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Towards future challenges in the measurement and modelling of night sky brightness

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ABSTRACT
In ground-based astronomy, the brightness of the night sky is the limiting factor that determines the efficacy of any particular telescope in terms of detecting faint objects. Proper measurement and monitoring of night sky brightness (NSB) is therefore key to protecting sites of astronomical observatories from light pollution and maximizing their scientific productivity. However, current data sources and modelling approaches exhibit practical shortcomings that significantly limit their utility. By considering the current situation in measuring light pollution, we identify opportunities for improvements. These include defaulting to spatially resolved sky brightness measurements, routinely incorporating spectral information and polarization, and collecting simultaneous meteorological data. Given the acute threat to astronomy posed by rapidly increasing NSB around the world, we argue that the time has come for the standardization of NSB measurement and monitoring methods and protocols.

Key words: atmospheric effects – light pollution – methods: numerical – methods: observational.

1. INTRODUCTION

The observed increase in the brightness of the night sky around the world is attributable to light emissions from ground-based artificial light sources. This results from increased anthropogenic activity at night, multiplying the amount of electromagnetic (EM) radiation emitted into the outdoor nocturnal environment. Large, diffuse ‘light domes’ are visible over most world cities due to waste associated with the overuse of artificial light at night. Light scattered in the lower atmosphere, known as ‘skyglow’, lowers the contrast of astronomical objects against the background night sky and impairs their visibility (Barentine 2022), while light emitted at small negative elevation angles can reach far from its source into sensitive natural spaces (Kocifaj & Kómar 2016). This has known negative consequences for living organisms including humans (Falchi et al. 2011); represents energy waste typically accompanied by an increase in ground-level illumination at significant distances from human settlements (Duriscoe, Luginbuhl & Elvidge 2013); and imposes limits on studying the cosmos (Green et al. 2022).

The proliferation of solid-state lighting products using light-emitting diodes (LEDs) in the past decade is a possible explanation for the rapid changes in night-sky brightness (NSB) seen around the world during the same time period (Kyba et al. 2017; Kyba et al. 2023). LED technology achieves the highest luminous efficacy among commercially available sources. LED outdoor lighting continues to be implemented in new applications and locations, and its significance to the problem of skyglow continues to grow.

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For these reasons, systematic and comprehensive programmes for monitoring the night-time light field state in the open atmosphere have become a major challenge to the light pollution community. Such efforts aim to both improve our understanding of light propagation into the ambient environment and allow for its more accurate quantification or even forecasting. Understanding this phenomenon is a basic prerequisite to suggest appropriate remedies that may gradually improve nocturnal conditions and to predict changes we could expect from lighting retrofits. This goal cannot be achieved without sophisticated models and measuring techniques. Ideally, we would like to fully characterize the EM field through its complex electric ($\boldsymbol{E}$) and magnetic ($\boldsymbol{H}$) components. However, most of the optical sensors traditionally used in night-time light monitoring systems detect only the total irradiance. Here we argue that a more complete description of the light field that can be practically obtained includes information on both the spectral content and polarization state of light rays, and further that it is necessary to also know the momentary state of the atmosphere and its optical properties at the time NSB data are collected.

2. CURRENT SITUATION IN MEASURING LIGHT POLLUTION

In light pollution research, many measurement techniques and devices are available, each with its own advantages and disadvantages. Since the study of artificial light at night (ALAN) is highly interdisciplinary, the methods used can be more or less appropriate for various research objectives (Hänel et al. 2018; Levin et al. 2020; Kocifaj et al. 2023a). The brightness of the night sky at the zenith is the richest data product available from both monitoring networks (Posch, Binder & Puschnig 2018) and individual experiments (Jechow et al. 2016). Such observables belong to a wider class of broad-band radiance data gathered by means of single-channel devices (Barentine 2022).

Relatively small spatial inhomogeneities of night sky brightness (NSB) around the zenith have led to the wide use of single-channel photometers for rapid estimation of the night sky state (Hänel et al. 2018). They are cheap and portable, operate autonomously, and allow for straightforward data interpretation. Due to their typically wide opening angles, the basic prerequisite for the correct use of this type of optical system is a nearly uniform radiance field. Nevertheless, these devices are occasionally applied to radiance mapping in different sky areas (Zamorano et al. 2014; Abousheli̇b et al. 2019; Caruana et al. 2020; Yilmaz & Ozdemir 2021), which can result in errors due to optical blur of steep radiance gradients within the instrumental field of view. This generally goes hand-in-hand with individual or commonly shared limitations resulting in erroneous reduction and analysis of time-series measurements.

One of the greatest challenges facing users of devices aiming to measure the state of ALAN in both urban and rural areas is a lack of spectral resolution depending on the instrument. Most notably in times of large-scale municipal lighting conversions and changes in the spectral power distributions of light sources, this effect must not be disregarded when deducing information on changing patterns of light pollution (Sánchez de Miguel et al. 2017). This obviously implies agreement between instruments as a matter of complex evaluation, solely possible if all parameters of ground-based light sources are known and a common zero point established.

On the contrary, Earth-orbiting satellites have received much attention in terms of providing large-scale observations of night-time lighting from Earth's surface with the possibility of analysing whole cities or even countries (Cinzano, Falchi & Elvidge 2001; Falchi et al. 2016). While this may seem straightforward, it is in fact a very sophisticated approach in consideration of certain highly problematic influences. Examples include the diffuse counterpart of direct light often being not distinguishable from noise (Sánchez de Miguel et al. 2020), recognizing that different observation angles lead to detecting disparate light sources and therefore intensities, and relying on inadequate revisit times (Kyba et al. 2022).

Furthermore, the spectrum of light emitted from outdoor lighting in different directions may not be accurately represented among satellite remote sensing data. Different lighting technologies are often used preferentially for different purposes such as street and area lighting, advertising signs, illumination of public monuments, and so forth. These sources tend to differ not only in terms of their spectral power distributions, but also in their angular emission functions. As a result, the weighted contributions of different lighting types to the total light emission from an area on the ground vary according to the zenith angle of the emitted light. Spectrum recordings taken along the direction of a satellite's orbit can therefore change with the sensing angle. This makes reliable identification of different types of lighting installations in a city very difficult.

Despite these limitations, such data are of global significance in supporting statements about the state of development implied by the growing rate and spatial distribution of ALAN (Sánchez de Miguel et al. 2022). At the same time, the dominant source of global nighttime radiance data with regular temporal cadence, the Visible Infrared Imaging Radiometer Suite Day-Night Band, underestimates the true extent of ALAN compared to ground-based approaches (Kyba et al. 2023).

Irrespective of the individual limitations of devices themselves, there is a challenge faced jointly by all light-pollution measurement approaches. Long-term remote sensing observations of NSB in particular suffer from detecting not only time-varying artificial light levels, but also influences of variable atmospheric phenomena such as the night airglow or seasonally occurring meteorological effects (Puschnig et al. 2023). The influence of both sources is modulated by absorption and scattering of light by clouds and other atmospheric constituents. Such impacts can be potentially disproportionate, making any given night inaccurately comparable to adjacent nights, and even less so to those in varying seasons (Wallner & Kocifaj 2019). This certainly raises the question of how to manage long-term analyses of light pollution from measurements that enable accurate and detailed conclusions. Methods involving a static 'standard sky' unpolluted by ALAN to which to refer observations are out of the question, as no such indicator is available due to continuously varying conditions (Duriscoe 2013; Barentine 2022). This is easily explainable, as atmospheric impacts and the visibility of celestial objects depends on one's location and the season during the time of observation. Models always simulate specific situations, which cannot be seen as arbitrarily usable for every set of circumstances in general. A new 'standard' must be constructed for each set of observing circumstances so as to properly extract the anthropogenic component of night-sky brightness by subtraction of the modelled natural night sky.

Proper interpretation of NSB requires understanding the amplitude fluctuations of the optical signal under variable atmospheric conditions. This is a basic prerequisite to extract net trends in NSB as a function of specific parameters such as aerosol optical depth (AOD). Unlike lab experiments, field measurements can scarcely be conducted under well-controlled conditions. For this reason, we cannot isolate the impact of a single meteorological parameter; thus, data recorded are usually the result of a synergy of multiple effects, some of them altering the signal detected. There are only very limited possibilities to treat this problem by redesigning the measurement setup, so the signal correction with respect to atmospheric conditions is only possible by concurrent monitoring using other data sources and relevant radiative transfer models in post-processing.

For instance, during clear sky conditions, AOD can increase if the relative humidity of the air rises. Aerosol particles suspended in the air then efficiently take up the water and grow in size (Zhao et al. 2022). In this process, the scattering cross-section increases and the scattering phase function reshapes. Consequently, the intensity of the light beam progressively decays as it traverses the lower atmospheric layers and scattered photons concentrate along the direction of beam propagation. Due to its apparent impact on light attenuation and scattering, relative humidity influences NSB distributions at both small and large distances from cities (Fig. 1).

In spite of all factors discussed up to this point, common measurement devices are still useful for continuous (long-term) time-series measurements of the intensities and colours of the night sky (Bará, Lima, Zamorano 2019; Robles et al. 2021). It is important none the less to point out that they contain more than the expected amount of information on the monitored environment. For instance, measuring the artificial zenith NSB with two devices positioned at the limiting altitudes of an atmospheric layer can provide information on AOD in the lower atmosphere (Kocifaj & Bará 2020a), which in turn is a key element in forecasting the propagation of ALAN into the ambient environment.

In addition, diffuse light around cities contains more complete information on city lights independent of whether recorded by satellites (Kocifaj & Bará 2020b; Sánchez de Miguel et al. 2020;

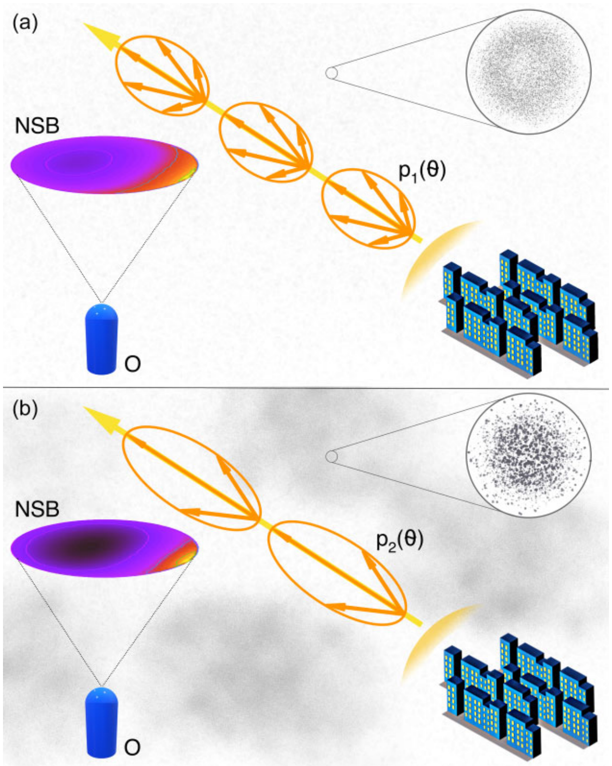

Figure 1. Schematic view of the reshaping of NSB patterns due to varying particle sizes that track relative humidity changes. a) A turbid airmass tends to scatter light efficiently to forward directions (as demonstrated with phase function $p_1(\theta)$ in the topmost graphics), thus the associated NSB distribution recorded by an all-sky scanner (O) gradually increases from zenith towards the horizon in the direction of a light source. b) The forward lobe of the scattering pattern $p_2(\theta)$ becomes gradually more pronounced under elevated relative humidity as particles rapidly grow in size. The resulting NSB gradient is much steeper, showing a deeper minimum in the zenith and more sharp maximum towards a light source.

Kocifaj & Bará 2022) or by ground-based devices (Kocifaj et al. 2021). Unlike area-limited directional remote sensing of cities, the light scattered in the air enveloping a city originates from whole-city (cumulative) light emissions into all directions. The processes of forming the diffuse light are complex and depend on the aerosol content of the monitored atmospheric volume over a city. The physics of light scattering makes the extraction of initial light spectra a demanding task, yet one worth the effort mainly because the spectral 'fingerprint' of whole-city light is implicitly included in the diffuse component of ground-reaching radiation.

A need for progressively more accurate and higher resolution monitoring of light fields in the night-time atmosphere is critical for two reasons. First, data harvested from large territories are crucial for development of all-sky forecasting models and to test theories; however, to make the models widely applicable, it is necessary to identify and implement a methodology for mining the input data. And secondly, measurement of the light-field state also serves as a base to retrieve information on the momentary state of the local atmosphere (see Fig. 2). Most models are still limited to ground level, but adding satellite measurements of the Earth's surface at night (Kyba et al. 2022) will be highly beneficial since both terrestrial and orbital data form complementary sets.

3. USING MODELLING TO FILL GAPS IN EXPERIMENTAL DATA

Night-light data systematically collected by light monitoring networks over large territories is essential to global NSB forecasting. As we cannot realistically place monitors everywhere throughout the world, many of the most sensitive and vulnerable places are exactly those for which we rely on satellite remote sensing to help predict NSB. Therefore, accurate modelling becomes a crucial 'force multiplier', since the modelled radiance field adds significant value to ground-based and satellite observations and fills the gap between the capabilities of these measuring techniques and the present needs of environmental, atmospheric, biological, or conservation studies. Modelling is essential in order to estimate the impact of city lights at intermediate distances to a site, simply because there is no other way to obtain this information. There is distinct value in this approach. For instance, considering only the value of existing astronomy infrastructure at remote locations and the costs associated with finding and developing new sites, it is important to make accurate predictions in places one cannot otherwise monitor.

Along with reliable predictions of how much light at night reaches an arbitrary place in 3D space, modelling the nocturnal light field also is expected to enable correct interpretation of a number of experimental data. This approach links skyglow to air pollution levels (Kocifaj & Barentine 2021) and predicts the impacts of different lighting technologies (Aubé et al. 2018), assuming different scenarios in urbanized areas with results applicable to energy savings and environmental protection. Impact studies based on modelling may also offer another lever on light pollution problems that are heretofore unexplored, poorly understood, or unknown, but whose solutions may yield added benefits to society. For instance, we already know that the amount of energy scattered into the whole of 3D space strongly depends on the scattering cross-section (C_{sca}) of each aerosol particle (Mishchenko 2014). Since the scattering efficiency is a function of particle size, it is uncertain whether a constant mass of aerosols emitted from a pollution source (e.g. a chimney) will manifest in different skyglow levels in case the source emissions only differ in particle size ranges. This poses a question of whether processes resulting in particle production (and typically having impact on air pollutants transport) can also change the amplitudes of NSB within a geography of interest. Here, modelling affords a unique and irreplaceable tool for potential alternative technologies in manipulating skyglow.

The majority of existing modelling activities investigate light pollution in urban and suburban areas. This is because it is easy to make observations with high signal-to-noise (S/N) ratio values in these settings, and also that simple models are readily applicable when single scattering dominates over relatively short distances. The effects of multiple scattering and aerosol optical depth become increasingly important as the optical path lengths increase. Existing measurement devices tend to yield data with lower S/N values in such cases, and properly treating multiple scatterings is computationally intensive. For these reasons, the modelling strategy is complicated for instances of rural sites or very naturally dark areas where little to no light is usually emitted, but which suffer from pollution by light sources at intermediate to large distances. Examples are protected areas like national parks and nature reserves inhabited by astonishing varieties of wildlife species that are extremely sensitive to low amounts of light at night (Grubisic et al. 2019).

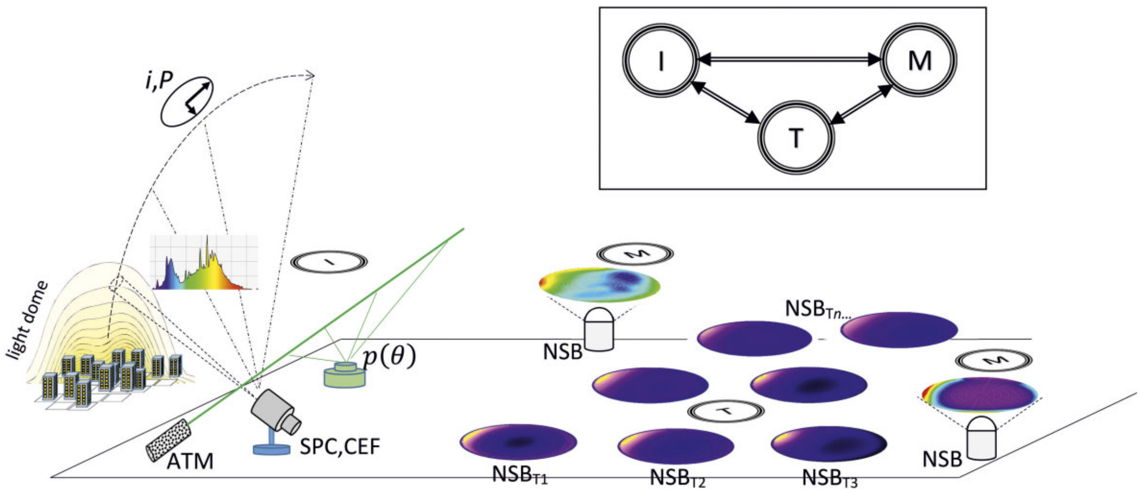

Figure 2. Complementarity and mutual integrity of theoretical and experimental characterizations of artificial light at night. Top right corner: Inversion of radiometry data (I) provides inputs to the radiative transfer theories (T) that make the simulation of missing NSB data possible at any site (T1... Tn), especially where direct measurements (M) are difficult to undertake or are unavailable due to a sparse distribution of measuring facilities. On the contrary, (M) are needed to constrain (T), which are necessary for the development of (I) to retrieve the optical properties of the atmosphere and ground-based light sources. As an example, radiometry data including intensity, *i*, or polarization, *P*, of the night sky taken from zenith towards the position of light source at the horizon provide information on the city emission function (CEF), while the spectral composition (SPC) of the integrated (whole-city) light source can be extracted from the spectral fingerprint of the light dome over a city. Active optical sensing of a laser beam when traversing the lower atmospheric layers is a source of information on atmospheric (ATM) optical properties, e.g. the scattering phase function $p(\theta)$ for a range of scattering angles θ. These parameters are inputs to T, which are capable of forecasting the propagation of artificial light to any point in 3D space, thus filling in the gap between experimentally determined NSB distributions.

4. SOLUTION ATTEMPTS FOR HIGH QUALITY RESEARCH IN THE FUTURE

Unlike present experimental capabilities, differences between the readings of a detector when operated under different atmospheric turbidity conditions can also provide additional information on, e.g. prevailing aerosol morphology expressed through the so-called aspect ratio, a parameter that relates the longest particle dimension to the length of its transverse axis (Bi et al. 2018; Nie & Mao 2023). We urgently need this information in order to understand potential NSB amplitude fluctuations at large angular distances from the source of light, such as an entire city.

In particular, the zenith NSB is impacted by photons scattered to angles $> 90^\circ$ (Kocifaj et al. 2023b). For this angular range the scattering properties of irregularly shaped and spherical particles differ markedly. Independent of whether the particles are prolate or oblate, their differential scattering cross-sections ($dC_{sca}/d\Omega$) show signatures different from those for volume-equivalent spheres; here, $d\Omega$ is an elementary solid angle. Since ($dC_{sca}/d\Omega$) changes by several orders of magnitudes as particle size grows, it is convenient to introduce the scattering phase function p, a dimensionless quantity derived from the differential scattering cross-section $p = (dC_{sca}/d\Omega) \times (4\pi/C_{sca})$. For blue light and a particle population with a peak radius of $\approx 2\,\mu$m, the side-scattering phase function of oblate or prolate ellipsoids is one order of magnitude larger than that for spherical targets (Lin, Bi & Dubovik 2018). Therefore, future research should extend measurement platforms to collect more information about the optical properties of the local atmosphere. Portable, low-cost devices appropriate for achieving this goal include, e.g. low-cost lasers and polar nephelometers.

Although intensity measurement is obviously much more common in the field of light pollution, a considerable fraction of the information on the night-time environment is only revealed when measuring the remaining field elements, namely polarization. Polarization measurements are important since they provide additional information on the modulation and distortion of artificial light as it travels from source to detector. Polarization is also a significant influence on animal orientation at night (Barta et al. 2014; Wang et al. 2016), but very few experiments have been made to date, some during twilight (Cronin, Warrant & Greiner 2006) or under clear sky conditions with moonlight (Horváth 2004).

When initially unpolarized light is scattered by atmospheric constituents, specifically aerosols and air molecules, new and unexpected polarization features of the night sky can result. The shape of aerosol particles in particular is one of the factors that determines the polarization of electromagnetic radiation; see e.g. fig. 4 in Dubovik et al. (2006). Aerosol-induced polarization of artificial light is superimposed on the measured optical signal; however, the signal distortion is unknown since polarimetric instruments are still (and mistakenly) not regarded as necessary elements of NSB radiometers. The correct interpretation of optical data is then scarcely possible.

In addition, particle shape influences the scattering phase function and thus has direct impact on measured night sky radiances. By measuring the polarization state of light we can infer the prevailing aspect ratio of aerosol particles, the parameter that characterizes their non-sphericity. Knowing the aspect ratio of aerosols significantly improves the accuracy of NSB predictions by incorporating more realistic properties into models.

Taken together, both the parallel and perpendicular polarization components offer one more dimension than that available from photon intensity alone. From two independent, orthogonally polarized wave components we can obtain additional information about the monitored system that otherwise must be known a priori. This is akin to adding another vector to a system of linearly independent equations.

Orienting the development of future generations of NSB measurement and monitoring systems towards a design allowing for retrieval of all four Stokes parameters would provide more complete information. Because the Stokes parameters form a complete set of quantities needed to characterize any nighttime light field, their measurements can be used either for significantly more accurate retrieval of an unknown parameter or for obtaining information about several unknown parameters concurrently. Measurement of the Stokes parameters is possible by using polarizers and retarders, but the task can be experimentally and economically demanding. Simplifications are possible in certain cases, such as when only the degree of linear polarization is to be measured. The reader is referred to literature sources (e.g. Mishchenko 2014) for the fundamentals of such measurements.

Experiments made in Berlin (Kyba et al. 2011) reported greater than expected changes in the lunar skylight polarization due to urban lighting; namely, polarization was found to be low compared to what we could expect from basic theories. Polarization is presumed to increase proportionally with distance from cities as their lights behave more like point sources whose directionality lowers the suppression of polarization efficiency.

While the resulting degree of polarization is expected to be small, measuring it in the field is not an impossible task. Nevertheless, it underscores the need for development of novel measurement devices operating under extremely low intensities of diffuse light. An example of such a device is the photomultiplier-equipped portable sky scanner (Kocifaj, Kómar & Kundracik 2018), which performs spectroradiometry of the night sky to a sensitivity threshold of a few μcd m^{-2}, comparable to the typical luminance of the airglow.

Furthermore, it is unclear if the fairly low values of the degree of linear polarization recorded in urban areas would also be found in natural spaces and what the differences in the spectral features of polarized light under low- and elevated-turbidity conditions would be. Theory suggests that the degree of linear polarization generally decreases as the scattering angle approaches 0° (forward scattering) or 180° (backscattering), and peaks in side-scattering directions. A possible explanation for low linear polarization of diffuse light in and near cities is that the detector readout is due to a complex superposition of scattering signals that differ in reference scattering planes and scattering angles. Simply put, the signals travel from different azimuths and combine in a non-preferred way, thus resulting in efficient suppression of their individual polarization features.

Increasingly distant cities subtend a progressively narrower interval of azimuths, thus approaching stepwise the approximation of point sources of light. The scattering plane is then conserved, meaning that the degree of linear polarization should increase. Nevertheless, the parallel (i_1) and perpendicular (i_2) components of the polarized radiance (i) are both too small to be recorded by simple devices, and they depend on the nature of the aerosol particles. Future campaigns should therefore aim to provide aerosol and NSB characterization simultaneously. In addition, resolving the nature of i_1 and i_2 is very useful in understanding NSB distributions, their accurate predictions, and their interpretation. A case study should be directed towards interpretation of the measured ratio of i_1/i_2, which strongly depends on scattering angle; thus, polarization measurements can be used to extract information on the angular emission patterns of two different cities that nevertheless yield similar NSB values.

In order to address the challenge of missing atmospheric parameters, we recommend that systematic monitoring of ALAN should be supported by continuous gathering of meteorological data. The key aerosol parameters are AOD, the asymmetry parameter (ASY), and the single-scattering albedo (SSA). In addition to relative humidity (due to its impact on all three parameters), there are a few other important meteorological measurements. Since different air pollution sources can be distributed at different azimuths from a given measurement site, and we might analyse back-trajectories for long range transport, it is useful to know the prevailing wind direction. The visibility relates to AOD, and the ambient air pressure is important in the modelling of Rayleigh scattering, particularly for sites at significant elevation above sea level.

Here, aerosol characterization by direct or indirect measurements is of special importance. Measurements could include the use of, e.g. particulate samplers, permitting the direct characterization of aerosol size distribution and composition, while indirect measurement rather refers to other types of satellite- or ground-based atmospheric optical sensing such as using laser or lidar sources. Naturally, there is a big gap between the input data we ideally require and what is realistically possible to measure. Theoretical modelling is thus a key step in simulating the missing data.

In principle we are not lacking in the fundamental theory, but rather its application in practice is often fraught with complexity. We may construct a theory which implements many details, but such a theory becomes inapplicable since the number of input parameters is very large and their value generally unavailable. This is why we need models well-tailored to the experimental inputs and theories that allow for interpretation of common observables. To complete an example introduced in Sec. '*Current situation in measuring light pollution*', we emphasize that modelling humidity-induced changes to NSB is one approach of how we can substitute the missing AOD or fill in the gaps between AODs on varying temporal and spatial scales. Theoretical modelling appears to be a useful tool for analysis of short- and long-term ALAN observations performed in the framework of large monitoring networks.

To arrive at concrete statements on light pollution and its evolution in time, skyglow measurements increasing in resolution and data density, including environmental information, are needed. This includes the modification of monitoring networks, shifting their focus from 1D to 2D observations. This promotes the opportunity to incorporate all-sky information from the whole celestial hemisphere rather than near the zenith alone, giving more information on the location, domination, and dispersion of individual radiating sources. However, for the purpose of understanding not only the optical but also the spectral distortion of light emissions under different atmospheric conditions, the next step is an expansion to a truly 3D measurement technique involving spectral information about many arbitrary points on the sky. These spectral fingerprints could be a game-changer for light pollution research, especially regarding the identification of varying lighting technologies prevailing in urban areas. They may also promote better understanding of the radiative transport of ALAN in different atmospheric layers.

5. CONCLUDING REMARKS

This work gives our perspective on the current state of measuring light pollution; considers the possibility of including modelling approaches in the analysis of ALAN; and identifies future needs for interdisciplinary research in the field. We find that the quantification of light in the nocturnal environment becomes only more important, necessitating a shift from urban to rural areas in associated observations. Here, current techniques and methods show some critical weaknesses, particularly in their long-term reliability. Light pollution has in recent decades drawn increasing attention from scientists, conservationists, and resource managers alike, resulting in the need for more accurate measurement devices, data acquisition and management. Realizing that such future growth opportunities are accompanied by high technical demand, we have enumerated current needs as we are able to identify them today. However, unlike the current situation involving huge numbers of available instruments, the question must be asked whether increasing concerns in the inter-comparison of such can be bypassed, or – and maybe one of the most important future needs – a technical standard in measurements can be achieved. Given the need for more global collaboration in a great variety of research fields including light pollution, it is our evaluation that there is the need for such in the near future.

DATA AVAILABILITY

All data is available in the main text.

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