

First 3-beam lidar observations of Noctilucent Clouds (NLC) at mid-latitudes

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Abstract: Noctilucent Clouds are a tracer for the dynamics in the atmosphere at 80 km to 85 km altitude. NLCs are formed in the polar summer mesopause region when and where the temperature is below the frost-point temperature. Occasionally, the clouds reach mid-latitudes, where temperatures are on average above the frost point. We operate a vertical-pointing daylight-capable Rayleigh-Mie-Raman (RMR) temperature lidar and a Doppler RMR lidar with two 25° off-zenith beams at Kühlungsborn/Germany (54°N, 12°E), complemented by the SIMONE meteor radar network. By doing so, we get temporal, vertical and horizontal information about the NLC with a distance of ~40 km between the three fields of view. Results from the first case studies are presented.

1. Introduction

Noctilucent Clouds (NLC, also called Polar Mesospheric Clouds, PMC) have been known from visual observations for nearly 140 years [1, 2]. Detailed studies of their origin in the past decades allow us to use them as a tracer for the dynamics of the upper mesosphere and lower thermosphere. NLCs consist of ice particles of several 10s of nanometers size. They are formed in the polar summer mesopause region if the temperature gets below the frost point. The clouds are moved by 3-D winds and sedimentation until they eventually sublimate if the temperatures get too high [3]. When traveling in the cold phases of planetary waves, tidal and gravity waves, NLC can also be observed at mid-latitudes, even if the average temperatures are above the frost point [4].

NLC have been observed for more than 25 years by our vertical-pointing Rayleigh-Mie-Raman (RMR) lidar at Kühlungsborn/Germany (54°N, 12°E) [5]. Daylight filtering has allowed for a complete diurnal coverage since 2010 [6]. The summer seasons 2022 and 2023 are the first, where we have added a co-located Doppler-RMR lidar using two beams pointing 25° off-zenith northward and eastward. By this, we get not only temporal and vertical, but also horizontal information about the NLC with a distance of ~40 km between the three fields of view. The lidar soundings are complemented by

wind observations of the co-located SIMONE Germany meteor radar network [7].

We will give a summary of the RMR lidars at our site in Section 2, present first case studies of the 3-beam NLC observations in Section 3, and describe our conclusions in Section 4.

2. Instrumentation

Three different RMR lidars have been used for this study since 1997. All are based on the emission of the second harmonic of injection-seeded Nd:YAG lasers (532 nm). The first laser emitted 30 pulses per second with an overall ~12 W power at 532 nm. Backscattered light was received by combined telescopes of 50 cm diameter and detected by high-sensitive photomultiplier tubes [8]. This lidar was used for either tropospheric aerosol soundings or middle atmosphere aerosol/temperature soundings, with the latter being limited to nighttime.

In 2010, we started observations with the next-generation RMR lidar, designed for temperature and aerosol soundings in the middle atmosphere at day and night [5]. The laser emitted 30 pulses per second, but with up to ~18 W of power. This lidar is continuously updated and automated, now utilizing a 100 Hz laser with ~70 W at 532 nm. Soundings are semi-automatically performed whenever the weather permits.

The third RMR lidar at our site is a Doppler wind/temperature system, installed in 2021 [9].

It uses a laser with 100 Hz repetition rate that is divided by a fast mirror in two beams at 50 Hz. Overall power is ~ 50 W at 532 nm. For this study, both beams are tilted 25° off-zenith, either northward or eastward. Soundings are limited to nighttime, but again running semi-automatically.

Figure 1 shows the location of the fields of view (FOV) at ~ 80 km altitude of the three beams used since autumn 2021. The vertical beam is at 54.12°N , 11.77°E .

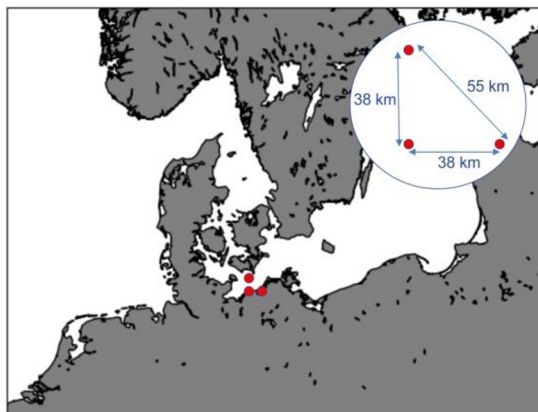


Figure 1. Map of NLC sounding region with vertical/north/east field of view.

The lidar data are complemented by wind observations with the SIMONe meteor radar network [7]. The SIMONe network at our location shares two transmitters and different receivers in northern Germany and Denmark.

3. Observations

NLC occurrence rates have been continuously measured since 1997 at our site. Figure 2 shows the interannual variation of occurrence rates. NLC are observed between 0% and nearly 20% of the total sounding time in summer (approx. June/July). The probability of NLC is highest in periods of low solar activity, related to the larger water vapor concentration and lower temperatures [5, 10]. In the most recent years, increasing solar activity has led to a decrease in NLC occurrence rates. Future studies will show whether there is a general positive trend in NLC occurrence above our site, as suggested by some studies because of middle-atmosphere climate change [11, 12].

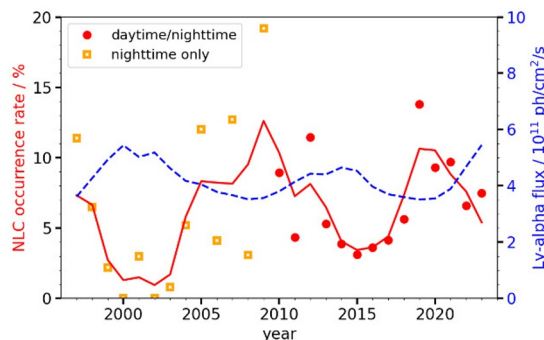


Figure 2: Interannual variation of NLC occurrence rates. The red line is a 3-year average. Ly- α data is taken from [13].

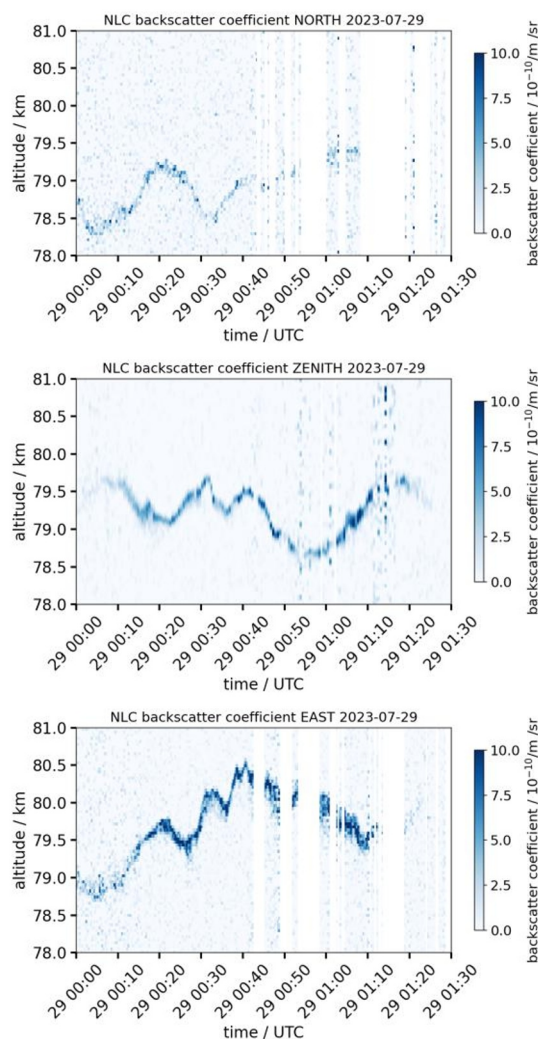


Figure 3: NLC backscatter coefficient at 532 nm in the night 28/29 July 2023 in the northward (top), zenith (middle), and eastward (bottom) beam. Resolution of the data is about 30 s and 45 m.

In 2022 and 2023, overall six NLCs have been observed in all three beams. This data combines temporal and vertical, but to some extent also horizontal, information. Figure 3 shows a part

of the soundings in the night of 28/29 July 2023. A thick and patchy NLC was already observed earlier in the same night, and around 0:00 UTC another, thin cloud appeared in all three beams. The zenith beam caught the NLC a few minutes after the others, suggesting an advection of the cloud from the north-east, as typical for our site [14]. As expected, the NLC occurred in all FOVs at about the same height between 79 km and 80 km and with a similar thickness of only about 100-200 m. On the other hand, the data show substantial differences in the cloud structure in the different FOVs. The north beam observed for the whole time a weaker part of the NLC ($\sim 5 \cdot 10^{10}$ /m /sr), while the backscatter coefficient was much higher in the east FOV ($\sim 10 \cdot 10^{10}$ /m /sr). Furthermore, the altitude variation in the three FOVs did not agree. While the altitude variation is roughly similar in north and east FOV between 0:00 UTC and 0:20 UTC, it was completely different thereafter. For the whole time, the altitude variation in the zenith beam did not resemble any other FOV.

The wind in the mesopause region was directed south-westward for the whole night (Figure 4). In the beginning of the night, where the thick/patchy NLC was observed at ~ 82 km (not shown), the wind speed showed only little variation up to 86 km. After midnight UTC, the wind speed decreased substantially above 83 km altitude. Future analyses of wind and temperature data from lidar and radar will show whether these changes in the wind structure are related to gravity waves.

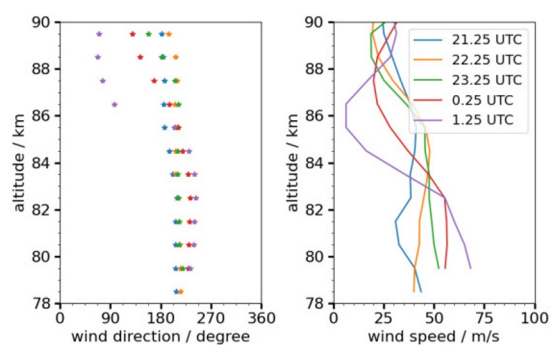


Figure 4: Hourly wind profiles (1 km resolution, 30 min Gaussian window) observed by SIMONe above Kühlungsborn in the night 28/29 July 2023.

4. Conclusions

NLC occurrence is strongly dependent on ambient temperatures and water vapor concentrations. This means, they are an

important indicator for the state of the atmosphere in a region, where decade-long time series are sparse. Our lidar observations starting in 1997 show a clear anti-correlation with solar activity. This can be explained by reduced water vapor concentration and rising temperatures at high solar activity.

In general, NLCs are formed at polar latitudes and advected to our mid-latitude site by southward wind. Though, simultaneous observations in three nearby fields of view (~ 40 km apart) show surprising differences. The timing of altitude variations observed in each of the beams does not mimic the ambient mean wind. Instead, we expect the small-scale structure of the clouds to be determined by gravity waves which generally propagate against the mean wind. In the future, we will examine the relevance of gravity waves for NLC structure in detail. Our lidar observations of NLC plus wind and temperatures in the whole mesosphere in combination with the radar wind soundings provide a well-suited data set for the investigation of middle atmosphere dynamics on various scales.

5. References

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