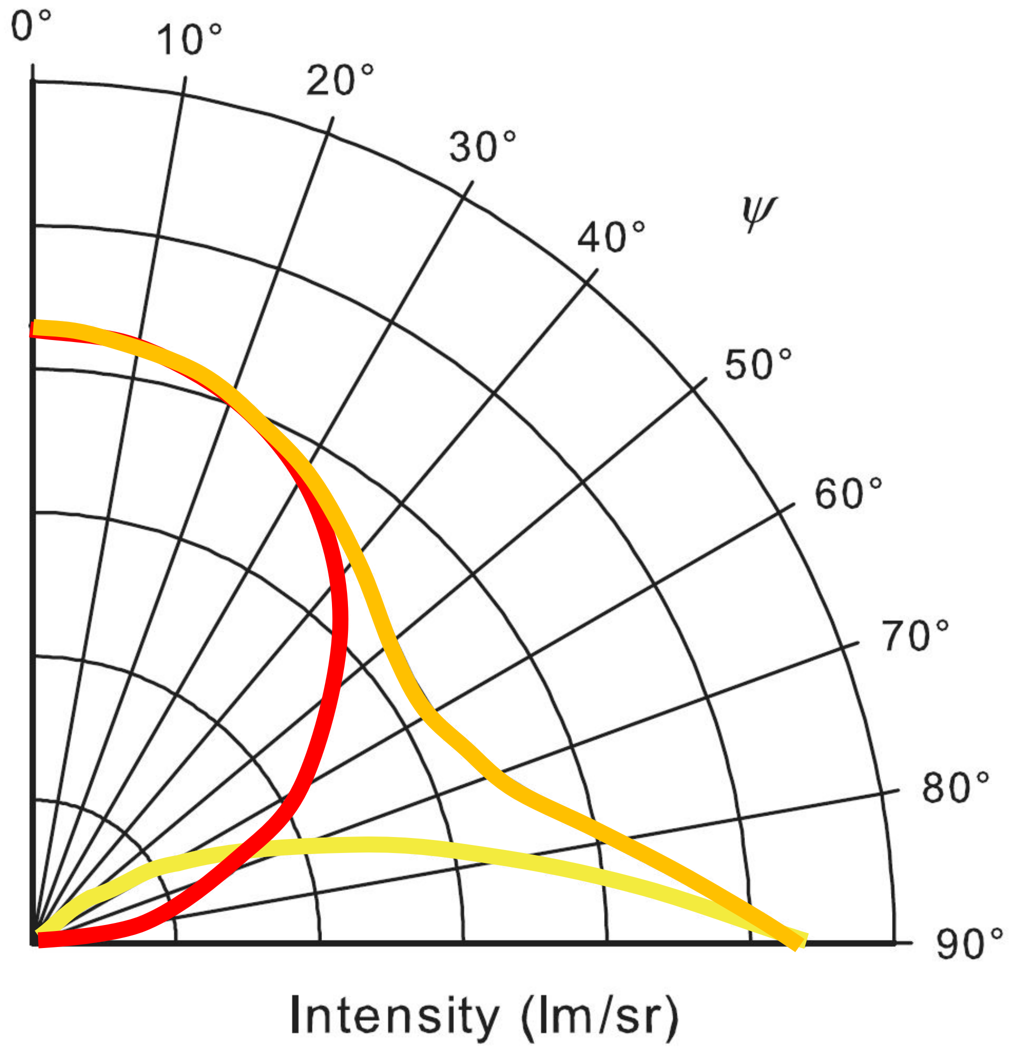
Photo Credit: NPS Natural Sounds and Night Skies Division

Atmosphere

		CLOUDLESS				CLOUDY
Atmospheric conditions		**ATM1**	**ATM2**	**ATM3**	**ATM4**	**ATM5**
Clouds		No	No	No	No	Yes
Cloud Details	Altitude of the cloud base (km)	N/A	N/A	N/A	N/A	1
	Spectral albedo (select data file)	N/A	N/A	N/A	N/A	Altocumulus.cld
Aerosols	Reference aerosol optical thickness at 500 nm	0.1	0.1	0.5	0.5	0.5
	Angstrom exponent	0.3	1.5	0.3	1.5	1.0
	Scale height for the molecular atmosphere (km)	8.0	8.0	8.0	8.0	8.0
	Vertical gradient of the aerosol concentration (1/km)	0.65	0.65	0.65	0.65	0.65
Data files for	single scattering albedo	constant_background.ssa				
	asymmetry parameter	constant_background.ssa				
Horizon	No light blocking objects near horizon					

Aerosol Robotic Network (AERONET): https://aeronet.gsfc.nasa.gov/

Emission Function + Percent Uplight



- (yellow) Fraction of light emitted downward and isotropically reflected (assuming a 15% ground reflectance)
- (red) Fraction of light radiated directly upward, proportional to ψ^4 (above 90°)
  - 0%: "full cut-off" fixtures
  - 2% and 5%: typical and relatively poor drop-lens cobra heads
  - 10%: good quality acorn top, assumed in other sky glow models
- (orange) Combined product of downward-reflected and upward-emitted quantities

Garstang's City Emission function:

$$B(Q, q, z_0) = 2\boldsymbol{Q}(1 - \boldsymbol{q}) \cos z_0 + 0.554\boldsymbol{q} z_0^4$$

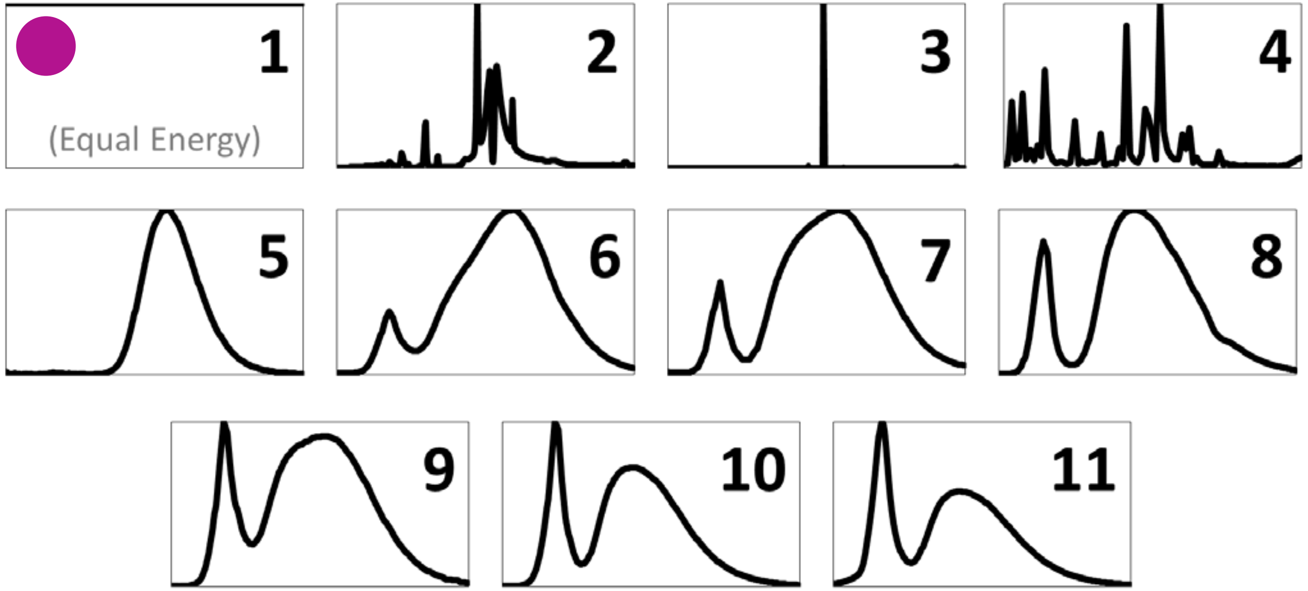
15% ground reflectance

downlight quantity

uplight quantity

Luminaire Characteristics: Spectral Content

Input SPDs (normalized to maximum output of 1)

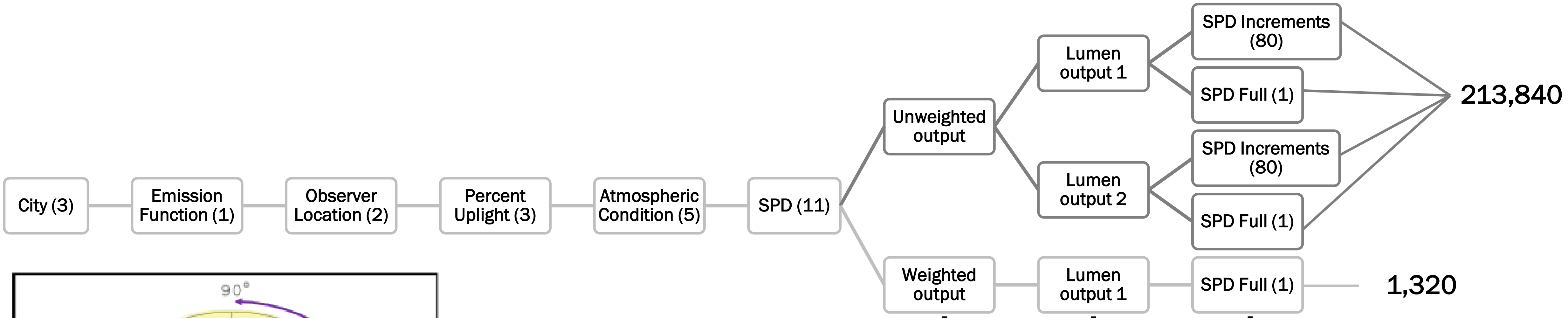


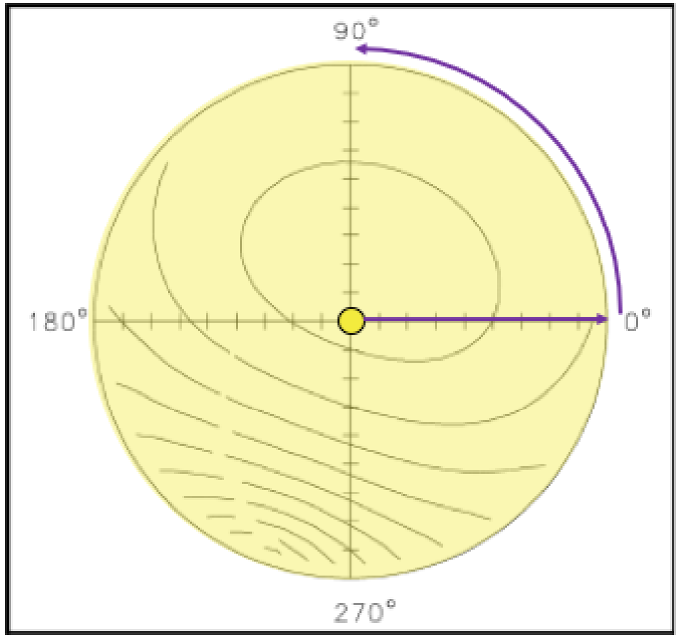
Specifications and Calculated Metrics/Values

	SPD1	SPD2	SPD3	SPD4	SPD5	SPD6	SPD7	SPD8	SPD9	SPD10	SPD11
Source type	N/A[A]	HPS	LPS	MH[B]	LED[C]	LED	LED	LED	LED	LED	LED
CCT (K)	5455	2041	1778	3924	1872	2704	2981	3940	4101	5197	6101
photopic lux	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
scotopic lux	2265	629	218	1381	445	1173	1188	1345	1650	1797	1970
S/P ratio (relative to HPS)	3.60	1.00	0.35	2.19	0.71	1.86	1.89	2.14	2.62	2.85	3.13

[A] Equal Energy
[B] Metal Halide
[C] PC Amber LED

Additional Variables



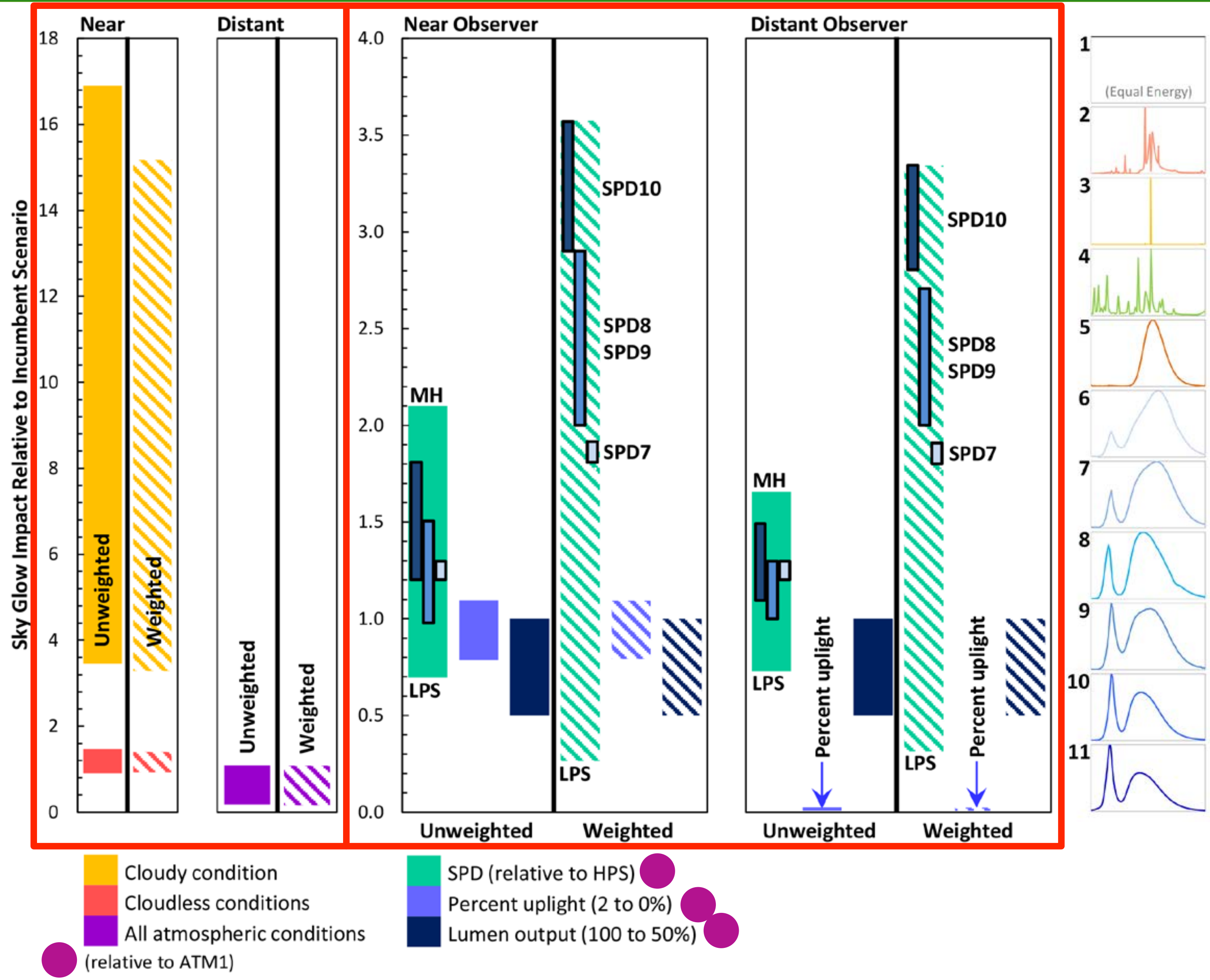


Unweighted: irradiance (W/m^2)
Weighted: scotopic illuminance (cd/[m^{2}sr])

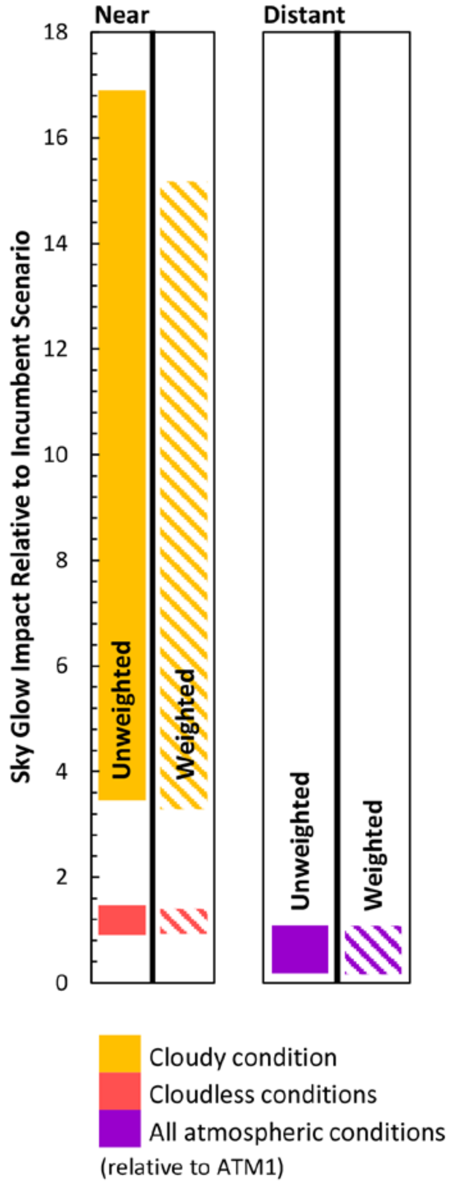
SPD Full: 380 to 780 nm
SPD Increments: 5 nm bands

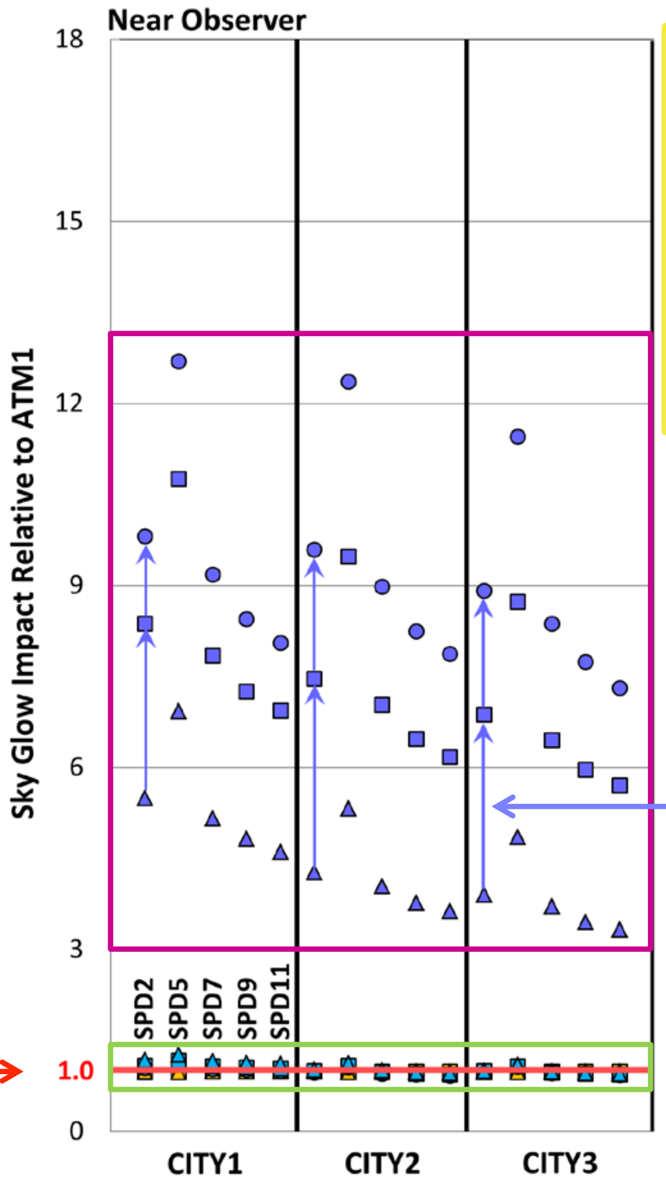
Lumen output 1: 100%
Lumen output 2: 50%

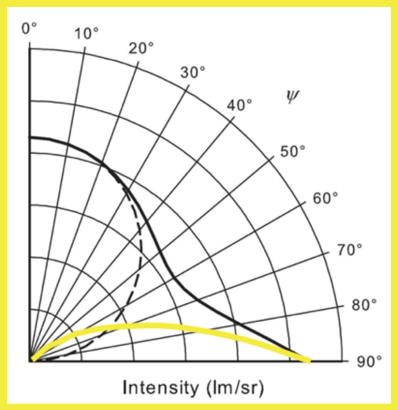
Individual Impacts



Atmosphere: Near Observer





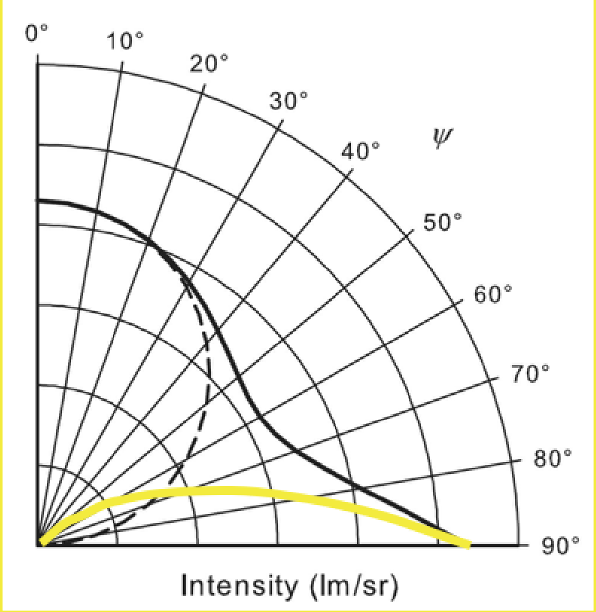


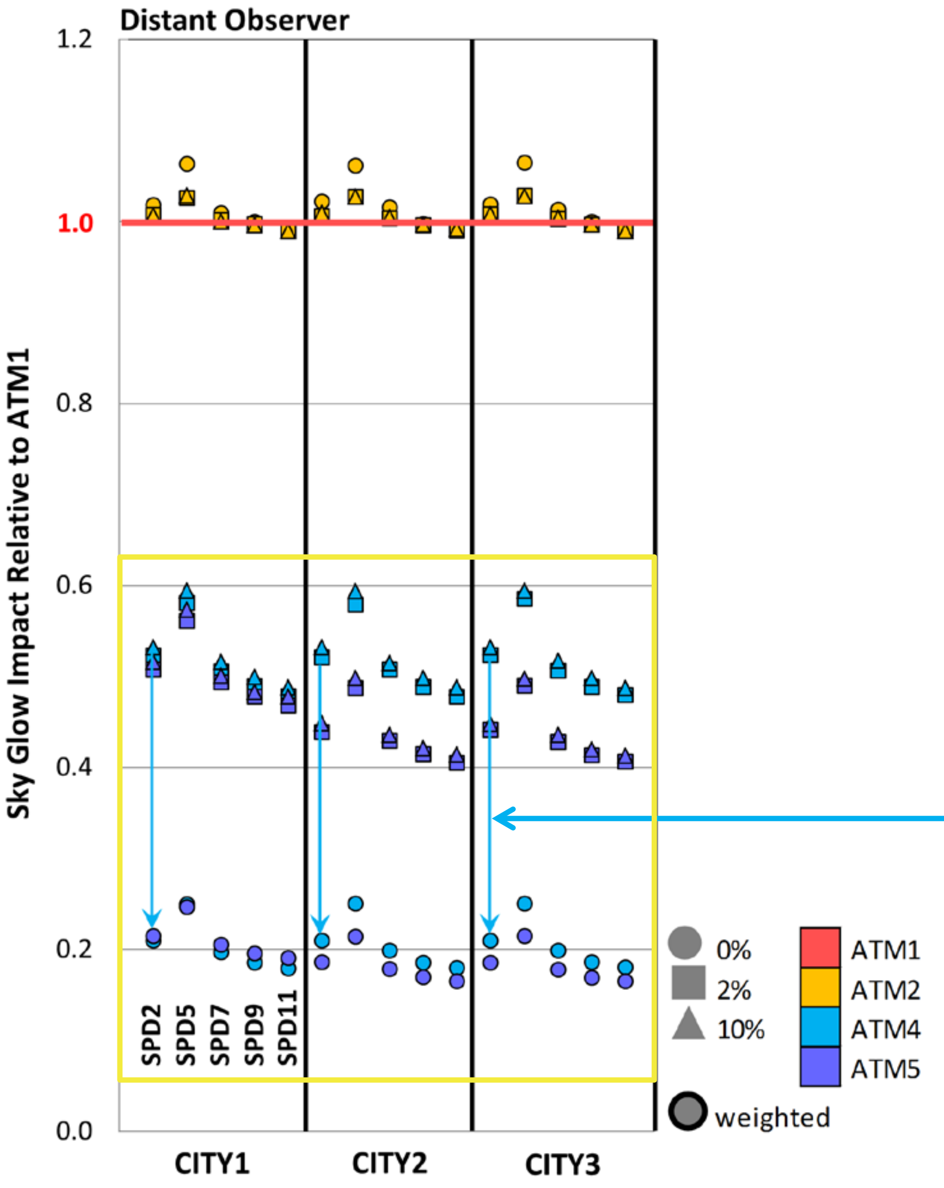
clouds act as amplifiers

cloudless:
decrease uplight → decrease sky glow

cloudy:
decrease uplight → increase sky glow

Atmosphere: Distant Observer

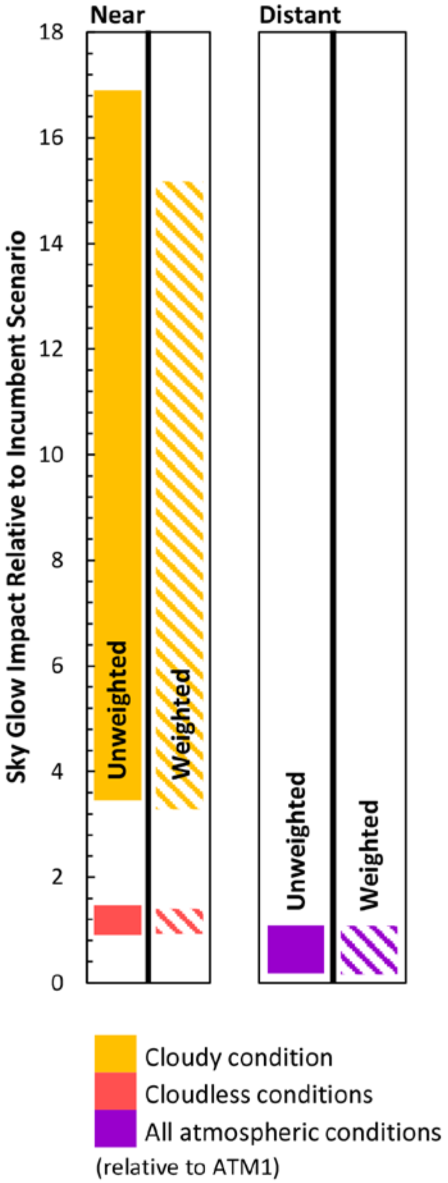




observers only receive light at low elevation angles

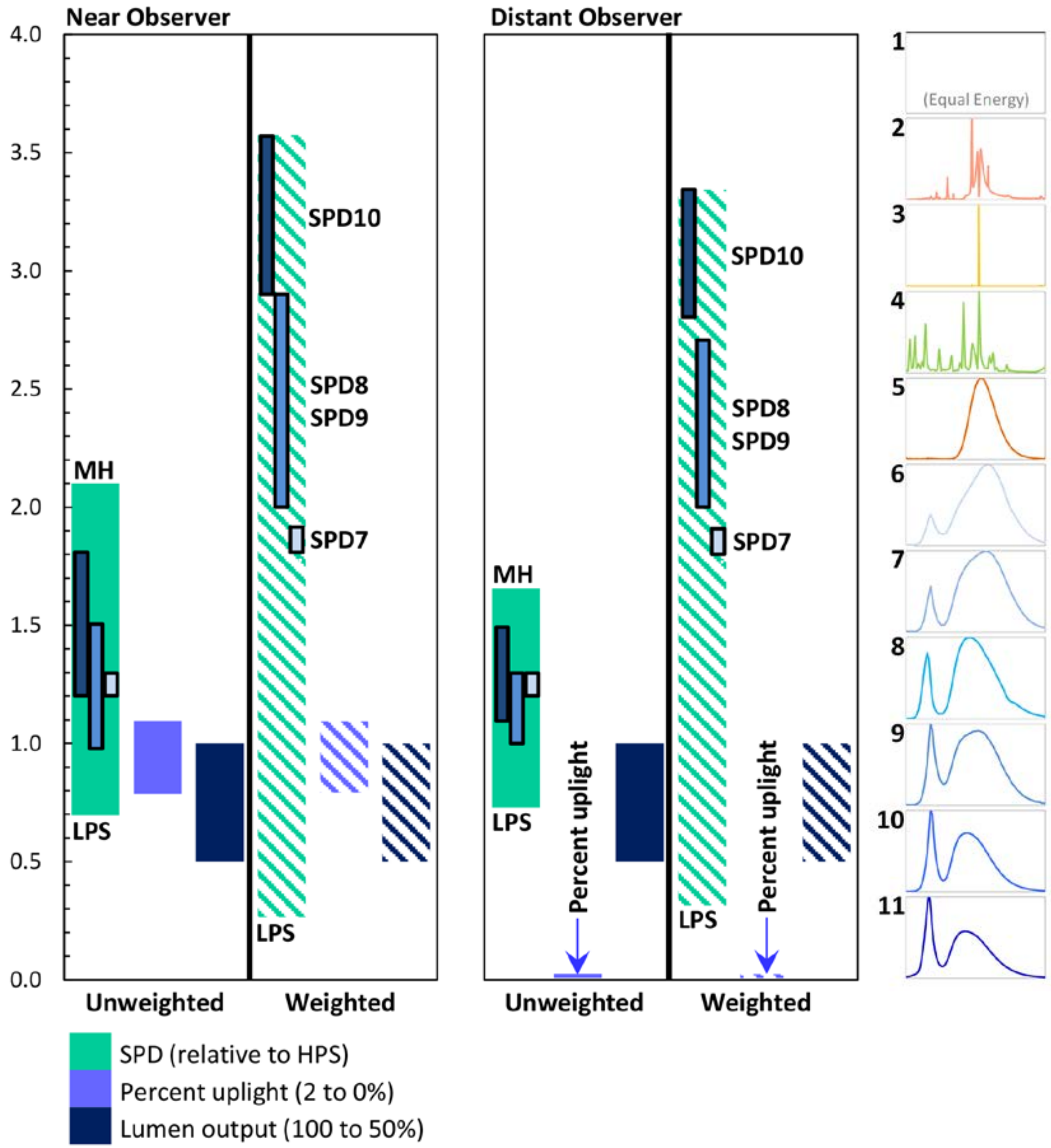
decrease uplight → decrease sky glow

Atmosphere


Near
Distant
Sky Glow Impact Relative to Incumbent Scenario
0
2
4
6
8
10
12
14
16
18
Unweighted
Weighted
Unweighted
Weighted
Cloudy condition
Cloudless conditions
All atmospheric conditions
(relative to ATM1)


Near Observer
Distant Observer
Sky Glow Impact Relative to ATM1
18
15
12
9
6
3
1.0
0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CITY1
CITY2
CITY3
CITY1
CITY2
CITY3
0%
2%
10%
ATM1
ATM2
ATM3
ATM4
ATM5
unweighted
weighted

Lumen Output, SPD, Percent Uplight

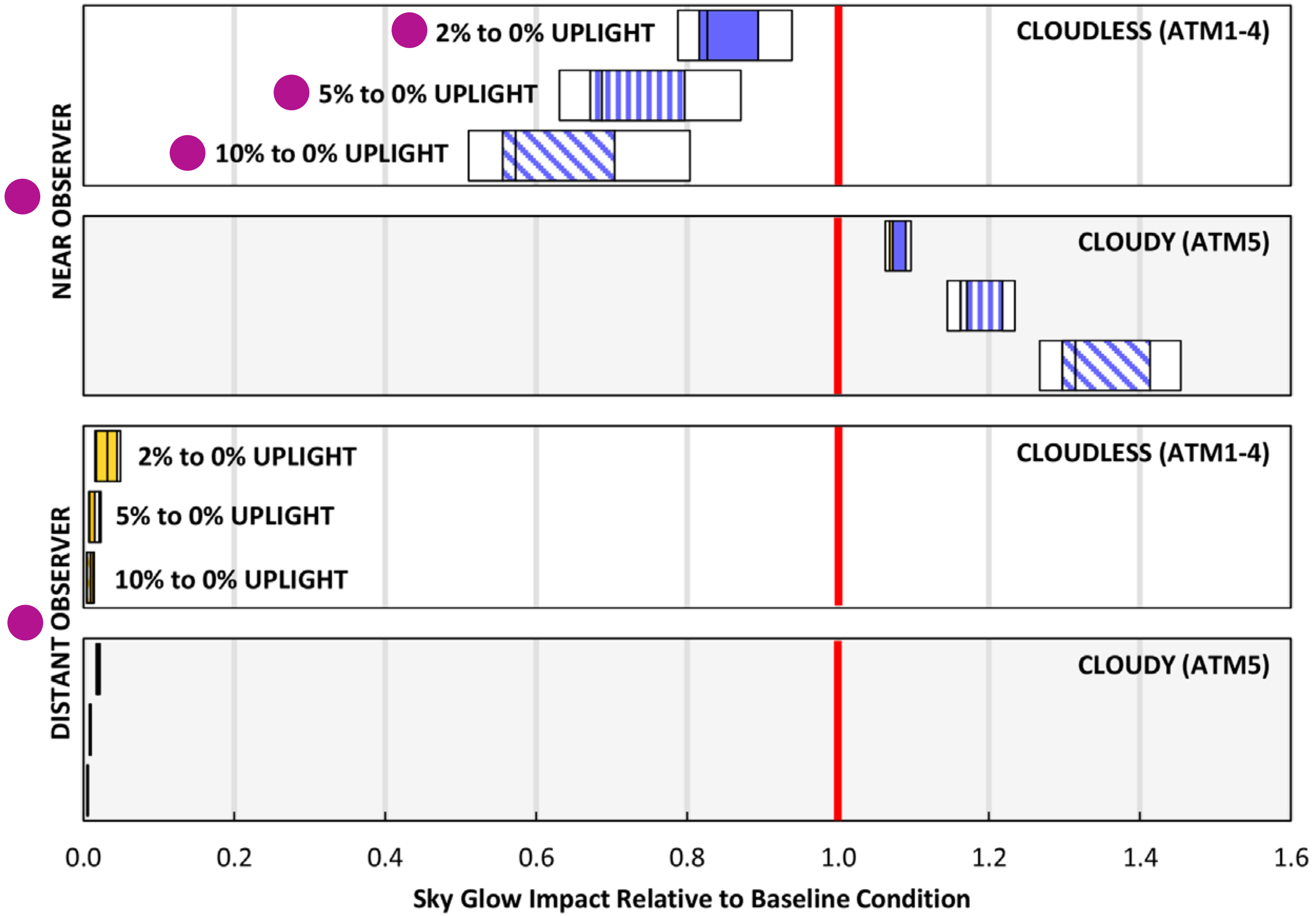


Calculated relative impacts:

- for SPD, compared to HPS
- for percent uplight, 0% compared to 2% uplight
- for lumen output, 50% compared to 100%

The relationship between lumen output and sky glow is **linear.**

Percent Uplight

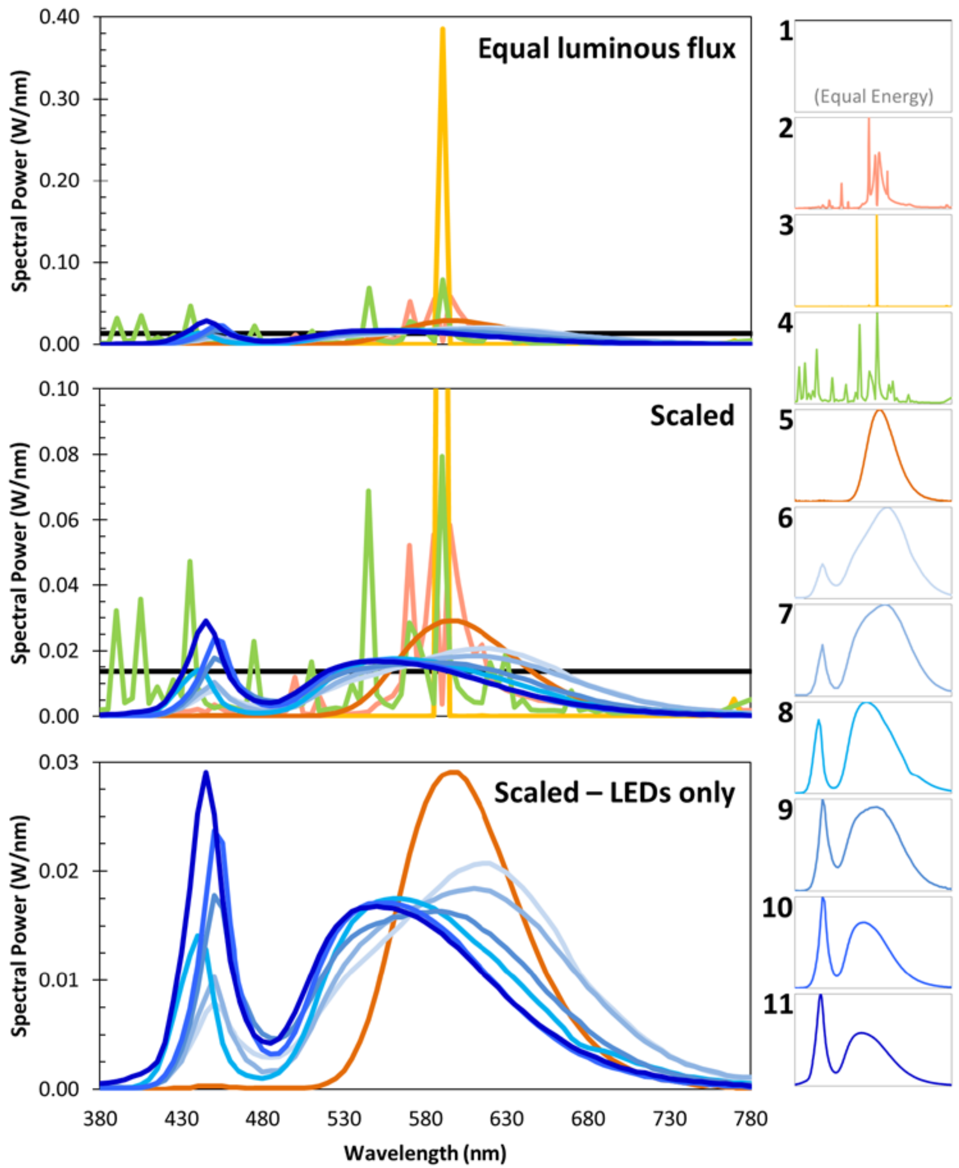


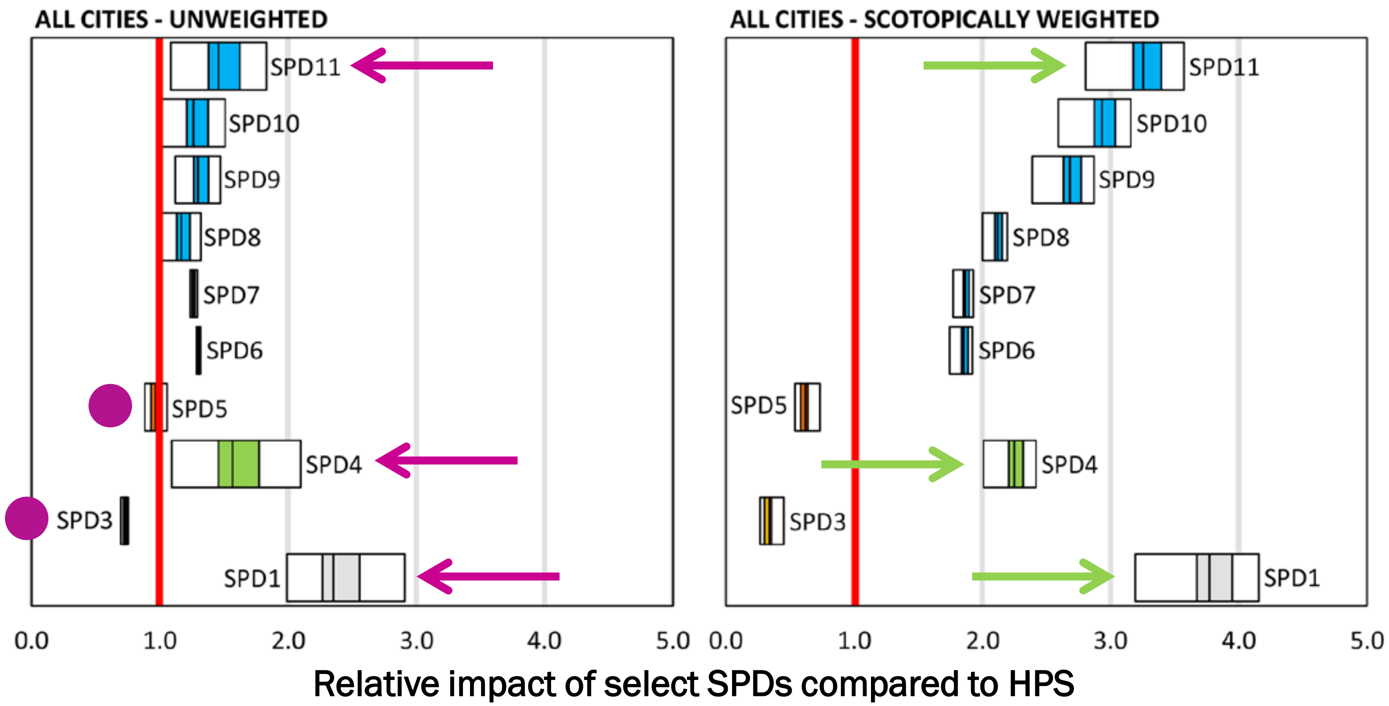
For near observers under clear conditions, reducing uplight reduces sky glow.

The **only circumstance** under which reducing the percent uplight increases sky glow is under cloudy conditions for the near observer.

For distant observers, sky glow is **virtually eliminated** at 0% uplight.

SPD

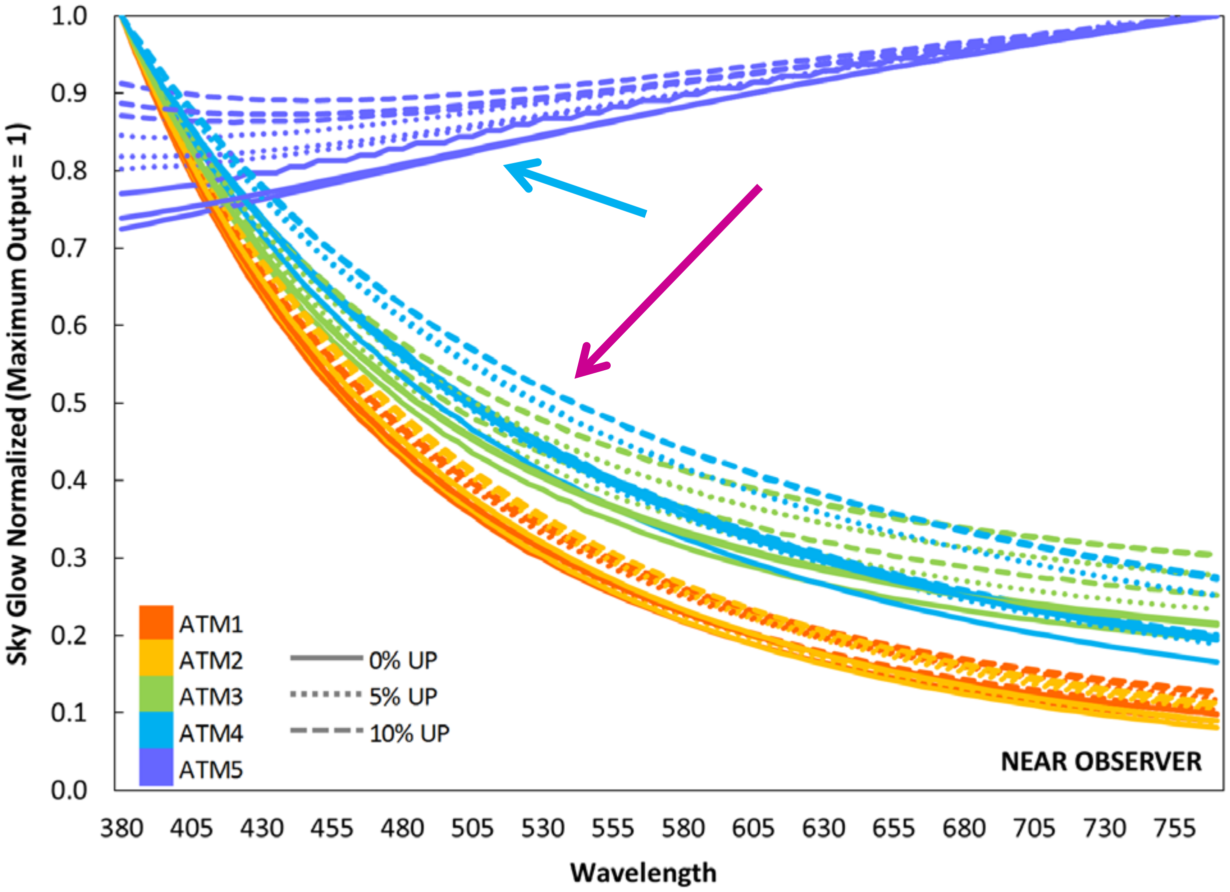


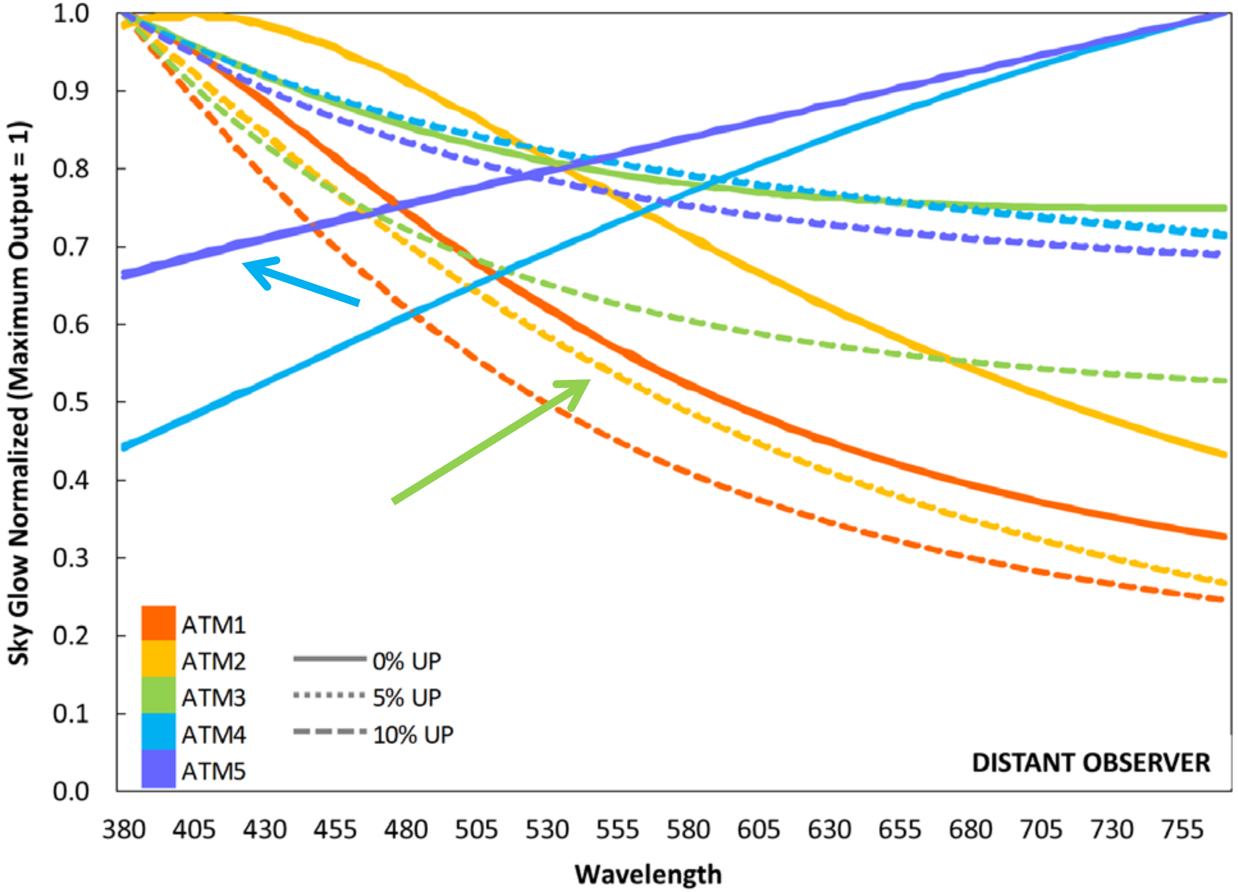


→ the greater the amount of short wavelength energy, the greater the range in impact

→ scotopic weighting further emphasizes these impacts

Atmosphere & Uplight



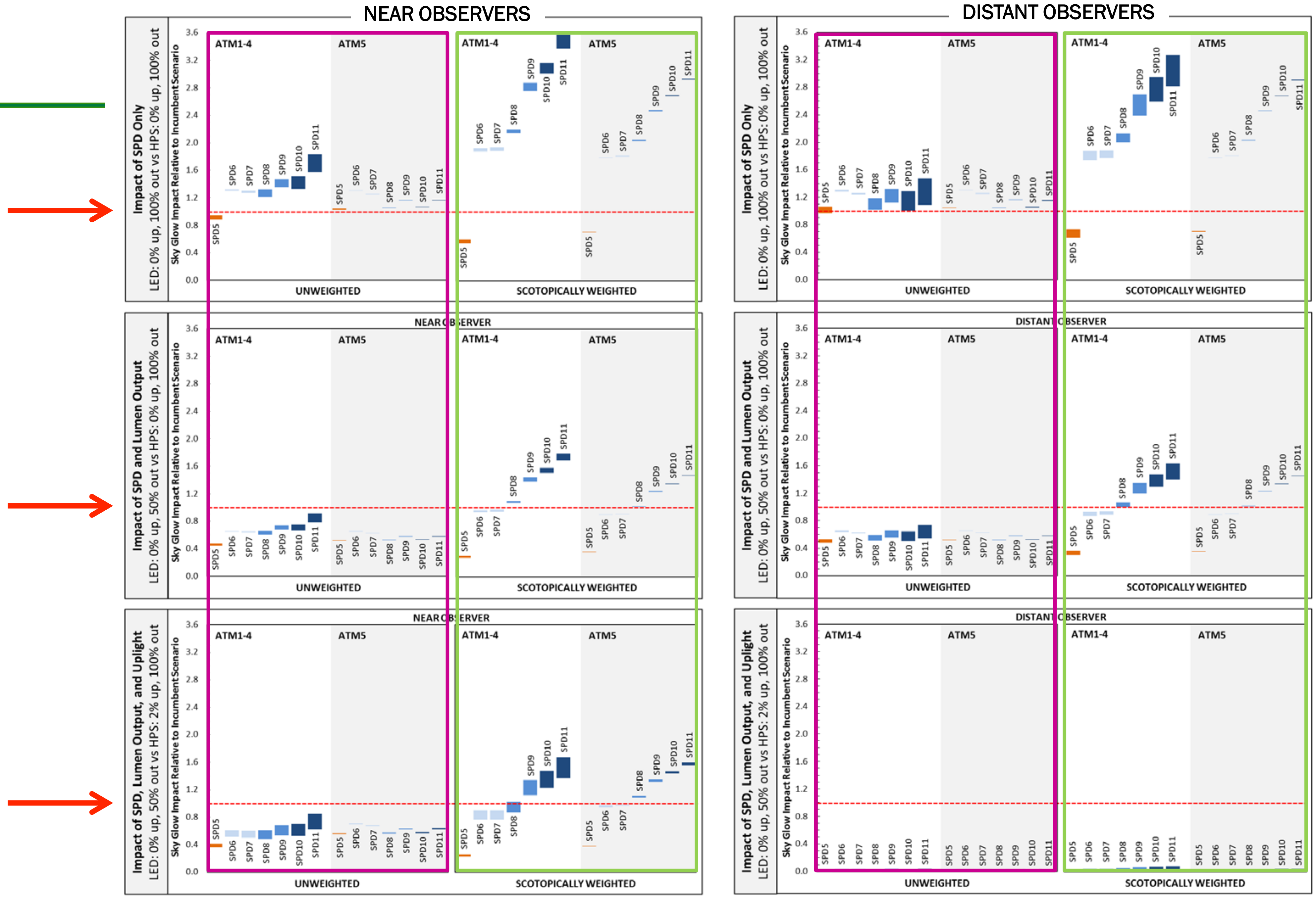


Clear conditions: greater short wavelengths relative to longer wavelengths

Cloudy conditions: less of a difference in short and long wavelength propagation → sky glow SPD is more similar to source SPD

Both effects are less pronounced for observer outside of city as shorter wavelengths are attentuated

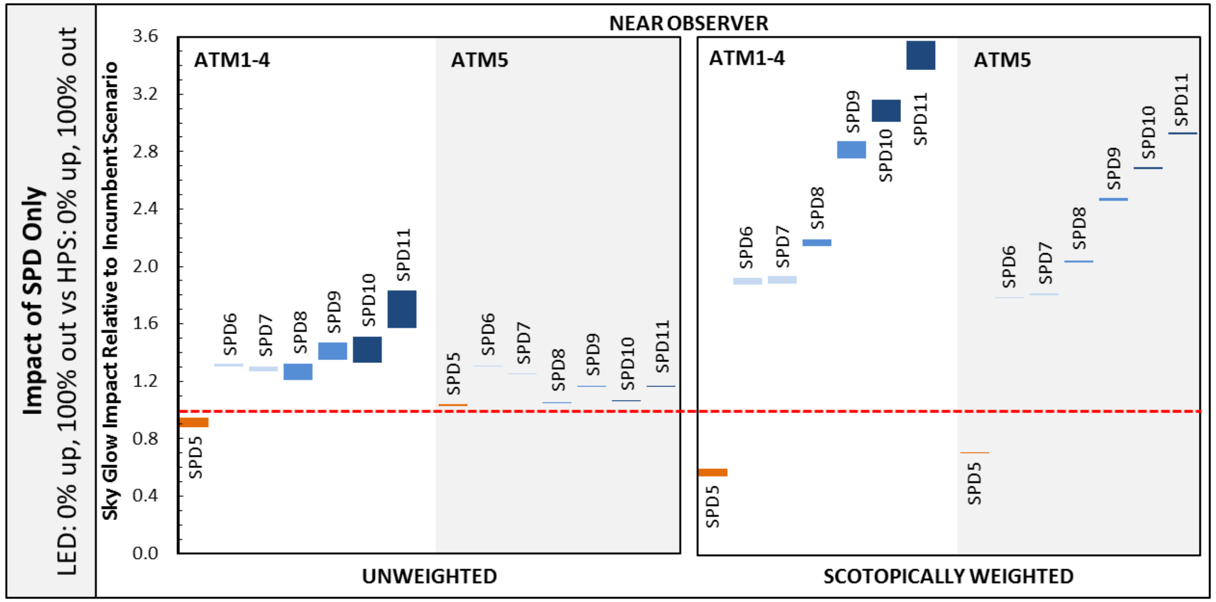
Overall


NEAR OBSERVERS
DISTANT OBSERVERS
Impact of SPD Only
LED: 0% up, 100% out vs HPS: 0% up, 100% out
Impact of SPD and Lumen Output
LED: 0% up, 50% out vs HPS: 0% up, 100% out
Impact of SPD, Lumen Output, and Uplight
LED: 0% up, 50% out vs HPS: 2% up, 100% out
Sky Glow Impact Relative to Incumbent Scenario
ATM1-4
ATM5
SPD5
SPD6
SPD7
SPD8
SPD9
SPD10
SPD11
UNWEIGHTED
SCOTOPICALLY WEIGHTED
NEAR OBSERVER
DISTANT OBSERVER

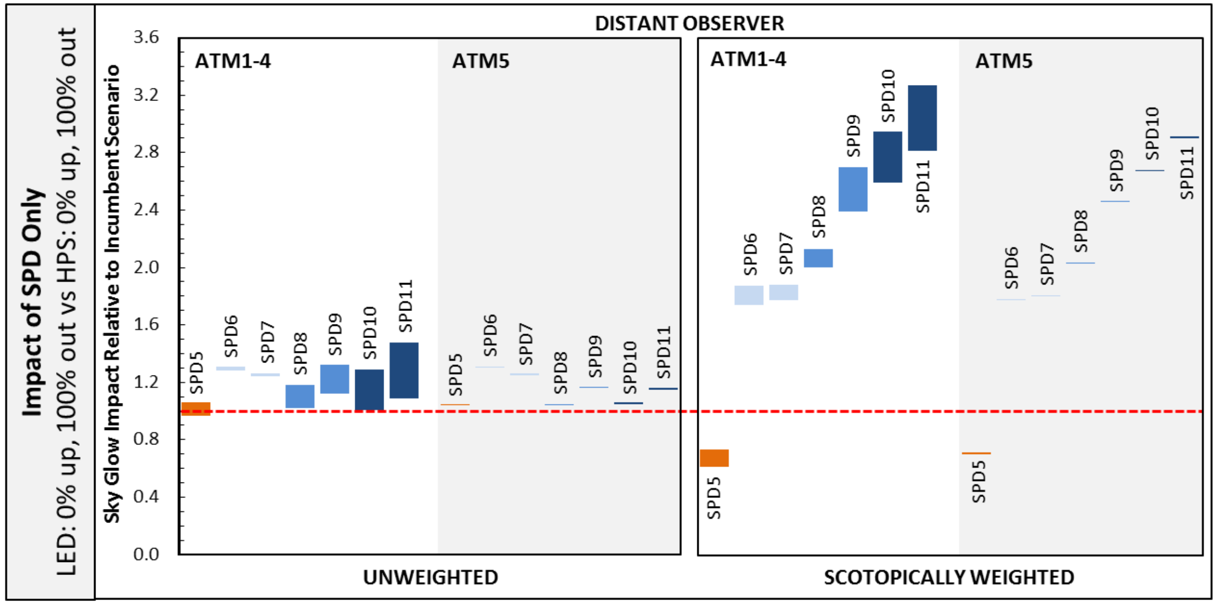
Overall

TOP CHARTS show the effect of replacing the baseline HPS SPD with the various LED SPDs.

NEAR OBSERVERS



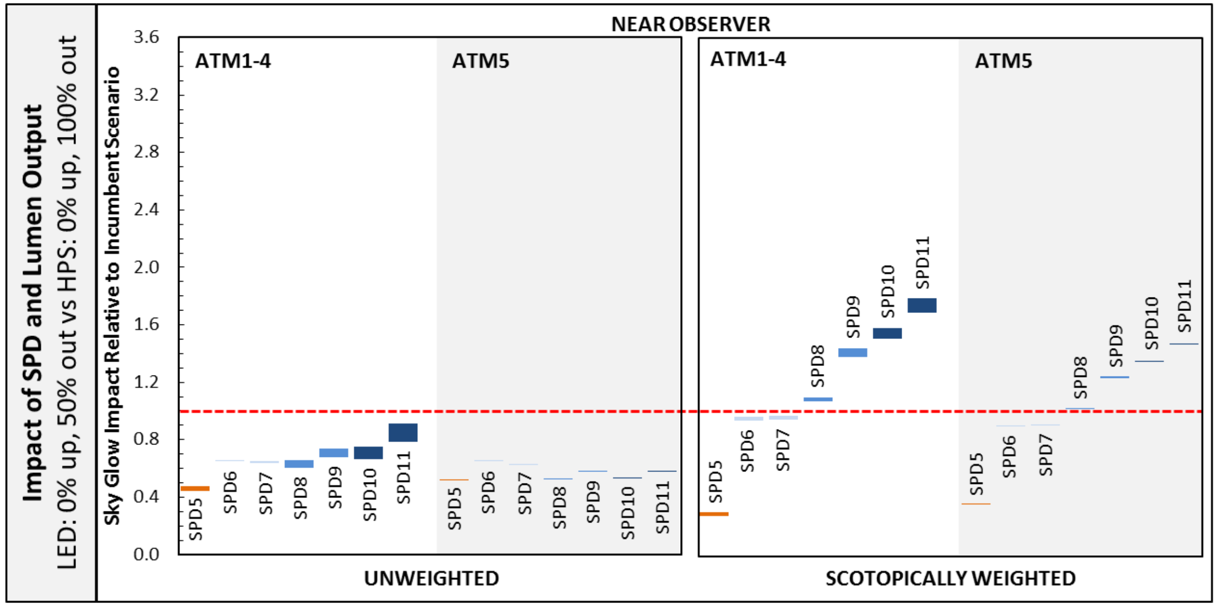
DISTANT OBSERVERS



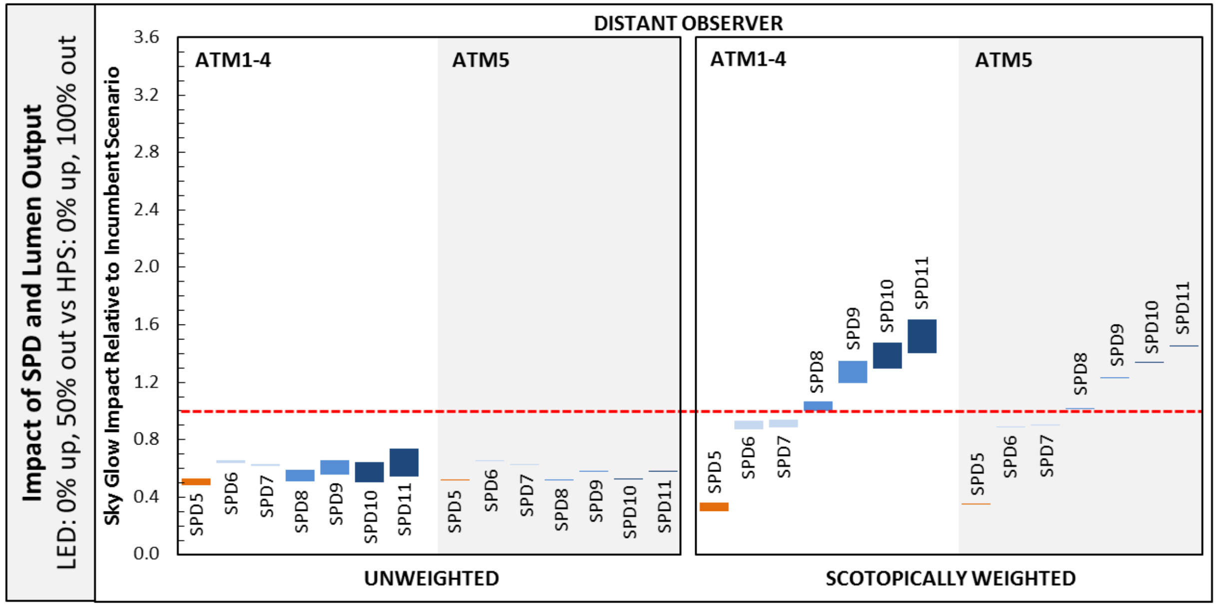
Overall

MIDDLE CHARTS add the effect of reducing luminaire lumen output by half compared to the baseline HPS.

NEAR OBSERVERS



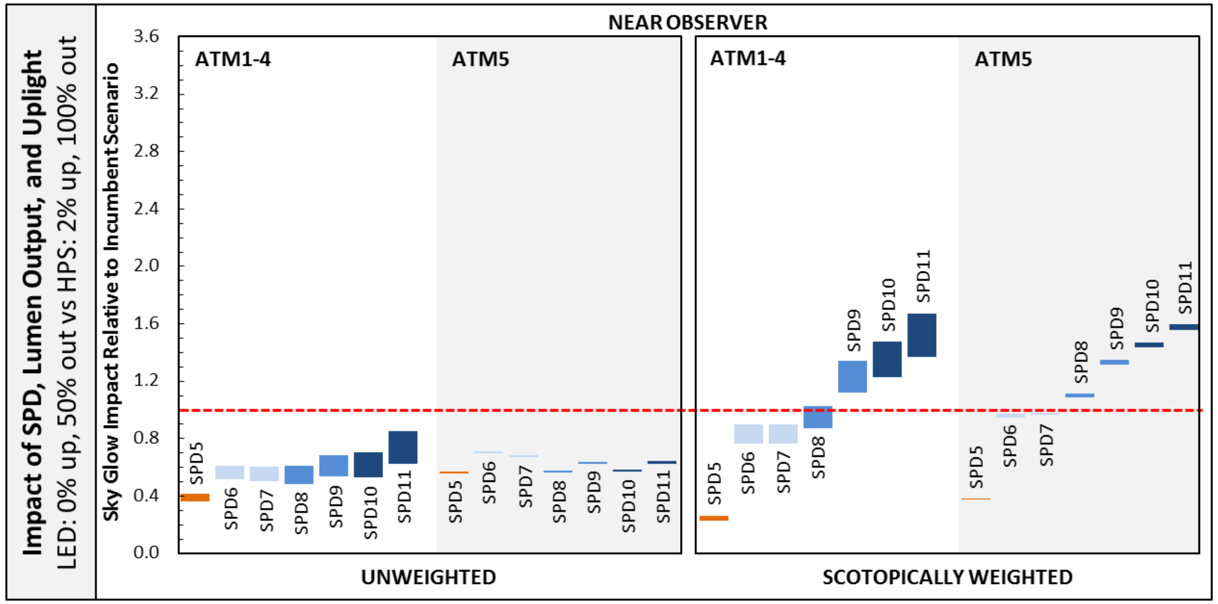
DISTANT OBSERVERS



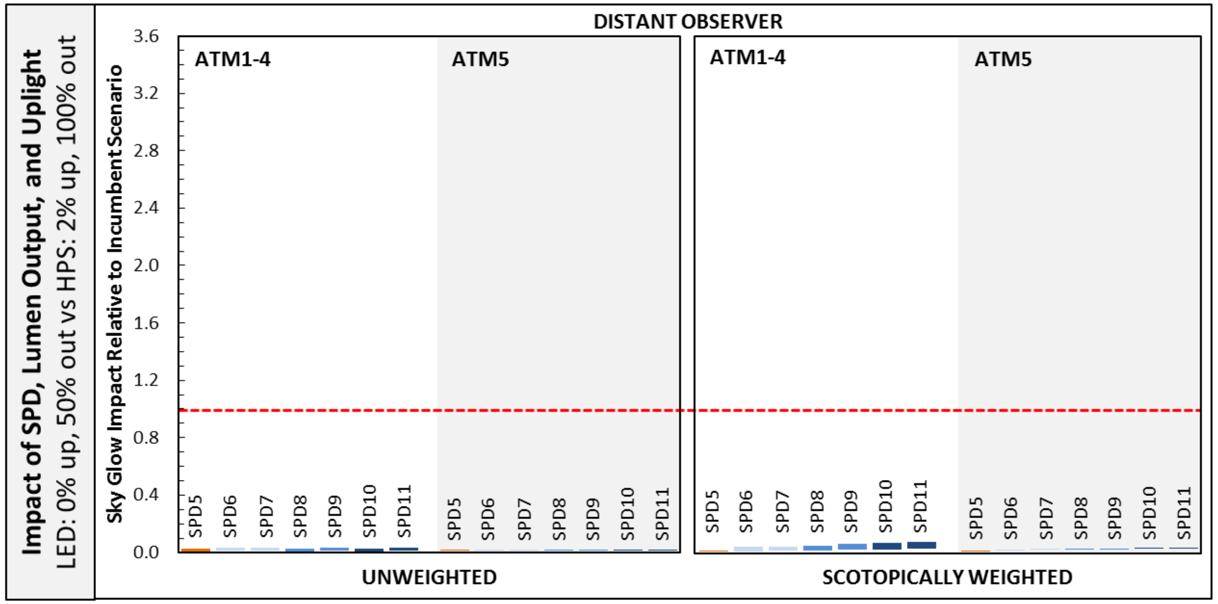
Overall

BOTTOM CHARTS further add the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2%. <u>This is a typical U.S. conversion</u>.

NEAR OBSERVERS



DISTANT OBSERVERS

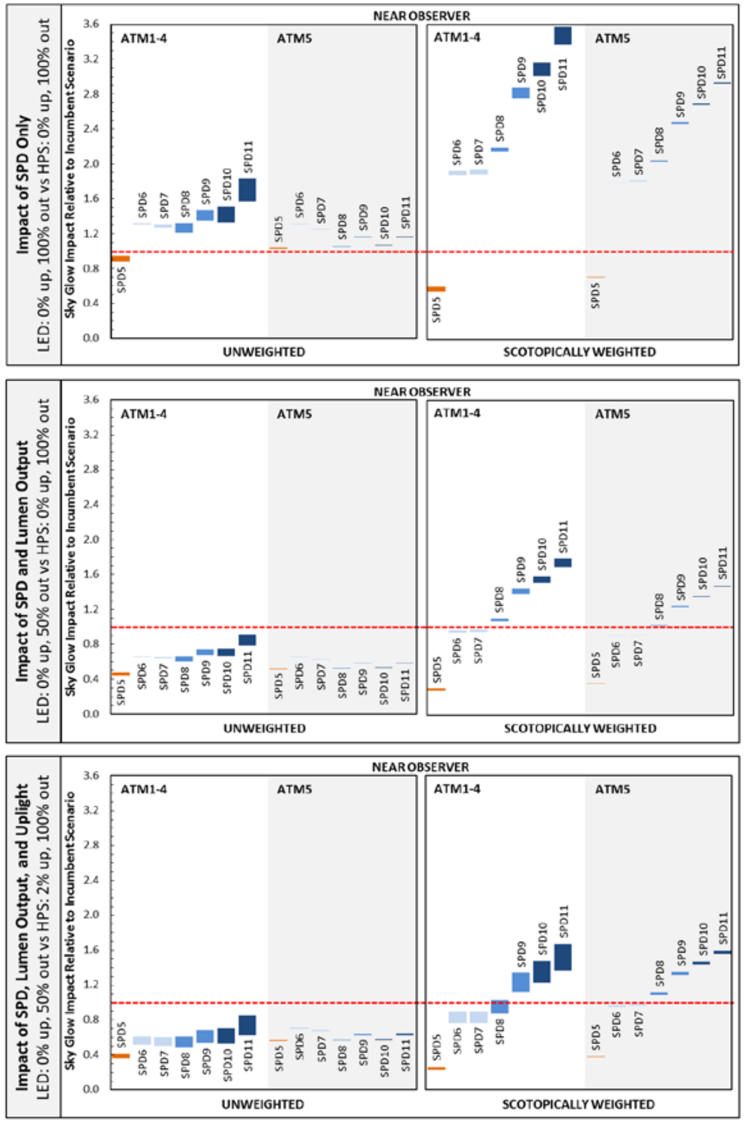


Overall

Short wavelength content does contribute towards increased sky glow but CCT is not always a reliable predictor of impact.

In a typical U.S. conversion, all unweighted results show reduced sky glow for all LEDs.

NEAR OBSERVERS



Much of the current public discussion reflects this comparison of SPD in isolation of the other factors.

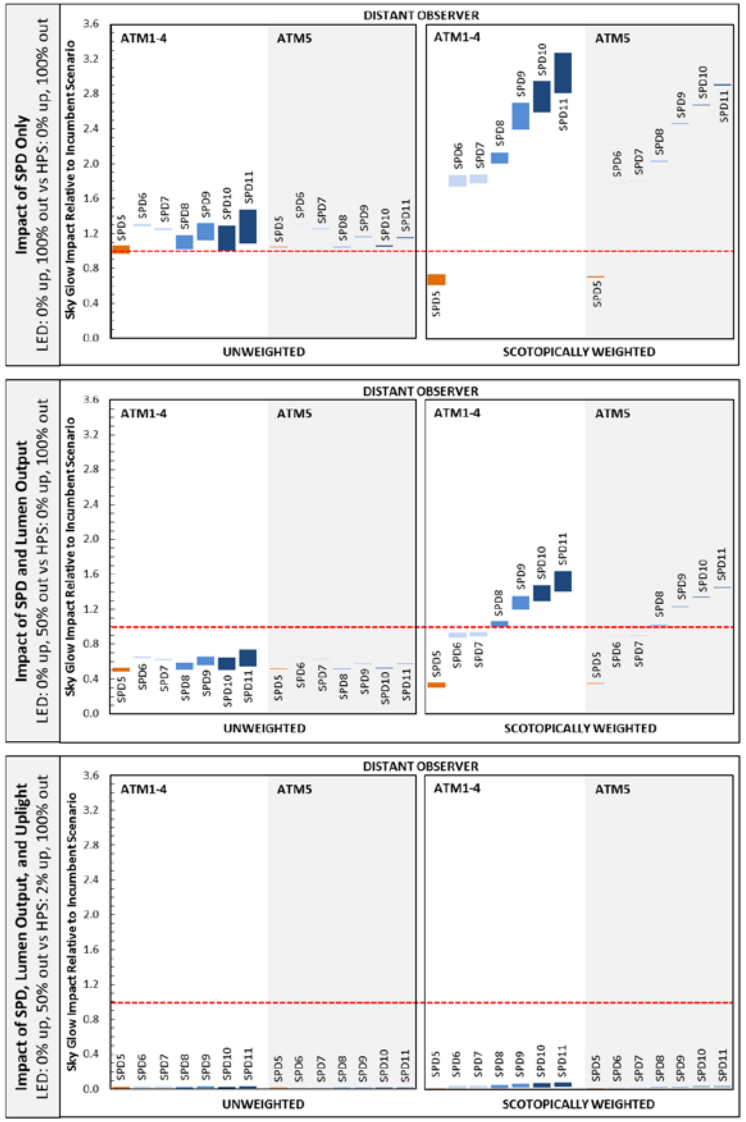
When scotopically weighted, some LED products reduce sky glow while others increase it.

Reduction in uplight from 2% (primarily emitted at low elevation angles) to 0% increases the range of impacts.

Overall

Greater variability compared to near observer due to impact of different atmospheric effects.

DISTANT OBSERVERS



Much of the current public discussion reflects this comparison of SPD in isolation of the other factors.

When scotopically weighted, some LED products reduce sky glow while others increase it.

Reducing 2% uplight to 0% virtually eliminated sky glow (by 95+%) for all LEDs, when unweighted and scotopically weighted.

If you're looking for more…

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

An Investigation of LED Street Lighting's Impact on Sky Glow

April 2017

Prepared for:

Solid-State Lighting Program
Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

Prepared by:

Pacific Northwest National Laboratory

https://energy.gov/sites/prod/files/2017/05/f34/2017_led-impact-sky-glow.pdf

UNISKY

UNIFIED SKY-LUMINANCE MODEL

PROJEKT APVV - 0177 - 10

APVV | ÚSTARCH SAV | UK | SvF STU

PROJECT | PUBLICATIONS | THEORY | MODELING | APPLICATIONS AND OUTPUTS | LITERATURE | CONTACT

SkyGlow Simulator

SkyGlow Simulator can model overcast and/or clear sky radiance and luminance patterns in night-time regime for arbitrarily sized & shaped city models. For more detail read Guidelines that are part of SkyGlow v.5c distribution. If you choose to use this tool, please send email to kocifaj@savba.sk "registering" as a user.

However, if you use SkyGlow Simulator, we request that you reference some of the papers on which SkyGlow Simulator is based:

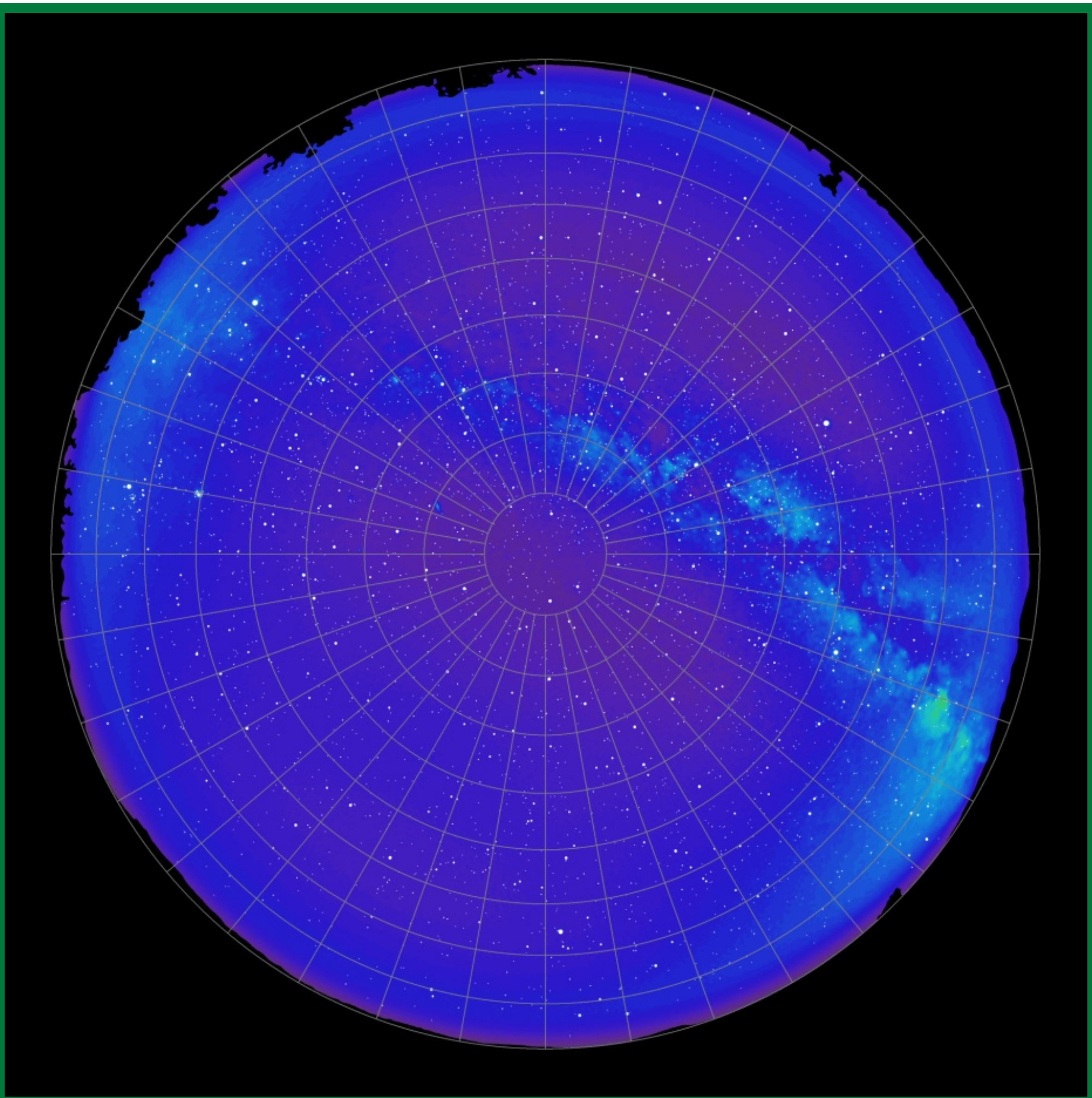
- Kocifaj, M. (2007). Light-pollution model for cloudy and cloudless night skies with ground-based light sources. Applied Optics 46, pp. 3013-3022.
- Kocifaj, M. (2008). Light pollution simulations for planar ground-based light sources. Applied Optics 47, pp. 792-798.
- Kocifaj, M., Aube, M., Kohut, I. (2010). The effect of spatial and spectral heterogeneity of ground-based light sources on night-sky radiances. Mon. Not. R. Astron. Soc. 409, pp. 1203-1212.
- Kocifaj, M. (2012). A numerical experiment on light pollution from distant sources. Mon. Not. R. Astron. Soc. 415, pp. 3609-3615.
- Kocifaj, M. (2014). Modeling the night-sky radiances and inversion of multi-angle and multi-spectral radiance data. Journal of Quantitative Spectroscopy & Radiative Transfer 139, pp. 35-42.
- Kocifaj, M. (2014). Night sky luminance under clear sky conditions: Theory vs. experiment. Journal of Quantitative Spectroscopy & Radiative Transfer 139, pp. 43-51.
- Kocifaj, M., Solano-Lamphar, H. A. (2014). Quantitative analysis of night skyglow amplification under cloudy conditions. Mon. Not. R. Astron. Soc. 443, pp. 3665-3674.

http://unisky.sav.sk/?lang=en&page=aplikacia&subpage=glow

Questions?

Thank you for your participation!

Tess Perrin
Pacific Northwest National Laboratory
Tess.Perrin@pnnl.gov



Related resources:

https://energy.gov/eere/ssl/street-lighting-and-blue-light

- Webinar: The Impact of LED Street Lighting on Sky Glow
- Sky Glow Investigation Report
- Frequently Asked Questions: Street Lighting and Blue Light
- Webinar: Get the Facts on LED Street Lighting
- SSL Posting: Getting the Facts Straight About LED Street Lighting