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Skyglow changes over Tucson, Arizona, resulting from a municipal LED street lighting conversion

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ABSTRACT

The transition from earlier lighting technologies to white light-emitting diodes (LEDs) is a significant change in the use of artificial light at night. LEDs emit considerably more short-wavelength light into the environment than earlier technologies on a per-lumen basis. Radiative transfer models predict increased skyglow over cities transitioning to LED unless the total lumen output of new lighting systems is reduced. The City of Tucson, Arizona (U.S.), recently converted its municipal street lighting system from a mixture of fully shielded high- and low-pressure sodium (HPS/LPS) luminaires to fully shielded 3000 K white LED luminaires. The lighting design intended to minimize increases to skyglow in order to protect the sites of nearby astronomical observatories without compromising public safety. This involved the migration of over 445 million fully shielded HPS/LPS lumens to roughly 142 million fully shielded 3000 K white LED lumens and an expected concomitant reduction in the amount of visual skyglow over Tucson. SkyGlow Simulator models predict skyglow decreases on the order of 10–20% depending on whether fully shielded or partly shielded lights are in use. We tested this prediction using visual night sky brightness estimates and luminance-calibrated, panchromatic all-sky imagery at 15 locations in and near the city. Data were obtained in 2014, before the LED conversion began, and in mid-2017 after approximately 95% of $\sim$18,000 luminaires was converted. Skyglow differed marginally, and in all cases with valid data changed by $< \pm 20\%$. Over the same period, the city's upward-directed optical radiance detected from Earth orbit decreased by approximately 7%. While these results are not conclusive, they suggest that LED conversions paired with dimming can reduce skyglow over cities.

1. Introduction

The conversion of the world's lighting from conventional to solid-state lighting (SSL) technologies is among the most significant changes to the way we light our world at night since the invention of electric light itself. Environmental pollution from artificial light at night (ALAN) has already reached significant levels in many parts of the world. [1] Improved luminous efficacy among SSL products is hypothesized to lead to a "rebound" effect, furthering global dependence on ALAN as cost savings are redirected into the deployment of additional outdoor lighting. [2–5] The conversion to SSL has also brought significant changes to the spectrum of artificial light radiated into the global nighttime environment, shifting a considerable amount of emission to shorter wavelengths. A number of known and suspected hazards to wildlife ecology and human health have been identified that are thought to result from exposure to short-wavelength ALAN. [6–8].

The spectrum shift in new SSL systems is also thought to yield increases to skyglow, which is the diffuse luminescence of the

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night sky attributable to light emitted from sources on the ground that is scattered back toward the ground from molecules and aerosols in the Earth's atmosphere. Enhanced short-wavelength light emissions associated with blue-rich white LED are subject to strong Rayleigh scattering in the atmosphere, resulting in higher scattering probabilities, associated with the formation of skyglow, than light of longer wavelengths. Radiative transfer models therefore predict that conversion from older technologies to solid-state lighting should result in more skyglow, even when the system outputs are matched lumen-for-lumen. [9] Clouds, fog, and other sources of opacity at optical wavelengths in the lower atmosphere amplify skyglow [10], leading to higher sky luminance values and resulting increases in ambient light level at ground level in cities. As the world increasingly adopts SSL, we expect the associated problems to be exacerbated unless the lighting conversions involve corresponding reductions in the overall light levels employed. However, relatively few communities to date have experimented with reducing lighting levels as they convert their municipal lighting systems to solid state.

It is often held in media coverage of SSL conversions that moving from legacy lighting technologies to LED lighting will reduce "light pollution" because almost all new luminaire designs are fully shielded and LEDs are highly directional light sources. [11–14] However, a casual survey of the same media stories reveals that most municipalities are driven toward converting by lower total cost of ownership enabled by the improved luminous efficacy of LED luminaires. The rebound effect and impact of shifting the spectrum of light emitted by street lighting systems to short wavelengths can displace the potential benefits of SSL to communities. Claims about the purported benefits of SSL may well be dubious, and a lack of sound research can perpetuate unfounded myths about these benefits. [15–17] To the extent that conversion to SSL results in changes to skyglow over cities, there is a strong need to measure conditions before and after the implementation of LED conversions and identify strategies that successfully ensure they do not aggravate the problem.

Tucson, Arizona (U.S.), elected to reduce lighting levels during the conversion of its municipal street lighting system from a mixture of high-pressure sodium (HPS) and low-pressure sodium (LPS) to 3000 Kelvin correlated color temperature white LED in 2016–2017. The design of Tucson's LED lighting system involved the migration of over 4.45×10^8 fully shielded HPS/LPS lumens to roughly 1.42×10^8 fully shielded 3000 K white LED lumens, resulting in a total lumen reduction of 62.8%. The maximum illuminance directly beneath each street light at the road surface dropped from 60 lx to 17 lx (−72%) as HPS lighting was removed and replaced with LED luminaires. The program was undertaken by the City of Tucson in part to help protect the assets of several major professional astronomical observatories located nearby, whose collective impact to the local economy is significant. [18].

We obtained an interesting and unique dataset in the Tucson area in 2014 that serves as a point of comparison for skyglow after the 2016-17 LED conversion. The data were part of a student project to inter-compare different methods of characterizing the brightness of the night sky through both direct detection of sky radiance and indirect sensing of sky brightness using visual limiting stellar magnitude estimates. While the project goal was to inter-calibrate different measurement methods, the data set forms a record of sky brightness conditions in and around Tucson in the years just prior to the LED conversion. Further, the data were collected in early summer, when weather conditions are typically most favorable for night sky brightness measurements. New data collected after the LED conversion is complete (or nearly so) may reveal changes in skyglow attributable to the new lighting system, if street lighting comprises a significant component of the city's overall light emission budget. [19].

This dataset enables us to address a fundamental question: did the skyglow over Tucson change as the result of reduced lighting levels implemented during the municipal LED street lighting conversion? Any net change would be attributable to a combination of greater molecular scattering, as a consequence of fractionally more short-wavelength light emitted by the new LED system, and lower overall light emission, resulting from the City of Tucson's decision to reduce the number of lumens emitted per City-owned luminaire. Since the molecular content of the lower atmosphere fluctuates only by a few percent, we cannot attribute any net change of skyglow to only molecular scatter.

Aerosols are the only atmospheric constituent that can vary significantly, thus modulating skyglow. There is no doubt that backscatter of light is mostly due to molecular scatter, but this is true only if: (1) the particles are large compared to air molecules; and, concurrently, (2) the number concentration of aerosol particles is several orders of magnitude smaller than that of molecules. The size distribution of particles in urban air is conventionally characterized by three modes. The smallest nucleation mode contains particles sized < 0.1 μm and is formed by condensation of hot vapor from combustion sources and from chemical conversion of gases to particles. These particles, or even the smallest fraction of accumulation-mode particles, can affect the backscatter significantly also, because the number concentration of these particles is usually high. [20] We therefore endeavored to obtain night sky radiance measurements under comparable atmospheric conditions in order to reduce the chance that differing turbidity would mask skyglow effects properly attributable to light source changes.

Assuming that (1) the reduction of lumens during the LED conversion outweighed the increased upward light scattering contribution resulting from shifting the spectrum of lighting toward shorter wavelengths, and (2) municipal street lighting accounts for a significant fraction of the overall upward-directed light emissions from Tucson, we expected skyglow to decrease over Tucson as a consequence of the conversion. Further, the expected reduction in skyglow was simply proportional to the reduction in the municipal street lighting emission, adjusted according to the anticipated increase in light scattering. This is because no other changes were made: luminaire mounting height, pole spacing, target albedo and other factors were left unchanged during the conversion. In order to address the research question, we compared the observations with results of radiative transfer model runs describing both the "before" and "after" conversion scenarios. We also measured change in the upward-directed radiance from the city as seen by Earth-orbiting satellites.

This paper is organized as follows. First, in Section 2, we describe the radiative transfer model used to predict relative skyglow changes after the completion of the Tucson LED conversion project. Next, in Section 3, we review the site selection and measurement methods for ground-based skyglow observation campaigns in 2014 and 2017. The results are presented in Section 4 along with an analysis in the context of our modeling outcomes. Finally, in Section 5, we summarize our work, point out its limitations, and comment on the applicability of the results to other LED conversion efforts.

2. SkyGlow Simulator predictions

2.1. Light clustering approach

The algorithm we have used to model the sky radiance and luminance distributions for Tucson is based on the theory developed by Kocifaj [21] and improved in later releases. The software