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The relation of outdoor lighting characteristics to sky glow from distant cities

DM Duriscoe MA[a], **CB Luginbuhl** BS[b] and **CD Elvidge** PhD[c]
[a]U.S. National Park Service Night Skies Program, Bishop, CA, USA
[b]U.S. Naval Observatory Flagstaff Station, Flagstaff, AZ, USA
[c]NOAA National Geophysical Data Center, Boulder, CO, USA

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Five cities in the southwest United States were selected for an analysis of the impact of outdoor lighting practices on nighttime sky glow as observed from distances of 8–67 km. Data from the Suomi National Polar-orbiting Partnership (NPP) satellite visible infrared imaging radiometer suite day/night band were used to identify light sources for input to an atmospheric sky glow model. Total lumens of outdoor lighting were estimated by matching modelled to observed anthropogenic sky luminance at ground locations. The results of two conservative treatments were then modelled for each city: all outdoor luminaires fully shielded with the current lumen amount, and fully shielded luminaires with a lumen amount scaled to 2075 lm capita^{-1}, matching Flagstaff, Arizona. The results indicate 42–88% reductions in average all-sky glow utilizing these 'best practices' for environmental conservation.

1. Introduction

Areas of sparse population exist in the western United States that combine with dry climate and clear air to generate excellent night sky quality. Night sky quality is explicitly recognized as a protected resource for many national parks and natural areas in this region. Sky glow from cities and towns often appears as isolated domes of light along the horizon at these sites. This situation creates opportunities for exploring the relationship between outdoor lighting practices and the amount of atmospheric sky glow produced. Photometric observations of anthropogenic sky glow may be correlated with the results from a sky glow model. Worldwide sky glow predictions have been constructed using the location and intensity of upward anthropogenic light measured from satellite observations of the earth at night.[1]

The Suomi NPP satellite has been operational since 2011 and carries a scanning radiometer on board known as VIIRS (visible infrared imaging radiometer suite). The device includes a broadband imaging detector with high sensitivity, suitable for detecting anthropogenic sources of light on the earth's surface with high precision and accuracy, known as the VIIRS day/night band (DNB).[2,3] A preliminary product was released in December 2012 which presented a cloud-free composite of the earth at night from 75° north to 65° south latitude.[4] The radiance calibrated data are at a resolution of 15 arc seconds of longitude and latitude, or 463 m at the equator, and were compiled from data acquired in April and October of 2012. The data are single channel, high dynamic range, but with a spectral response biased towards the red end of the visible spectrum compared to the photopic or scotopic luminous efficiency functions established by the

Address for correspondence: Dan Duriscoe, U.S. National Park Service Night Skies Program, 351 Pacu Lane, Bishop, CA, USA
E-mail: dan_duriscoe@nps.gov

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Commission Internationale de l'Éclairage (CIE). The methods used to construct the composite are described by Baugh *et al.*[5]

A sky glow model developed by Garstang may be used to predict the effects of outdoor lighting on sky brightness (luminance) as seen from an observing site some distance from the city centre.[6–8] Along a given path through the atmosphere, the model estimates the amount of light added through scattering, as well as removed by extinction (arising from both scattering and true absorption). Garstang's treatment uses an effective wavelength of 550 nm and a two-component atmosphere consisting of molecules and aerosols. The amount of aerosol is defined through a parameter K which sets the ratio of total molecular to aerosol scattering. It has been used successfully to predict and evaluate the effects of outdoor lighting on sky quality at astronomical observatories.[9]

Photoelectric photometers and charge-coupled device (CCD) detectors have been used to quantify night sky luminance in the absence of moonlight to evaluate the impacts of sky glow on astronomical observations.[10–12] Most of these site evaluation efforts focus on the region of the sky with a zenith angle less than 60°, ignoring the portions of the sky most affected by anthropogenic sky glow. Recently, all-sky fisheye cameras capable of calibrated sky luminance measurements have provided a rapid means of evaluating the entire sky.[13–15]

The U.S. National Park Service has collected all-sky luminance data with a 0.05° resolution mosaicking CCD camera system since 2001.[16] Improved accuracy in estimating the anthropogenic component of sky luminance is achieved using an all-sky subtraction of a natural sky luminance model.[17] These data are photometrically calibrated in a broadband system approximating the Johnson–Cousins Astronomical V band and the CIE photopic curve. Both observations and modelling demonstrate that the amount and shielding of outdoor lighting has strong effects on sky glow. In this study we explore the potential reductions in sky glow that would be achieved with environmentally protective lighting design – conservative amounts in fully shielded luminaires. We use the term 'best practices' in this context and make no attempt to investigate details of outdoor lighting design to meet certain illuminance, uniformity, energy conservation, or human vision specifications. We emphasize that certain communities, such as Flagstaff, Arizona, have chosen to install outdoor lighting that limits sky glow, and this example is applied to other cities. Beginning with light geographic distribution and amount derived from the VIIRS DNB data and calibrated using a study of Flagstaff lighting published by Luginbuhl *et al.*,[18] supplemented by conservative assumptions of shielding, uplight angular distribution intensity, and near-ground blocking, we develop models to match observed sky luminance profiles. We then predict the effects on sky glow of both fully shielded lighting and conservative outdoor lighting amounts as reflected by the practices in Flagstaff, Arizona.

2. Methods

2.1. Analytical approach

We begin with three sources of data for the city of Flagstaff, Arizona: (1) photometrically calibrated CCD camera observations of sky glow from a site at some distance from the city, (2) a complete outdoor lighting inventory including lumen output and average per cent uplight, and (3) observations of upward radiance from the VIIRS DNB orbiting detector. The summed radiance for Flagstaff is compared to the total inventoried luminous output, determining the ratio between VIIRS DNB and luminous flux. We distribute the total inventoried lumen output over the land according to the observed VIIRS distribution. Using each lumen-calibrated VIIRS grid cell as lighting amount input to a sky glow model, we compare the modelled result to ground-based CCD camera observations for verification. We then apply the radiance-to-lumen calibration ratio on a cell-by-cell basis to the VIIRS database over the southwest United States to estimate lumen output over this region. Data from the location of four other cities are each used as lighting amount input, and a model of sky glow as seen from observation sites near these cities is produced. Again, the modelled result for each city is compared to CCD camera observations for verification. If a significant discrepancy is observed, the difference is assumed to result from a different relationship between VIIRS radiance measurements and lumen output for that city. The calibration ratio is scaled in these cases to achieve agreement. After this adjustment, estimates of current lumen output for each of the four cities are calculated. Finally, we use the derived descriptions of current lumen output for all five cities as input to the sky glow model as a baseline to estimate the effects of two treatments: Changing the uplight fraction to zero, and changing the lumen amount to match that of Flagstaff as measured in lumens per capita. We consider Flagstaff's lumens per capita amount resulting from a sustained community effort to protect night sky quality and representing a 'best practices' target for other cities. The predicted sky glow amount and distribution for each treatment is compared to current baseline conditions.

2.2. Study area and cities selected

The study area includes a portion of the southwest United States. This region often experiences cloudless atmospheric conditions and low concentrations of atmospheric aerosols, which improve the quality of both observed sky glow data and results from sky glow modelling. A map of the region is shown in Figure 1.

The cities (or metropolitan areas) selected for analysis, including population size, latitude and longitude, observing site name, and the distance and azimuth from the observing site to the city centre, are given in Table 1. Flagstaff, Arizona, the 'First International Dark-Sky City' was selected as an example of best practices because of its efforts to protect dark night skies. Also, a complete outdoor lighting inventory was available for this city, allowing a calibration point for sky glow model inputs and for comparing the satellite data radiance values to known on-the-ground installations. Winslow, Arizona; Page, Arizona; and Moab, Utah were selected as relatively isolated small cities that illustrate sky glow impacts to an area of otherwise near-pristine night skies. Finally, Las Vegas, Nevada was included because of its regional significance to the night skies of the desert southwest. Analysis of Las Vegas included seven conterminous communities: Las Vegas, North Las Vegas, Henderson, Spring Valley, Paradise, Sunrise Manor, and Enterprise.

2.3. Upward light estimate based upon VIIRS DNB

The location on the earth's surface and relative intensity of upward light sources within cities were estimated using information from VIIRS DNB satellite data. False colour renderings of the pattern of upward light as detected by the VIIRS instrument are shown for the each study city in Figure 2(a)–(e).

The VIIRS DNB data exhibit varying background levels at values of approximately $0.3\,\mathrm{nW\ cm^{-2}\,sr^{-1}}$. The cumulative contribution of this background over a wide area can represent a significant contribution to the total radiant flux. After examining the areas of interest for each city, we decided to reset the zero point of the data at $0.3\,\mathrm{nW\ cm^{-2}\,sr^{-1}}$ to effectively screen out radiance not associated with outdoor lighting.

We extracted and analysed VIIRS DNB data in ESRI ArcGIS$^{\mathrm{TM}}$ software. Besides

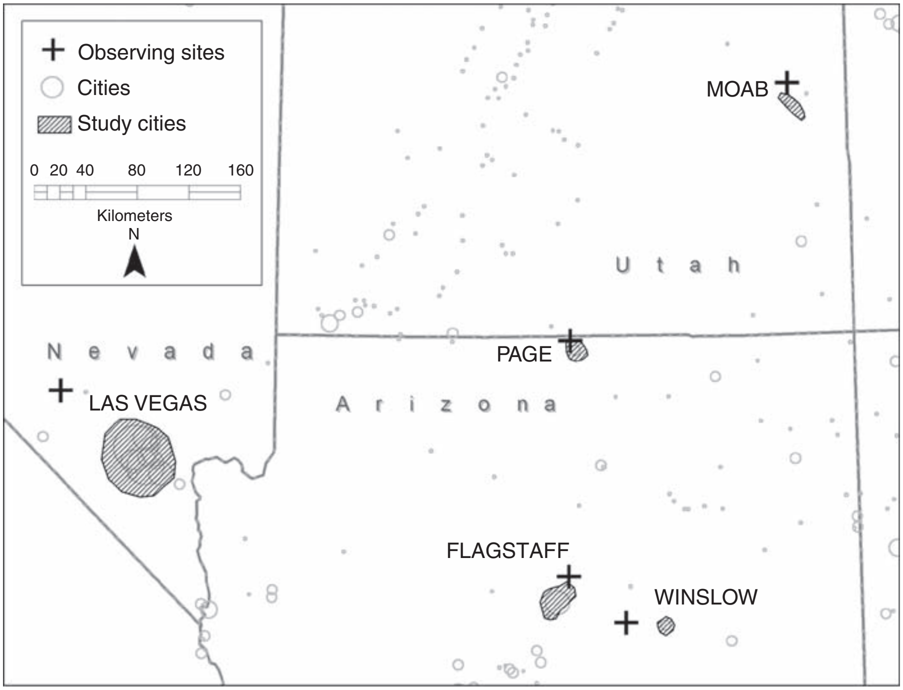

Figure 1. Map of a region in the southwest United States showing cities selected for analysis and the observing sites

Table 1. Cities and observing sites used in the analysis

City name	Population 2010 Census	Observing site name	Distance to city centre (km)	Azimuth (site to city)
Flagstaff, AZ, area	76000	Sunset Crater	21.8	205
Winslow, AZ	9652	Meteor Crater	29.9	93
Page, AZ	7652	Wahweap Overlook	8.1	150
Moab, UT	5101	Balanced Rock	14.6	174
Las Vegas, NV, area	1951269	FS Road 535	67.0	125

subtracting the background, we effectively defined the city limits by zeroing the adjacent undeveloped areas. The census data 'populated place' boundary was superimposed to define the population of each metropolitan area. An average and a sum of radiant flux for all cells within each city's defined limits were then computed. These statistics form the basis for upward radiance and installed lumens estimates for each city.

2.4. Calibration to Flagstaff lighting inventory

A comprehensive inventory of outdoor lighting for Flagstaff for 2003 was available, including lamp types, luminaire shielding, and luminaire lumen output (i.e. luminous flux escaping from luminaires, accounting for luminaire losses).[19] The late-night lumen output of Flagstaff (140 000 000 lm) estimated in this study was adjusted to account for growth between 2003 and 2012. We also

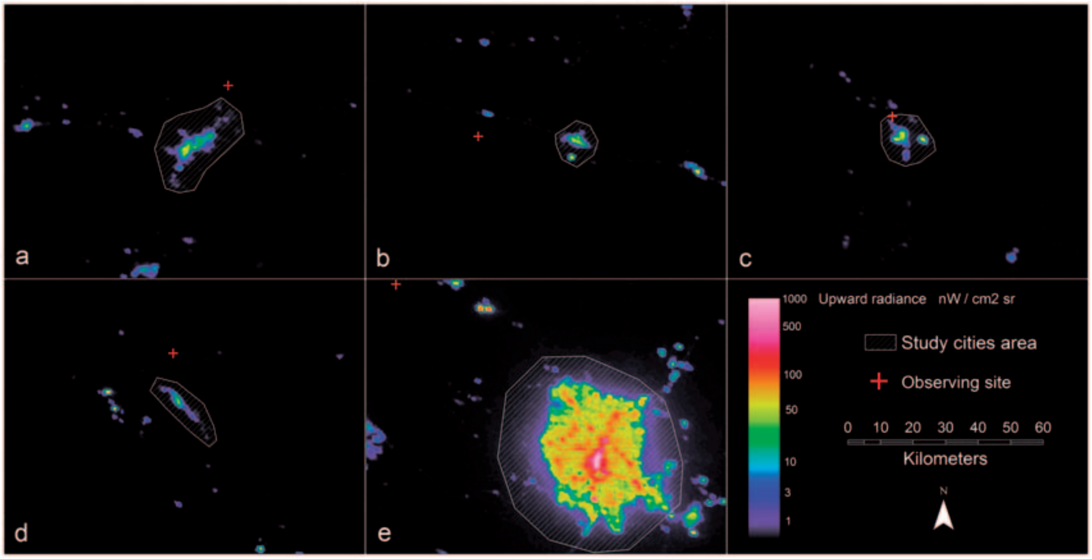

Figure 2. Maps of each study city: (a) Flagstaff, (b) Winslow, (c) Page, (d) Moab, and (e) Las Vegas showing the upward radiance observed by the VIIRS day/night band sensor in false colour and the observing site location (red '+') from which the field data of sky glow were collected. Outlined areas indicate approximate city boundaries (available in colour online)

included the adjacent communities of Dorney Park, Fort Valley, and Belmont, using an estimate based upon the number of residents, an estimated number of residents per house, and the per house lighting output (604 lm) and shielding (38% up) from the Flagstaff study. These adjustments brought the total installed luminaire lumens to 158 000 000 lm. The total radiant intensity from the Flagstaff area was measured at 42725 W sr^{-1} by summing the radiance from each cell in the DNB grid and multiplying by the total land area in cm^2. The ratio of total inventoried installed lumens to total upward radiant intensity observed by DNB yields a value of 3698 lm W^{-1} sr. We make the assumption that the DNB radiance is a useful measure of the upward luminous flux. The accuracy of predictions using this scale factor for other cities will thus depend upon their similarity to Flagstaff in terms of near-ground blocking, albedo characteristics, and light source spectrum. We use the observed sky glow data to verify that the upward flux estimates for cities other than Flagstaff represent accurate estimates of the true amount, given the sky glow model assumptions. This is an important objective of this work and represents the first such exploration of the VIIRS database.

2.5. Observed sky glow from cities

Figure 3 shows sky glow from each city as observed by the NPS mosaicking camera. Anthropogenic sky glow (i.e. observed minus modelled natural) in micro-candela per metre squared (μcd m^{-2}) was extracted from the observed sky glow mosaic at a 1° of zenith angle interval along a meridian through the sky aligned with the city centre. These observed values were compared to output from the sky glow model (Section 2.6) to adjust the initial estimate of luminaire lumens for each city determined from the VIIRS

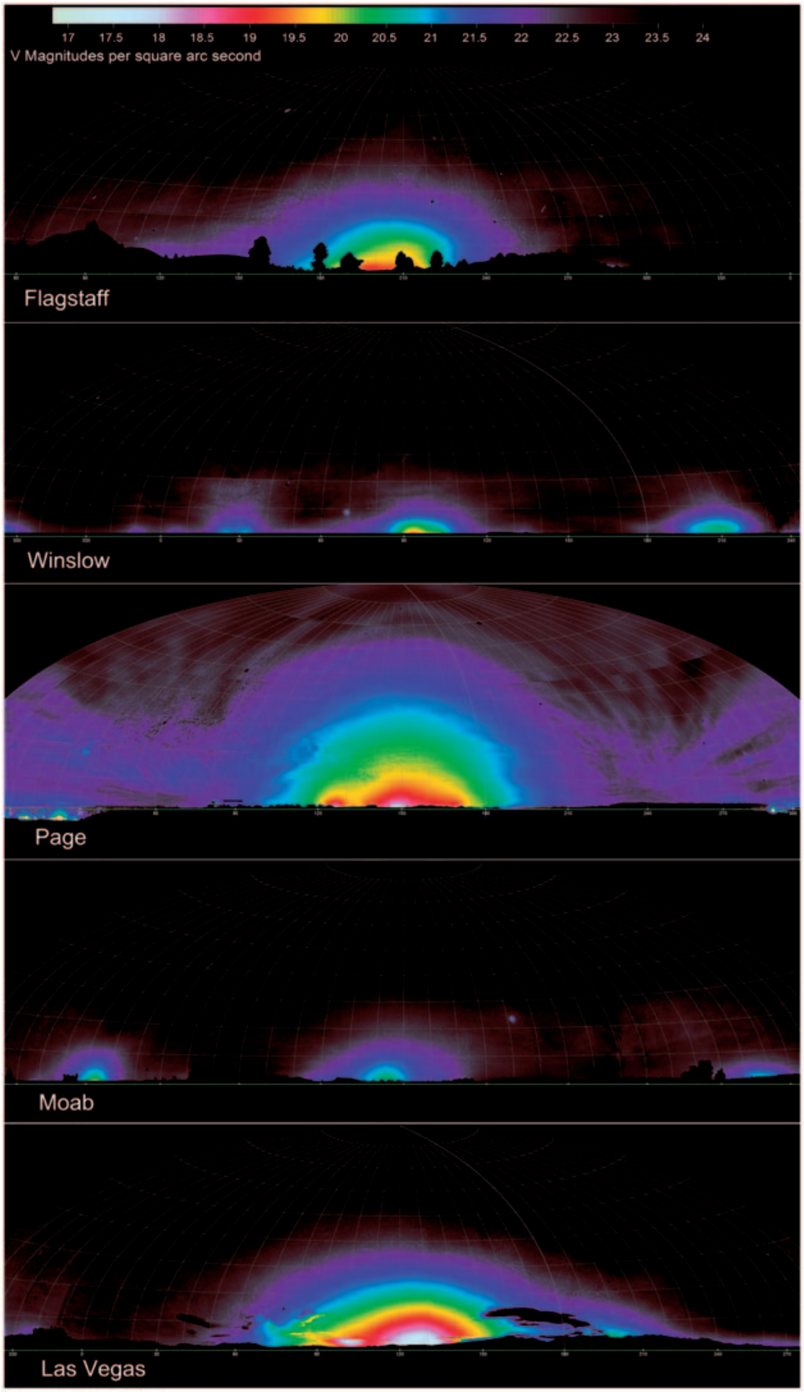

Figure 3. Observed anthropogenic sky glow for the five cities investigated (in Hammer–Aitoff equal area projection; grid lines are at 10° intervals) (available in colour online)

DNB radiance and Flagstaff scale factor described in Section 2.4.

2.6. Sky glow model parameters

A sky glow model developed by Garstang[6–8] was used to predict the sky luminance for comparison to the observations described in Section 2.5, as well as all-sky maps shown in Section 3. Inputs to the sky glow model include: (1) the location of the centre of each DNB grid cell in latitude, longitude, and elevation; (2) the estimated luminaire lumens obtained from the DNB radiance for each cell multiplied by the Flagstaff calibration scale factor (Section 2.4); (3) the angular distribution of upward emitted light as defined by Garstang,[6] with a ground reflection of 0.15[6] and direct uplight fraction of 0.10;[19] (4) a blocking profile (blocking parameters $E_b = 0.3$ and beta = 0.1) arising from the blocking of light rays by objects in the near-ground environment as described by Luginbuhl *et al.*;[18] (5) the aerosol content of the atmosphere, calculated from the atmospheric extinction coefficient measured from observations of standard stars in the data for each observation; and (6) the altitude of the observer and the light source, determined from a digital elevation model.

Outputs from the model included predicted anthropogenic sky luminance in $\mu cd\ m^{-2}$ along the meridian through the centre of the city in 1° zenith angle increments and predicted sky luminance over the entire sky. The all-sky predictions were fitted to a contour surface using a spline algorithm and this surface displayed with the same colour ramp as the observed data in ArcGIS software for direct visual comparison.

3. Results

3.1. Sky glow model for Flagstaff

The VIIRS DNB per pixel radiance measures were used to geographically distribute the 158 000 000 lm determined from the corrected Flagstaff lighting inventory described in Section 2.3. The modelled and observed profiles for Flagstaff are shown in Figure 4. This result represents a successful corroboration of four separate components used to measure and predict sky glow impacts from a city: The photometric measurements from Sunset Crater and subsequent natural sky subtraction, the on-the-ground lighting inventory, the distribution of aggregate lumens from the inventory according to the VIIRS DNB relative upward radiance data, and the modified Garstang modelling process.

3.2. Sky glow model fit to observations for other cities and adjusted lumens per capita

The VIIRS DNB radiance maps were converted to luminous flux using the Flagstaff scale factor described in Section 2.4 and the resulting anthropogenic sky glow predictions compared with the observations. The predicted sky glow from the city of Winslow, Arizona fits the observed data well. However, for the other three cities, the luminous fluxes derived using the Flagstaff scale factor produced sky luminance predictions slightly to significantly greater than those observed. Table 2 summarizes these results. The need for this correction reveals that the VIIRS DNB measures cannot be immediately translated into on-the-ground fixture lumens given the sky glow model assumptions, which are the same for each city. Possible reasons for this include different surface albedos, different near-ground blocking from vegetation or buildings, or a higher fraction of unshielded light reaching the VIIRS DNB detector. Also, the reader is cautioned to not immediately infer that the sky glow models representing 'current conditions' for each city other than Flagstaff accurately portray the existing lighting practices. They are approximate representations and therefore essentially become hypothetical

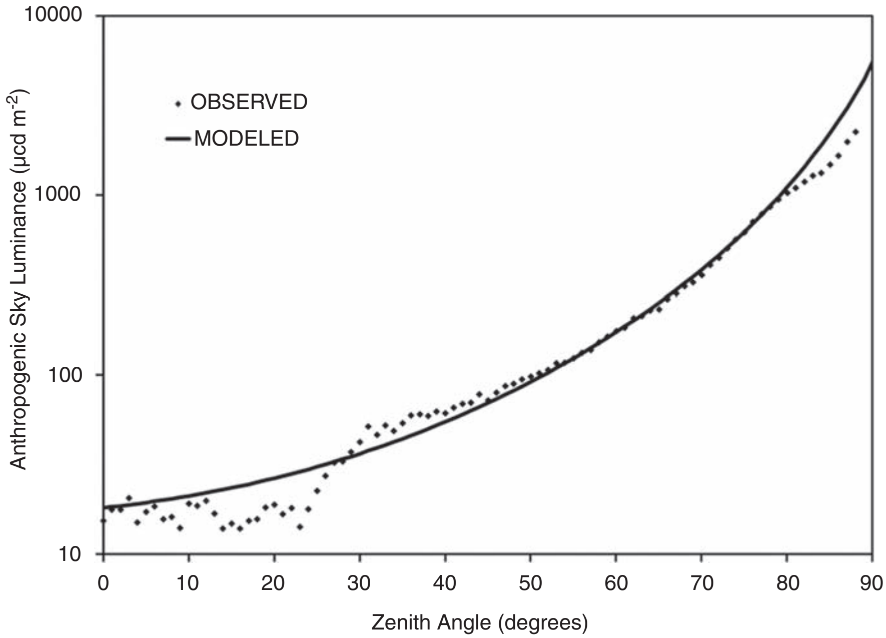

Figure 4. Observed and modelled luminance profiles for Flagstaff as seen from Sunset Crater National Monument, 21.8 km from the city centre

Table 2. Lumens per capita predicted by VIIRS DNB measures and measured by a model fitted to observed anthropogenic sky glow

City name	Predicted lumens per capita from DNB	Predicted lumens per capita from sky glow model fit	Adjustment resulting from Flagstaff model fit	Calculated lumens per capita ratio (city to Flagstaff) based on sky glow model fit
Flagstaff, AZ	2075[a]	2075	1	1
Winslow, AZ	6275	6275	1.00	3.02
Page, AZ	10368	5702	0.55	2.75
Moab, UT	7655	3828	0.50	1.84
Las Vegas, NV	7680	6528	0.85	3.15

[a]*Calibration point derived from on-the-ground inventory*

cities, given that certain model parameters are held constant for all cities.

3.3. Sky glow predictions for fully shielded and best practices lighting

Revised models for each city were developed to explore the consequences of improved lighting practice on sky glow. The first, developed for all five cities in the study, maintained the lumen output determined in Section 3.3 but converted all lighting to zero uplight or fully shielded luminaires. The second, developed for all cities except Flagstaff, reduced the luminous output per capita to that measured for Flagstaff (2075 lm capita^{-1}). Figure 5 shows the results of the models (column 2 for fully shielded, column 3 for shielded plus 2075 lm capita^{-1}) compared to the model of current conditions (column 1) as sky luminance maps. The all-sky average

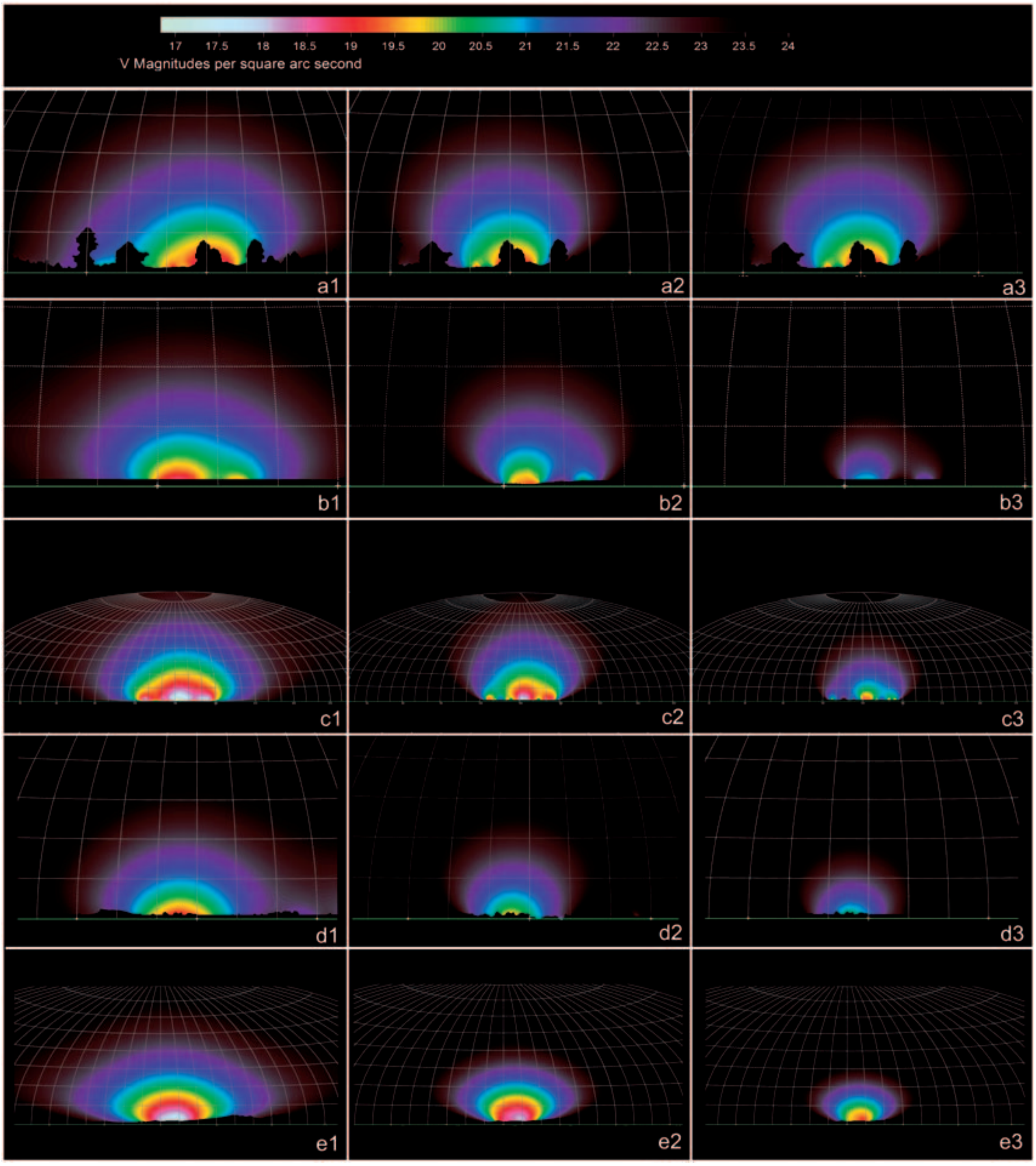

Figure 5. False colour representations of predicted sky glow from outdoor lighting as seen at each observing site in Hammer–Aitoff projection with 10° grid overlay (horizon at bottom, zenith at top) for each of the cities investigated with three outdoor lighting scenarios. Cities are arranged in rows: (a) Flagstaff, (b) Winslow, (c) Page, (d) Moab, and (e) Las Vegas. Lighting scenarios are in columns; column 1 = current conditions, column 2 = current lighting amount with full shielding, and column 3 = lighting amount same as Flagstaff (2075 lm capita^{-1}) + full shielding ('best practice') (available in colour online)

accurately represents the predicted total photon flux from anthropogenic sky glow arriving at the observer's location from all directions in the sky and is therefore a good indicator of environmental impact. Note that the scale is different for each city, indicated by the varying separation in the 10° grid lines, depending on the light dome overall size in the sky. The predicted reductions in sky glow over the meridian from zenith to horizon through the centre of each city light dome are shown in Figure 6 as a ratio to current conditions with zenith angle. In addition, three all-sky luminance indicators are presented in Table 3. Zenith luminance will affect astronomical observations, average all-sky luminance is the most unbiased indicator of light escaping into the environment, and the area of brightest luminance is a good indicator of human visual impact, since in a relatively dark environment the eye will be attracted to the brightest area of the sky.

These results reveal that merely shielding outdoor lighting produces very significant reductions in sky glow. This effect is most pronounced when the observer is at a greater distance from the city and in areas near the zenith. The shielded models for Las Vegas and Winslow (67 and 30 km from the observer, respectively) predict reductions to 28 and 55% of current conditions at the zenith, while Page (8 km distant) shows a reduction in zenith sky luminance to 79% of the current situation. Note, however, the large reductions in sky glow nearer the horizon ('Brightest area luminance' in Table 3) predicted for Page resulting from shielding. A reduction in installed lighting amount produces a directly proportional reduction in sky glow. Therefore, cities that are currently calculated to have much higher lumens per capita installed than our best practices standard of Flagstaff (such as Winslow, Page, and Las Vegas, see Table 2) could realize significant improvements in sky glow over all zenith angles at observing sites located any distance from the city centre. The all-sky statistics shown in Figure 5 and Table 3 indicate potential dramatic reductions in overall environmental impact for the shielded + 2075 lm capita^{-1} models, to 12–25% of current conditions.

4. Discussion

4.1. Use of VIIRS DNB data for measuring luminous output

We found that the VIIRS DNB cloud-free mosaic provided an excellent source for the geographical position and relative amount of escaped anthropogenic light over the surface of the earth for the cities we investigated. However, the conversion of VIIRS DNB radiance to absolute luminous flux appears to be uncertain within as much as a factor of two in the cities we examined. We believe this may be influenced by the following factors: (1) the vertical distribution of escaped light may be highly variable from city to city and is not available from the VIIRS DNB cloud-free composite, (2) the albedo of the ground surface may vary from city to city or even within cities, and (3) for large cities like Las Vegas, Nevada, near vertically upward-directed building facade lighting may be recorded strongly by the DNB sensor but may not lead to a proportional amount of sky glow when observed from a distant location on the ground.

These results do not imply that the uncertainties found in applying unadjusted VIIRS DNB data to a sky glow model render the data unusable for landscape scale analyses. They do indicate, however, the need for ground truthing of this type of remotely sensed data. For future work, the detailed Flagstaff inventory/VIIRS correlation provides a starting point. Methods employing a combination of remotely sensed and on-the-ground measures will minimize errors and may be required on a city-by-city basis to achieve an acceptable level of precision.

4.2. Use of VIIRS DNB data for measuring energy waste

A gross measure of the efficiency of outdoor lighting use in cities may be obtained by calculating their total upward radiant flux (watts). These numbers result from measures of DNB radiant intensity (see Section 2.3) times the effective solid angle into which the radiant flux emits. We assumed isotropic emission from the land surface into the

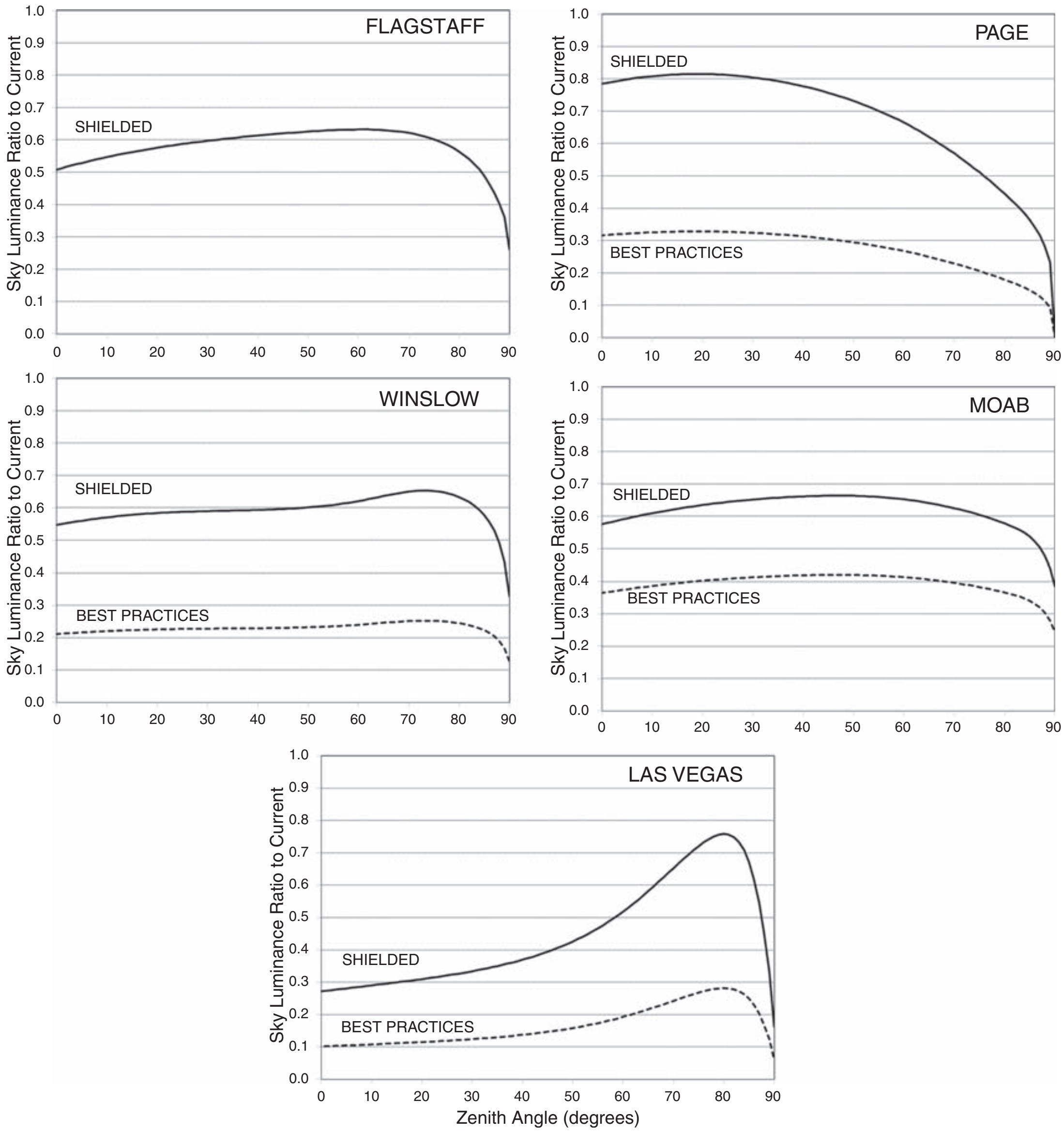

Figure 6. Sky glow reduction ratio along the meridian from zenith (zenith angle 0°) to horizon (zenith angle 90°) resulting from implementation of fully shielded luminaires (solid line) and fully shielded + lighting amount reduced to 2075 lm capita^{-1}, referenced to current conditions, for each of the cities investigated

Table 3. Predicted sky glow indicators for each observing site and treatment, luminance in μcd m^{-2}

Site (City)	Zenith luminance (μcd m^{-2})			Average all-sky luminance (μcd m^{-2})			Brightest area luminance (μcd m^{-2})		
	Current	Shielded	Best practices	Current	Shielded	Best practices	Current	Shielded	Best practices
Sunset Crater (Flagstaff)	13	8	8	63	37	37	6840	4930	4930
Meteor Crater (Winslow)	6	4	1	31	14	5	3880	2500	828
Wahweap Overlook (Page)	65	52	21	331	143	48	44600	20800	5480
Arches N P. (Moab)	7	4	3	35	16	9	3010	2170	786
FS Rd. 535 (Las Vegas)	37	10	3	239	89	28	22300	6910	2500

hemisphere above it, or 2π steradians. Assuming isotropic emission, the radiant flux in watts is computed from the radiant intensity summed over the area of the city, multiplied by 2π steradians. DNB radiant watts per person and per square kilometre were also calculated and the results are presented in Table 4. These results imply that Flagstaff is significantly more energy efficient and protective of night skies than the other cities, measured in both watts per person and watts per square kilometre. The total upward watts measured from the Las Vegas, Nevada area is overwhelmingly larger than the other cities, though the watts per capita appears moderate: roughly four times that of Flagstaff and comparable to Winslow and Moab. The calculated upward watts per unit land area of Las Vegas is massive, however, nearly 12 times that of Flagstaff. The calculated lumens per capita, using the Flagstaff scale factor, suggests that Page has higher outdoor lighting amounts per person than the other cities, including Las Vegas.

We found that the absolute upward radiant flux measured by VIIRS DNB drastically underestimated a measure derived from the Flagstaff on-the-ground inventory. Assuming an average of 50 lm W^{-1} for the lighting in Flagstaff, the VIIRS DNB estimate compares to about one-fifth the estimate deduced from the lighting inventory. Therefore, we cannot recommend the use of the DNB data to directly calculate energy waste from outdoor lighting in absolute units. Some potential reasons for the observed discrepancy include: Upward radiant flux is unlikely to be an isotropic function of zenith angle, and this function may vary among cities; absorption and scattering reduce the number of photons reaching the satellite.

4.3. Estimating upward light from each city resulting in sky glow

The significant adjustments often required to predict luminous flux based on VIIRS DNB radiance and the Flagstaff radiant flux-luminous flux calibration lead us to conclude that the use of a model fit to the actual observed sky glow pattern from a city produces a more accurate estimate of the total upward lumens. The last column in Table 2 represents our best estimate of the relative installed lighting amounts on a per capita basis. The most important part of our investigation is the effects of outdoor lighting on sky luminance as observed from the ground, and we consider field observations a must for accurate verification of any model based upon remotely sensed upward flux.

4.4. Effects of best practices outdoor lighting on sky glow

We have defined best practice for outdoor lighting in cities in terms of the use of a conservative number of lumens per capita and

Table 4. Upward radiant flux for the cities investigated in this study

City name	Population 2010	Illuminated city area (km^2)	Total upward radiant flux from VIIRS (W)	Upward radiant flux per capita (W $person^{-1}$)	Upward radiant flux per unit area (W km^{-2})	Calculated fixture lumens per capita from VIIRS
Flagstaff, AZ	76000	164.3	42700	0.56	260.1	2075[a]
Winslow, AZ	9652	52.8	17823	1.84	337.7	6275
Page, AZ	7252	51.0	20373	2.80	399.3	10368
Moab, UT	5101	59.2	10581	2.07	178.5	7655
Las Vegas, NV	1951269	1288.7	3783955	1.93	3114.7	7680

[a] *Calibration point derived from on-the-ground inventory*

100% fully shielded luminaires. The combination of lower amounts of light with the elimination of direct uplight is shown to be a very effective solution producing significant reductions in sky glow. We should also consider the application of adaptive lighting for both public and private applications, which would lower the after-hours lumens per capita even further.

We can interpret the results presented in Table 4 further given the knowledge that the sky glow model predicts a linear decrease in sky luminance with a given decrease in lighting amount. While we suggest that the example of Flagstaff at about 2000 lm $capita^{-1}$ represents 'best' practices, by dimming streetlights and/or businesses shutting down outdoor lighting after hours, this amount might be reduced to 1000 lm or lower in the early morning hours, resulting in proportional anthropogenic sky glow reductions. For cities like Winslow, or Las Vegas, which we estimate currently at over 6000 lm $capita^{-1}$, a reduction to 1000 combined with full shielding is predicted to result in a more than 90% reduction in anthropogenic sky glow near the zenith as observed from a distant location (see the Las Vegas graph in Figure 6).

While not analysed in this paper, the third leg of night sky quality protection is the use of amber or yellow light sources such as high-pressure sodium, low-pressure sodium, or amber LED. Recent research has identified that scotopic vision (significantly more blue-sensitive and red-insensitive than photopic) must be addressed in sky glow analysis as whatever adaptation level is most applicable to on-the-ground lighting practices (photopic or mesopic); scotopic is clearly the proper response to consider when observing night skies in most situations.[20] If sky glow has a redder (or yellower) colour, it will be significantly less bright to the dark-adapted (scotopic) human eye, effectively reducing visual impacts, particularly at sites more remote from cities such as national parks and other protected areas where complete dark adaptation is possible and desirable. Outdoor light that both dims and shifts in colour from white in the evening to yellow or amber in the early morning is an excellent mitigation strategy.[21] In future, analyses comparing traditional photopic (555 nm peak) to scotopic (507 nm peak) wavelengths may reveal more accurately the effects of the spectral component of outdoor lighting practices on visually observed sky glow.

5. Conclusions

The use of full shielding and conservative lighting amounts are outdoor lighting practices that will obviously reduce sky glow. This paper presents a quantitative estimate of the resulting magnitude of sky glow mitigation which may be achieved when entire cities employ these practices. The corroboration of predicted and observed sky glow measures reported for the case of Flagstaff, Arizona represents a validation of the methods employed to derive these estimates. Extrapolation to other cities is possible using VIIRS DNB satellite data if ground-based observations of sky glow are available. This analysis provides land managers and city planners a tool for estimating impacts of outdoor lighting on protected areas near cities and the benefits of improved shielding and total output limits.

This study shows that responsible best practice lighting installations reduce sky glow at the zenith 20–90% and 42–82% over the entire sky when viewed from a distant location. These reductions will significantly mitigate the impacts of outdoor lighting on visual sky quality. Protected areas (wilderness, national parks, wildlife preserves) are set aside for their natural characteristics and ecosystem processes. The design of outdoor lighting in cities located outside of these areas has rarely considered potential conflict with the intent of such preserves. However, as light escaping from our urban environments travels great distances through the atmosphere,[22] and especially as human infrastructure and development is built to the very boundaries of such areas, light reflected and scattered by the atmosphere will erode environmental quality. Through the widespread use of shielding, reductions in lighting amounts, and yellow or amber colour, it is possible to maintain the natural nocturnal character of areas near cities.

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