Decadal observations of particle sizes and water vapor content of noctilucent clouds

G. Baumgarten, U. Berger, J. Fiedler, J. Hildebrand, N. Kaifler, F.-J. Lübken

Leibniz-Institute of Atmospheric Physics at the University of Rostock, Kühlungsborn, Germany
Why NLC Observations?

- NLC are an impressive visual phenomenon, documented observations since 120 Years.
- Difficult to investigate atmospheric trace gases at this altitude directly → NLC as tracer.
- NLC are a sensitive tracer (+1 km change of cloud altitude: Temperature +3K or H₂O -60%).
- NLC show variability on different time scales visualize the Dynamics in the mesopause region.
- Particle properties are important for microphysical processes in the clouds and with their environment.
- What is a good proxy for year to year variations / trends?
Freeze-drying of the polar mesosphere

von Zahn and Berger, 2003

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Freeze-drying of the polar mesosphere

von Zahn and Berger, 2003
Active soundings of NLC are challenging!

**Photon budget:**
- Laser emission: $10^{18}$ photons / pulse
- 90% exported to space
- 10% scattered below 20 km
- 0.01% scattered between 20-100 km
- $10^{-7}$ scattered between 80-100 km

**Setup of RMR Lidar**

**Lasers:**
- Injection seeded Nd:YAG
- $\lambda$'s: 355, 532, 1064 nm
- 30 Hz repetition rate
- 2 x 55 MW peak power @ 532nm

**Telescopes:**
- 1.8 m diameter
- 180 µrad field–of–view (~18 m at 100 km distance)

**Detectors:**
- 4 pm spectral bandwidth
- Single photon counting
Measurement Method: Lidar

- brightness
- altitude (centroid)
- vertical extent (FWHM) \( \delta z \)
- occurrence = NLC- / total- time
- time resolution ~ 15 min

\[
\beta_{NLC}(z) = (R(z) - 1) \cdot \beta_M(z)
\]

\[\beta_{\text{max}}, \beta_{\text{total}}, z_c, \delta z\]
Lidar observations in Northern Scandinavia
Using three widely separated colors (355 nm, 532 nm, 1064 nm) we calculate simultaneously:

- particle size
- distribution width
- number density
Method of Measurement (Active Sounding)

- The lidar provides simultaneous and common-volume measurements of altitude-dependent volume backscatter coefficients $\beta$ at the wavelengths of 355, 532, and 1064 nm and at any solar zenith angle (independent of LT).

- We calculate color ratios

$$CR(\lambda_1, \lambda_2, z) = \frac{\beta(\lambda_1, z)}{\beta(\lambda_2, z)}.$$  

$\lambda_1=355, 1064 \text{ nm}; \ \lambda_2=532 \text{ nm}$

- Our standard resolution values are 14 min and 150 m.

- Optical Model: T-Matrix for spheres, spheroids and cylinder
Altitude dependence of particle properties

Particle properties depend on altitude ... in a complicated way.

Strong clouds, 2006 – 2011

E.g. Baumgarten and Fiedler, GRL, 2008

All clouds, 2006 – 2011
What do we learn from particle size and distribution width?

Baumgarten et al., ACP, 2010

standard clouds

particle size

normalized probability [1]
What causes the increase of distribution width?

Vertical gradient in particle size needed

![Graph showing eddy diffusion and particle size (r)]
year to year variations at the peak of the NLC layer
Size, number density and volume

Number density varying by factor of 3

Volume density varying only slightly

40 ng/m^3

update from
Baumgarten et al., JGR, 2008
Volume density not a good proxy? what about

Cloud water content (at the peak of the layer)

<table>
<thead>
<tr>
<th>NLC class</th>
<th>Ice volume density $V \ [10^{-14} \text{ cm}^3/\text{cm}^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>faint clouds</td>
<td>$\approx 1.5$</td>
</tr>
<tr>
<td>weak clouds</td>
<td>$\approx 3$</td>
</tr>
<tr>
<td>medium clouds</td>
<td>$\approx 4.5$</td>
</tr>
<tr>
<td>strong clouds</td>
<td>$\approx 8$</td>
</tr>
</tbody>
</table>

(Baumgarten et al., JGR 2008)

$CWC_{\text{class}} = OF_{\text{class}} \times V_{\text{class}}$

faint clouds: most often
strong clouds: largest variability and $5 \times$ more water

e.g. Stevens et al., 2007
Variations of NLC Occurrence and Cloud Water Content

CWC variation over day:
- factor ≈ 9 (only strong clouds)
- factor ≈ 3 (all clouds)
Old: only at the peak
New: vertical integral
Ice water column and the total ice mass

Decrease of total ice mass?
IWC and comparison to LIMA model

Why is the agreement to LIMA good in altitude, brightness, radius, and frequency of occurrence but **bad** in IWC?
Where do we find the most water in NLC?

![Graph showing the distribution of water in NLC](image-url)
Diurnal variation of IWC

Only small diurnal variation of IWC (and not yet understood)
Size, distribution width and number density

Small variations of the vertical integrated particle size

Even smaller variations of the distribution width

Huge variations of the vertical integrated number density ~ factor of 5
How does NLC intermittency affect the ice water column?
How does … for different instruments?

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Area (km)</th>
<th>Volume (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lidar</td>
<td>500 m x 20 m x 40 km</td>
<td>0.4 km$^3$</td>
</tr>
<tr>
<td>CIPS</td>
<td>1.5 km x 5 km x 5 km</td>
<td>38 km$^3$</td>
</tr>
<tr>
<td>SOFIE</td>
<td>1.5 km x 5 km x 300 km</td>
<td>2250 km$^3$</td>
</tr>
<tr>
<td>SCIA</td>
<td>1.5 km x 400 km x 1000 km</td>
<td>600000 km$^3$</td>
</tr>
</tbody>
</table>

Time [UT] on 29./30.07.2008

Max: 55.4
Err: 0.5
Min: 0.1

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What is relevant for long-term NLC evolution?

Zonal mean ice mass = IWC x OF

Huge day to day and year to year variations of zonal mean IWC / ice mass due to NLC intermittency
Summary

Aerosol properties (particle size, number density (N), distribution width) holds information about water content, temperature and turbulent mixing.

Not so simple transfer from brightness to volume density and finally total ice mass. (e.g. due to varying N, not even for integrated aerosol properties)

Year to year variations of zonal mean ice water column mainly affected by occurrence frequency, only ~20% caused by IWC changes.

IWC of strong clouds seems to be decreasing.
How to compare ground and space based observations
Detection threshold estimation
CIPS PMC observations above Scandinavia

CIPS has high resolution and a large Field of view (Germany fits in one frame)
Vision of light detection and ranging (lidar) 120 years ago...

Jesse, MZ, 1887

1960s: careful efforts ...

1989: first detection of NLC by lidar

“ It will be thrown a bunch of intensive parallel electrical light onto the clouds .... “
Altitude of NLCs

controlled by temperature and H\textsubscript{2}O mixing ratio

Observed $\Delta z = +1\text{km}$ corresponds to

- $\Delta T \sim +3\text{ k}$
- $\Delta H\textsubscript{2}O \sim -60\%$

increased photo dissociation of H\textsubscript{2}O by increased solar Ly-Alpha