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THE INFLUENCE OF ATMOSPHERIC ELEMENTS ON LIGHT POLLUTION

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Christoph Rammelmüller

Abstract

Context

Aerosol and other atmospheric particles are important modulators of night sky brightness due to their manifold impacts on spectral and angular properties of scattered light caused by artificial light at night emitted from ground-based sources like urban areas. With the increased amount of light from one year to the other, this issue becomes more and more of a problem for astronomical observatories all over the world.

The Upper Austrian light monitoring network, consisting out of 23 Sky Quality Meter (SQM) distributed over the provincial area, and air quality network, provides the data for this research. Data can be traced back to 2014 when the SQM network was built. Atmospheric elements being able to be included are PM₁₀, PM_{2.5}, CO, SO₂, NO and NO₂.

Aims

The aim of this master's thesis is to establish a connection between aerosols and light pollution, which would not only enhance the understanding of light pollution in general but also provide a valuable extension to theoretical sky brightness models.

Methods

After careful data reduction (it should be noted that the influence of cloud cover over the period under consideration could not be taken into account due to insufficient data), the Kolmogorov-Smirnov test is applied as the main statistical method to demonstrate a direct correlation between light pollution and air pollution.

Results

This work demonstrates the direct correlation between light pollution and aerosols in the atmosphere, offering insights into how variations in aerosol concentration impact light pollution distribution. Despite the complexity of isolating individual aerosol influences, standardized methodologies are needed for effective comparison. Moving forward, future research should focus on refining methodologies and addressing gaps in understanding, such as the influence of cloud cover, to develop more effective strategies for mitigating light pollution.

Kurzfassung

Context

Aerosole und andere atmosphärische Partikel sind wichtige Modulatoren der Nachthimmelhelligkeit aufgrund ihrer vielfältigen Auswirkungen auf die spektralen und Winkeleigenschaften von gestreutem Licht, das durch künstliches Licht verursacht wird, das nachts von bodengestützten Quellen wie städtischen Gebieten ausgestrahlt wird. Mit der zunehmenden Lichtmenge von Jahr zu Jahr wird dieses Problem für astronomische Observatorien auf der ganzen Welt immer mehr zu einem Problem.

Das oberösterreichische Lichtmessnetz, bestehend aus 23 über das Landesgebiet verteilten Sky Quality Meter (SQM) und Luftqualitätsnetz, liefert die Daten für diese Forschung. Die Daten können bis ins Jahr 2014 zurückverfolgt werden, als das SQM-Netzwerk aufgebaut wurde. Atmosphärische Elemente, die aufgenommen werden können, sind PM10, PM2,5, CO, SO₂, NO, und NO₂.

Aims

Ziel dieser Masterarbeit ist es, einen Zusammenhang zwischen Aerosolen mit Lichtverschmutzung zu finden, der nicht nur das Wissen über Lichtverschmutzung im Allgemeinen verbessern würde, sondern auch eine nützliche Erweiterung theoretischer Himmelshelligkeitsmodelle liefern würde.

Methods

Nach einer sorgfältigen Datenreduktion (wobei hinzugefügt werden sollte, dass der Einfluss der Bewölkung über die betrachtete Periode, aufgrund von unzureichender Datenlage nicht berücksichtigt werden konnte) wird als statistische Methode der Kolmogorow-Smirnow-Test angewandt, um eine direkte Korrelation zwischen Lichtverschmutzung und Luftverschmutzung zeigen zu können.

Results

Diese Arbeit zeigt die direkte Korrelation zwischen Lichtverschmutzung und Aerosolen in der Atmosphäre und bietet Einblicke darin, wie Variationen in der Aerosolkonzentration die Verteilung der Lichtverschmutzung beeinflussen. Trotz der Komplexität der Isolierung individueller Aerosoleinflüsse sind standardisierte Methoden für einen effektiven Vergleich erforderlich. Zukünftige Forschung sollte sich darauf konzentrieren, Methoden zu verfeinern

Kurzfassung

und Wissenslücken zu schließen, wie beispielsweise den Einfluss von Wolkenbedeckung, um wirksamere Strategien zur Minderung der Lichtverschmutzung zu entwickeln.

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1 Light Pollution

The term "light pollution" (also known as "light bell," "light smog," or "light emission") could be misunderstood because clean light is not polluted. It is the light itself that "pollutes" the natural darkness of the night by illuminating it. Our view of the sky is clouded by light pollution. In addition to air, water, and soil pollution, light pollution also belongs to the field of environmental pollution. What is meant by this is an excessive use of artificial light, which alters nature. The light that reaches the layers of the Earth's atmosphere is reflected by the layers of the atmosphere, dust, or water and scattered over a large area. The air is brightened when penetrated by the light, creating a fog of light, or light smog, over the cities. The main causes are street lighting, neon signs, leisure facilities, cars, and illuminated buildings. The same applies to industrial plants. The strong laser emitters, often used as advertising in discotheques, are particularly concerning, as are the ever-stronger high beams of motor vehicles and an increasing number of Christmas lights. In recent years, not only has the irradiated area, but also the intensity of the irradiation with light, steadily increased. Light pollution primarily occurs in densely populated areas of industrialized countries.

In an era of rapid urbanization and technological advancement, the interplay between atmospheric phenomena and human-induced environmental changes has become increasingly complex and consequential. Among these intricate relationships, the connection between aerosols and light pollution stands out as a critical area of study, with far-reaching implications for our planet's health and the well-being of its inhabitants. This thesis delves into the multifaceted interactions between these two environmental factors, exploring their origins, dynamics, and impacts on astronomical observations.

Aerosols and light pollution have an interesting interrelationship that has significant impacts on our environment and health. Aerosols, tiny particles suspended in the atmosphere, can scatter and amplify artificial light in urban areas, increasing light pollution. At the same time, light pollution can influence the chemical processes that contribute to the formation and alteration of aerosols. Researching these connections is crucial to better understand the effects on ecosystems, human health, and climate change. A deeper understanding could lead to more effective strategies for reducing air pollution and light pollution, ultimately contributing to improving the quality of life in urban areas and protecting the natural environment.

1.1 The History of Light Pollution

Light pollution, a global phenomenon traceable back to the early 20th century, is caused by artificial ground-based illumination and manifests in various forms, including light trespass, atmospheric light scattering, and expansive luminous "domes" enveloping urban areas. This anthropogenic phenomenon was notably observed in 1924 by Johann Palisa (1848-1925), an astronomer at the University Observatory of Vienna. Palisa documented (Figure 1.1) that the cessation of electrical lighting at midnight allowed for the visibility of stars up to six times fainter than those normally perceptible, even at a distance of nearly four kilometers from the city center.

In diesen Gegenden sind dann kaum noch Sterne 2. Größe zu erkennen, während gleichzeitig im Osten, Norden und Westen in viel geringerer Höhe viele und schwächere Sterne mit freiem Auge zu sehen sind. Diese Übelstände wachsen an Stärke von Jahr zu Jahr. Erst besondere Ereignisse bringen dem Beobachter die Steigerung des Übelstandes zum Bewußtsein. So z. B. wurde in Wien vor dem Weltkriege die Ringstraße mit Bogenlampen beleuchtet. Um Mitternacht wurden die Bogenlampen ausgeschaltet, und sofort konnte ich um $1\frac{1}{2}$ bis 2 Größenklassen schwächere Sterne sehen. Ein zweites Ereignis trat im August 1923 ein. Ich hatte im Juli den Planeten 995 [1923 NP] verfolgt und hoffte, auch noch im August ihn sehen und beobachten zu können. Obwohl ich an der richtigen Stelle suchte, konnte ich doch keine Spur von ihm erblicken. Wie erstaunt aber war ich, als mir Dr. Mündler eine ganze Reihe von im August angestellten Beobachtungen desselben Planeten mitteilte. Nun wird jedermann begreifen, wie sehr die Arbeitsfreudigkeit herabgestimmt wird, wenn er sieht, daß der fünfmal mehr Sternlicht auffangende 27-Zöller nicht das zu leisten imstande ist, was der 12-Zöller in Heidelberg leistet. Ich fing an zu glauben, daß meine Sehkraft nachgelassen habe, aber auch das ist nicht der Fall, denn vergleichende Beobachtungen mit einem jüngeren Kollegen, der auch auf schwache Sterne eingeübt ist, ergaben, daß ich immer noch schwächere Sterne wahrnehmen kann. Solche Wahrnehmungen bringen den Beobachter immer wieder auf den Gedanken, daß die Wiener Sternwarte mit ihrem großen Refraktor heute nicht mehr auf dem richtigen Platze steht, und daß es an der Zeit ist, an ihre Verlegung zu denken und zu schreiten.

Wien, 1924 Mai. J. Palisa.

Figure 1.1: Palisa is mentioning light Pollution in May 1924. Reproduced with permission.

While light pollution is indicative of energy inefficiency and suboptimal lighting installations, its long-term consequences, particularly on human health, have often been

1.1 The History of Light Pollution

overlooked. However, the rapid expansion of areas affected by artificial night lighting has led to increased public awareness as nocturnal environments become progressively brighter.

The impact of light pollution is particularly pronounced in densely populated regions such as Vienna and its environs. In the absence of artificial illumination, clear night skies typically exhibit a measured brightness of approximately 21.8-22 mag/arcsec². In contrast, Vienna's sky brightness measures 18.5-19.0 mag/arcsec² at best, representing a 25-fold increase in brightness due to the logarithmic nature of astronomical magnitude scales.

The ramifications of light pollution extend far beyond reduced stellar visibility. As elucidated by Posch et al. (2013), it significantly impacts both human and wildlife populations. Terrestrial life has evolved over billions of years to adapt to the diurnal cycle, resulting in the establishment of circadian rhythms across diverse organisms. In humans, this rhythm typically manifests as diurnal activity and nocturnal regeneration, the latter facilitated by the hormone melatonin. Melatonin synthesis, which occurs exclusively in darkness, is inhibited by light pollution, particularly the blue spectrum components of artificial lighting. This disruption has been associated with increased incidences of breast and prostate cancer among urban populations exposed to high levels of nocturnal illumination.

The ecological impact of light pollution is equally concerning. Migratory birds, for instance, can become disoriented by artificially illuminated structures, while sea turtles may be fatally attracted to terrestrial light sources. These phenomena can result in mortality rates reaching thousands of individuals annually per affected country.

The pervasive nature of light pollution is evidenced by its global distribution, as comprehensively illustrated in the 'World Atlas of the Artificial Night Sky Brightness' by Falchi et al. (2016b). This seminal work utilizes satellite data to provide a visual representation of the worldwide extent of artificial illumination (Figure 1.2). The atlas reveals a strong correlation between population density and the prevalence of artificially lit areas, underscoring the anthropogenic origin of this phenomenon. The data presented quantify the ubiquity of light pollution: approximately 83% of the global population resides in areas affected by skies polluted with artificial light at night (ALAN). This percentage is even more stark in Europe and North America, where over 99% of inhabitants are exposed to light-polluted skies. The dynamic nature of light pollution is intrinsically linked to demographic shifts, urban expansion, and evolving lighting technologies. Kyba et al. (2017) conducted a temporal analysis of light pollution trends, revealing that artificially illuminated areas expanded at an average annual rate of 2.2% between 2012 and 2016. This growth contributed to a total global increase of 9.1% over the same period (Sánchez de Miguel et al., 2021). Furthermore, Kyba et al. (2017) reported an annual increase in total radiance of 1.8%, while the brightness of already lit areas intensified at a rate of 2.2% per annum. These findings underscore the progressive nature of light

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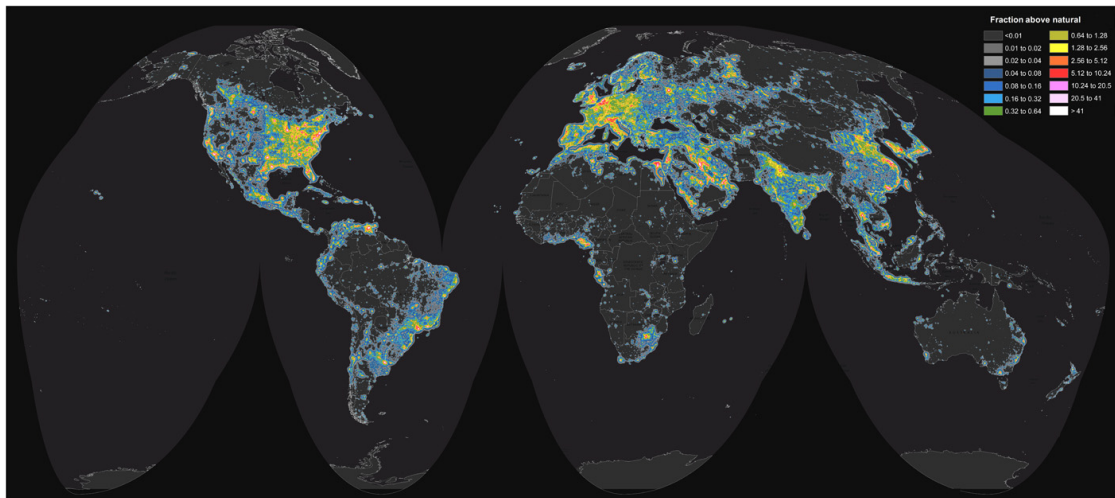


Figure 1.2: The global map of artificial illumination, derived from Falchi et al. (2016b). The hues represent the proportion of man-made illumination in the sky relative to its natural luminosity. Reprinted with permission.

pollution as an escalating environmental concern. Austria's light pollution patterns align with global trends, exhibiting higher levels of artificial illumination in urban centers. Puschnig et al. (2019) noted that the state capitals of Austria's federal states demonstrate particularly elevated values. As anticipated, Vienna, the national capital, emerges as the most significant source of light pollution within the country. In contrast, the central regions of Austria, dominated by the Alps and characterized by sparse population, offer some of the least light-polluted areas in Europe, providing a stark juxtaposition to the urban light profiles. This spatial heterogeneity in light pollution levels within Austria presents both challenges and opportunities for mitigation strategies and further research into the ecological and health impacts of ALAN. The existence of relatively pristine dark sky areas in the Alpine regions may serve as valuable control sites for comparative studies, while the heavily light-polluted urban centers offer critical case studies for examining the full spectrum of light pollution effects and potential remediation measures.

1.2 Natural Light Sources

Sun

The sun is probably the most prominent and brightest source of light in the sky. With a light temperature ranging from 3000 Kelvin to 5600 Kelvin, it irradiates the atmosphere, which in turn refracts the blue portion of the light so much that the sky turns blue. Not a single star can be seen anymore. The sun only does this during the day. At night the sun disappears, and other light sources appear in the sky. But even after disappearing below the horizon (0° to about 18° below the horizon), it still illuminates the sky for a while. This afterglow of the atmosphere is called "astronomical twilight."

Another interesting fact that you learn during an astronomy study is that the refractive index of the atmosphere is $n = 1.00029$ (in a vacuum, it is $n = 1$). This means that stars appear elevated, the closer they get to the horizon, and when the sun apparently touches the horizon with its bottom, it has actually already disappeared underneath the horizontal line.

Air-glow

Airglow is created in the mesopause and thermosphere by light emissions from atoms and molecules that are excited by chemical processes. Harsh UV and X-ray radiation from the sun breaks down oxygen molecules (O_2) into atomic oxygen (O), which is responsible for the high temperatures in the thermosphere. Atomic oxygen recombines very slowly to form O_2 , thus representing a reservoir for the energy originating from the UV radiation that drives chemical reactions during the night, leading to the emission of airglow.

The direct excitation of atoms and molecules by UV radiation cannot be solely responsible for the nocturnal airglow, as they return to their ground state within a few minutes, emitting light. Shortly after sunset, there would no longer be any airglow without the energy storage in the form of atomic oxygen. It can be seen in photos taken from Earth orbit as a predominantly green glowing layer. The intensity of the airglow varies greatly and cannot be predicted on shorter timescales. At least some of the emission lines involved have an obvious connection with the sunspot cycle. The more active the sun is, the more UV light it emits, leading to an increased formation of atomic oxygen in the upper atmosphere. As mentioned above, airglow is caused by - sometimes complex - chemical reactions that are triggered by atomic oxygen. Depending on the atoms and molecules involved, these reactions take place at different levels, resulting in specific emission lines arising in each case. This results in different airglow layers at altitudes of about 85 to 300 kilometers.

The following list shows a comprehensive inventory of the chemical elements responsible for various airglow phenomena (Khomich et al., 2008), delineating their respective contributions to atmospheric luminescence:

- 86-87km: Red and infrared light emissions from hydroxyl (OH) radicals
- 90-100km: Green light emission (558nm) by atomic oxygen
- 92km: Emission in yellow light (approx. 590nm) by sodium (in the form of gaseous sodium bicarbonate)
- 95km: Emission in blue light by molecular oxygen
- 150-300km: Red light (630nm) emissions from molecular oxygen

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Upwards, these layers are limited by the fact that the density of the atoms and molecules involved is too low for the respective chemical reactions to take place on a significant scale. The lower limits mark the range from which the excitation energy is dissipated by collisions with other atoms and molecules before it can be emitted as light. Below about 86 km, the density of the atmosphere is so high that no airglow layers can exist. It is important to note that it takes 1 second for an excited O atom to return to its ground state by emitting light with a wavelength of 558 nm. Under the pressure conditions prevailing on the ground, an air molecule undergoes millions of collisions with other molecules during this period. Consequently, the typical emission lines of the airglow cannot appear at all under normal pressure. They are therefore referred to as "forbidden lines."

Zodiacal Light or false Dawn

In spring and fall, a rare spectacle can be seen on the horizon: the zodiacal light. To witness this phenomenon, wait for a moonless and clear night, find an elevated vantage point outside of the city, and look west after sunset. For about two hours, a cone of light of a few degrees appears in the waning twilight, centered on the ecliptic.

The zodiacal light is an ecliptic phenomenon caused by numerous tiny dust particles orbiting the sun on the ecliptic plane, just like the Earth and all other planets. These dust particles reflect and scatter light from the sun that has just set, creating a cone of light on the horizon as bright as the Milky Way. However, the zodiacal light can only be seen when the sun has disappeared far enough below the horizon (at least 18 degrees), and the particles must not be too far away from the sun, so they are still sufficiently illuminated (maximum distance from the sun is 40°). Additionally, the cone of light must extend more than 10 degrees above the horizon since everything below is obscured by the atmosphere.

Stars

The main part is contributed by approximately ~ 1300 visible stars and only a fraction of the brightness comes from the other 10^{11} stars located in the Milky Way. Of course, this number of visible stars depends on where you look at the night sky from, not to mention the light pollution itself. There is an interesting work on this by Cinzano and Falchi (2020), creating an atlas of visible stars. The brightness of the Milky Way is variable, with the main part being emitted from the galactic plane. This galactic cycle of brightness has its minimum in December and its maximum in July.

Moon

Unfortunately, one of the most interesting objects in the night sky is also known for its cyclical light pollution - the moon. Reflected sunlight, mostly UV and optical radiation, illuminates the nights at full moon time with a visible magnitude of $\sim -12\text{mag}$. For

example, astronomical studies of very dark objects must always include the lunar cycle in their observations.

We will discuss this issue in more detail later when it comes to data reduction. At this point, it should be mentioned that moonlight is extremely important for the animal and plant world and cannot be regarded as "bad" light pollution, despite its negative impact on observational astronomy.

Aurora Borealis

The Sun emits a solar wind, which consists of energetic particles such as electrons, protons, and a small amount of helium. It takes approximately 18 hours for the solar wind to reach Earth's magnetic field, also known as the magnetosphere. However, the particles cannot penetrate all the way to the Earth's surface, as they first collide with the magnetic field lines.

These magnetic field lines are oriented northwards, perpendicular to the trajectory of the protons and electrons. The collision generates the Lorentz force, which deflects the electrically charged particles at right angles to their original path, and also perpendicular to the magnetic field. As a result, the solar wind particles are deflected around the magnetosphere.

When the energetic particles combine with the Earth's own atoms, the Northern Lights, also known as Aurora Borealis, are formed. In Figure 1.3, for example, they appear mostly pinkish and reddish, which is due to high concentrated oxygen in the upper atmosphere.

Clouds

Large cities can be easily identified from a distance due to a bright halo of light that spreads overhead, which is caused by the extensive radiation emitted from sources such as advertising, streetlights, and traffic. This light is scattered in the air and reflected towards the ground, causing clouds to appear illuminated over urban centers at night, while in rural areas they appear as dark patches in the sky, obscuring the stars. Sciezor (2020) showed the fact, that clouds can amplify this effect dramatically, making night in the city increasingly resemble day for many creatures.

Moonless nights in the city are generally brighter than in the countryside, but this difference is much more pronounced when there is complete overcast. In such conditions, readings of light pollution in the city can climb up to four times higher than those in rural areas on a summer full moon night, for taking a closer look, see Kyba et al. (2011b). Cloud cover also affects light pollution within the city itself; on an overcast night, the readings can be ten times higher than on a clear new moon night.

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Figure 1.3: Aurora Borealis seen in Upper Austria. Photograph taken by: Rico Feyrer.

1.3 Types of Light Pollution

Light pollution is a broad term that refers to numerous problems, all of which are caused by inefficient, unattractive, or unnecessary use of artificial light. Specific types of light pollution include light trespass, over-illumination, glare, light clutter, and sky glow. An offending light source often falls into more than one of these categories.

Light Trespass

Light trespass, also known as "fall light," occurs when a light source casts light beyond the property lines, accidentally illuminating other households, businesses, or areas. Spillover light is the most personal form of light pollution since there are only few rules to regulate where, when, or how much light is undesirable. A common instance of spillover light is light from a night light coming through an opening and illuminating a room, light from outdoor wall lights that direct light upward to the sky rather than to the ground, or light from a neighbor's beam or security light shining over the fence and illuminating your property.

Over-Illumination

Over-illumination is the excessive or inefficient use of illumination, such as leaving lights on when they are not in use, using poorly designed lighting that illuminates areas that do not need to be lit or illuminates areas more brightly than necessary. This results in high energy consumption over time. The health effects of over-illumination include increased frequency of headaches, worker fatigue, medically defined stress, and a decrease in sexual function and an increase in anxiety. This is a fairly straightforward issue. If the lights are on when they aren't needed, the environment is being unnecessarily illuminated. Streetlights turning on too early or offices in a building not turning off their lights at night are both forms of light pollution.

Light Clutter

Light clutter refers to excessive groups of lights, especially bright or flashing lights, which can lead to confusion, distract from important issues, and potentially cause accidents. Light clutter is a major concern for drivers and pilots, as it can cause disorientation and confusion. It is particularly noticeable on streets where streetlights are poorly designed, or where brightly lit advertising overwhelms the roads. Light clutter is also a hazard in the aviation environment, where aviation safety lighting must compete for visual attention with non-relevant lighting.

Glare

Glare occurs when intense light is reflected off a surface, resulting in a painful or uncomfortably bright "glare" that can make normal vision of that particular area very difficult. Glare is the visual sensation one experiences when stray light, light in the visual field, is greater than the light to which the eyes are adapted. Depending on the intensity, glare can result in reduced contrast, color perception, and visual performance.

Nighttime Sky Glow

Sky glow originates from natural and artificial sources, although poorly designed and targeted artificial lights are the chief source of sky glow. Sky glow occurs when light is directed straight into the atmosphere, accidentally or deliberately, where it is dispersed by dirt and gas particles, creating a dome-like glow that covers the night sky. The glow reduces the contrast between the stars and the galaxies in the sky, making celestial objects difficult to observe even with a telescope. Light domes also disrupt the polarization of moonlight, which nocturnal animals use to navigate. Glow domes are visible in cities and towns throughout the world, and they appear in a variety of sizes, such as large domes over city centers or smaller domes above over-illuminated commercial areas and sports centers or stadiums. Cloud coverage, snow, trees, and the amount of dirt and gas particles in the air can intensify sky glow. According to the National Park Service, artificial sky

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glow from major cities is visible up to 200 miles away in numerous national parks. For example, the bright lights of Las Vegas are visible in Nevada’s Great Basin National Park, located 295 miles west of the city, and in California’s Death Valley National Park, located 118 miles west of the city. The lights are even visible in Bryce Canyon, as you can see in the paper by Green et al. (2022) National Park in Utah, known as one of the darkest spots in North America, located over 260 miles northeast of the city.

LED

In recent years, the widespread adoption of Light Emitting Diodes (LEDs) for outdoor lighting applications has significantly transformed the urban landscape. While LEDs offer numerous advantages, including energy efficiency and longevity, their use has also raised concerns about the exacerbation of light pollution.

Despite their advantages, LED lighting can contribute to various forms of light pollution. One primary concern is skyglow, the brightening of the night sky caused by upward-directed light emissions. LEDs emit light across a broad spectrum, including blue wavelengths that scatter more easily in the atmosphere, leading to increased skyglow.

The problem with many satellite sensors is that they are optimized to detect light emissions within certain spectral bands that are relevant for Earth observation tasks such as land cover mapping, vegetation monitoring and cloud detection. These sensors may not be fine-tuned enough to detect the narrow spectral peaks associated with blue LED emissions. As a result, they may have limited or no sensitivity to the blue part of the light spectrum emitted by LEDs. This means that in cities that are switching to LED lighting, satellite data suggests that light pollution is decreasing, see Hillger et al. (2013) and Miller et al. (2012). One of the most striking examples of this phenomenon is the city of Milan, which was largely converted to LEDs in 2014, for further readings see Kyba et al. (2017).

1.4 Atmosphere and scattering

Our atmosphere plays a central role in the scattering of light and the creation of light pollution. The gases and particles contained in the atmosphere interact in various ways with incoming light. In the context of increasing urbanization, the issue of light pollution is gaining importance.

Light scattering is a fundamental physical phenomenon that explains how light interacts with matter. It describes how light rays change direction when they encounter particles or molecules. This concept is crucial for understanding many natural phenomena and plays an important role in the study of light pollution. In the following sections, we will examine various types of light scattering that are particularly relevant for the description and analysis of light pollution. These scattering processes help us understand how artificial light spreads in the atmosphere and what effects it has on our environment. Knowledge of these scattering phenomena forms the basis for developing strategies to reduce and

control light pollution.

1.4.1 Rayleigh scattering

Rayleigh scattering is the elastic scattering of light by particles that are small compared to the wavelength (λ) of light and sufficiently far apart that there is no interaction between them. Rayleigh scattering can occur both in pure gaseous substances (e.g., air) and on foreign particles. It is particularly impressive in air; it is therefore sometimes referred to as air scattering (Bates, 1984).

Since there is a fixed phase relationship between the incident radiation and the scattering waves emitted by the individual particles, an irregular spatial distribution of the scattering particles is necessary for the occurrence of Rayleigh scattering. In pure substances, the irregularity of the particle arrangement is a consequence of the density fluctuations. Because of the statistically random instantaneous position of the scattering centers, Rayleigh scattering is incoherent, i.e., the intensity of the scattered radiation results from the summation of the intensities of the individual scattered waves.

The differential scattering cross-section for Rayleigh scattering at a macroscopic volume V of a gaseous medium is given by:

$$\sigma(\theta) = \frac{2\pi V}{N\lambda^4} [n^2(\lambda) - 1]^2 (1 - \cos^2\theta) \quad (1.1)$$

Here, θ denotes the scattering angle, N the particle density, and $n(\lambda)$ the wavelength-dependent refractive index of the medium. The right-hand side of the equation, related to the unit volume, is called the Rayleigh scattering function.

Rayleigh scattering is extremely wavelength dependent and follows the following relationship:

$$\sigma \propto \lambda^{-4} \quad (1.2)$$

The symmetry of the scattering is preserved as long as the particle size is small compared to the wavelength of the light. In the pure atmosphere, these conditions are largely met. Deviations occur due to the presence of aerosols, where the particles are much larger (Mie scattering), and due to multiple scattering.

1.4.2 Mie scattering

Mie scattering is the elastic scattering of light from particles whose radius is of the order of the wavelength of light. Based on Maxwell's equations, G. Mie developed a rigorous theory of scattering from spherical particles of any size, taking into account the electrical conductivity of the particles. The electromagnetic field of the scattered radiation results in the form of a series expansion, with the individual terms corresponding to multipole radiation of various orders. The scattered radiation in Mie scattering is partially polarized. With spherical symmetry of the scattering particles, the scattering process is rotationally symmetrical with respect to the direction of incidence. An important

1 Light Pollution

statement of Mie's theory is that the radiation is increasingly scattered in the forward direction with increasing particle radius R , which is called the Mie effect.

The strength of the Mie Scattering is often characterized by a relative scattering cross-section

$$K = \frac{\sigma_{\text{tot}}}{\pi R^2} \quad (1.3)$$

namely related to the geometric particle cross-section. σ_{tot} denotes the total scattering cross-section (related to a particle). The relative scattering cross-section is tabulated for numerous values of the refractive index n . It is a function of the scattering parameter $\kappa = 2R/\lambda$ oscillating around the value 2.

Mie scattering plays a large role in atmospheric optics (Jackel and Walter, 2008) . It occurs when sunlight hits fog, haze, or aerosol particles. These are always particles of different sizes. This generally leads to a flattening of the maxima and minima of the above curve.

Mie scattering is only weakly dependent on wavelength and follows the following relationship:

$$\sigma \propto \lambda^{-1} \quad (1.4)$$

Recently, it has been possible to extend the theory to non-spherical particles and their distributions (Hourahine et al., 2012). Deviations from the spherical shape, as well as size distributions of spheres, lead to flattening of the maxima and minima of the curve that indicates the dependence of the scattering cross-section on the scattering parameter. This makes it clear that a correct interpretation of particle distributions from experimentally determined scattering cross-sections must also take information about their shape into account.

1.4.3 Backscattering

Backscattering refers to a reflection of light back to its source. In the case of light pollution, it is usually a diffuse reflection from the atmosphere. Scattering in the reverse direction ($\theta = 180^\circ$) is usually weaker than in all other directions within the framework of classical physics, but can be stronger than scattering in neighboring directions due to quantum mechanical effects or interference effects. Coherent backscatter is also responsible for the high brightness of the full moon.

Backscattering can occur in a wide variety of physical situations, such as:

- Diffuse Reflection caused by large particles and Mie scattering
- Inelastic Collisions between electromagnetic waves and the transmitting medium
- Elastic collisions between accelerated ions and a sample

- Compton scattering, commonly used for X-ray imaging.

Backscattering is most visible directly over cities on cloudy nights. City lights shine on the clouds from below, and much of it reflects back, illuminating the city again.

However, backscattering can also be seen on cloudless, seemingly clear nights. When the air is filled with exhaust fumes and aerosols (Ceolato and Berg, 2021), this "bell" of pollutants reflects light back toward the city.

1.4.4 Sidescattering

Sidescattering is a phenomenon that occurs in Earth's atmosphere and plays a significant role in various scientific disciplines, including meteorology, climatology, and remote sensing. This text aims to provide an overview of sidescattering and its implications in atmospheric studies.

Sidescattering refers to the process where radiation, such as sunlight or electromagnetic waves, is scattered by particles in the atmosphere in a direction perpendicular to the incident beam. Unlike forward scattering, where the scattered radiation moves in the same direction as the incident beam, sidescattering results in a change in the direction of the radiation.

According to Mie theory, which describes the scattering of electromagnetic waves by spherical particles, the intensity and angular distribution of the scattered radiation depend on various factors, including the particle size, composition, and the incident wavelength. Sidescattering typically occurs when the incident radiation interacts with particles that are larger than the wavelength of the incident beam.

Several factors influence the extent and characteristics of sidescattering in atmospheres. The concentration and size distribution of aerosol particles in the atmosphere significantly impact the scattering process (Wang et al., 2020). Larger particles tend to exhibit stronger sidescattering compared to smaller particles. Additionally, the refractive index of the particles, which is related to their composition, affects the scattering behavior. Atmospheric conditions, such as humidity and temperature, can also influence sidescattering through their impact on the aerosol properties.

Sidescattering has important implications in atmospheric research. In remote sensing applications, such as satellite observations or lidar measurements, sidescattering provides valuable information about the vertical distribution and properties of aerosol particles. By analyzing the angular distribution of scattered radiation, scientists can retrieve important atmospheric parameters, including aerosol optical depth, size distribution, and composition. Furthermore, sidescattering plays a role in radiative transfer models (e.g. Monte Carlo simulations by Modrić et al. (2009) used to study climate and weather

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patterns, as it affects the distribution of energy in the atmosphere.

Measurement techniques, such as ground-based lidar systems and satellite-based instruments, have been developed to study sidescattering in atmospheres. These techniques enable the retrieval of aerosol properties and the characterization of sidescattering patterns on various spatial scales.

1.4.5 Forwardscattering

Forward scattering occurs when radiation, such as sunlight or electromagnetic waves, is scattered by particles in the atmosphere in the same direction as the incident beam, without significantly altering its original path. To grasp the concept of forward scattering, it is essential to delve into the fundamental principles of scattering theory, particularly Mie theory. Forward scattering typically takes place when the incident radiation interacts with particles that are smaller than the wavelength of the incident beam.

In many cases, forward scattering is much stronger than scattering in other directions, so it has a comparatively large differential cross-section (de Kok and Stam, 2012). A well-known example from everyday life is the scattering of light by dust particles in the air: if you look almost in the direction of the light source (e.g. when sunlight falls into a dark room), the dust particles can be seen clearly as bright points.

1.5 General influences of light pollution

In the following chapter, we will explore the critical importance of restricting light pollution. We'll delve into how excessive artificial lighting affects both our environment and our well-being. Our discussion will cover potential health consequences for humans, as well as the impact on ecosystems and wildlife.

1.5.1 Effects on Human Health

The circadian rhythm is a biological clock that regulates the daily cycle of sleep and wakefulness in living organisms. It is a critical aspect of human physiology and is regulated by the suprachiasmatic nucleus (SCN) in the hypothalamus (Hannibal, 2022), which receives input from the retina's light-sensitive ganglion cells.

Exposure to artificial light at night, which disrupts the circadian rhythm, has been linked to an increased risk of several health problems, including cancer (Al-Naggar and Al-Maktari, 2021). It is thought that this is due to the suppression of the hormone melatonin, which is produced by the pineal gland in response to darkness and plays a crucial role in regulating the circadian rhythm. Melatonin is also a potent antioxidant and has been shown to have anti-cancer properties. Another study by Helbich et al. (2020) suggests a relation between light pollution and depression.

1.5 General influences of light pollution

Several epidemiological studies have suggested that long-term exposure to artificial light at night is associated with an increased risk of several cancers, including breast, prostate, and colorectal cancers. A 2021 meta-analysis of 1157 studies found a significant association between long-term exposure to residential light at night and an increased risk of breast cancer in women, as indicated in the paper by Wu et al. (2021).

The evidence suggests that exposure to artificial light at night can have a significant impact on human health, and steps should be taken to minimize exposure, particularly during the nighttime hours. This includes using low-intensity lighting at night, avoiding bright screens before bedtime, and reducing light pollution in urban areas. Further research especially in this area is needed to better understand the underlying mechanisms and to develop effective strategies for mitigating the health risks associated with light pollution.

More Light, more safety?

Often, when searching for ways to reduce light pollution, one comes across the statement that street lighting is important in preventing crime and the better-lit streets are, the fewer crimes are committed. However, if one were to take this statement to the extreme, there should be little or no crime during the day when the sun shines from the sky without a cloud. Of course, that's not true. Street lighting is not the only factor in crime and theft, but it does raise questions about how much street lighting is necessary and whether, at some point, the opposite is achieved.

The reference to safety at night suggests that beyond a certain point, around 50 lux, the perceived safety does not increase drastically and may even stagnate. This finding questions the excessive over-illumination due to the perceived safety. According to this study by Gaston et al. (2015), the most efficient range is around 30 lux.

The link between crime and night light is complex. Poorly installed light sources can create areas with insufficient or no lighting, providing protection for criminal activities. Additionally, the extreme contrast between areas of light and darkness can reduce peripheral visibility, and night vision of potential witnesses is severely compromised by this type of lighting.

1.5.2 Effects on the Economy

Light pollution can also have significant effects on the economy, particularly in the areas of energy consumption, tourism, and real estate.

This gradual loss of electricity, summed up over a large area, makes a significant contribution to commercial and economic changes. Especially in times like these (2024), when energy prices are soaring and inflation is driving up costs.

1 Light Pollution

Let's consider some numbers, using the example of the United States. According to the study of Hunter and Crawford (1991) and supported by the International Dark-Sky Association¹, one-third of the country's lighting is unused or could be reduced. This third is equivalent to 30 million barrels of oil (1 barrel = 158.987 liters) and 8.2 million tons of coal, and this every year. It is worth mentioning that the United States consumes the most kilowatt-hours per inhabitant in the world and has the lowest price per kilowatt-hour.

This represents approximately \$7 billion in value annually, according to Gallaway et al. (2010). The amount of fossil fuel that is wasted can release 14.1 million tons of CO₂ into the atmosphere every year. In retrospect, this increases the additional costs many times if one includes the damage caused by climate change.

1.5.3 Effects on Wildlife

The detrimental effects of light pollution extend beyond the realm of human concerns, as wildlife is also significantly impacted. This issue has recently gathered increased attention due to mounting evidence of the negative effects on animals' behavior, physiology, and ecology. The primary impact of light pollution on wildlife is the disturbance of natural patterns of light and dark, which animals rely on for their daily and seasonal behaviors. Nocturnal animals such as bats, moths, and fireflies depend on the darkness of night to navigate, communicate, and hunt for food. Artificial lights disrupt these natural patterns, confusing and disorienting animals and leading to changes in their behavior. Consequently, reduced reproductive success, decreased survival rates, and altered migration patterns can ensue.

Moreover, light pollution also impacts animals' circadian rhythms (Yang et al., 2020), which regulate their sleep patterns and hormone levels. The excess light can interfere with these rhythms, leading to reduced hormone production, immune system suppression, and other health problems. For example, sea turtles that hatch on brightly lit beaches often become disoriented and are unable to find their way to the ocean, resulting in high mortality rates (Berry et al., 2013)). In addition to these physiological effects, light pollution can impact the ecology of an ecosystem. Artificial lights can attract insects, which in turn attract predators such as birds and bats. This can lead to changes in the predator-prey balance and potentially alter the composition of the entire ecosystem.

Another issue is the impact of light pollution on the breeding and migration patterns of birds, see Cabrera-Cruz et al. (2018) and Burt et al. (2023)). Many bird species rely on the stars to navigate during migration. However, artificial lights can disorient them and cause them to become lost or disoriented, leading to lower breeding success rates. To mitigate the negative effects of light pollution on wildlife, several steps can be taken.

¹<https://darksky.org/app/uploads/2021/01/Light-Pollution-Wastes-Energy-and-Money-English.pdf>, last accessed on 02.07.2024

1.6 Light Pollution and the horrendous impact on Astronomy

One solution is to reduce the intensity and amount of artificial light used. Shielding and directing the light sources can also reduce the amount of light that is dispersed into the environment (Falchi et al., 2011), helping to minimize the impacts on wildlife.

1.6 Light Pollution and the horrendous impact on Astronomy

Light knows no boundaries, it spreads freely until blocked or diffused. Dark nights have long since become a rarity. A third of humanity, including 80% of North Americans and 60% of Europeans, cannot see the Milky Way in the sky. Over 90% of Americans and Europeans live under light-polluted night skies (Falchi et al., 2016a). Approximately 38% of the US population is persistently exposed to light pollution that is 41 times brighter than the natural background brightness of the night sky.

Light pollution has become a growing concern for astronomers worldwide (especially for ground-based observations, see Green et al. (2022), as it poses significant challenges to astronomical research. This text explores the adverse effects of light pollution on various aspects of astronomical research, including observations, data collection, and scientific advancement. By understanding these impacts, we can recognize the urgency of addressing light pollution to preserve the integrity and progress of astronomical research.

Impaired Observations and Visibility:

Light pollution results in skyglow, a brightening of the night sky caused by artificial lighting. This excess illumination diminishes the visibility of celestial objects, making it difficult to observe faint stars, galaxies, and other cosmic phenomena. The reduced contrast between celestial objects and the background sky limits astronomers' ability to detect and study distant and dim sources, hindering the overall depth and quality of observations (Perez, 2023).

Distorted Photometry and Imaging:

Accurate photometry, the measurement of light intensity from celestial objects, is essential for many astronomical studies. Light pollution introduces unwanted variations and fluctuations in readings due to the increased background brightness. This interference compromises the precision and reliability of photometric data, making it challenging to accurately determine the true characteristics of observed objects. Similarly, light pollution distorts imaging, causing color shifts and reducing the clarity and fidelity of astronomical images.

Limitations on Spectroscopic Studies:

Spectroscopy plays a crucial role in understanding the physical properties of celestial objects through the analysis of their light spectra. However, light pollution adds a significant level of noise to the observed spectra, reducing the ability to discern fine spectral features. This interference hampers the accuracy and resolution of spectroscopic measurements, impeding detailed analysis and interpretation of the data.

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Impact on Transient Events:

Transient events such as supernovae, comets, and meteor showers are time-sensitive astronomical phenomena. Light pollution poses a significant obstacle in detecting and monitoring these events due to the diminished visibility and increased difficulty in capturing their faint and brief signals. Consequently, valuable opportunities for studying the dynamics and evolution of such events are lost or compromised.

Inhibition of Dark Sky Research Facilities:

The establishment of dark sky research facilities in remote areas has been crucial for minimizing light pollution's impact on astronomical research. However, the encroachment of artificial lighting sources into these areas can compromise the effectiveness of such facilities. Light pollution restricts the full potential of these dark sky sites, limiting the quality of observations and data collection.

Light pollution significantly undermines the progress and quality of astronomical research. It diminishes the visibility of celestial objects, distorts photometric and spectroscopic measurements, and poses challenges in studying transient events. Addressing light pollution through comprehensive lighting regulations, public awareness campaigns, and the promotion of dark sky initiatives is essential to safeguard the integrity of astronomical research, preserve the wonders of the universe, and enable scientific advancements that deepen our understanding of the cosmos.

1.7 A bright look into a (hopefully) dark future

But among the many problems caused by increasing light pollution, there are also enough counter-movements to restore the balance. In this concluding section of the introducing chapter, I would like to talk briefly about the outstanding work of those researchers and activists who want to preserve our night sky and make a noticeable contribution to ensuring that there is no light waiting for us at the end of the tunnel.

Dark Sky Parks

Dark Sky Parks are designated areas that prioritize the preservation of natural darkness, limiting light pollution to provide exceptional opportunities for stargazing and appreciating the nocturnal environment. Dark Sky Parks play a crucial role in raising awareness about the adverse effects of light pollution and promoting the appreciation of the night sky. By creating designated areas with minimal artificial lighting, these parks provide a sanctuary for both astronomers and the general public to observe and connect with the wonders of the universe. Moreover, they contribute to the conservation of nocturnal wildlife and ecosystems that rely on natural darkness for their survival.

To qualify as a Dark Sky Park, certain criteria must be met. The International Dark-Sky

1.7 A bright look into a (hopefully) dark future

Association (IDA)², a leading organization in light pollution mitigation, has established a set of guidelines for such designations. These include implementing lighting policies that prioritize dark sky preservation, conducting regular sky quality measurements to ensure compliance, and raising public awareness about the importance of preserving natural darkness.

Dark Sky Parks provide astronomers and astrophotographers with unparalleled opportunities to observe celestial objects and capture stunning images of the night sky. Additionally, these parks serve as educational hubs, hosting workshops, lectures, and public outreach programs to engage visitors and foster an understanding of the importance of dark skies and the impacts of light pollution. Dark Sky Parks also offer unique tourism and economic development prospects, attracting visitors who seek pristine night skies and contributing to local economies through astronomy-related tourism and activities.

The establishment and management of Dark Sky Parks require collaboration between various stakeholders, including government entities, landowners, local communities, and astronomy enthusiasts. It involves creating lighting ordinances to regulate outdoor lighting, implementing appropriate lighting fixtures and technologies that minimize light pollution, and monitoring sky quality regularly. Additionally, educating the public and local communities about the benefits of dark skies and promoting responsible lighting practices are crucial for long-term success.

Dark Sky Parks have gained international recognition, with several notable examples worldwide. For instance, the Natural Bridges National Monument in Utah, USA, was the first park certified as an International Dark Sky Park in 2006. Other renowned Dark Sky Parks include the Aoraki Mackenzie International Dark Sky Reserve in New Zealand, Brecon Beacons National Park in Wales, and Mont-Mégantic Dark Sky Reserve in Quebec, Canada. Each of these parks showcases the commitment to preserving natural darkness.

There are several Dark Sky Parks in Austria that have been designated by the International Dark-Sky Association (IDA). These parks include national parks, nature reserves, and other protected areas that strive to preserve the pristine beauty of the night sky. Examples of Dark Sky Parks in Austria include the Gesäuse National Park, the Hohe Tauern National Park, and the Kalkalpen National Park.

Dark Sky Parks serve as beacons of darkness in an increasingly illuminated world. By safeguarding natural darkness and reducing light pollution, these parks provide invaluable opportunities for scientific research, environmental conservation, education, and leisure. Their establishment and ongoing efforts contribute to a global movement aimed at protecting our view of the cosmos and fostering a deeper connection with the natural wonders of the night sky.

²<https://darksky.org/>, last accessed: 2024-05-2

2 Light Pollution Monitoring Network in Upper Austria

The datasets of the Upper Austrian light measurement network have proven to be an excellent source for exploring the night sky over Upper Austria (see Posch et al. (2018) and Puschnig et al. (2022)). They show good coverage in terms of different light pollution levels and spatial distribution. The originally 23 stations were able to capture a variety of different conditions, ranging from very heavy light pollution in central Linz to natural skies, such as those at Feuerkogel.

The establishment of the extensive Sky Quality Meter (SQM) network in Upper Austria has been a significant undertaking, initiated in 2014 by the county authority responsible for environmental conservation¹. The network's considerable size, comprising 23 stations, includes both remote locations and urban areas. Over the course of 2015 and 2016, more than 10 million Night Sky Brightness (NSB) measurements were conducted exclusively in Upper Austria.

Figure 2.1 and Figure 2.2 shows a detailed description of the 23 stations. This includes information on the coordinates and dates of establishment, allowing for a comprehensive overview of the network's geographical distribution and temporal evolution. See Figure 2.1 and Figure 2.2.

2.1 Light Measurement stations

The locations were divided into three categories based on population (Statistics Austria): urban, suburban, and rural. Locations with **more than 20,000 inhabitants** are classified as urban, and those with **less than 20,000 inhabitants** are considered suburban. If a location has a low to no permanent population, it is classified as rural. Each location is equipped with a weatherproof enclosure and a sky quality meter (SQM), which is aligned 10 degrees north of the zenith.

2.2 Sky Quality Meters

Sky quality meters (SQMs) are devices that measure the brightness of the night sky. They are used to quantify the level of light pollution in an area and provide important data for

¹<https://www.land-oberoesterreich.gv.at/159659.htm>

2 Light Pollution Monitoring Network in Upper Austria

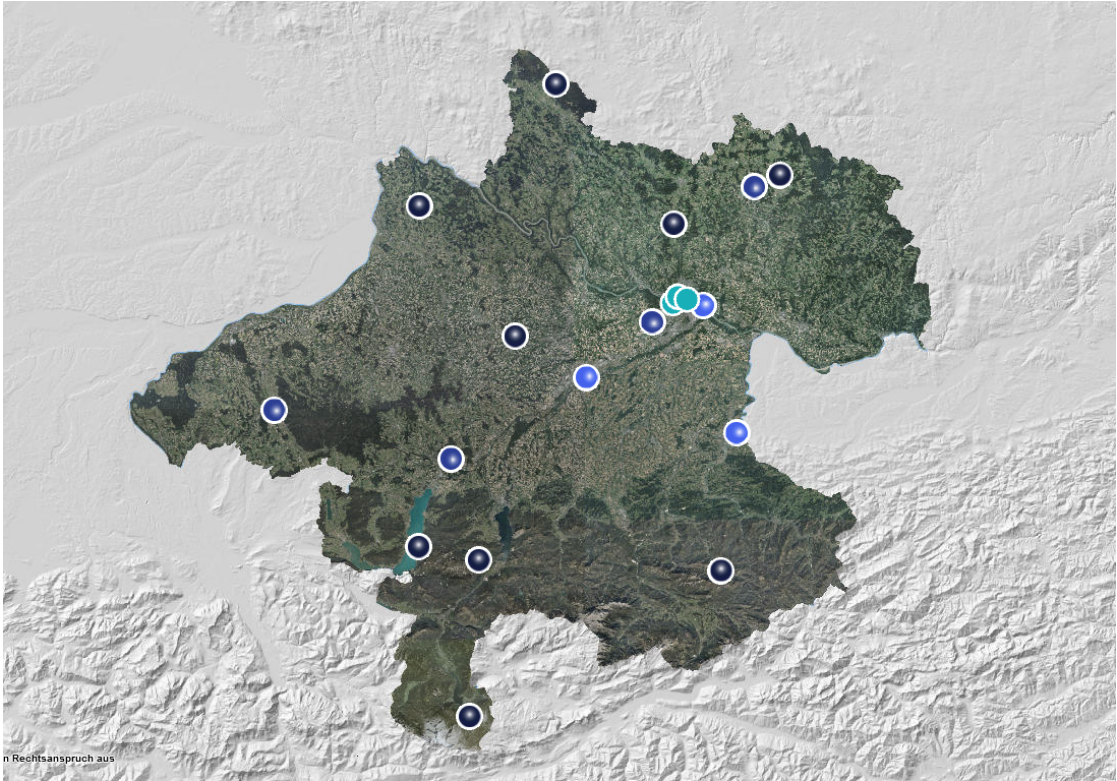


Figure 2.1: Light measurement sites Upper Austria Map. Source: DORIS ^a (Digitales Oberösterreichisches Raum-Informationssystem).

^a<https://www.doris.at/themen/umwelt/lichtverschmutzung.aspx>

astronomers, ecologists, and urban planners. Sky quality meters are relatively simple to use and are widely available, making them an important tool for assessing and monitoring light pollution.

Sky quality meters work by measuring the amount of light in a specific wavelength range. SQMs are designed to measure the brightness of the sky in the V-band (Cinzano, 2005), which is the wavelength range of light visible to the human eye. The device consists of a photometer, which is a sensor that detects the amount of light, and a microprocessor that calculates the brightness of the sky. The output is usually given in units of magnitude per square arcsecond, which is a standard measure of sky brightness.

There are several types of sky quality meters available, including handheld meters, fixed meters, and all-sky cameras. Handheld meters are the most common type and are used for field measurements. They are small, portable, and easy to use, making them ideal for surveys of light pollution in different locations. Fixed meters, on the other hand, are permanently installed in a location and provide continuous monitoring of the night sky.

2.2 Sky Quality Meters

Code	Name	Latitude N	Longitude E	Elevation [m] (m above sea level)	operational since (YYYY-MM-DD)
{urban}					
GRA	Graz-Lustbühel	N 47°4'2"	E 15° 29'37"	484	2014-01-01
IFA	Wien	N 48° 13'54"	E 16° 20'3"	231	2012-03-01
LSM	Linz-Schlossmuseum	N 48° 18'19"	E 14° 16'58"	287	2014-09-06
LGO	Linz-Goethestraße	N 48° 18'19"	E 14° 18'30"	259	2014-09-06
LSW	Linz-Sternwarte	N 48° 17'36"	E 14° 16'6"	336	2014-09-06
STY	Steyr	N 48° 2'57"	E 14° 26'32"	307	2014-09-06
STW	Steyregg-Weih	N 48° 17'19"	E 14° 21'13"	331	2014-09-06
TRA	Traun	N 48° 14'8"	E 14° 15'11"	269	2014-12-05
WEL	Wels-Rathaus	N 48° 9'23"	E 14° 1'29"	317	2014-09-06
{intermediate}					
BRA	Braunau	N 48° 15'40"	E 13° 2'41"	351	2014-09-06
GRI	Grieskirchen	N 48° 14'4"	E 13° 49'33"	336	2015-05-21
FRE	Freistadt	N 48° 30'33"	E 14° 30'7"	512	2015-05-21
MAT	Mattighofen	N 48° 5'50"	E 13° 9'6"	454	2014-12-15
PAS	Pasching	N 48° 15'31"	E 14° 12'36"	292	2014-12-15
VOE	Vöcklabruck	N 48° 0'21"	E 13° 38'43"	434	2014-12-15
{rural}					
BOD	Nationalpark-Bodinggraben	N 47° 47'31"	E 14° 23'38"	641	2016-06-29
FEU	Feuerkogel	N 47° 48'57"	E 13° 43'15"	1628	2015-03-25
FOA	Mitterschöpl	N 48° 5'3"	E 15° 55'24"	880	2012-11-16
GIS	Giselawarte	N 48° 23'3"	E 14° 15'11"	902	2014-09-01
GRU	Grünbach	N 48° 31'50"	E 14° 34'30"	918	2014-09-06
KID	Kirchschlag-Davidschlag	N 48° 26'31"	E 14° 16'26"	813	2014-12-15
KRI	Krippenstein	N 47° 31'23"	E 13° 41'36"	2067	2015-11-04
LOS	Losenstein-Hohe Dirn	N 47° 54'22"	E 14° 24'40"	982	2015-05-21
MUN	Münzkirchen	N 48° 28'45"	E 13° 33'29"	486	2014-09-06
ULI	Ulrichsberg-Schöneben	N 48° 42'20"	E 13° 56'44"	935	2015-05-21
ZOE	Nationalpark-Zöblboden	N 47° 50'18"	E 14° 26'28"	899	2014-09-06

Figure 2.2: Light measurement sites in Upper Austria. Figure by Posch et al. (2018). Reprinted with permission.

They are typically used in observatories or other scientific institutions. All-sky cameras are another type of sky quality meter that uses a camera to take pictures of the entire sky. The images are then analyzed to determine the brightness of the sky.

Sky quality meters have several important applications. Astronomers use SQMs to measure the brightness of the night sky and to identify areas where light pollution is particularly severe. This information is used to select observing sites and to plan astronomical observations. Ecologists use SQMs to measure the effects of light pollution on nocturnal animals, such as birds, insects, and bats. Urban planners use SQMs to assess the level of light pollution in cities and to design lighting schemes that minimize the impact on the environment and human health.

Sky quality meters are also used by citizen scientists and amateur astronomers to measure the level of light pollution in their local area. This can help raise awareness about the impacts of light pollution and encourage communities to take action to reduce it. In recent years, several smartphone apps have been developed that allow users to

measure the brightness of the night sky using the camera on their phone. While these apps are not as accurate as dedicated sky quality meters, they provide a convenient way for people to get involved in citizen science projects and contribute to our understanding of light pollution.

2.2.1 Loosing Sensitivity

There are several reasons why sky quality meters may lose sensitivity. One common reason is that the sensor inside the meter may become dirty or damaged. Over time, dust, dirt, and other particles can accumulate on the sensor, which can reduce its ability to detect light. In some cases, the sensor may become scratched or otherwise damaged, which can also affect its sensitivity.

Another reason why sky quality meters may lose sensitivity is that the battery inside the meter may start to wear out. As the battery loses its ability to hold a charge, the meter may not be able to operate at peak performance, which can affect its sensitivity. In some cases, the battery may need to be replaced in order to restore the meter's sensitivity.

Puschnig et al. (2021) examined long-term zenithal night sky brightness (NSB) measurements during twilight at three locations: Vienna, Potsdam-Babelsberg, and Stockholm. They used Sky Quality Meters (SQMs) over 5-9 years, focusing on solar zenith angles between 96° and 97° to minimize artificial light at night (ALAN) influence. The data showed strong seasonal variations in NSB.

An instrumental darkening effect was observed, with linear slopes of:

- Stockholm: $34 \pm 4 \text{ mmag}_{SQM} \text{ arcsec}^{-2} \text{ yr}^{-1}$
- Potsdam-Babelsberg: $46 \pm 2 \text{ mmag}_{SQM} \text{ arcsec}^{-2} \text{ yr}^{-1}$
- Vienna: $53 \pm 2 \text{ mmag}_{SQM} \text{ arcsec}^{-2} \text{ yr}^{-1}$

They investigated potential atmospheric factors (aerosol optical depth, particulate matter, ozone) that might explain this darkening trend. However, no significant atmospheric trends were found that could account for the observed darkening effect in SQM measurements.

Changes in the environment can also affect the sensitivity of sky quality meters. For example, if there is a lot of moisture in the air, the sensor may not be able to detect as much light as it would in dry conditions. Similarly, if the temperature is too hot or too cold, this can also affect the meter's sensitivity.

Like any electronic device, they may experience wear and tear with regular use, which can affect their performance. In some cases, the meter may need to be replaced in order to restore its sensitivity. To ensure accurate readings, it's important to calibrate sky quality meters regularly and to take care of them properly. This may involve cleaning the sensor, replacing the battery, and storing the meter in a cool, dry place when not in use.



Figure 2.3: In Upper Austria, the 23 Sky Quality Meters (SQMs) are protected by durable black-coated iron cylinders, replacing the typical plastic enclosures. These housings feature multiple sharp spikes on top to deter birds from perching and soiling the equipment. The region has deployed only SQM-LE models, which come with built-in ethernet connectivity. Source: Posch et al. (2018). Reprinted with permission.

2.2.2 How far can a SQM see

The sensitivity of the SQM is one of the primary factors affecting how far it can see. Different SQMs have different sensitivities, which are usually expressed in magnitudes per square arcsecond. This value indicates the change in brightness that the SQM can detect. A more sensitive SQM will be able to detect fainter stars and galaxies, allowing it to see further into the night sky.

The level of light pollution in the area also plays a significant role in determining how far a SQM can see. Light pollution is caused by artificial light sources, such as streetlights, buildings, and cars, which scatter light into the atmosphere and create a bright skyglow that obscures stars and other celestial objects. In areas with high levels of light pollution, a SQM will not be able to see as far as it would in a dark-sky location.

The transparency of the atmosphere is also important when considering how far a SQM can see. The Earth's atmosphere absorbs and scatters light, making objects in the night sky appear fainter than they would in a vacuum. The amount of absorption and scattering depends on several factors, including the altitude of the observing site, the temperature and humidity of the air, and the presence of atmospheric aerosols such as dust, smoke, and pollution. In general, a transparent atmosphere will allow a SQM to see further than an opaque or hazy one.

2 Light Pollution Monitoring Network in Upper Austria

To provide a specific example, a SQM with a sensitivity of 21.5 magnitudes per square arcsecond can typically detect stars as faint as magnitude 6.5 in a dark-sky location with little light pollution and a transparent atmosphere. However, in an urban area with high levels of light pollution and a hazy or polluted atmosphere, the same SQM may only be able to detect stars with a magnitude of 4.5 or brighter. In other words, the SQM would not be able to see as far into the night sky in the urban location due to the increased light pollution and atmospheric absorption and scattering.

2.2.3 Astronomical Unit "Magnitudes"

The astronomical unit magnitude (AUM) is a measure of the brightness of celestial objects, particularly those in the solar system, as seen from Earth. It is defined as the brightness of an object that would have an apparent magnitude of 0.15 when observed from an average distance of one astronomical unit (AU), which is the average distance between the Earth and the Sun. AUM is primarily used for measuring the brightness of planets, asteroids, and comets, and is particularly useful for comparing the brightness of objects at different distances from Earth.

The AUM system takes into account the fact that the apparent brightness of an object depends not only on its actual luminosity but also on its distance from Earth. As an object moves farther away from Earth, its apparent brightness decreases due to the inverse square law, which states that the intensity of light decreases with the square of the distance from the source. By using the AUM system, astronomers can compare the brightness of objects at different distances and gain insights into their properties, such as their size and reflectivity.

In practical terms, an object with an AUM of 1 would appear about 2.5 times brighter than an object with an AUM of 2 when observed from one AU away. The AUM scale is logarithmic, so each increase in AUM by one unit represents a decrease in brightness by a factor of about 2.5. For example, Jupiter has an AUM of about -2.7, while Saturn has an AUM of about 0.5. The AUM system is an important tool for astronomers studying the solar system and helps to provide a consistent and standardized way of measuring the brightness of celestial objects.

2.2.4 Sky Brightness

The astronomical definition of sky brightness refers to the amount of light that reaches the Earth's atmosphere from celestial objects and the background sky. It is a crucial parameter for observational astronomy, as it affects the detectability and quality of astronomical images. Sky brightness is typically measured in units of magnitude per square arcsecond or square degree. The lower the value, the darker the sky and the better the observing conditions.

2.3 Limiting factor in light pollution data

Sky brightness is influenced by a variety of factors, including the Moon's phase and altitude, the presence of artificial light pollution, and the amount of dust and aerosols in the atmosphere. These factors can change the spectral distribution of the sky brightness, which can affect the quality of observations in certain wavelength ranges.

The astronomical definition of sky brightness differs from other definitions used in environmental or ecological studies, which measure the brightness of the sky at zenith or in a particular direction, rather than over the whole sky. This difference arises from the fact that astronomical observations often require a wide field of view and long integration times, making it necessary to take into account the background sky brightness over a large area.

$$SkyBrightness = \frac{mag}{arcsec^2} \quad (2.1)$$

2.3 Limiting factor in light pollution data

As I began my master's thesis, I quickly realized the importance of carefully defining the study's scope. Various factors, notably the sheer number of locations and atmospheric elements, had the potential to substantially augment the overall volume of data to be analyzed. Thus, it became essential to establish a timeframe for observation that would be deemed "natural" and appropriate for capturing relevant information.

The lower limit of this observational period naturally came to be with the inception and subsequent operation of the lighting network in 2014. The introduction of this infrastructure set a definitive starting point from which to embark upon our investigation. However, determining an upper limit for the observation period presented an initial challenge, requiring meticulous scrutiny and evaluation of the available data.

Regrettably, it came to light that all locations were devoid of light pollution data for the year 2019. Delving deeper into this issue, it was discovered that these critical data had not been appropriately stored, rendering them inadequate for inclusion in our study. Consequently, the absence of comprehensive data for that particular year posed an obstacle to establishing a predefined upper limit.

Therefore, given the absence of reliable data for the year 2019, it became evident that the upper limit of the observation period needed to be determined by the data itself. This approach necessitated a comprehensive analysis of the available information and subsequent adjustments to ensure the integrity and validity of our findings. By allowing the data to guide the upper limit of our study, we aimed to maintain accuracy and ensure that our research remained firmly grounded in the observed reality of the light pollution phenomenon.

3 Air Quality Monitoring Network in Upper Austria

The automatic air measurement network in Upper Austria has been in operation since January 1977. In 2021, a total of 30 points were measured (see Figure 3.1), of which 7 were only for meteorology. Among the 23 pollutant measuring stations, 15 were operational year-round, while the others were only operational for part of the year. In addition to these, Upper Austria also has background measuring stations operated by the Federal Environment Agency, namely Enzenkirchen and Zöbelboden.

The measuring stations used in this study are equipped with state-of-the-art continuously recording measuring devices (Air Quality Report 2021 (Regina Pürmayr et al., 2021)). A computer system controls the measuring devices and generates half-hourly mean values from the recorded raw data. These values are then sent to the measuring network center via mobile communications, where they are retrieved by a Windows server. In addition to the half-hourly mean values, the server also collects status information, device error messages, test logs, and other relevant data every 30 minutes. The server checks for limit or threshold value exceedances and, if necessary, sends an alert to the on-call service.

To ensure data continuity and accuracy, the half-hourly mean values are stored in the station computer for approximately 20 days. Additionally, minute mean averages can be generated and stored in a ring buffer for several days. The control center can access these values periodically or in response to specific needs. Overall, the sophisticated technology and data management system used in this study provide high-quality and reliable data for the analysis and interpretation of air quality trends in Upper Austria.

The stations and gauges undergo routine maintenance at a two-week interval. For most of the pollutant measuring devices, an automatic functional check is conducted approximately once a day by releasing zero gas and test gas. The measurement uncertainty is calculated on a quarterly basis, and the accuracy of the measurement is verified multiple times a year using an independent standard. Additionally, the measuring devices are regularly subjected to a general service in accordance with the manufacturer's specifications.

Measurement uncertainty

With the accredited methods for measuring gaseous pollutants, a maximum combined measurement uncertainty of $\pm 15 \%$ can be expected (trust level of about 95 %).

3 Air Quality Monitoring Network in Upper Austria

To ensure compliance with the EU Air Quality Directive 2008/50/EG, particle measurement must have a combined measurement uncertainty of no more than 25%. Equivalence tests have been carried out to compare the gravimetric method and optical particle measuring devices from Grimm, and these have been found to be compliant with the directive. However, a location-dependent factor must be applied to these devices. Since 2010, only methods that have passed the equivalence test may be used to monitor compliance with limit values.

How to access the data

Immediately after the transmission of the current measured values from the station computers to the measuring network center, the data is forwarded to the databases of the Federal Environment Agency and the city of Linz. In exchange, air quality data measured by these institutions are received and integrated into the measuring network database.

The current measured values, including those that have not yet been viewed, can be accessed through the website¹ of the province of Upper Austria. Under the "Topics" section, followed by "Environment and Nature" and "Air," half-hourly, hourly, and daily mean values of the currently operated air measuring stations can be viewed online. Furthermore, the website allows the user to scroll back several years from the present time to access historical data.

3.1 Which atmospheric Elements are available

3.1.1 Ozone O₃

Ozone (O₃) is an unstable molecule consisting of three oxygen atoms that rapidly decomposes to dimeric oxygen. The name ozone originates from the Greek word *ozein* which means "to smell", as it has a characteristic odor. It is a potent oxidizing agent, and high levels of ozone can be harmful to human health. The gas has a pungent odor similar to chlorine at high concentrations, but it is odorless at low concentrations. The odor threshold is 40 µg/m³, although individuals may become desensitized to the smell over time. Pure O₃ is an unstable, blue diamagnetic gas at room temperature that solidifies below 192.5 °C to a black-purple solid prone to explosive decomposition to O₂.

Ozone forms in the atmosphere in three main ways:

- High-energy solar radiation splits oxygen molecules in the stratosphere into two individual atoms, which each combine with another oxygen molecule to form ozone. This process of splitting oxygen molecules using high-energy UV radiation with a wavelength of <0.242 µm is known as photodissociation.
- Through a thunderstorm: Ozone (but also nitric acid and other substances) is produced by the electrical current flow between the cloud and the ground during

¹<https://www.land-oberoesterreich.gv.at>

3.1 Which atmospheric Elements are available

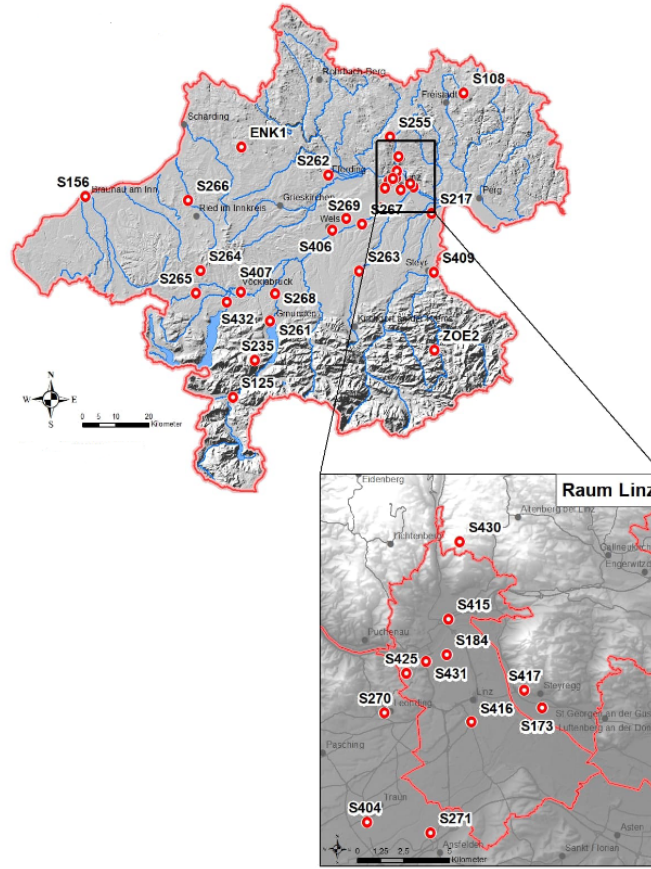


Figure 3.1: Map of the air quality measuring stations in 2021. The small image section shows a zoom of the greater Linz area and the measuring stations located there. Source: Air quality annual report 2023. Reprinted with permission.

the lightning discharge.

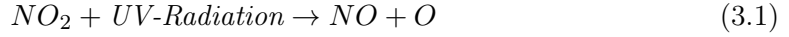
- At ground level, ozone is formed from a reaction between nitrogen dioxide NO_2 and oxygen O_2 under the influence of UV radiation.

In atmospheric studies, ozone is measured in Dobson units (DU), where one Dobson unit represents the number of ozone molecules required to form a layer 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere. Although ozone exists in the atmosphere at a concentration of a few parts per million in the stratosphere, it is mainly formed and destroyed in a cycle with molecular oxygen, known as the ozone-oxygen cycle. Ozone in the stratosphere is beneficial as it absorbs the sun's ultraviolet radiation. However, in the air we breathe, even lower concentrations of ozone can be harmful to human health, and locally varying ozone pollution can cause respiratory tract irritation.

3 Air Quality Monitoring Network in Upper Austria

In areas with low pollution levels, the ozone concentration during summer may actually be higher compared to urban environments. This phenomenon can be attributed to the high concentration of nitrogen oxides (NO) in cities, which is primarily derived from vehicle exhaust emissions. Although, NO plays a significant role in suppressing the formation of ozone through the following reactions:

For producing ozone:



At the same time, ozone is broken down again by NO:



If volatile hydrocarbons or CO were not present in the lower layer of the air, an equilibrium between O_3 , NO, and NO_2 would be established depending on solar radiation, and no further ozone would form. More sunlight leads to the formation of more ozone and less NO_2 , as NO_2 is broken down by UV radiation. However, urban areas, where NO is emitted by cars and industry, experience faster ozone depletion compared to rural areas, as shown in reaction 3.3. Additionally, rural areas often contain more easily attacked hydrocarbons by OH radicals.

3.1.2 Nitrogen Oxides

Nitrogen oxides (NO_x) is a collective term used for gaseous oxides of nitrogen, comprising several nitrogen-oxygen compounds due to the presence of various oxidation states of nitrogen.

Nitrogen oxides, also referred to as NO_x , are a group of reactive nitrogen compounds that are primarily produced through the combustion of fossil fuels. Their presence in the atmosphere can have detrimental effects on both human health and the environment.

Nitrogen oxides are endothermic compounds that are formed by burning fossil fuels or from other industrial processes with external energy supply. They have various technical applications, such as dinitrogen tetroxide in rocket technology or nitrous oxide for hot flames. However, nitrogen oxides are also known to react with water in the atmosphere, forming acidifiers that can irritate and be toxic to humans. Consequently, environmental policies have been implemented to regulate their emission. Nitrous oxide, in particular, has medical and technical uses, but unintentional releases during technical and agricultural processes can act as a greenhouse gas and contribute to ozone depletion.

The primary source of nitrogen oxides in urban areas is traffic emissions, with diesel vehicles contributing the largest share. Unlike industrial emissions that are often released

3.1 Which atmospheric Elements are available

through tall chimneys, traffic emissions are released at ground level, making them particularly detrimental to human health.

Nitrogen Monoxide NO

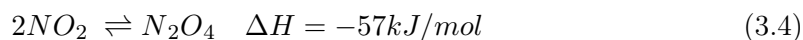
Nitrogen monoxide, also known as nitric oxide (NO), is a colorless gas with a sharp, sweet odor. It is a naturally occurring gas that is produced in the atmosphere by lightning and microbial processes in soils and water bodies. Additionally, NO is also produced by human activities such as fossil fuel combustion, industrial processes, and transportation. NO has a boiling point of -151.7°C (-241°F) and a melting point of -163.6°C (-262.5°F). At room temperature, it is a gas that is slightly soluble in water. It is relatively stable in the atmosphere, with a half-life of around 5 days, and is primarily removed by oxidation to nitrogen dioxide (NO₂). NO plays a critical role in atmospheric chemistry as a precursor to the formation of other pollutants such as nitrogen dioxide (NO₂), ozone (O₃), and particulate matter (PM). It also plays a role in regulating the amount of ozone in the stratosphere and is involved in the nitrogen cycle, which is essential for the growth of plants and other organisms.

NO has both beneficial and harmful effects on human health. In small concentrations, NO can dilate blood vessels and improve blood flow, making it useful in the treatment of pulmonary hypertension and other cardiovascular diseases. However, exposure to high concentrations of NO can cause respiratory irritation, lung damage, and other health problems.

Nitrogen Dioxide NO₂

Nitrogen dioxide, NO₂, is a highly reactive, red-brown gas that emits a pungent chlorine-like odor. It has the ability to easily liquefy and can be found in trace amounts in the atmosphere, with the highest concentrations near the ground.

The critical temperature for NO₂ is 157.8°C and the critical pressure is 10 MPa. Above 200°C , NO₂ decomposes into O₂ and NO, it is also relatively soluble in water, strongly oxidizing and has a pungent odour. The red-brown paramagnetic NO₂ has a strong oxidizing effect and is in equilibrium with the diamagnetic colorless dinitrogen tetroxide N₂O₄, whereby this equilibrium shifts to the left with increasing temperature:



N₂O₄ and NO₂ exhibit properties similar to the mixed anhydride of nitric acid and nitrous acid. When reacted with alkali hydroxide solutions, they form nitrates and nitrites, such as:



3 Air Quality Monitoring Network in Upper Austria

When NO_2 is discharged into water, disproportionation to nitric acid and nitrous acid takes place, with the latter decomposing in the acidic solution to form NO_2 , NO and water.

In the presence of air, NO is oxidized to NO_2 , so that ultimately all the introduced NO_2 is converted into nitric acid:

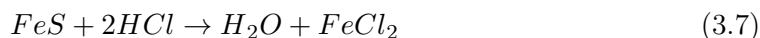


The European Union has established an annual limit value of 40 g/m^3 NO_2 for the protection of human health. Austria has set a more stringent limit of 35 g/m^3 (including a 5 g/m^3 tolerance margin) as an annual mean. However, the World Health Organization has reported that negative health effects on the population can occur at annual concentrations below 20 g/m^3 . Recent studies have suggested that there is no threshold for NO_2 below which health effects can be ruled out. As a result, even low NO_2 values below 10 g/m^3 may have negative effects on health.

3.1.3 Hydrogen sulphide H_2S

Hydrogen sulphide (H_2S) is a highly toxic gas that emits a foul odor, resembling the smell of rotten eggs, even in very small concentrations. It is composed of sulphur and hydrogen and is flammable, colorless, and slightly soluble in water. Hydrogen sulphide is a weak acid, forming sulphides and hydrogen sulphides as its salts. It is present in nature as a variable component of natural gas and crude oil, volcanic gas, and dissolved in spring water. It is also produced during the decomposition of biomass, such as animal carcasses, leaf litter, and sludge formation in eutrophic lakes, as well as in landfills and high-pressure sewage pipes, and as a result of digestive processes in the intestine.

Hydrogen sulphide is a weak acid with a pK_a value of 7.05, similar to sulphurous acid. When its aqueous solution reacts with heavy metal salts, it produces insoluble sulphides, which are useful in the cation separation process. Detection of the gas is done using lead acetate paper, as it reacts with lead(II) ions, forming black lead sulphide (PbS), or iron(II) ions, forming black iron sulphide (FeS). In the laboratory, hydrogen sulphide can be produced by dripping hydrochloric acid onto iron sulphide.



The above recovery reaction is also reversible. Under natural conditions (pH 5–10), hydrogen sulphide in aqueous solution can be bound with iron(II) chloride to form iron sulphide.



The use of iron for the removal of sulphur is a widely accepted practice in various applications, including biogas, digester gas, and sewage systems. This is due to the strong affinity of iron towards sulphur, which effectively removes it from the gas. The presence

3.1 Which atmospheric Elements are available

of sulphur dioxide in the gas after combustion could cause severe corrosion problems in gas engines, making sulphur removal essential.

Hydrogen sulphide burns with a blue flame when exposed to air, producing sulphurous acid (H_2SO_3) and other by-products. Over time, when exposed to air, sulphur separates from the aqueous solution.

Hydrogen sulphide gas can undergo comproportionation with sulphur dioxide gas in the presence of water vapour, resulting in the formation of sulphur and water (known as flue gas desulfurization, a redox reaction). Similarly, it reacts with chlorine gas to form sulphur and hydrogen chloride gas (hydrochloric acid). When burned in the presence of oxygen, it forms sulphur dioxide and water vapour. Additionally, hydrogen sulphide gas is known to be a potent reducing agent.

3.1.4 Sulphur Dioxide SO_2

Sulphur dioxide (SO_2) is the anhydride of sulphurous acid (H_2SO_3). This toxic, colourless gas has a pungent odor and sour taste. It is mainly produced by the burning of fossil fuels such as coal or petroleum, which can contain up to 4% sulphur. This contributes significantly to air pollution and is the cause of acid rain. When sulphur dioxide is oxidized by oxygen, it forms sulphur trioxide, which then reacts with water to form sulphuric acid (H_2SO_4). Various flue gas desulfurization processes are used to prevent this. Liquid sulphur dioxide is a valuable solvent due to its ability to dissolve numerous substances.

In the food industry, sulphur dioxide is used as a preservative and antioxidant (under the designation E 220) for dried fruit, potato dishes, fruit juices, jam, and wine. It is also used to produce sulphuryl chloride (SO_2Cl_2) and thionyl chloride (SOCl_2). Sulphur dioxide is an important starting material for the production of sulphur trioxide, which is used to produce concentrated sulphuric acid using the contact method. Sulphur dioxide is also used in the manufacture of chemicals, medicines, and dyes, and in the bleaching of paper and textiles.

However, high concentrations of SO_2 can damage people, animals, and plants. The oxidation products can cause acid rain, which endangers sensitive ecosystems and can damage buildings and materials. To reduce SO_2 emissions, developed industrialized countries have been using low-sulphur or sulphur-free combustibles and fuels over the past two decades.

3.1.5 Carbon Monoxide

Carbon monoxide, a silent specter in our atmosphere, weaves its way through the tapestry of scientific inquiry. This colorless, odorless gas, a simple union of one carbon and one oxygen atom, holds a place of profound significance across chemistry, environmental

3 Air Quality Monitoring Network in Upper Austria

science, and health studies.

Picture, if you will, a molecule so small yet so impactful. Its linear structure, bound by a triple bond, gives it a molecular weight of just 28.01 grams per mole. In the dance of states, carbon monoxide prefers to waltz through the air, boiling at a frigid -191.5 degrees Celsius and only solidifying at an even more extreme -205 degrees. At room temperature, it's a wisp in the wind, barely tipping the scales at 1.25 grams per liter.

This elusive gas plays hard to get with water, barely dissolving at 3.5 milligrams per liter. Yet, it's quick to take flight, its low vapor pressure a testament to its flighty nature. And beware the flame - carbon monoxide's flammability makes it a dangerous dance partner for any spark or open fire.

From whence does this ghostly gas emerge? Primarily, it's the unwanted child of incomplete combustion, born from the inefficient burning of fossil fuels, biomass, and other carbon-rich materials. It seeps from vehicles, factories, and even our own homes. But nature, too, has a hand in its creation - volcanoes belch it forth, wildfires release it into the sky, and even the very air we breathe slowly oxidizes methane into this compound. The implications of carbon monoxide's presence ripple far and wide. In our environment, it's a troublemaker, contributing to the haze of ground-level ozone and diminishing air quality, especially in the concrete jungles of our cities. For us humans, it's a silent threat, sneaking into our bloodstream and hijacking our hemoglobin, potentially leading to dire consequences if we breathe too much.

Yet, for all its dangers, carbon monoxide finds purpose in human hands. In the realm of industry, it becomes a useful tool - a reducing agent in metallurgy, a building block for chemicals like methanol and acetic acid. Its behavior during combustion fascinates engineers, guiding the design of everything from car engines to power plants.

3.1.6 Particular Matter

Particulate matter (PM) is a complex mixture of solid and liquid particles suspended in the atmosphere. These particles can have various sources, including natural phenomena like dust storms or wildfires, and human activities such as transportation, industry, and energy production. PM can be classified based on its aerodynamic diameter, with fine particulate matter (PM_{2.5}) having a diameter of 2.5 micrometers or less, and coarse particulate matter (PM₁₀) having a diameter of 10 micrometers or less.

Fine particulate matter (PM_{2.5}) is a major air pollutant of concern due to its ability to penetrate deeply into the lungs and cause adverse health effects, including respiratory and cardiovascular diseases. PM_{2.5} is produced by a variety of sources, including combustion processes such as vehicle engines and power plants, as well as secondary particles formed from the reaction of precursor gases in the atmosphere.

3.1 Which atmospheric Elements are available

The physical conditions that affect the behavior of PM in the atmosphere include atmospheric stability, wind speed, and precipitation. Atmospheric stability refers to the degree to which air tends to rise or sink. When the air is stable, pollutants are trapped close to the surface, leading to higher concentrations of PM. In contrast, when the air is unstable, pollutants are more easily dispersed, leading to lower concentrations. Wind speed also plays a role in the dispersion of PM, with higher wind speeds leading to more rapid dispersal. However, under certain conditions, such as during temperature inversions, wind speed may not be enough to disperse pollutants. Precipitation can also affect PM concentrations by scavenging particles from the atmosphere and depositing them on the ground.

The health effects of PM_{2.5} have been extensively studied, and it has been linked to various respiratory and cardiovascular diseases. Long-term exposure to PM_{2.5} has also been associated with premature death. In addition to its effects on human health (WHO-Report, 2003), PM can also have environmental impacts, including reduced visibility, crop damage, and changes in climate (Ścieżor and Kubala, 2014).

To address the issue of PM pollution, various measures have been taken, including the use of air filters and pollution control technologies in vehicles and industries, as well as regulations on emissions. In addition, individuals can take steps to reduce their exposure to PM, such as avoiding outdoor activities during times of high pollution and using air purifiers indoors.

4 Observation sites

The selection of optimal combinations of individual measuring stations presents a complex challenge, particularly in urban environments such as Linz (see Figure 4.1), where numerous permutations exist for pairing air quality monitoring stations with light measurement stations. In contrast, rural areas offer a more straightforward selection process, as the coincidence of air quality and light measurement stations is typically limited to proximate installations. Nevertheless, to ensure a systematic and rigorous approach to station selection, the following criteria have been established:

Selection Criteria

1. Astronomical reference
2. Geography
3. Imitate Environment
4. Population of the surrounding area
5. Distances between air quality measurement stations and light pollution measurement stations
6. Available measurement data

To facilitate a comprehensive comparative analysis of data across diverse geographical contexts, this study incorporates a stratified sampling approach. Specifically, two urban, two suburban, and two rural areas have been selected as representative case studies. This methodological design serves a dual purpose: firstly, it enables a nuanced examination of light pollution dynamics across varying degrees of urbanization; secondly, it allows for the exploration of potential correlations between light pollution intensity and ambient pollutant concentrations.

The inclusion of these distinct environmental categories is intended to elucidate the complex interplay between anthropogenic activities, atmospheric composition, and light pollution patterns. By juxtaposing data from urban centers, transitional suburban zones, and rural landscapes, this research aims to uncover potential gradients in light pollution severity and to assess the relative influence of pollutant concentrations on nocturnal illumination levels.

4 Observation sites

Furthermore, this comparative framework is designed to shed light on the eminent influence of various factors on light pollution, potentially revealing location-specific trends or universal patterns that transcend geographical boundaries. The insights gleaned from this multi-faceted analysis are expected to contribute significantly to our understanding of light pollution as a multidimensional environmental phenomenon.

To elucidate the methodological approach employed in the selection process of measurement stations, this study presents a detailed case analysis using Linz as an exemplar. This urban center serves as a paradigmatic instance, demonstrating the rigorous selection criteria applied uniformly across all measurement stations, encompassing both light and air quality monitoring facilities.

The Linz case study is structured to provide a comprehensive overview of the selection methodology, offering insights into the decision-making process and the rationale behind each choice. This exemplar is designed to be representative of the broader selection process implemented throughout the study area.

4.1 Urban environments

An urban location can be defined as a site where the night sky is strongly illuminated by artificial lighting, typically by a factor of 100 more than the natural brightness of the night sky. In addition, there is a significant absence of the lunar cycle, but a strong seasonal variation (marked by $2 \text{ mags}_{\text{SQM}}/\text{arcsec}^2$). Compared to the other location types, the higher night sky brightness in urban areas is due to a strong infrastructure development, such as well-lit streets, shops, illuminated billboards, etc. Clouds can also greatly contribute to the illumination of the night sky in urban locations. The typical zenithal night sky brightness for an urban site ranges from 17 to $18.5 \text{ mags}_{\text{SQM}}/\text{arcsec}^2$.

4.1.1 Linz

Linz, the capital of the Austrian federal state of Upper Austria, boasts a population of almost 207,247 inhabitants (as of January 1, 2022) and is the third largest city in Austria, following Vienna and Graz. Due to the presence of several light and air measurement stations in Linz, it is imperative to compare and evaluate the existing measurement stations to determine which one is best suited for the purpose of this study.

Light pollution data is collected simultaneously at 3 different locations in the greater Linz area:

Goethestraße

The light pollution measurement site known as "Goethestraße" is situated on the rooftop of the Upper Austrian Provincial Inspection Station. The surrounding area is predominantly densely built residential areas interspersed with some green spaces. To

the southwest, approximately 200 meters away, is the Linz Design Center, which hosts various events. The industrial area and port are located to the west, about 1 km away. The city center is approximately 1.6 km away, measured as the crow flies.

Schlossmuseum

The light pollution measuring point "Schlossmuseum" is situated on the roof of the Schlossmuseum Linz, in the heart of the old town, surrounded by densely populated residential buildings and the museum's green spaces. The Danube flows past to the north, separating Linz from Alt-Urfahr. Towards the west, the Freinberg rises and the density of residential areas decreases somewhat. In this direction, several buildings are permanently illuminated at night, including the Lentos, Ars Electronica Center, and Archotel. To the south of the measuring station lie the Linzer football stadium and the main train station.

Sternwarte

The light pollution measuring point "Sternwarte" is situated at the balcony of the Johannes Kepler observatory in Linz, making it the most remote station in the city. The surrounding area is mainly covered with loosely built-up residential areas, with a garden center and a dog run zone located nearby. The Linz football stadium is about 600 meters away to the east, while the A7 motorway and the Linz main station are situated to the south-east. The measuring station is approximately 2 km away from the center of Linz in a relatively isolated location.

Air quality data is collected simultaneously at five different locations in the greater Linz area:

Linz 24er Tower

The air quality measuring station located within the A7 motorway loop, after the "Linz-Urfahr" exit, has been operational since 1979. It is named after the 24er Tower, an artillery bunker built in 1830, also known as "Ehrentrude." The primary purpose of this measuring station is to measure the effects of traffic coming from Freistadt. The station is situated directly on the Danube and is surrounded by the Danube Bridge from below. To the north of the 24er Tower air measurement station is the St. Magdalena district of Linz, with approximately 12,000 residents. The port of Linz is situated to the southeast of the station and is mainly used by logistics and industrial companies, with only 34 of the 736 buildings declared as apartments. The center of Linz is located southwest of the A7 Autobahn loop.

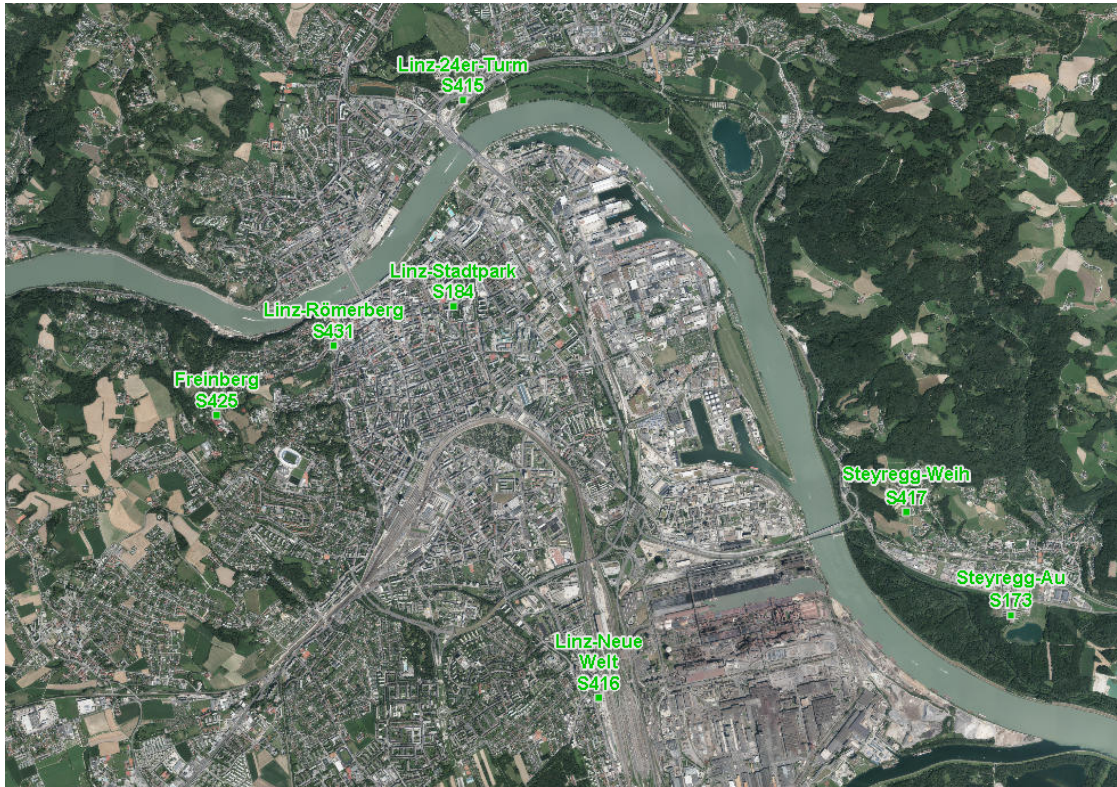


Figure 4.1: Air quality measuring stations in the greater area of Linz, including Steyregg

- The distance between the air quality measuring station 24er Turm and the light pollution measuring station at Goethestraße is **2.68 km**.
- The distance between the air quality measuring station 24er Turm and the light pollution measuring station attached to the Castle Museum is **2.32 km**.
- The distance between the air quality measuring station 24er Turm and the light pollution measuring station attached to the Johannes Kepler observatory is **4.02 km**.

Neue Welt

The air quality measuring station "Neue Welt" is strategically located within the tram loop of Wienerstraße in the Spallerhof district of Linz, which is home to about 13,000 residents. It provides valuable data to measure the air quality of the area, particularly due to its proximity to significant transport links such as the busy B1 federal road, the A7 Autobahn, and the Unionstraße, Wiener Straße, and Voestalpine traffic junctions, all within a radius of 1.6 km. Furthermore, the station is located approximately 600 meters from the heavy industrial area of the Voest Alpine, which spans over about 5 km² towards

Measured components at 24er Tower (air pollutants and meteorological variables)	
Ozone	12/85 - 12/92
PM 10	12/00 -
PM 2.5	03/16 -
Nitrogen Oxides	07/79 -
Sulphur Dioxide	07/79 -
Hydrogen Sulphide	-
Relative Humidity	04/93 -
Carbon Monoxide	07/79 -

Table 4.1: List of measured atmospheric elements at 24er Tower.

the west.

To the northwest of the measuring station is the center of Linz, located about 3.5 km away. Additionally, the Wasserwald, a 1.5 km² natural area that is part of the Scharlinz water protection area, is located less than 500 meters to the southwest. This location provides a unique opportunity to study the impact of different environmental factors on the air quality of an urban area.

- The distance between the air quality measuring station "Neue Welt" and the light pollution measuring station at Goethestraße is **3.02 km**.
- The distance between the air quality measuring station "Neue Welt" and the light pollution measuring station attached to the Castle Museum is **4.27 km**.
- The distance between the air quality measuring station "Neue Welt" and the light pollution measuring station attached to the Johannes Kepler observatory is **4.10 km**.

Measured components at Neue Welt (air pollutants and meteorological variables)	
Ozone	05/82 -
PM 10	12/00 -
PM 2.5	08/10 -
Nitrogen Oxides	05/82 -
Sulphur Dioxide	03/82 -
Hydrogen Sulphide	05/82 -
Relative Humidity	03/82 -
Carbon Monoxide	05/82 -

Table 4.2: List of measured atmospheric elements at Neue Welt.

Stadtpark

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The air quality measuring station "Stadtpark" was installed on October 29th, 2008, and is situated at the northern end of the park. It measures air quality near the center of Linz, located only 750 meters from the main square of the city. The immediate surroundings consist mostly of residential buildings, parks, and the Kepler Med Campus 3 (former AKH).

To the east and southeast, the station is approximately 1.5 to 2.5 km away from the port and heavy industrial area, as well as the A7 motorway with the Hafenstraße and Prinz-Eugen-Straße junctions. In the north, the Danube River runs adjacent to the station, and other facilities such as the Tips Eisarena, hotels, and the Takak factory can be found nearby. Additionally, some busy roads such as Gruberstraße are also located in the vicinity of the station.

- The distance between the air quality measuring station "Stadtpark" and the light pollution measuring station at Goethestraße is **1.06 km**.
- The distance between the air quality measuring station "Stadtpark" and the light pollution measuring station attached to the Castle Museum is **1.08 km**.
- The distance between the air quality measuring station "Stadtpark" and the light pollution measuring station attached to the Johannes Kepler observatory is **2.56 km**.

Measured components at Stadtpark (air pollutants and meteorological variables)	
Ozone	05/14 -
PM 10	11/08 -
PM 2.5	06/09 -
Nitrogen Oxides	10/08 -
Sulphur Dioxide	-
Hydrogen Sulphide	04/11- 01/14
Relative Humidity	10/08 -
Carbon Monoxide	-

Table 4.3: List of measured atmospheric elements at Stadtpark.

Freinberg

The Freinberg air quality measuring station is situated on the western edge of Linz, atop a large transmission mast (127m) attached to the hilltop. The surrounding area comprises residential neighborhoods in the suburbs of Linz. The station is approximately 1.70 km to the east of the city center. To the north, the Freinberg extends further towards the Danube. The Tips Arena is located to the southeast, with Linz's main train station lying further beyond. Towards the west, the density of inhabited areas decreases rapidly, giving way to meadows, fields, and forests. The city of Leonding lies approximately 2.15 km to the southwest of the station.

- The distance between the air quality measuring station "Freinberg" and the light pollution measuring station at Goethestraße is **3.03 km**.
- The distance between the air quality measuring station "Freinberg" and the light pollution measuring station attached to the Castle Museum is **1.44 km**.
- The distance between the air quality measuring station "Freinberg" and the light pollution measuring station attached to the Johannes Kepler observatory is **435 m**.

Measured components at Freinberg (air pollutants and meteorological variables)	
Ozone	05/00 - 01/03
PM 10	05/00 - 01/03
PM 2.5	-
Nitrogen Oxides	05/00 - 01/03
Sulphur Dioxide	-
Hydrogen Sulphide	-
Relative Humidity	04/01 - 01/03
Carbon Monoxide	-

Table 4.4: List of measured atmospheric elements at Freinberg.

Römerberg

The Römerberg air quality measuring station is located in the heart of Linz, just 450 meters from the main square. The station is situated at the southern exit of the Römerberg tunnel, which is a significant and busy traffic point in the city. The B 139 federal road passes right next to the measuring station and provides one of the few connections to the A7 motorway further south. The surrounding area is densely populated with residential buildings.

The port and heavy industrial area is located approximately 4 km to the east, while to the north, the Danube separates Linz from Alt-Urfahr beyond the 286-meter-long Römerberg tunnel. The Gugl, a hill on which the Linzer stadium is located, rises to the southwest. About 1.6 km to the south is Linz's main train station.

- The distance between the air quality measuring station "Römerberg" and the light pollution measuring station at Goethestraße is **1.95 km**.
- The distance between the air quality measuring station "Römerberg" and the light pollution measuring station attached to the Castle Museum is **246 m**.
- The distance between the air quality measuring station "Römerberg" and the light pollution measuring station attached to the Johannes Kepler observatory is **1.48 km**.

Measured components at Römerberg (air pollutants and meteorological variables)	
Ozone	12/85 - 12/92
PM 10	12/00 -
PM 2.5	06/11 -
Nitrogen Oxides	10/97 -
Sulphur Dioxide	10/97 - 11/03
Hydrogen Sulphide	-
Relative Humidity	10/97 -
Carbon Monoxide	10/97 -

Table 4.5: List of measured atmospheric elements at Römerberg.

Steyregg-Weih

The air quality measuring station "Steyregg-Weih" is located on the Obernberg, approximately 1.25 km west of the center of Steyregg. Positioned on hilly terrain 80 meters above the Danube valley, the station overlooks a loosely built-up residential area and extensive agricultural land, with nearly 5,000 residents living in the immediate vicinity.

To the west of the station, approximately one kilometer away, lie the industrial area of Voest, the chemical park, and the port of Linz. In contrast, the north-northwest area comprises mostly forests and small isolated communities amidst agricultural land, while the south of the station is separated from Steyregg by a small loop of the Danube, with the outgoing industrial area on the opposite bank.

In 2008, pollutant measurements were moved to Steyregg-Au, while precipitation continues to be collected and analyzed. However, the amount of precipitation has not been continuously measured since 1998.

- The distance between the air quality measuring station "Steyregg-Weih" and the light pollution measuring station at Goethestraße is **3.60 km**.
- The distance between the air quality measuring station "Steyregg-Weih" and the light pollution measuring station attached to the Castle Museum is **5.57 km**.
- The distance between the air quality measuring station "Steyregg-Weih" and the light pollution measuring station attached to the Johannes Kepler observatory is **6.34 km**.

Steyregg-Au

The air quality measuring station in "Steyregg-Au" is located 670 meters south of the center of Steyregg, on the edge of a community with a population of about 5,000. The station is situated in a rural floodplain area, bounded by the Danube to the south. The

Measured components at Steyregg-Weih (air pollutants and meteorological variables)	
Ozone	04/82 - 04/08
PM 10	12/00 - 03/08
PM 2.5	-
Nitrogen Oxides	05/82 - 04/08
Sulphur Dioxide	03/82 - 04/08
Hydrogen Sulphide	05/82 - 04/08
Relative Humidity	03/82 -
Carbon Monoxide	04/82 - 04/08

Table 4.6: List of measured atmospheric elements at Steyregg-Weih.

local environment is characterized by agricultural land, with the industrial area located approximately 2.5 km away.

Unfortunately, in June 2013, the Steyregg-Au measuring station was destroyed by flooding. However, it was restored and put back into service later that summer.

- The distance between the air quality measuring station "Steyregg-Au" and the light pollution measuring station at Goethestraße is **4.88 km**.
- The distance between the air quality measuring station "Steyregg-Au" and the light pollution measuring station attached to the Castle Museum is **6.82 km**.
- The distance between the air quality measuring station "Steyregg-Au" and the light pollution measuring station attached to the Johannes Kepler observatory is **7.42 km**.

Measured components at Steyregg-Au (air pollutants and meteorological variables)	
Ozone	04/08 - 04/14
PM 10	05/06 - 02/08; 04/08 -
PM 2.5	05/15 -
Nitrogen Oxides	05/06 - 02/08; 04/08 -
Sulphur Dioxide	05/06 - 02/08; 04/08 -
Hydrogen Sulphide	09/06 - 02/08; 04/08 - 05/13
Relative Humidity	10/97 -
Carbon Monoxide	10/06 - 02/08; 04/08 -

Table 4.7: List of measured atmospheric elements at Steyregg-Au.

4.1.2 Steyr

The air quality measuring station in Steyr is located on a small hilltop on the eastern outskirts of the city, approximately 20 meters above the surrounding area. The area

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around the station consists of a loosely built-up residential area with ample green spaces. The busy federal road B122 runs to the south of the station. The industrial area of Steyr is located 500 meters to the east, which is mainly occupied by the BMW plant. Another industrial hotspot is located approximately 1.1 km to the south-west, which includes Steyr Automotive and Steyr Precision Technology. The city center is approximately 2 km away to the south-west. The Enns River flows through the city from the north, dividing it into two halves, the western and eastern parts.

The light pollution measuring station is attached directly to the air quality measuring station.

Measured components at Steyr (air pollutants and meteorological variables)	
Ozone	05/91 -
PM 10	08/01 -
PM 2.5	10/12 -
Nitrogen Oxides	08/91 -
Sulphur Dioxide	07/78 -
Hydrogen Sulphide	-
Relative Humidity	07/78 -
Carbon Monoxide	08/91 - 05/17

Table 4.8: List of measured atmospheric elements at Steyr.

4.2 Intermediate environments or suburban environments

In long-term observations, suburban areas exhibit less pronounced circalunar rhythms and a moderate seasonal variation characterized by fluctuations in the range of 1-1.5 mags_{SQM}/arcsec². When comparing urban and suburban locations, a gradual shift between the two categories can be observed. If suburban measuring stations are situated in close proximity to larger settlements, the night sky brightness is affected in most terrain conditions, resulting in values ranging from 18.5 to 20 mags_{SQM}/arcsec².

4.2.1 Vöcklabruck

Vöcklabruck is a small township located in the Hausruckviertel region of Upper Austria with a population of approximately 12,500 people as of January 2022. The air quality measuring station is situated on the eastern outskirts of the city in close proximity to meadows, detached houses, a lightly trafficked road, and the Ager River. The surrounding area comprises of commercial enterprises and sparsely built residential areas. The federal road B1, a major thoroughfare, passes through the city about 400 meters away from the station. The town square is approximately 1.31 km to the northwest. The Eternit Austria

factory is located about 500 meters to the south-west of the measuring station.

The light pollution measuring station is located atop the district authority building in Vöcklabruck, approximately 1.74 km away from the air quality measuring station.

Measured components at Vöcklabruck (air pollutants and meteorological variables)	
Ozone	-
PM 10	01/01 -
PM 2.5	10/12 -
Nitrogen Oxides	05/02 -
Sulphur Dioxide	07/78 -
Hydrogen Sulphide	06/85 -
Relative Humidity	07/78 -
Carbon Monoxide	-

Table 4.9: List of measured atmospheric elements at Vöcklabruck.

4.2.2 Braunau am Inn

Braunau am Inn is the oldest and most populous town in the Innviertel region of Upper Austria, with approximately 17,400 inhabitants (as of January 2022). It forms a cross-border center with the German town of Simbach am Inn. The air quality measuring station is located less than 300 meters from the city center, next to the Braunau bus terminal in the parking lot of a special school. The immediate vicinity is densely populated, and there is a busy road nearby. Additionally, several industrial companies, including a concrete plant to the south, an aluminum plant to the southwest, and a larger industrial and commercial area to the northwest, are all within approximately 3km. The B148, the main traffic artery, runs past the southern outskirts of the city, while Braunau train station is located to the west of the air measurement station.

The light pollution measuring station is located approximately 600 meters northeast of the air quality measuring station, attached to the roof of the district administration building.

4.3 Rural environments

In rural locations, the circalunar rhythm is strongly represented in the long-term plots. This means that the average night-time brightness varies considerably depending on the phase of the moon. Unlike urban and suburban locations, the night sky brightness in rural areas is not determined by the number of inhabitants, but rather by their proximity to settlements, as well as the geographic and topological features of the area. Typically, the mean values for the night sky brightness in rural areas range from 20-21.5 SQM/arcsec².

Measured components at Braunau (air pollutants and meteorological variables)	
Ozone	10/99 -
PM 10	01/01 -
PM 2.5	09/14 -
Nitrogen Oxides	10/99 -
Sulphur Dioxide	10/99 -
Hydrogen Sulphide	-
Relative Humidity	10/99 -
Carbon Monoxide	10/99 - 12/13

Table 4.10: List of measured atmospheric elements at Braunau.

4.3.1 Feuerkogel

The Feuerkogel, situated at an elevation of 1592m, is a mountain located west of Ebensee, adjacent to Lake Traunsee in Upper Austria. It marks the eastern end of the Höllengebirge range, which falls under the northern Kalkalpen, and lies between Traunsee and Attersee. The air quality measuring station is positioned around 100 meters to the west of the Feuerkogelbahn mountain station at a height of 1602 meters above sea level, amidst the alpine region. The station is surrounded by alpine pastures, individual trees, and houses like mountain huts and the mountain station. The town center of Ebensee is approximately 4 km away to the east, while to the south, industries such as Salinen Austria and the plastics manufacturer Polytec are located.

One advantage of this measuring station is that the light pollution measuring system is co-located with the air quality measuring station, as it is attached to the same container. This arrangement enables the simultaneous measurement of both air quality and light pollution levels at the same location and under the same environmental conditions, which can be beneficial for comparative studies and analysis.

Measured components at Feuerkogel (air pollutants and meteorological variables)	
Ozone	04/15 -
PM 10	01/16 -
PM 2.5	01/16 -
Nitrogen Oxides	10/15 - 03/18
Sulphur Dioxide	10/15 - 03/18
Hydrogen Sulphide	-
Relative Humidity	04/15 -
Carbon Monoxide	-

Table 4.11: List of measured atmospheric elements at Feuerkogel.

To accurately represent mountain conditions, measurements at various altitudes are necessary. Measuring points above 1000m were previously lacking in the Northern Alps,

making the data from the Feuerkogel station in April 2015 crucial in improving Upper Austria's forecast at all altitudes.

Moreover, the Feuerkogel station is essential in detecting long-distance transport phenomena, such as Saharan dust, volcanic ash, and exhaust gases from the valley. In 2016, the station was upgraded with measuring devices for PM 10 and PM 2.5 to enhance its capabilities.

4.3.2 Grünbach

Grünbach is situated at an altitude of 918 m, approximately 4 km northeast of the district capital Freistadt in Upper Austria. The air quality measuring station is located near the church of St. Michael, about 3 km east of Grünbach in Oberrachenödt. The station is surrounded by meadows and a lightly used road, with sparse residential development dominated by isolated farms and agricultural fields in the local area. A small quarry, located about 2 km away, is the only industrial activity in the vicinity. The topography of the area is characteristic of the Mühlviertel region, with a hilly landscape featuring numerous depressions and hilltops.

The light pollution measuring station is co-located with the air quality measuring station, attached to the roof of the container, enabling simultaneous measurements of both parameters.

Measured components at Grünbach (air pollutants and meteorological variables)	
Ozone	01/86 - 03/87; 11/95 -
PM 10	01/01 -
PM 2.5	11/09 -
Nitrogen Oxides	11/95 -
Sulphur Dioxide	01/86 - 03/87; 11/95 -
Hydrogen Sulphide	-
Relative Humidity	11/95 -
Carbon Monoxide	-

Table 4.12: List of measured atmospheric elements at Grünbach.

4.4 Selected Areas/Stations

After thorough examination of all locations based on the criteria established in 4, the following selection emerges:

For Urban environments:

- Linz Sternwarte
- Steyr

For intermediate and suburban environments:

- Braunau
- Vöcklabruck

For rural environments:

- Feuerkogel
- Grünbach

5 Data

5.1 Previous Attempts to correlate night sky brightness and aerosol content

The study by Posch et al. (2018) examined the relationship between Night Sky Brightness and PM₁₀ concentrations using monthly averages from the Vöcklabruck station in 2016. Analysis revealed a clear correlation: summer and early autumn exhibited lower PM₁₀ values and darker skies, while winter showed higher PM₁₀ levels and brighter skies. Both NSB and aerosol measurements were taken at the same location and elevation, ensuring direct comparability. This observed seasonal pattern suggests a potential link between air pollution and night sky brightness (see Figure 5.1), contributing to our understanding of environmental interactions.

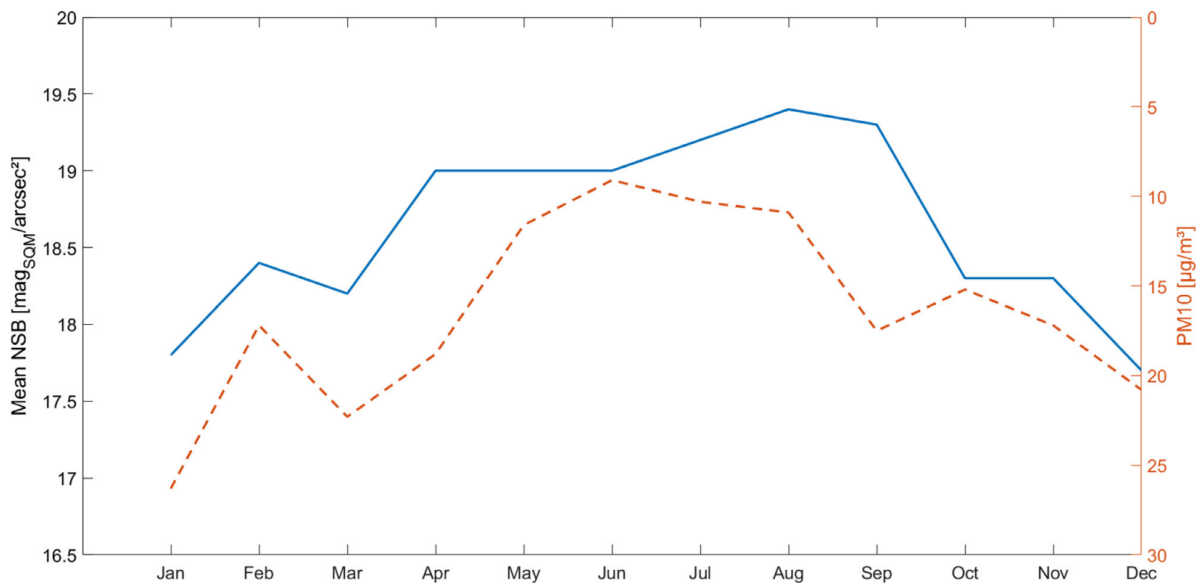


Figure 5.1: Correlation between Night Sky Brightness (solid line) and PM 10 concentration (dotted line) at the urban station Vöcklabruck in 2016. Both data sets consist of monthly average values. By Posch et al. (2018). Reprinted with permission.

5.2 Observation Period

The determination of the analysis time frame warrants careful consideration. The establishment of the light measurement network in 2014 serves as the starting point, necessitating the identification of an upper limit. Ensuring comprehensive data coverage for both air and light quality metrics was of utmost importance. Upon initial data collection and examination, a notable gap spanning the entirety of 2019 was observed in the downloaded light quality datasets from 2014 to 2023. Despite diligent inquiries made to relevant authorities, the whereabouts of the 2019 data remained unresolved. Consequently, the upper boundary of the observation period was established. This scientific inquiry thus focuses on the timeframe spanning from **January 1st, 2015, to December 31st, 2018**.

5.3 Downloading and Plotting the Datasets for the first time

One of the primary challenges encountered at the outset of this research endeavor pertained to the acquisition of comprehensive and relevant data. While the sources have been duly acknowledged and discussed in preceding chapters, the significant effort required to gather the extensive datasets has yet to be addressed. The initial step involved retrieving all pertinent light pollution data from the Upper Austrian Lighting Network for the designated study locations. Despite initial optimism, the process necessitated several iterations to accurately configure the parameters, a matter which will be elucidated further in subsequent sections.

Substantial complications emerged upon accessing and scrutinizing the air quality data for the first time. It became evident that the data available for rural areas was largely incomplete. Collaborative consultation with my supervisor, who also navigated this procedural challenge, confirmed that the issue did not stem from any errors on my part, but rather from the unavailability of the data itself. Consequently, a formal inquiry was expeditiously drafted and forwarded to the relevant authorities. Following an extended period of silence, a response was eventually received, requesting a detailed outline of the requisite data, as it was not accessible online due to unspecified reasons. Regrettably, the processing of this request was protracted, resulting in nearly two months elapsing before obtaining all the necessary data for comprehensive analysis. After this grueling ordeal, I had just under **4.000.000 data points** at my disposal.

The subsequent phase involved the initiation of data visualization through plotting the raw datasets. A preliminary iteration of this process was undertaken during the preparatory phase to provide a preliminary understanding. The primary objective at this juncture was to ensure the presence of discernible trends spanning the entirety of the four-year duration and across all measurement parameters. While a definitive correlation between light quality data and air quality data remains contingent upon rigorous statistical analysis, initial observations reveal apparent correlations. The following plots are generated

5.3 Downloading and Plotting the Datasets for the first time

employing the unused datasets sourced from the city of Steyr.

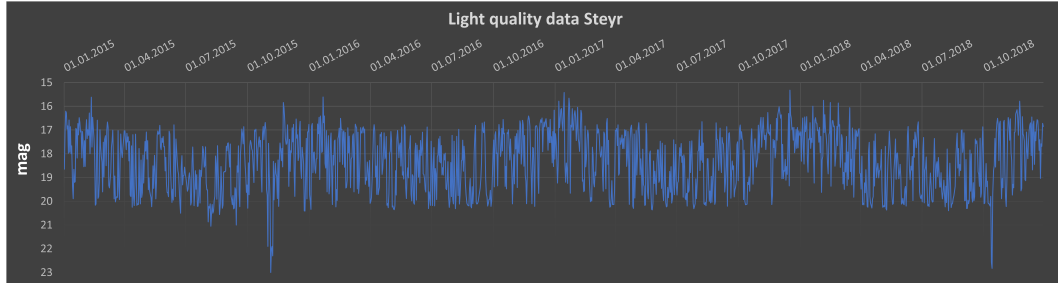


Figure 5.2: Light quality data from the city of Steyr

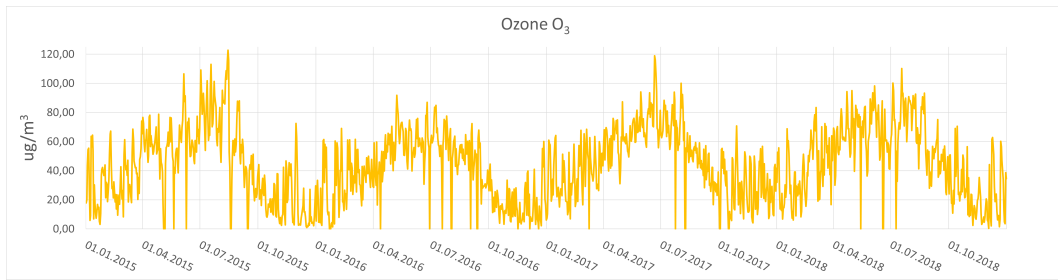


Figure 5.3: Air Quality data Ozone from the city of Steyr

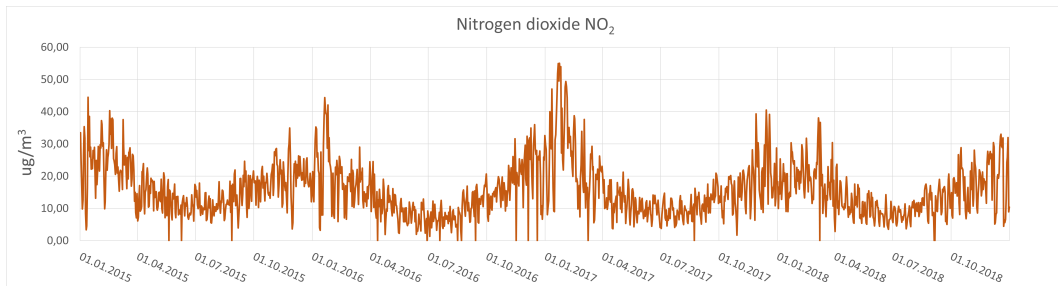


Figure 5.4: Air Quality data Nitrogen dioxide from the city of Steyr

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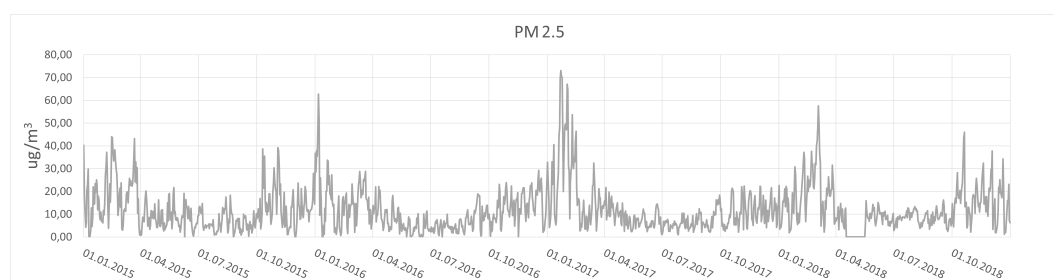


Figure 5.5: Air Quality data PM 2.5 from the city of Steyr

First Impression

An initial examination of the unprocessed raw data spanning the entire four-year period yields intriguing insights. It is important to emphasize that these plots remain unaltered and have undergone no reduction whatsoever. These plots represent the averaged brightness values and air quality data sourced directly from the Upper Austrian download platform. Subsequent plots will utilize minute-by-minute or hour-by-hour measurements, which undergo processing and adjustments to ensure greater accuracy in the results.

The **light quality data** reveal an average fluctuation range of approximately four magnitudes, exhibiting an annual recurrence, with peak values observed in winter and troughs in summer. As indicated by Kocifaj et al. (2014), this seasonal variation can be primarily attributed to winter snowfall, which significantly enhances ground reflectivity. This, in conjunction with cloud cover, amplifies atmospheric backscattering. Conversely, the absence of snow in summer, coupled with the foliage of trees and other vegetation, acts as a natural shield against unwanted artificial light. Throughout this study, we will explore the extent to which different sources of air pollution contribute to this phenomenon. In addition, there are outliers reaching approximately the 23 magnitude mark, likely attributable to erroneous measurements. Before we continue, let's look at the raw air pollution data and compare it to the light quality data.

An initial observation of the selected **air quality data** reveals a significant disparity: ozone (Figure 5.3) behaves inversely proportional to nitrogen dioxide and PM 2.5. This phenomenon was anticipated, as discussed in Chapter 4.1.1 regarding the formation and depletion of ozone at ground levels.

Upon comparison with light quality data, nitrogen dioxide (Figure 5.4) and PM 2.5 (Figure 5.3) exhibit a directly proportional relationship. Notably, the striking similarity among the individual air quality data curves (even with only three listed here) is apparent. The peaks of the air quality data align perfectly with those of the light quality data. However, the precise extent of the direct influence of this air pollution on light pollution warrants further detailed investigation.

5.4 Getting the data in shape

To maximize the significance and reliability of the collected data, a comprehensive reduction process is essential. This chapter delineates the sequence of reduction steps necessary for optimal data analysis. It is important to note that the application of each step in its entirety may not always be feasible due to various constraints, including time limitations and occasional insufficiency of available information.

The following sections will outline the rationale behind each reduction step, the theoretical framework supporting these methodologies, potential challenges in implementation, and alternative approaches where applicable.

While the ideal scenario would involve the thorough application of all outlined procedures, pragmatic considerations often necessitate a balanced approach between methodological rigor and practical limitations. This chapter aims to provide a transparent overview of both the intended reduction process and the actual procedures implemented, acknowledging any departures from the optimal methodology where they occur.

By presenting this information, we establish a clear foundation for the subsequent analysis and interpretation of results, ensuring that any conclusions drawn are contextualized within the scope and limitations of the data reduction process.

5.4.1 Astronomical Twilight

The data acquisition process is automated and conducted by the stations, which commence measurements at a threshold of approximately $5\text{--}7 \text{ mags}_{\text{SQM}}/\text{arcsec}^2$ every night. The data is temporally resolved at a rate of one measurement per minute for the Upper Austrian dataset. Due to variations in the length of nights throughout the year, a variable interval is selected based on the solar status rather than fixed time intervals. Nighttime averaging is thus conducted on all recorded values from the conclusion of astronomical twilight in the evening (when the sun is 18 degrees below the horizon) until the commencement of morning astronomical twilight, typically limited to periods when the solar position is below -18 degrees. This methodology ensures consistent conditions for averaging.

Even though the full moon is almost 400,000 times dimmer than the sun, we need to eliminate this source of interference for our data reduction. The problem is very simple to summarize, because on average we have a night sky brightness in the cities of about -15 to -19.25 magnitudes and the brightness of the moon is just under -13 magnitudes (Puschnig et al., 2014). It is therefore essential to take this influence into account and factor it out in order to correctly investigate the relationship between human-induced light pollution and air pollution. Without going into too much detail, I would like to briefly and concisely describe the process that ultimately led me to delete the measurement points that were distorted by moonlight.

The initial approach to address this issue appeared simpler than anticipated: subtracting the moon's brightness from the light brightness data. However, a significant challenge emerged upon closer examination. The datasets from the light measurement network are provided either as minute averages or day/night averages, which complicates matters. To achieve a more precise classification of the data, minute averages must be utilized to delineate the start and end points of the night. This necessitates minute-by-minute values for tracking the progression of the moon's brightness across the sky. In pursuit of a solution, I embarked on a search for a program or similar tool capable of accurately calculating these values. Unfortunately, this search proved unsuccessful. Following extensive research on this topic, it becomes evident why determining the precise brightness of the moon is an exceedingly challenging task.

Moon Phase: The brightness of the moon varies depending on its phase. A full moon is significantly brighter than a crescent moon, and the brightness gradually changes as the moon progresses through its phases.

Moon Position: The position of the moon in the sky also affects its brightness. When the moon is near the horizon, it may appear dimmer due to atmospheric effects such as atmospheric scattering and absorption. Conversely, when the moon is overhead, it may appear brighter.

Distance to the Moon: The distance between the Earth and the moon varies slightly over the course of its orbit, which can affect its apparent brightness. When the moon is closer to the Earth (at perigee), it appears slightly larger and brighter, while it appears smaller and dimmer when it is farther away (at apogee).

Atmospheric Conditions: Atmospheric conditions such as cloud cover, air pollution, and humidity can also influence the brightness of the moon. Clouds can block or scatter moonlight, reducing its apparent brightness, while air pollution and humidity can contribute to atmospheric scattering, further diminishing its brightness.

Instrumentation and Measurement Methods: Empirical measurements of moon brightness require precise instrumentation and measurement methods. Instruments such as photometers or Sky Quality Meters must be accurately calibrated and positioned to ensure reliable measurements. Additionally, variations in measurement techniques and environmental conditions can introduce uncertainty into the data.

Overall, the complexity of calculating moon brightness arises from the interplay of these factors, each of which contributes to the variability of moonlight intensity over the course of a night.

Following discussions with my supervisor, we opted to refine the datasets by removing the light pollution measurement points directly affected by moonlight.

5.4.2 The Thing with the clouds

The quality of the data was compromised to an uncertain extent by the level of overcast conditions, presenting an additional challenge in determining the accuracy and reliability of the datasets. Cloud cover plays a pivotal role in modulating light pollution levels by either amplifying or mitigating the effects of artificial lighting on the nocturnal environment. Clear skies allow artificial light to scatter and disperse over larger areas, exacerbating light pollution by creating sky glow and reducing visibility of celestial objects. Conversely, cloud cover can act as a natural filter, diffusing and absorbing artificial light, thereby attenuating light pollution and preserving the darkness of the night sky. The degree of cloud coverage, as quantified by metrics such as the Okta scale, directly influences the extent to which artificial light impacts the nocturnal environment (Kyba et al., 2011a).

Excessive artificial lighting in urban and suburban areas can lead to sky glow, a form of light pollution that illuminates the underside of clouds, creating a false impression of cloud cover density. Moreover, light pollution can affect the interpretation of satellite imagery used for cloud detection, as artificial light sources may be erroneously identified as clouds, particularly in urbanized regions.

5.4.3 Cloud Coverage Data in Upper Austria

In Upper Austria and other regions, various methods are used to determine the degree of cloud cover.

Manual Observation: Meteorologists and trained observers regularly conduct visual inspections of the sky to determine the degree of cloud cover. They often use reference tables or scales such as the Okta scale to estimate the percentage of the sky covered by clouds.

Automated Weather Stations: Modern weather stations are often equipped with sensors that can automatically monitor the degree of cloud cover. These sensors use various technologies such as infrared or light detectors to detect the presence and density of clouds.

Satellite Images: Satellites regularly provide high-resolution images of the Earth's surface, including cloud cover. By analyzing these images, meteorologists can monitor and predict the degree of cloud cover in real-time.

The regularity of manual observations, which is in Upper Austria the main Method, is carried out according to the standards and guidelines of the Austrian Meteorological Service (ZAMG - Central Institute for Meteorology and Geodynamics¹).

Typically, manual observations in Austria are conducted multiple times daily, especially at weather stations and airports. Key observation times usually include morning, midday,

¹<https://www.zamg.ac.at>

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and evening observations to ensure continuous monitoring of weather conditions.

Obtaining reliable data for each day and each measuring station presents challenges. An alternative approach to ensure data accuracy would involve deriving it from other measurements. However, after thorough consideration, this crucial aspect is not addressed within the scope of this study due to the considerable increase in effort it would entail. Nonetheless, it is recommended that future research endeavors consider integrating this aspect to enhance the comprehensiveness of the analysis.

6 Statistical Analysis

In order to obtain usable and comparable diagrams or statistical values from the reduced data, it will first be necessary to say a few words about the appropriate tool. The Kolmogorov-Smirnov (KS) test is used as the basis for quantifying the direct correlation between the light quality data and the air quality data. This statistical method enables an assessment of the association between these key variables. So let's start with a brief introduction to the Kolmogorov-Smirnov Test.

6.1 Kolmogorov-Smirnov Test

In the realm of statistical analysis, understanding and comparing distributions are fundamental tasks across various disciplines. The Kolmogorov-Smirnov test stands as a non-parametric method for assessing differences between two datasets' distributions (Massey, 1951). The KS test derives its theoretical basis from the cumulative distribution function, a fundamental concept in probability theory. Developed by Andrey Kolmogorov and Nikolai Smirnov in the early 1930s, the test quantifies the maximum difference between two empirical cumulative distribution functions. By comparing these functions, the KS test evaluates whether two datasets originate from the same underlying distribution, without requiring prior knowledge of the distribution type.

The cumulative distribution function (CDF), $F(x)$, of a random variable X is defined as:

$$F(x) = P(X \leq x) \quad (6.1)$$

where P denotes the probability measure. In essence, the CDF gives the probability that the random variable X takes on a value less than or equal to x .

For a dataset X consisting of n observations, the empirical cumulative distribution function (ECDF), denoted as $F_n(x)$, is constructed as follows:

$$F_n(x) = \frac{\text{number of observations} \leq x}{n} \quad (6.2)$$

In other words, $F_n(x)$ is the proportion of observations in X that are less than or equal to x . It provides an empirical estimate of the true underlying CDF based on the observed data.

The KS test statistic, D , quantifies the maximum vertical difference between the empirical CDFs of two datasets. Given two datasets X and Y , with empirical CDFs $F_X(x)$ and $F_Y(x)$ respectively, D is computed as:

$$D = \sup |F_X(x) - F_Y(x)| \quad (6.3)$$

This maximum difference captures the largest deviation between the two empirical distributions (Stephens, 1974).

The KS test is a hypothesis test used to assess whether two datasets follow the same distribution. The hypotheses are formulated as follows:

- **Null Hypothesis (H_0):** The two datasets X and Y are drawn from the same distribution.
- **Alternative Hypothesis (H_1):** The two datasets X and Y are not drawn from the same distribution.

The KS test evaluates the evidence against H_0 by comparing the observed value of D to critical values derived from the KS distribution or obtained through computational methods.

The distribution of the KS test statistic D under the null hypothesis (H_0) is known as the Kolmogorov-Smirnov distribution. Its cumulative distribution function is complex and depends on the sample sizes of the datasets being compared. Tables and computational algorithms are available to approximate critical values for various significance levels and sample sizes.

The theoretical foundations of the KS test provide the framework for comparing distributions without making assumptions about their underlying forms. Now we can prove the similarity between datasets and draw inference regarding their distributional characteristics.

6.2 Adjustments for these specific Datasets

Of course, the data sets are not ECDFs. This means that it is essential to process the data further in order to compare them adequately. First of all, there is the major problem of the fundamentally different units. The air quality data are given in magnitudes, a logarithmic scale. In comparison, all air quality data is scaled linearly. To avoid this first problem, the magnitude values are converted into candelas per square meter and thus also linearized.

6.2.1 Conversion from magnitudes to candelas

To convert magnitudes into a more physically meaningful quantity, such as luminance, we utilize the inverse relationship inherent in the magnitude scale.

The formula used to convert magnitudes to luminance is derived from the definition of magnitude:

$$m = -2.5 \log_{10}(F) \quad (6.4)$$

where m represents the magnitude and F represents the luminance in lumens per square arcsecond ($\text{lm}/\text{arcsec}^2$). By rearranging this equation, we can solve for luminance:

$$F = 10^{-\frac{m}{2.5}} \quad (6.5)$$

Once we have the luminance in lumens per square arcsec, the next step is to convert it to watts per square meter. This conversion involves considering the spectral sensitivity of the human eye, as well as the conversion factor between lumens and watts.

The conversion factor depends on the spectral distribution of light and is typically given in lumens per watt (lm/W). For the visible light spectrum, this conversion factor is approximately $683 \text{ lm}/\text{W}^1$ (SQMs detect approximately only visible light). Therefore, to convert luminance from lumens per square arcsecond to watts per square meter, the following equation is used:

$$F_{W/m^2} = \frac{F_{\text{lm}/\text{arcsec}^2}}{683} \quad (6.6)$$

Finally, to convert luminance from watts per square meter to candela per square meter, we divide the luminance in watts per square meter by the specific conversion factor for the visible light spectrum. This conversion factor is again approximately 683.

$$F_{cd/m^2} = \frac{F_{W/m^2}}{683} \quad (6.7)$$

6.2.2 First Normalization

Now that both data sets are linear, normalization can begin. First, the maximum value is determined from each data series and each individual value of the same data series is divided by this value. If x_i represents an individual data point and x_{max} represents the maximum value in the dataset, then the normalized value x_i can be calculated as:

$$x'_i = \frac{x_i}{x_{max}} \quad (6.8)$$

¹<https://spie.org/publications/spie-publication-resources/optipedia-free-optics-information/fg11p09luminousefficacy=>

6 Statistical Analysis

Where x_i is the original value of the data point, x_{max} is the maximum value in the dataset and x_i is the normalized value of the data point.

This is done for air quality data in the same way as for light quality data. This first normalization gives us a more direct comparison of the two very different data sets, as the basic distances between the individual values of each data series remain the same. So let's take a brief look into one of those normalized plots.

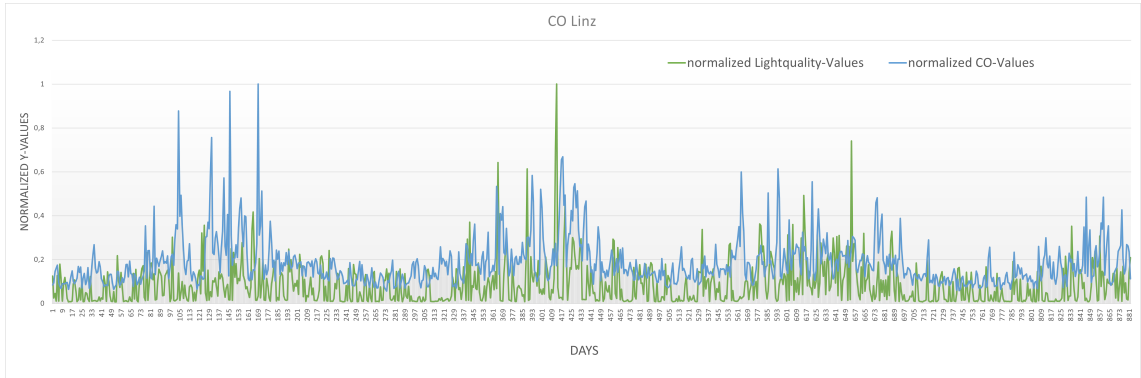


Figure 6.1: CO in the city of Linz

6.2.3 Summing up the data points

Figure 6.1 provides an initial visualization of the data, but it does not yet offer a deeper understanding of the potential relationship between light quality data and air quality data. To explore this relationship further, we adopt a method commonly used in statistical analysis, akin to the Kolmogorov-Smirnov (KS) test. In this approach, we aggregate all normalized data, allowing us to examine their cumulative characteristics and potential associations.

This summation of normalized data serves two primary purposes:

- **Aggregate Analysis:** By summing up the normalized data, we create a composite representation of both light quality and air quality metrics. This aggregated view enables us to identify overarching trends and patterns that may not be apparent when considering individual variables in isolation.
- **Comparison with KS Test Methodology:** The aggregation of normalized data aligns with the principle underlying the KS test, where the maximum difference between the two datasets is evaluated. While our objective may differ from that of the KS test, this methodological parallel underscores the rigor and relevance of our analytical approach.

By employing this aggregation technique, the aim here is to gain deeper insights into the potential interplay between light quality and air quality parameters. Subsequent analyses

6.2 Adjustments for these specific Datasets

will build upon this foundation, leveraging statistical methods to elucidate correlations, identify influential factors, and inform further investigation into the relationship between environmental variables.

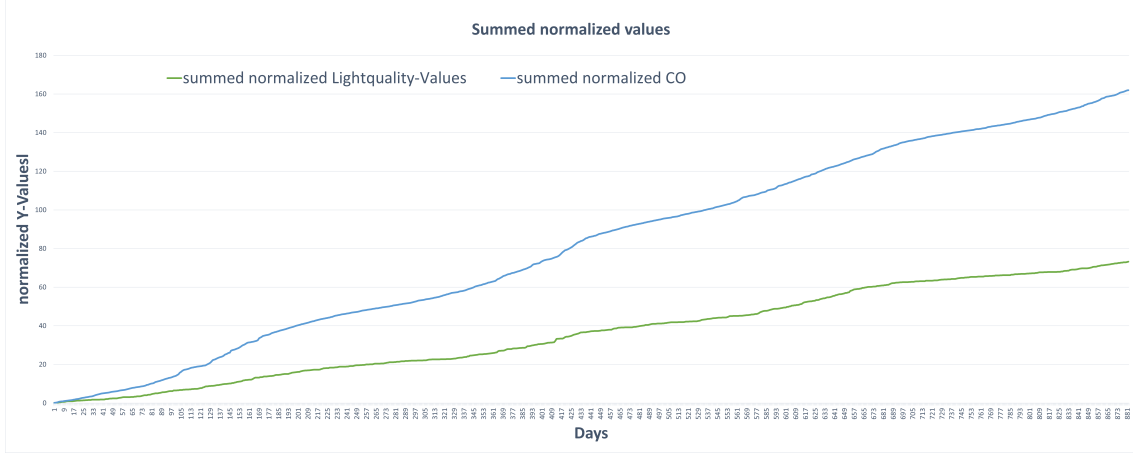


Figure 6.2: CO in the city of Linz

Only now is it possible for the first time to recognize the coherent trend line, which was previously only sparsely discernible. In order to compare the curves even more directly, I will carry out a second normalization, which unfortunately has serious consequences for our data this time.

6.2.4 Second Normalization

After performing the initial normalization, wherein each value was scaled to its own magnitude, the subsequent step involves standardizing the scale itself to a common reference point of 1. This transformation aims to render the datasets comparable by utilizing the concept of maximum distance, akin to the KS test. Equation 7.8 serves as the foundation for this second normalization process, albeit with a subtle modification. Instead of utilizing the maximum value x_{max} within each dataset, the final value of each dataset is employed.

$$x'_i = \frac{x_i}{x_{last}} \quad (6.9)$$

Consequently, each dataset's final value is standardized to 1. This approach facilitates the creation of standardized ratios, enabling meaningful comparisons between individual data points across different locations. Moreover, it facilitates the generation of insightful plots, allowing for immediate discernment of underlying connections within the data.

6 Statistical Analysis

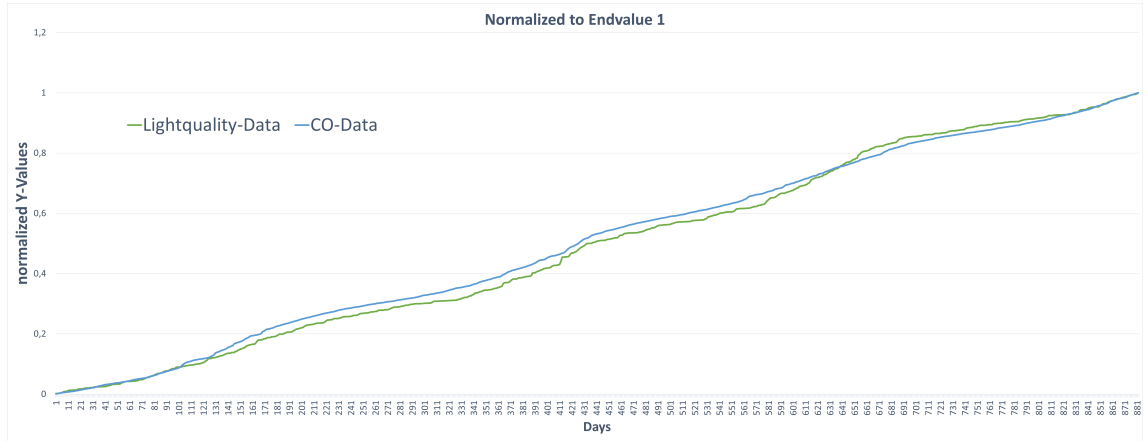


Figure 6.3: CO in the city of Linz

To assess the correlation between the progression of air quality and light quality data, we employ the mean value of individual distances. This is achieved by computing the variances between the doubly normalized air quality and light quality data, followed by deriving the arithmetic mean from this resultant data series.

$$y_{Airquality} - y_{Lightquality} = y_{Diffrenz} \quad (6.10)$$

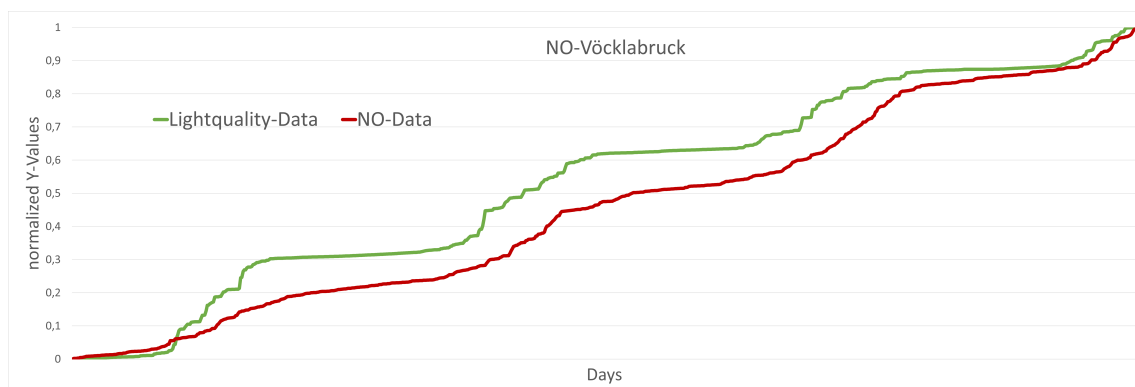
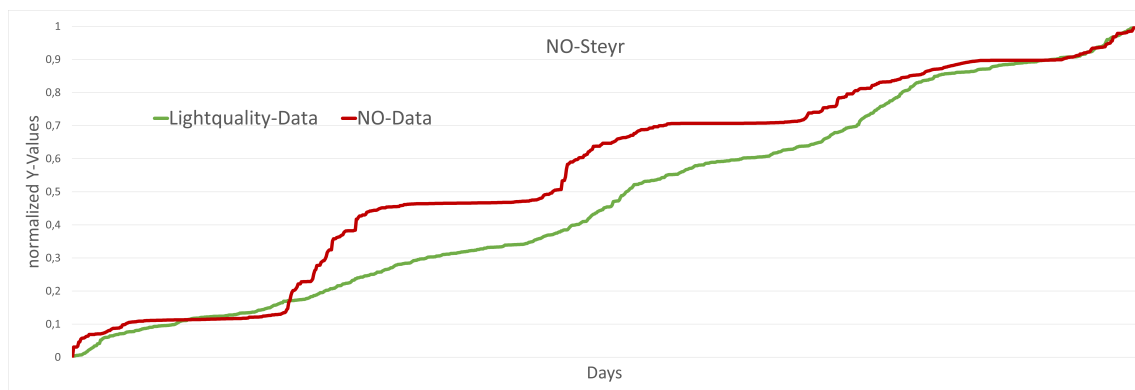
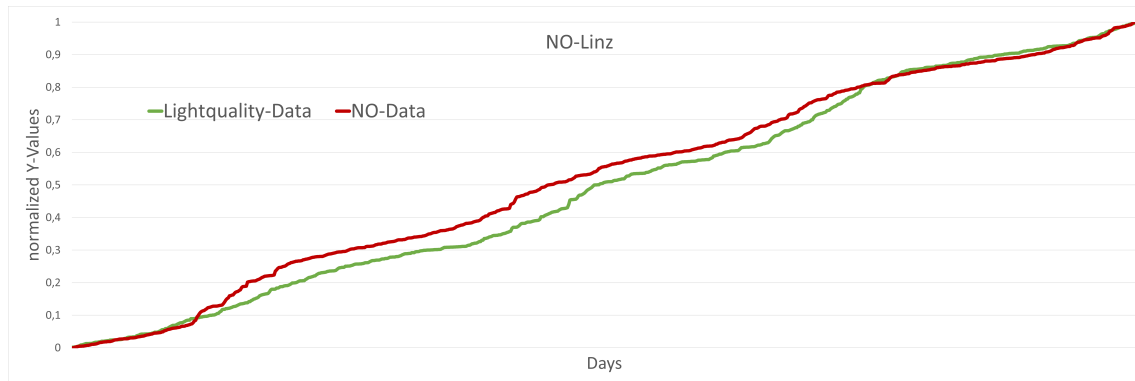
$$\bar{y}_{Diffrenz} = \frac{1}{n} \sum_{n=1}^k y_{n_{Diffrenz}} \quad (6.11)$$

Although the second normalization step diminishes some direct correlations' significance, a detailed examination of this issue will be provided in the "Problems with using the KS test" section.

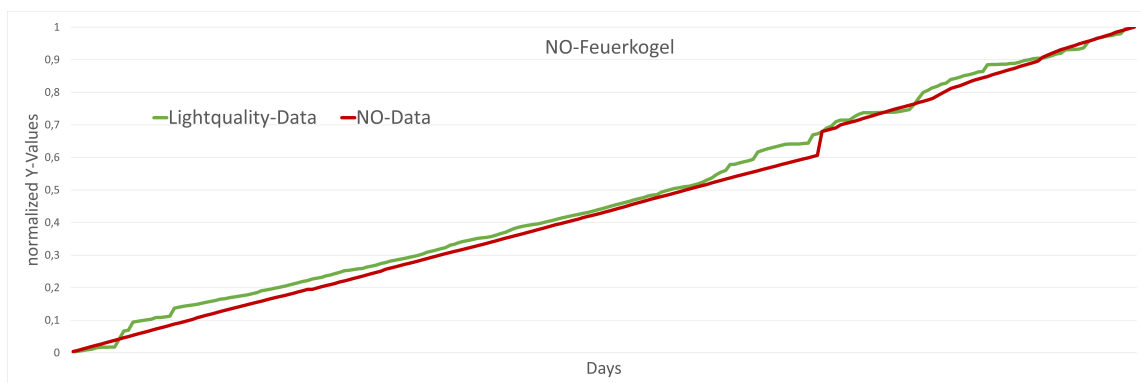
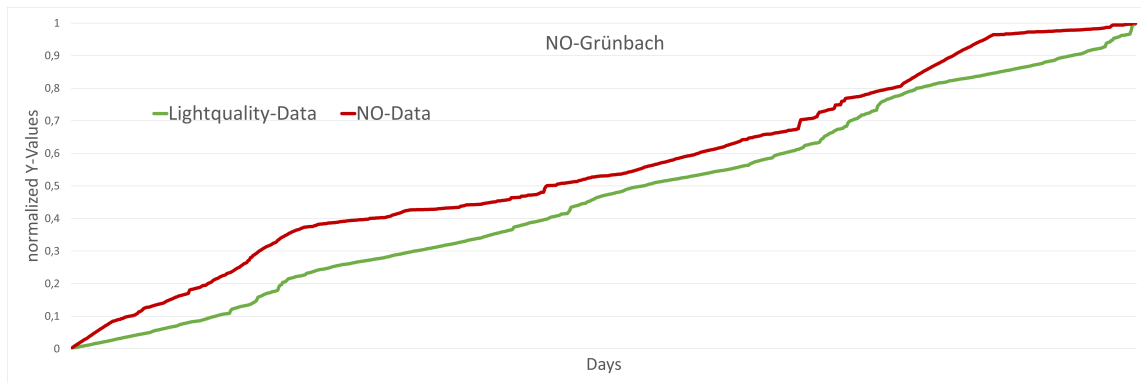
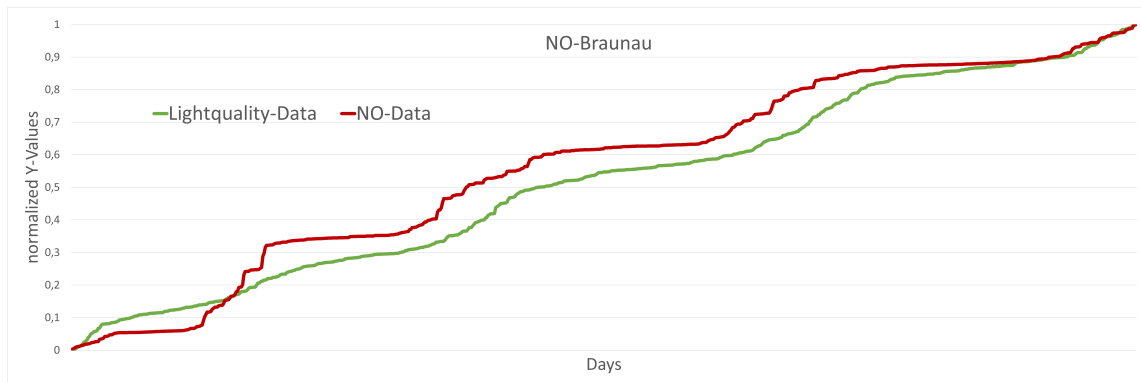
With all data processed accordingly, we can then proceed to compare individual datasets across various measuring stations, examining the correlation between air and light quality in urban, suburban, and rural settings.

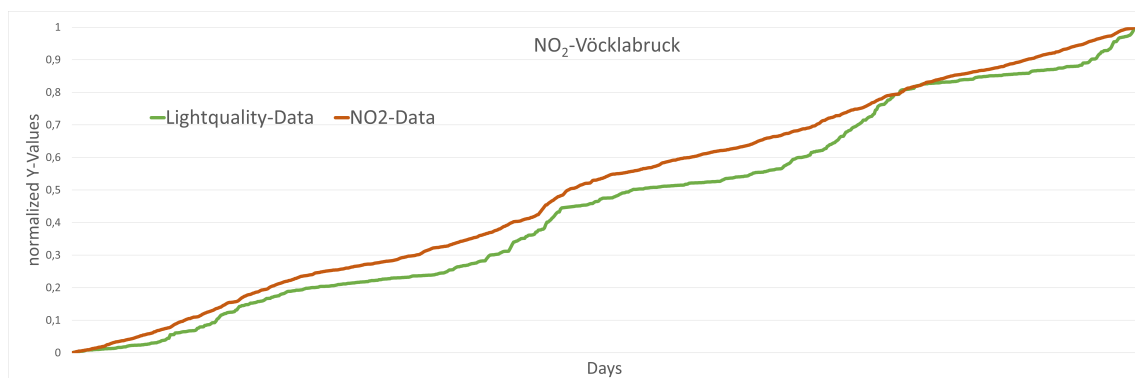
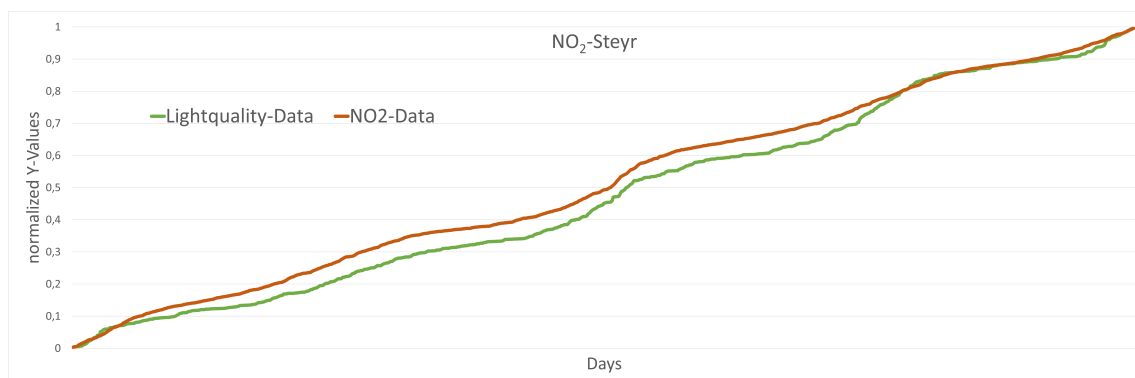
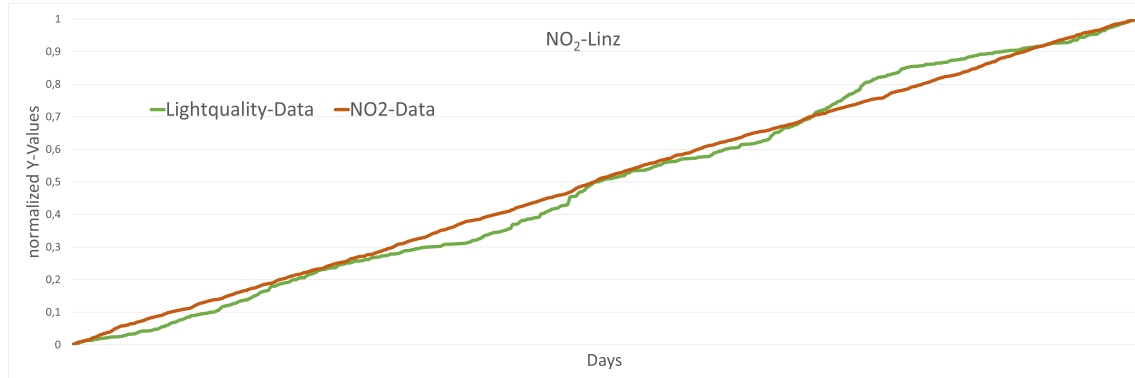
6.3 Plots & Tables

6.3.1 NO

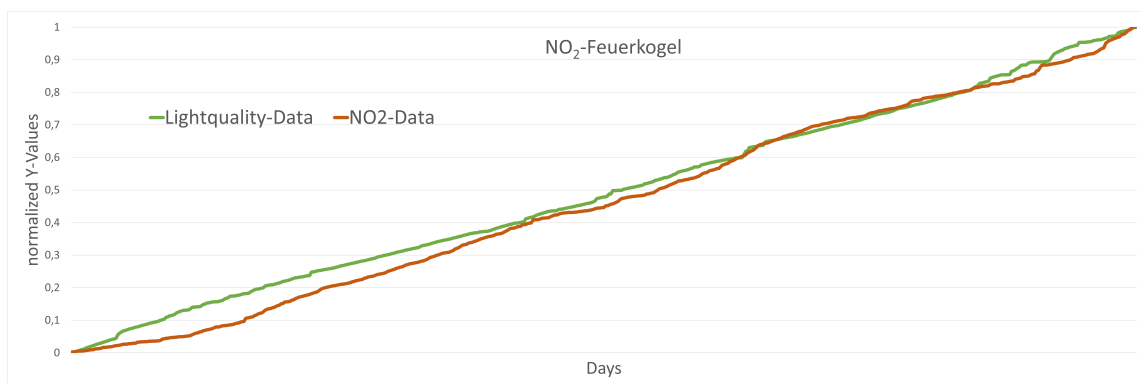
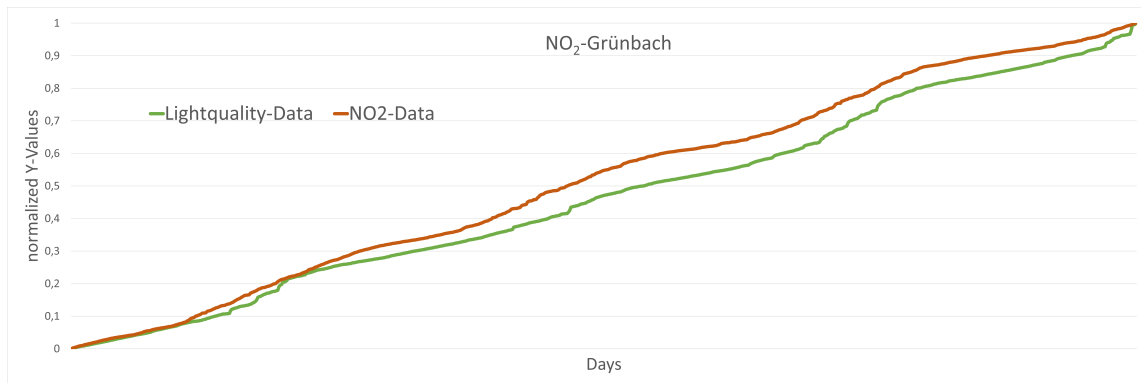
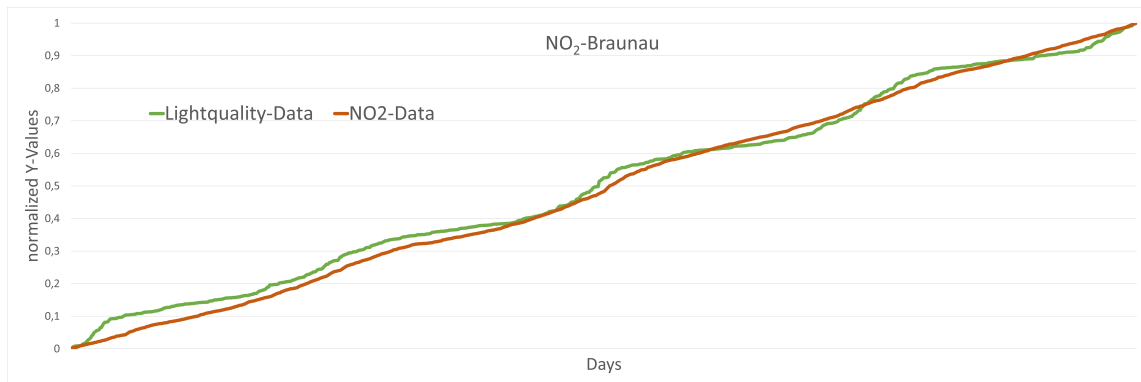


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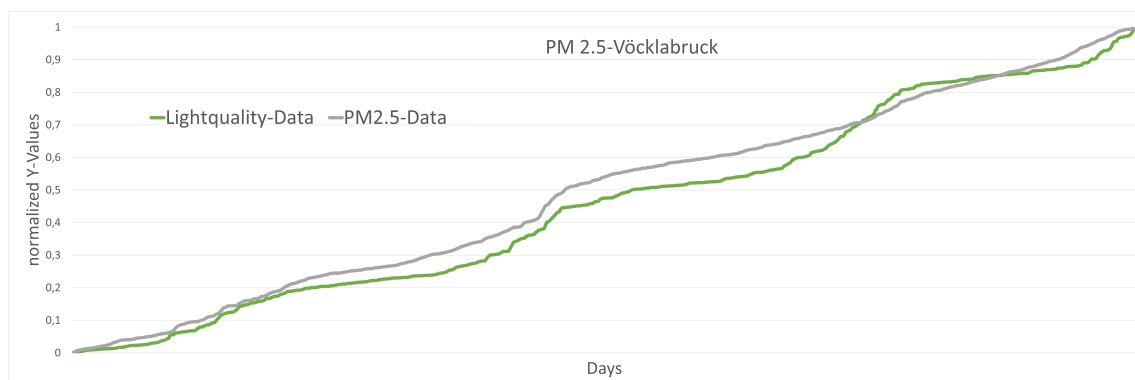
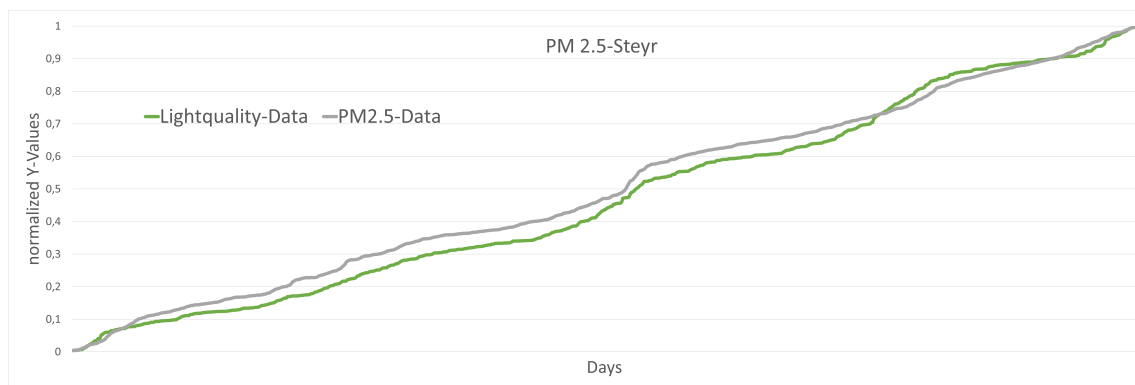
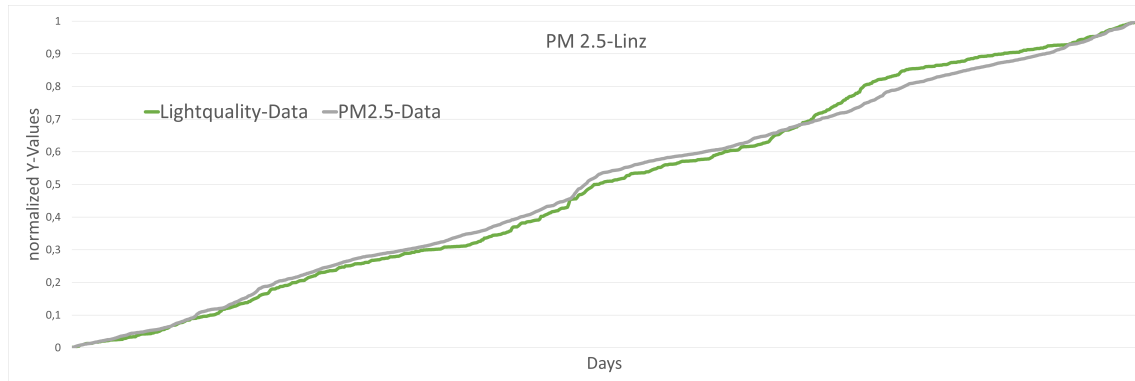


6.3.2 NO₂

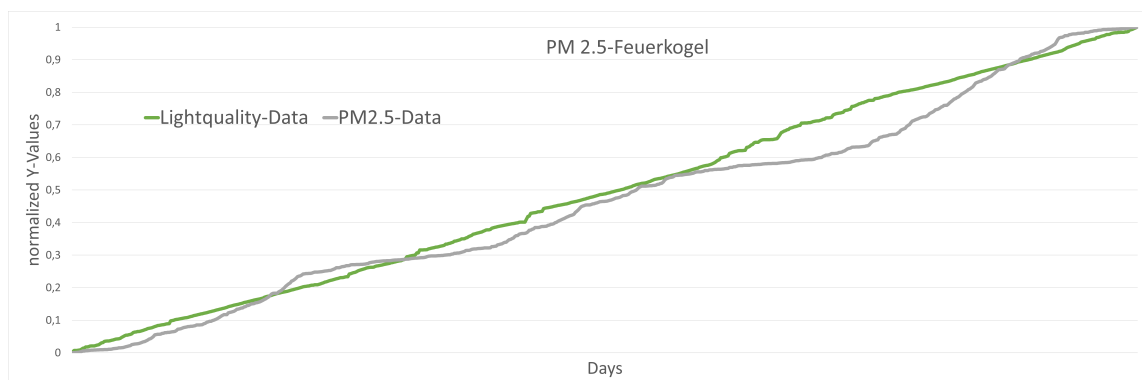
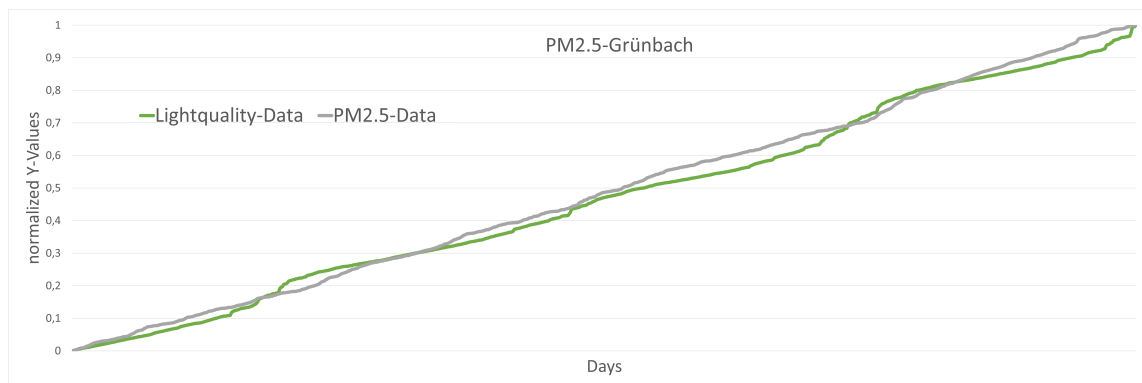
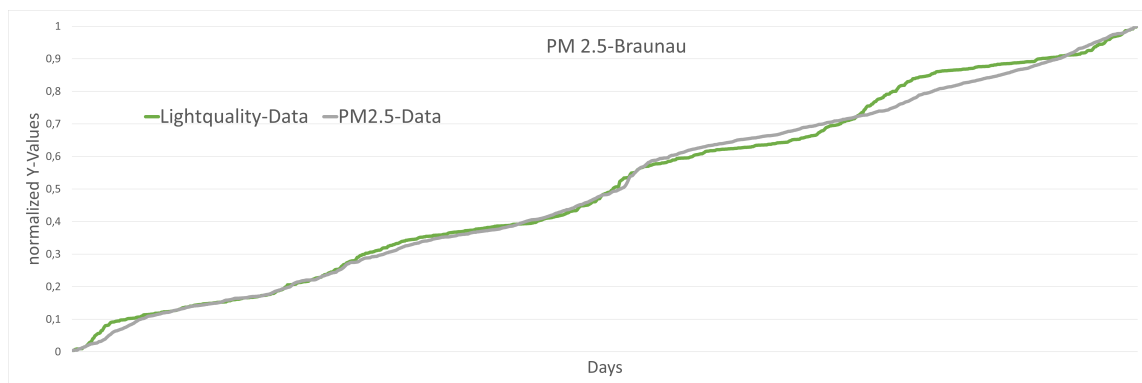
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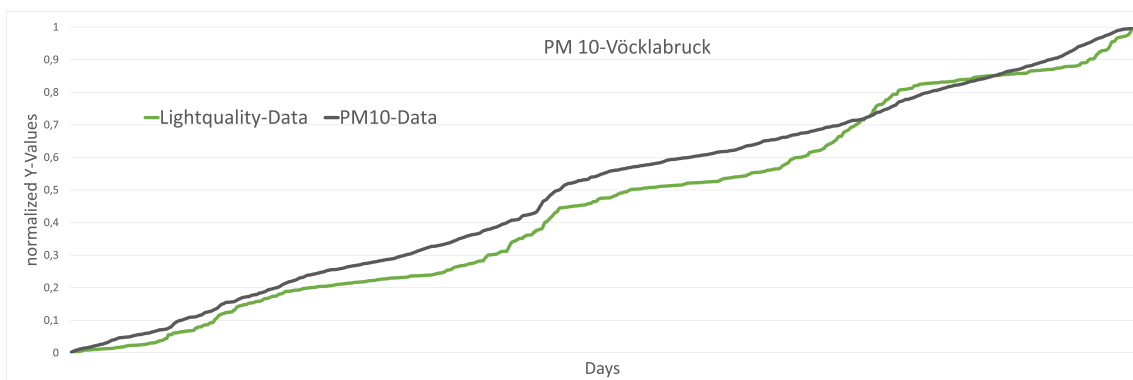
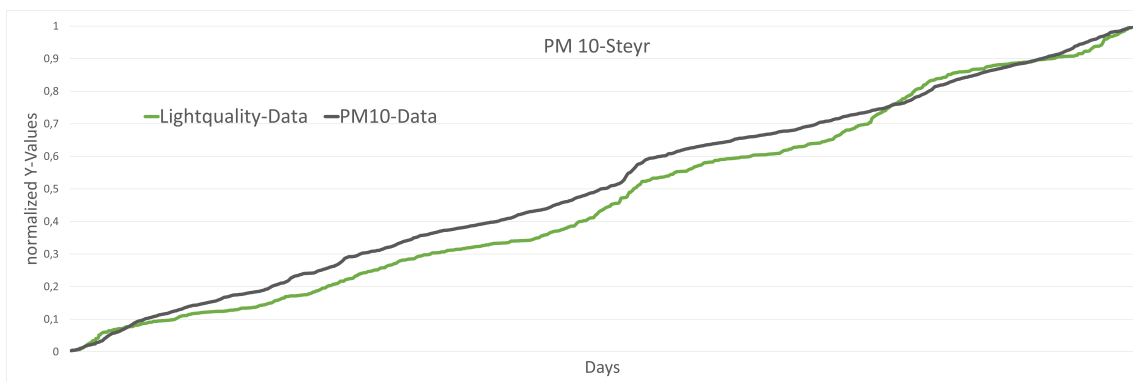
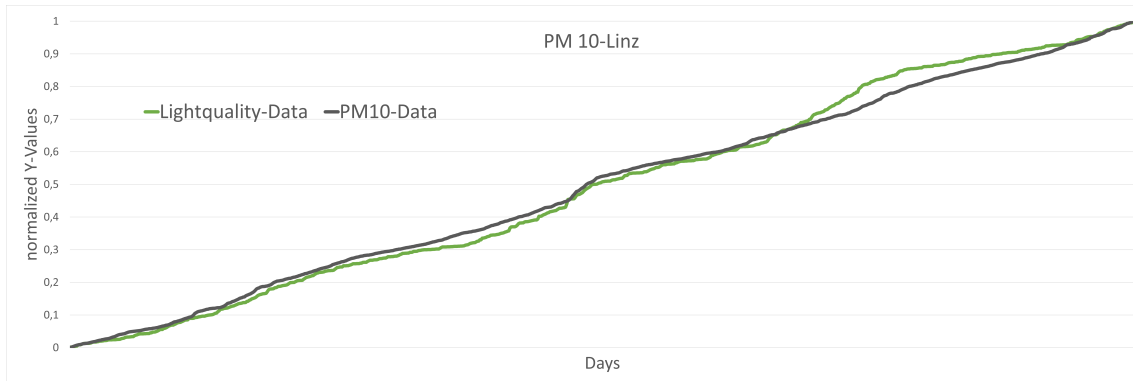
6.3.3 PM 2.5



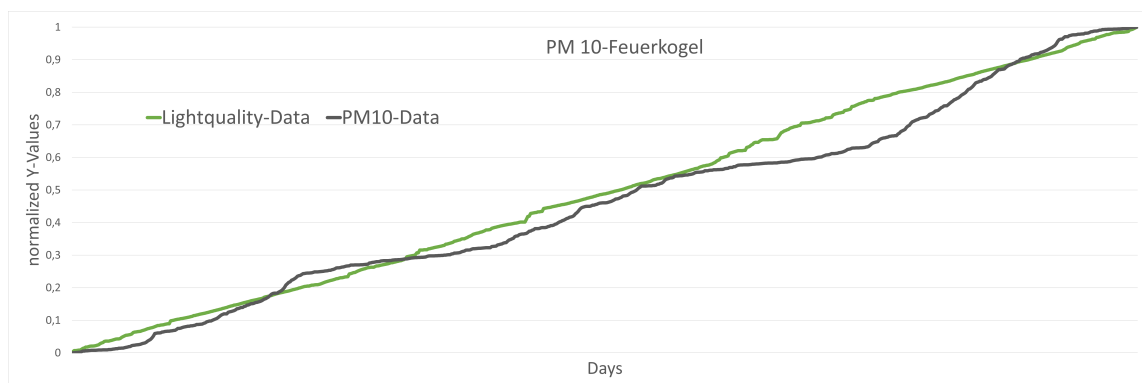
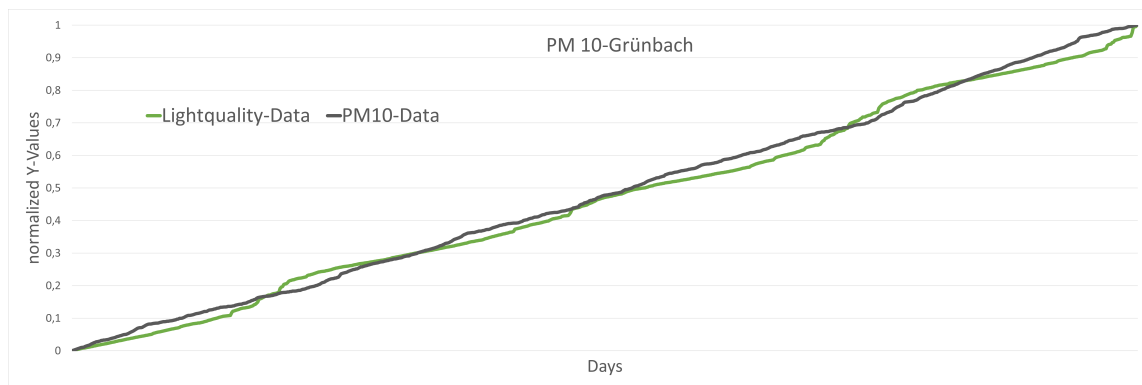
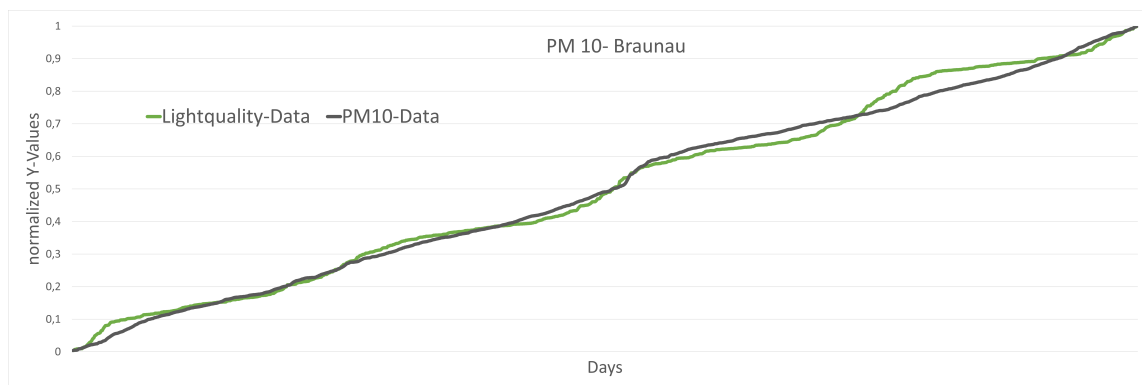
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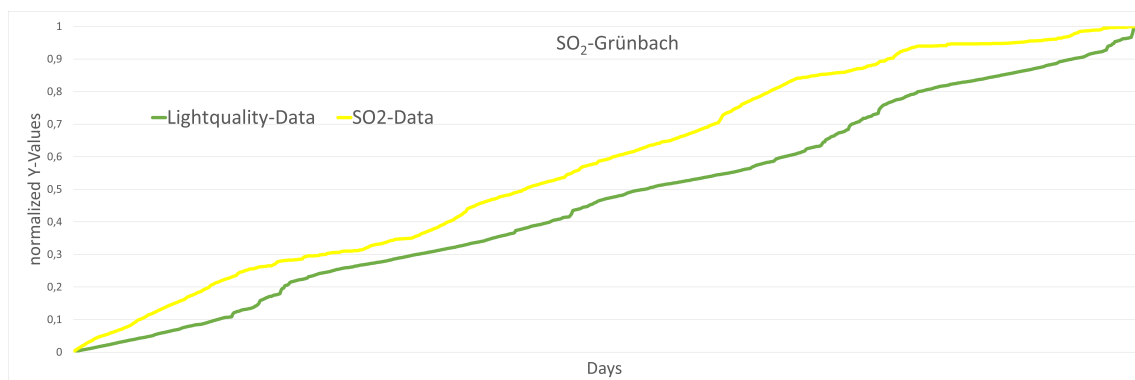
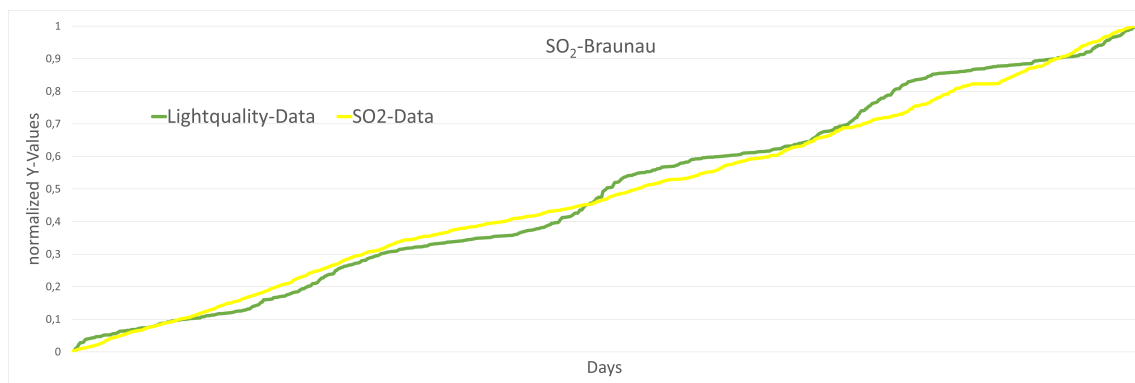
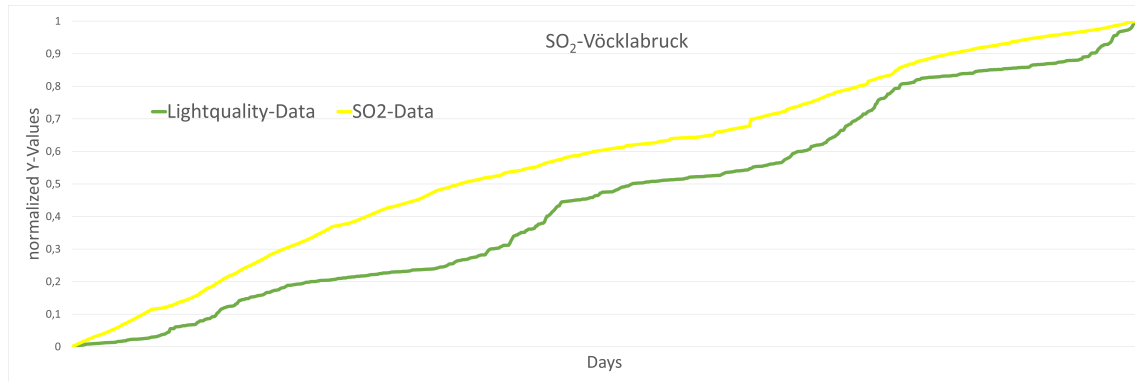


6.3.4 PM 10

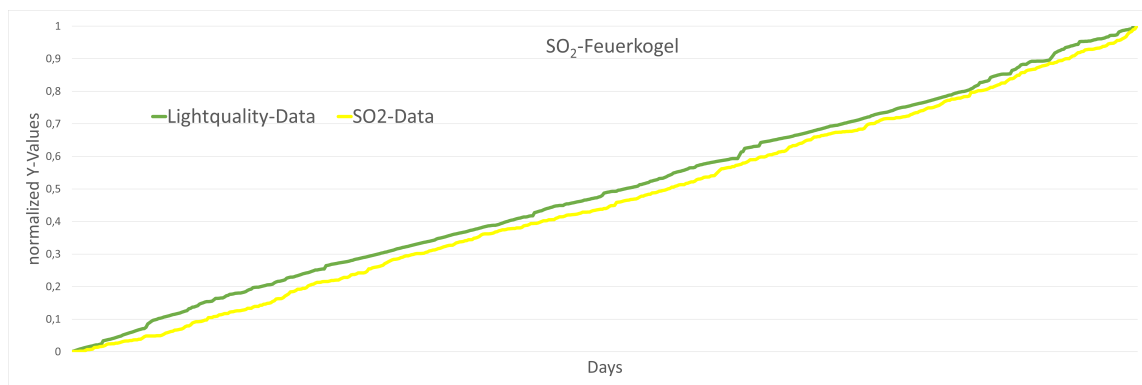


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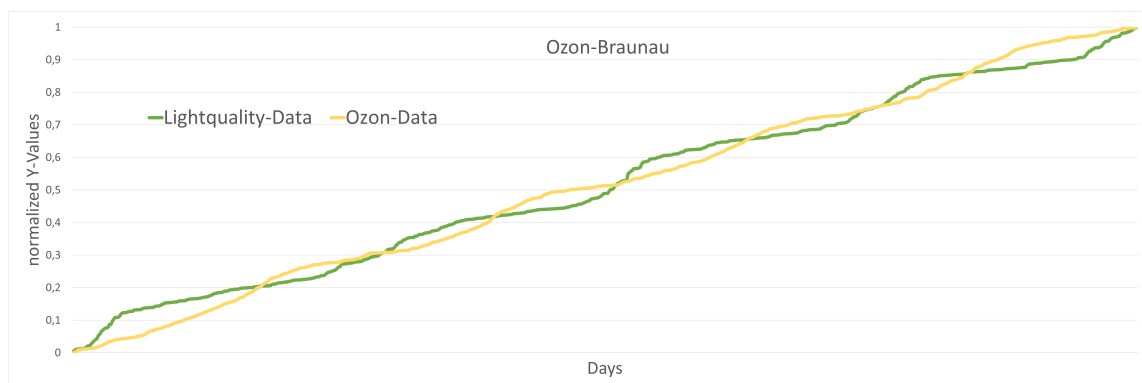
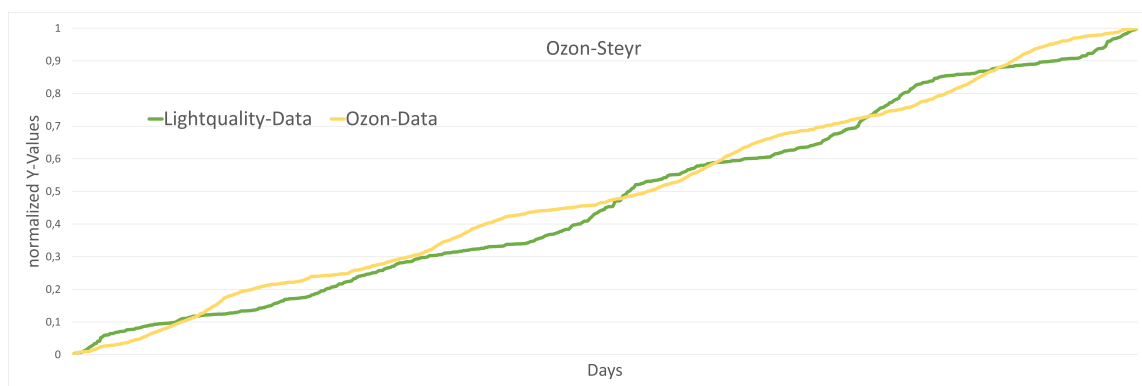


6.3.5 SO₂

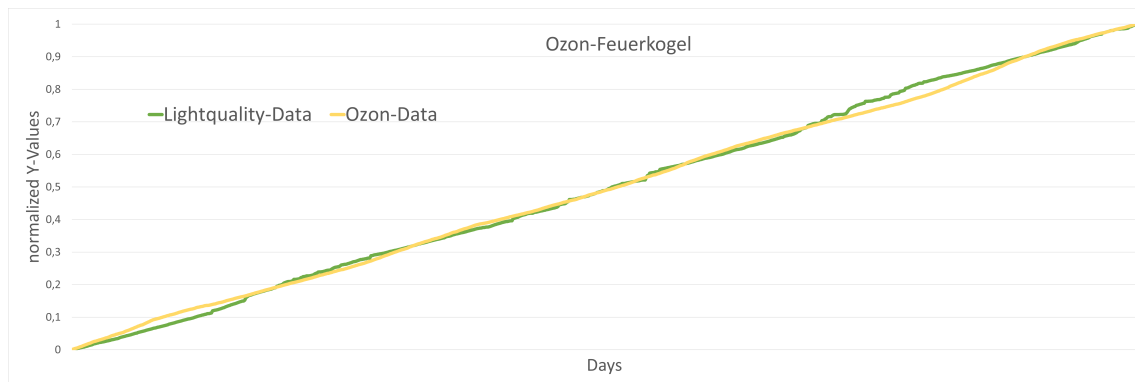
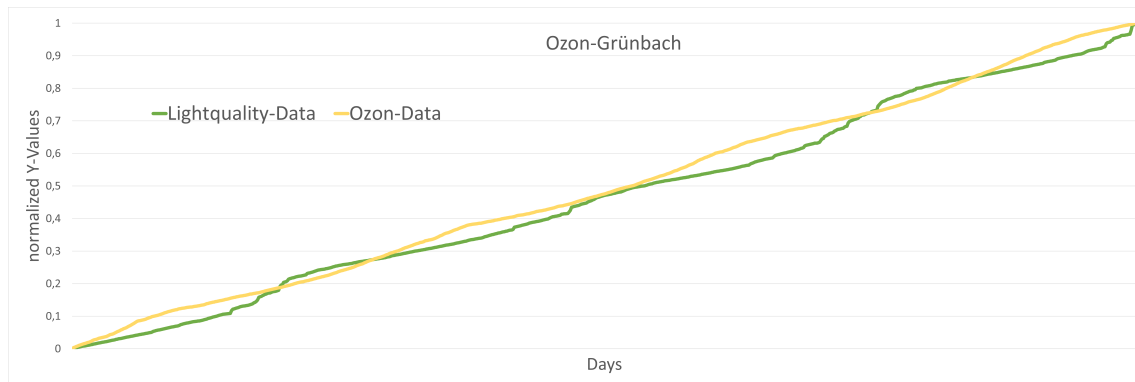
6 Statistical Analysis



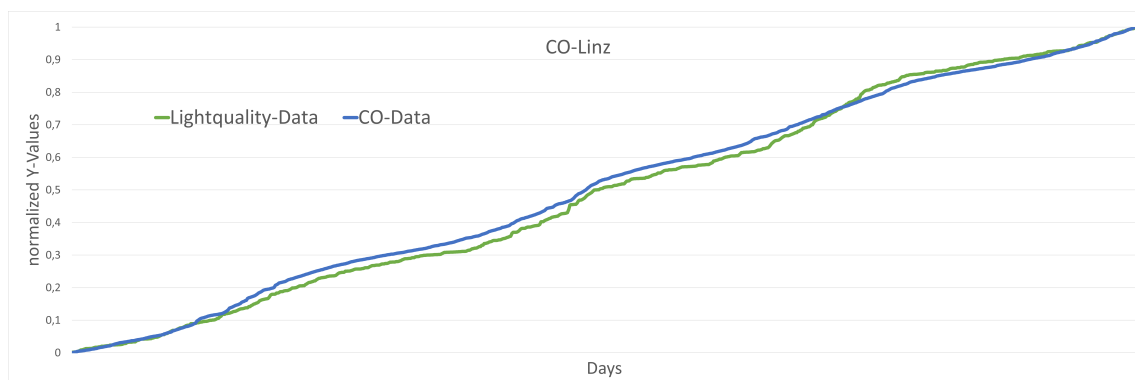
6.3.6 Ozon



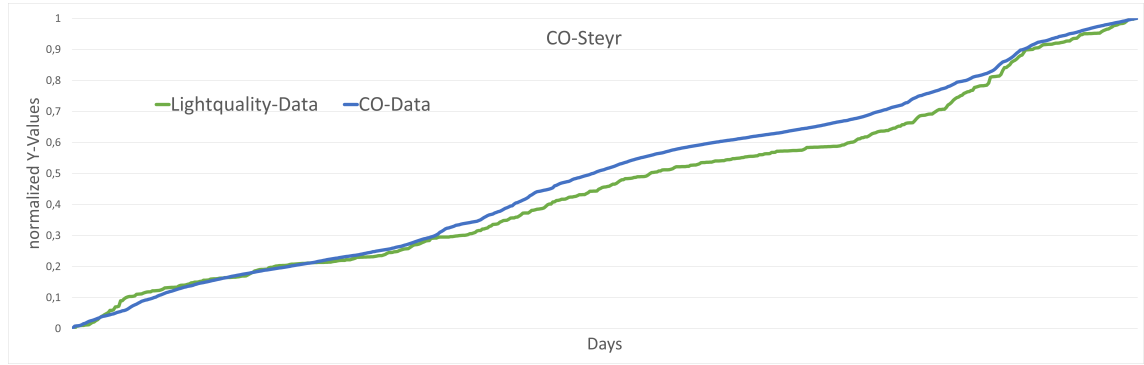
6.3 Plots & Tables



6.3.7 CO



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The tables below provide a clear insight into the diagrams in the “Plots” section above. In each of these tables, we compare certain values of individual aerosols at all locations to establish a trend in the data.

The **MAX** value (the index indicates whether it is the aerosol in question or the light quality data) is determined from the highest 10% of the data in order to smooth out any statistical outliers.

The **Mean Dis.** is the mean dissimilarity, the “D” from the KS test after the second normalization and is given as a percentage deviation (the air quality curve is compared with the light curve).

Furthermore, the **End Values (E.V.)** after the first normalization are given in order to quantify the difference in offset between the curves.

Finally, we can compare the **standard deviation** σ of the data to learn more about the general influence of the atmospheric composition (i.e. all aerosols in the air).

NO/LQ	MAX _{NO}	MAX _{LQ}	Mean Dis.	E.V. _{NO}	E.V. _{LQ}	σ_{NO}	σ_{LQ}
Unit	$\mu g/m^3$	mag	%	dim-less	dim-less	$\mu g/m^3$	mag
Linz	107,004	16,046	3,441	79,251	73,224	35,874	1,277
Steyr	29,647	16,475	8,229	30,225	94,055	11,934	1,369
Vöcklabruck	33,819	16,684	8,224	31,213	89,194	13,466	1,329
Braunau	46,145	16,755	5,840	28,445	55,807	18,880	1,207
Grünbach	0,489	19,661	8,575	66,307	60,263	0,182	0,790
Feuerkogel	0,907	20,323	2,224	13,651	39,598	0,802	0,941

Table 6.1: Final values NO

6.4 What we can perceive

Initially, one can observe a conspicuous and almost trivial correlation between the two datasets. It’s evident that as air pollution escalates, so does light pollution. Although there’s a general increase in light pollution across all measuring stations on average, we’ll disregard this for subsequent analysis. This correlation holds true consistently

6.4 What we can perceive

NO ₂ /LQ	MAX _{NO₂}	MAX _{LQ}	Mean Dis.	E.V. _{NO₂}	E.V. _{LQ}	σ _{NO₂}	σ _{LQ}
Unit	μg/m ³	mag	%	dim-less	dim-less	μg/m ³	mag
Linz	76,406	16,046	2,596	342,991	73,224	18,879	1,277
Steyr	38,392	16,475	3,583	214,710	94,055	10,416	1,369
Vöcklabruck	40,272	16,684	4,971	194,917	89,194	11,299	1,329
Braunau	44,340	16,755	2,270	264,927	63,983	10,819	1,207
Grünbach	14,578	19,661	4,779	142,498	60,263	4,129	0,790
Feuerkogel	6,319	20,323	3,155	70,054	95,569	2,204	0,941

Table 6.2: Final values NO₂

PM 2.5/LQ	MAX _{PM2.5}	MAX _{LQ}	Mean Dis.	E.V. _{PM2.5}	E.V. _{LQ}	σ _{PM2.5}	σ _{LQ}
Unit	μg/m ³	mag	%	dim-less	dim-less	μg/m ³	mag
Linz	40,227	16,046	1,959	175,637	73,224	10,873	1,277
Steyr	37,075	16,475	3,231	160,554	93,799	10,865	1,369
Vöcklabruck	36,734	16,684	3,886	127,695	89,194	11,293	1,329
Braunau	38,234	16,755	1,599	130,699	64,601	11,086	1,207
Grünbach	21,475	19,661	2,268	158,662	60,263	6,135	0,790
Feuerkogel	11,211	20,323	4,044	123,466	112,311	3,734	0,941

Table 6.3: Final values PM 2.5

PM 10/LQ	MAX _{PM10}	MAX _{LQ}	Mean Dis.	E.V. _{PM10}	E.V. _{LQ}	σ _{PM10}	σ _{LQ}
Unit	μg/m ³	mag	%	dim-less	dim-less	μg/m ³	mag
Linz	50,729	16,046	1,974	195,483	73,224	13,273	1,277
Steyr	42,005	16,475	4,299	177,808	93,799	11,629	1,369
Vöcklabruck	42,599	16,684	4,857	139,666	89,194	12,590	1,329
Braunau	45,265	16,755	1,933	131,645	64,601	12,680	1,207
Grünbach	28,157	19,661	2,248	159,435	60,263	8,076	0,790
Feuerkogel	15,351	20,323	4,076	122,039	112,311	5,140	0,941

Table 6.4: Final values PM 10

across various aerosols including NO, NO₂, PM 2.5, PM 10, SO₂, and CO. However, there's a notable exception, as discussed in Chapter 4 (3.1.1), concerning ozone. Ozone concentration typically diminishes at ground level, especially during summer months, owing to increased radiation output and reaction with other air pollutants. Consequently, we observe an inverse relationship with the light quality curve (Figure 6.3.6).

When certain aerosol concentrations surpass a certain threshold (regrettably, direct determination of this threshold isn't feasible here), a direct correlation becomes evident. In exceedingly remote and elevated areas like the Feuerkogel, this correlation diminishes. The Feuerkogel measuring station (and to some extent, the Grünbach station) exhibits

6 Statistical Analysis

SO_2/LQ	MAX_{SO_2}	MAX_{LQ}	Mean Dis.	$E.V._{SO_2}$	$E.V._{LQ}$	σ_{SO_2}	σ_{LQ}
Unit	$\mu g/m^3$	mag	%	dim-less	dim-less	$\mu g/m^3$	mag
Steyr	4,155	16,475	2,119	294,512	93,799	1,085	1,369
Vöcklabruck	3,820	16,684	1,187	49,395	89,194	1,385	1,329
Braunau	3,298	16,755	2,964	175,403	60,756	1,010	1,207
Grünbach	2,761	19,661	10,900	135,811	60,263	0,883	0,790
Feuerkogel	0,861	20,323	3,290	91,891	95,008	0,308	0,941

Table 6.5: Final values SO_2

$Ozon/LQ$	MAX_{Ozon}	MAX_{LQ}	Mean Dis.	$E.V._{Ozon}$	$E.V._{LQ}$	σ_{Ozon}	σ_{LQ}
Unit	$\mu g/m^3$	mag	%	dim-less	dim-less	$\mu g/m^3$	mag
Steyr	80,402	16,475	3,669	279,968	93,799	24,352	1,369
Braunau	72,112	16,755	3,300	179,985	47,988	23,219	1,207
Grünbach	124,258	19,661	3,050	373,983	60,263	27,077	0,790
Feuerkogel	130,151	20,323	1,197	514,101	141,291	21,669	0,941

Table 6.6: Final values Ozon

CO/LQ	MAX_{CO}	MAX_{LQ}	Mean Dis.	$E.V._{CO}$	$E.V._{LQ}$	σ_{CO}	σ_{LQ}
Unit	mg/m^3	mag	%	dim-less	dim-less	mg/m^3	mag
Linz	0,774	16,046	1,923	162,004	73,224	0,200	1,277
Steyr	0,587	16,475	3,478	162,182	54,601	0,163	1,369

Table 6.7: Final values CO

minimal fluctuations over the four-year observation period, serving as an excellent control sample. Here, concentrations and fluctuations of all measured aerosols (except ozone, which increases at higher altitudes) either decrease or are barely discernible. Notably, maximum light pollution values are approximately four orders of magnitude lower than those observed in urban and suburban areas, as evidenced by table values.

This nuanced understanding of the relationship between air and light pollution highlights the intricate interplay between various environmental factors. It underscores the complexity of atmospheric dynamics and the need for comprehensive analysis to unravel the underlying patterns. Furthermore, it raises questions about the potential impact of geographical and topographical factors on pollution levels.

Understanding the results of the mean dissimilarity (**Mean Dis.**) poses an initial challenge. At first glance, it may seem that the similarity of the curves improves with increasing concentrations of air pollution. However, upon closer examination, particularly in rural areas as observed in certain tables (see Table 6.1 6.2 6.5), it becomes apparent

that the similarity improves as the deviation "D" decreases. This phenomenon can be attributed to the exceedingly low levels of pollutants present, resulting in minimal fluctuations. Consequently, both the air pollution and light pollution curves exhibit limited variability, leading to smaller deviations. As a result, the mean dissimilarity decreases, indicating increased similarity between the curves

The interpretation of individual end values (**E.V.**) hinges on their incremental significance. Revisiting the calculation method outlined in the KS-test section, we sum up the normalized values to the actual maximum value, shedding light on the magnitude of individual step sizes in the final value. A high final value signifies higher average values within the data series, offering insights into the offset of the data under scrutiny. Despite losing this offset in the second normalization, where curves are adjusted to a uniform final value of 1, the shape and trend remain intact. This underlines the resilience of the overall pattern of the data, even with normalization procedures aimed at standardization.

Lastly, the standard deviation provides insight into the fluctuation range of the data, offering a means to assess the overall impact of the atmosphere and its aerosol content. In simpler terms, it allows us to evaluate the general variability of atmospheric conditions and their influence on light pollution. To accomplish this, we identify the minimum values of the averaged lower 10% of the light quality data and contrast them with the maximum values, elucidating the breadth of fluctuations within the dataset.

Lightquality	MIN_{LQ}	MAX_{LQ}	Δ-Difference
Unit	mag	mag	mag
Linz	19,731	16,046	3,685
Steyr	20,563	16,475	4,088
Vöcklabruck	20,695	16,684	4,011
Braunau	20,454	16,755	3,699
Grünbach	22,133	19,661	2,472
Feuerkogel	22,869	20,323	2,546

Table 6.8: Comparison between averaged minimum and maximum light quality values.

6.5 Discussion

At this stage, the analysis of the plots will be conducted, followed by a detailed comparison of the obtained results and values. While the previous section provided a more general overview, this section aims to present a thorough, in-depth examination of the data and its implications.

Comparison of the values and plots

It is evident that pollutant concentrations are generally highest in densely populated areas. An exception to this trend is the town of Braunau, which, as discussed in detail in Chapter 4.2.2, is characterized by the presence of heavy industry in its immediate vicinity, leading to higher pollution levels compared to Steyr (see Tables 6.1 to 6.5). Despite the elevated pollutant load in Braunau, the maximum light pollution MAX_{LQ} remains comparable to that of Steyr, which has twice the population. This observation further highlights the complex relationship between light pollution and air pollution.

An additional and particularly interesting finding is the improved alignment of the curves, quantified as Mean Dissimilarity (**Mean Dis.**), which becomes more pronounced as air pollution levels increase. This trend is especially evident in the comparison between urban and rural areas, as shown in the plots. The data reveals that in regions with higher concentrations of air pollutants (see Figures 6.3.3 and Figures 6.3.4), the curves exhibit a greater degree of alignment, suggesting a stronger correlation between environmental variables in areas with more severe pollution. This improved alignment with increasing pollution levels points to a more predictable relationship between the analyzed factors, such as pollutant levels and light pollution, in densely polluted urban environments.

In rural areas, however, this pattern is not observed. The absence of significant air pollution leads to a lack of seasonal trends, which are otherwise visible in urban regions. The rural plots, particularly those related to particulate matter, are dominated by statistical outliers rather than a consistent trend. This suggests that in areas with lower pollution levels, external environmental factors, such as meteorological conditions or localized activities, may introduce greater variability into the data, resulting in less predictable and more scattered patterns. The absence of a clear seasonal influence in rural areas further emphasizes the role of concentrated air pollution in structuring the data and influencing the degree of curve alignment. These findings highlight the complexity of environmental interactions in different geographical contexts and suggest that higher pollution levels may lead to more stable and consistent correlations between environmental factors, while lower pollution areas experience greater fluctuation and unpredictability in their data.

The deviations and variability in light pollution values reveal an intriguing trend. While these values remain low in rural areas, with standard deviations σ_{LQ} below 1, they increase significantly in urban and suburban regions. A similar pattern is observed with air pollution dispersion values σ_{AQ} , which also increase progressively, reaching the highest levels in Linz. However, at this point, the dispersion of light pollution decreases again (see Table 6.1: σ_{LQ} for Steyr at 1.369 compared to Linz at $\sigma_{LQ} = 1.277$). To confirm this observed trend, a more comprehensive data set would be desirable.

Although these statistical values are influenced by various complex factors, an interesting hypothesis emerges from the current analysis. It is possible that aerosols, above a certain concentration threshold, play a role in minimizing the variability of light pollution values

by acting consistently throughout the year. This could result in fewer clear nights after a certain pollution level is reached. However, this hypothesis must be considered in conjunction with light pollution levels, which tend to rise in densely populated areas. A more precise evaluation of the light conditions in the studied areas would be required to draw stronger conclusions regarding this relationship.

While the interaction between air pollution and light pollution appears complex, these findings suggest that aerosols may have a stabilizing effect on the scattering of light pollution values under certain conditions, warranting further investigation.

Sulfur dioxide (SO_2), ozone (as discussed in the previous chapter), and carbon monoxide (CO) are identified as problematic pollutants in this analysis because they cannot be reliably used as markers for a direct relation to light pollution. These pollutants either do not follow the light pollution patterns at all, or do so only to an imperceptible degree. In the case of CO, the observed correlation with light pollution is minimal (see Figures 6.3.5). This divergence is particularly noteworthy given the data limitations, as CO measurements are available from only two monitoring stations. This restricted data coverage may affect the robustness of the conclusions regarding CO's behavior, limiting the ability to generalize its trends across the study area.

One plausible explanation for the observed behavior of SO_2 is its relatively low concentration in the atmosphere, with maximum values typically ranging between 3 to 4 micrograms per cubic meter (see Table 6.5). This small amount may contribute to its limited influence on the overall pollutant patterns and its weak correlation with light pollution trends. Unlike other pollutants, such as particulate matter or nitrogen dioxide, which show a more direct relationship with light pollution, these specific pollutants appear to be governed by different environmental or atmospheric dynamics, which are not as closely tied to the factors driving light pollution.

As illustrated in Table 6.8, the fluctuation range observed in urban and suburban areas is approximately **4 magnitudes**. In contrast, the analyzed rural regions of Grünbach and Feuerkogel display a narrower range, nearly **1.5 magnitudes** lower, hovering around **2.5 magnitudes**. This notable disparity prompts closer examination.

Interestingly, the light quality data from rural areas do not exhibit any discernible trend, challenging the assumption of aerosols as the sole source of fluctuations in light brightness. This observation gains credence from the lack of measurable pollutants in these rural environments, albeit the limited presentation of air quality data in this paper.

Thus, it becomes apparent that the deviation in light brightness can be directly attributed to the heightened concentration of aerosols in urban and suburban settings. However, the precise nature of this contribution remains elusive, necessitating further investigation.

Moreover, the assumption that emitted light from these areas remained relatively constant throughout the observation period underpins our ability to quantify the general effect of aerosols on light pollution in urban and suburban areas. This quantification, falling just under **1.5 magnitudes**, provides valuable insight into the broader impact of

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aerosols on light pollution dynamics.

Nevertheless, unraveling the specific contributions of individual aerosols to this effect presents a formidable challenge. This underlines the need for future research efforts aimed at unraveling these complex relationships and improving our understanding of aerosol-induced light pollution.

7 Conclusion

7.1 General Comment

If this work can show one thing, it is that light pollution is directly linked to aerosols in the air. Through the detailed analysis presented in Chapter 6.3, we gain valuable insights into how variations in aerosol concentration shape the distribution of light pollution. However, it is important to note the complexity involved in isolating the individual influence of each aerosol on light pollution. Even with comprehensive measurements of aerosol concentrations, a standardized methodology would be required to effectively compare their effects.

Furthermore, there is room for improvement in data reduction techniques, particularly regarding the influence of clouds, which was not thoroughly investigated in this study due to data limitations. Despite these challenges, this work offers a compelling examination of the significant impact of aerosols on light pollution.

Moving forward, future research should focus on refining methodologies for quantifying and characterizing the relationship between aerosols and light pollution. This includes developing standardized approaches for analyzing aerosol data in relation to light pollution and addressing gaps in understanding, such as the influence of cloud cover. By advancing our understanding of these complex interactions, we can develop more effective strategies for mitigating light pollution and preserving the quality of the nighttime environment.

The main goal of this thesis was achieved, laying the groundwork for quantifying the intricate connection between light quality and air quality data.

Limitations with using the KS Test

Regrettably, the application of the Kolmogorov-Smirnov (KS) test revealed its limitations in effectively quantifying the direct relationship between individual aerosols and their impact on light pollution within the datasets under investigation. Despite earnest deliberations and multiple consultations with my supervisor, no feasible avenue within the KS test framework emerged to establish a precise link between the individual data sets. This realization underscored the intricate and multifaceted nature of the data, posing a significant challenge to conventional statistical methods.

With the implementation of the second normalization, initially seen as a potential remedy, we encountered a setback in terms of quantifying the correlation. However, it did offer a silver lining by providing a more comprehensive overview of the intricate interplay between air quality and light quality data over the observation period. This broader perspective illuminated the complex dynamics at play and hinted at the nuanced relationships between various environmental factors.

7 Conclusion

To delve deeper into this complexity and conduct a more granular analysis, it became evident that alternative statistical methodologies would be necessary. These methods would need to possess the capability to dissect individual correlations with greater precision and sensitivity than afforded by the KS test. While various possibilities were explored and considered throughout the course of this master's thesis, including extensive discussions and consultations with experts in the field, none yielded a satisfactory solution with this method.

The journey of exploration and discovery undertaken in this thesis highlighted not only the challenges inherent in studying the interaction between air pollution and light pollution, but also the limitations of existing statistical tools in capturing the intricacies of such relationships. Despite the setbacks encountered, the endeavor has contributed valuable insights to the broader discourse on environmental science and statistical analysis. Furthermore, it underscores the ongoing need for innovative approaches and interdisciplinary collaboration to tackle complex environmental issues effectively.

While the limitations of the KS test may have hindered our ability to establish a precise link between individual aerosols and light pollution, the journey has been invaluable in deepening our understanding of the complex interplay between air pollution and light pollution.

7.2 Implications for astronomical Observations

In recent decades, the consideration of light pollution has emerged as a critical factor in observational astronomy (Walker, 1970), particularly in the evaluation of potential observation sites for telescopes. As telescopes continue to increase in size, the impact of even minor disturbances in light pollution becomes increasingly pronounced. This is particularly relevant for the new generation of super telescopes, characterized by main mirror diameters exceeding 30 meters (Riddle et al., 2008), which necessitate comprehensive and meticulous studies on atmospheric behavior, light pollution, wind dynamics, and other related factors.

The selection of suitable observation sites for these advanced telescopes requires careful consideration of various environmental and atmospheric parameters to ensure optimal conditions for astronomical research. Therefore, understanding the intricate interplay between atmospheric conditions, light pollution, and observational requirements is crucial for identifying sites that can support the scientific goals of these cutting-edge telescopes. This underscores the importance of rigorous research and analysis in assessing the suitability of potential observation sites and mitigating the impact of light pollution on astronomical observations.

A study on the influence of light pollution on the largest scientifically used telescopes worldwide shows that observation sites should be stable against light pollution over long periods of time (Falchi et al., 2022). A total of 28 observation sites were examined, each equipped with a telescope with a mirror diameter of over 3 meters. Two thirds of the observation sites have already exceeded a critical limit.

Improving Light Pollution Models

Further exploration into the effects of atmospheric aerosols holds profound significance, particularly in the context of refining and advancing light pollution models and their predictive capabilities. The first attempts to model light pollution date back to the 1990s by Garstang (1991). Skyglow models (Kocifaj (2008) and Kocifaj and Kundracik (2016)), radiative transfer models like ILUMINA (Aubé et al., 2005), and GIS-based models (Chalkias et al., 2006) are integral tools in assessing and forecasting light pollution, and they stand to benefit greatly from the insights garnered through comprehensive aerosol studies.

The selection of observation sites for large telescopes, upon which not only substantial financial investments but also crucial research outcomes rely, has become increasingly challenging in recent years. This challenge is exacerbated by the relentless global progression of light pollution and air pollution, which pose significant threats to astronomical research and our understanding of the cosmos.

In view of these developments, it is essential to ensure that potential observation sites remain protected from light and air pollution in the coming decades. The preservation of pristine skies is essential not only for the integrity of astronomical observations, but also for the well-being of ecosystems and human health in the regions concerned.

Achieving this objective requires a multifaceted approach, beginning with a comprehensive understanding of the composition and dynamics of light pollution. By understanding the complex interactions between atmospheric aerosols and light pollution, researchers can make informed decisions and take effective action to mitigate the negative effects of these trends.

Furthermore, advancing our understanding of aerosol effects on light pollution can lead to the development of more accurate and robust predictive models. These models can aid in identifying and evaluating potential observation sites, ensuring that future astronomical facilities are optimally situated to minimize the impact of light pollution and maximize scientific discovery.

Continued investigation into the effects of atmospheric aerosols on light pollution is essential for advancing our understanding of this pressing environmental issue. By enhancing our predictive capabilities and guiding informed decision-making, such research contributes to the preservation of pristine skies and the advancement of astronomical research for generations to come.

7 Conclusion

If this work shows one thing, it is that there is still work to be done on the issue of aerosols in relation to light pollution. Unfortunately, this issue is too complex to consider its individual components independently, making it extremely difficult to make concrete predictions and solid suggestions on how we should deal with this issue, let alone fix it.

Nonetheless, this scientific paper shows the irrefutable link between light pollution and air pollution, and at the same time provides the first insights into how badly environmental degradation and atmospheric pollution are affecting our night skies and ourselves. If we're not doing it for science, we should do it for ourselves.

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