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The fractal perimeter dimension of noctilucent clouds: Sensitivity analysis of the area–perimeter method and results on the seasonal and hemispheric dependence of the fractal dimension

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ABSTRACT

The fractal perimeter dimension is a fundamental property of clouds. It describes the cloud shape and is used to improve the understanding of atmospheric processes responsible for cloud shapes. von Savigny et al. (2011) determined the fractal perimeter dimension of noctilucent clouds (or polar mesospheric clouds) for the first time based on a limited data set of cloud images observed with the CIPS (Cloud Imaging and Particle Size) instrument on board the AIM (Aeronomy of Ice in the Mesosphere) satellite. This paper builds on von Savigny et al. (2011) by first presenting a sensitivity analysis of the determination of the fractal perimeter dimension, and secondly presenting results on the seasonal and interhemispheric differences of the perimeter dimension of noctilucent clouds (NLCs). The same method as in the earlier study is applied to an extended data set of satellite images of noctilucent cloud fields taken with the CIPS experiment. The sensitivity studies reveal that cloud holes play an important role for the area–perimeter method, since excluding clouds with holes reduces the dimension value by up to 3%. The results on the fractal perimeter dimension over six NLC seasons from 2007 to 2009 demonstrate that the dimension values of the NLCs neither show significant differences between the seasons nor between the hemispheres.

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1. Introduction

NoctiLucent Clouds (NLCs) or Polar Mesospheric Clouds (PMCs) are optically thin clouds at about 83 km altitude (e.g., Lübken et al., 2008) exclusively occurring in the northern and southern polar summer mesopause region around summer solstice from about mid-May to mid-August in the northern hemisphere and from about mid-November to mid-February in the southern hemisphere. Summer upwelling and adiabatic cooling cause this to be the coldest region of the Earth's atmosphere (e.g., Lübken, 1999), which is essential for the NLCs, since they consist of water ice particles. Their fascinating appearance might be attributed to the fact that they shine in bluish and occasionally in orange colours, but also to their fractal shape. Like most systems and objects in nature clouds are fractals (Mandelbrot, 1991). Fractals are scale invariant, statistically self-similar and highly irregular objects featuring dimensions of non-integer values unlike the topological dimensions of simple objects. The (multi-) fractal nature of clouds results from the fractal nature of atmospheric dynamics. Scale invariance in cloud radiances, for instance, is often used in order to examine scaling models of atmospheric dynamics (e.g., Lovejoy et al., 1992; Lovejoy and Schertzer, 2013). The fractal perimeter dimension is a fundamental property of clouds. Lovejoy (1982) determined this dimension for tropospheric cloud and rain fields, and von Savigny et al. (2011) presented the fractal perimeter dimension of NLCs.

In this paper, we describe the algorithm used by von Savigny et al. (2011) in detail and discuss several aspects that affect the determination of the fractal perimeter dimension, i.e., the influence of holes in cloud fields and artificial edges caused by the border of the orbit scene. The non-negligible influence of holes on the fractal perimeter dimension of clouds is particularly a feature that has – to our best knowledge – not been discussed in any of the existing studies on the fractal perimeter dimension of natural objects. In addition, results on the fractal perimeter dimension of NLCs for different seasons and hemispheres are presented.

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The fractal analysis of NLCs is based on orbit images of cloud fields taken by the Cloud Imaging and Particle Size (CIPS) instrument (McClintock et al., 2009) on board the NASA Aeronomy of Ice in the Mesosphere (AIM) satellite (Russell et al., 2009). A specific algorithm identifies cloud clusters exceeding a certain albedo threshold and determines their area and perimeter. As the cloud area varies over about three orders of magnitude, the area–perimeter relation (Mandelbrot, 1991) is a reasonable method to derive the fractal dimension, and is therefore used in this study.

The characteristic spatial length scales of these clouds range from kilometers to thousands of kilometers, and it is an open question as to which dynamic processes are responsible for their shape and distribution. The physical processes in the upper atmosphere, appearing on the same scales, are not well understood. NLCs can act as a tracer of these unexplored phenomena in the mesosphere. The AIM mission was established to explore the relationship of NLCs and their atmospheric environment (Russell et al., 2009). So far, temperature, water vapour, cosmic dust influx (Thomas, 1996) and mesospheric dynamics (Hines, 1968; Turco et al., 1982) are assumed to be responsible for the NLC formation. In von Savigny et al. (2011) we suggested quasi-geostrophic 2-D turbulence as a possible candidate for the relevant dynamical mechanisms. The recent studies by Tuck (2010) and Schertzer et al. (2012) – providing experimental and theoretical evidence – suggest that scaling behaviour in atmospheric parameters is best explained within the framework of generalised scale invariance, rather than by 3-D or 2-D turbulence. A further possible candidate are gravity waves. They appear in the same scale range as NLCs and are assumed to be the more dominant mechanism in the mesosphere compared to turbulence (Fritts and Alexander, 2003). VanZandt (1982) presented power spectra of mesoscale horizontal velocity fluctuations in the troposphere and lower stratosphere, which show a $k^{-5/3}$ scaling behaviour that can be described by a gravity wave model. Hoffmann et al. (2010), who investigated energy spectra of meridional wind fluctuations in the upper mesosphere based on radar measurements, found $k^{-5/3}$ scaling behaviour from a temporal scale of 1 h up to the period of the semi-annual tide.

2. Instrument and data

For the results presented in this paper, measurements from the AIM CIPS instrument (McClintock et al., 2009) were used. AIM is the first satellite mission dedicated to observing NLCs. It was launched on April 25th, 2007, into a sun-synchronous, 600-km altitude orbit, and began measurements on 24 May, 2007. The AIM CIPS instrument provides daily images of small-scale NLC structures with high spatial resolution over an entire NLC season, covering the polar region up to about 85° in latitude.

Details of the CIPS sampling and retrieval algorithm are described by Lumpe et al. (2013). Briefly, CIPS comprises four nadir-viewing, wide-angle cameras that measure scattered solar radiation in a spectral passband of 265 ± 7.5 nm. The cameras are arranged in a cross pattern, with a total instantaneous field of view of 120° (along-track) by 80° (cross-track). This covers about $2000 \times 1000\ \mathrm{km}^2$ at the NLC height of about 83 km. On each orbit 27 four-camera images are acquired, one every 43 s. These images are processed as described by Lumpe et al. (2013) yielding 15 individual orbits of data each day with 25 km^2 ($\sim 5 \times 5\ \mathrm{km}^2$) spatial resolution. Orbits overlap at the highest latitudes to give full coverage above about 70° latitude.

For any single location, CIPS measurements are made at a large range of scattering angles, which enables determination of the scattering phase function. Discriminating between NLC and background Rayleigh scattering takes advantage of the fact that Rayleigh scattering is symmetric about a scattering angle of 90°, whereas NLC scattering is weighted toward forward scattering (Bailey et al., 2009; Lumpe et al., 2013). The NLC albedo, which is the parameter analysed here, is calculated after subtracting the Rayleigh scattering contribution to the total observed signal. It is defined as the ratio of the NLC scattered radiance to the incoming solar irradiance, in units of sr^{-1}.

In this study, CIPS level 2 data were used. This data product contains retrieved cloud parameters (albedo, particle radius, and ice water content) on an orbit-by-orbit basis, with 25 km^2 resolution. Due to the variation of the scattering angle and view angle of the observations along the orbit, the measurements are phase-compensated, i.e., normalised to a scattering angle of 90° and a view angle of 0°. Typically the albedo varies between $0 \times 10^{-6}\ \mathrm{sr}^{-1}$ and $100 \times 10^{-6}\ \mathrm{sr}^{-1}$, while very few values exceed $80 \times 10^{-6}\ \mathrm{sr}^{-1}$. CIPS NLC frequencies and albedos have been shown to compare well with measurements from the Solar Backscatter Ultraviolet instruments by Benze et al. (2009, 2011).

Two different versions and time periods of the data set have been considered in this work. We used v4.10 data for the NH 2007 NLC season. This is the same data as in von Savigny et al. (2011) and is therefore also used here for the sensitivity studies. On the other hand, for the extended data set from 2007 to 2009 for both hemispheres, v4.20 data is used, as this is the current data version. The slight difference between CIPS v4.10 and v4.20 data does not influence the result of the fractal perimeter dimension.

3. Analysis method and algorithm

3.1. The area–perimeter relation

We examined the 2-dimensional CIPS cloud field scenes based on the area–perimeter relation. Mandelbrot (1991) suggested using this relation to investigate the structure of planar shapes. For any family of standard planar objects, there exists the following relation between area A and perimeter P:

$$A \propto P^2 \Leftrightarrow P \propto A^{1/2} \tag{1}$$

Classic examples include smooth and simple objects like circles, which have the exact relation of $P = 2\pi^{1/2}A^{1/2}$, and squares with $P = 4A^{1/2}$. This relation is different for fractal objects featuring contorted perimeters. Hence, another method to determine the fractal dimension is necessary, which involves the so-called fractal perimeter dimension D. The utilisation of D makes it possible to derive a coherent relation between area and perimeter. The idea is that the perimeter rises relative to the area with increasing irregularity of the shape. The set of fractal curves, like the perimeter of a fractal object, fills more space than a simple line. This is expressed by the fractal dimension, which is then a number between 1 and 2. Accordingly, the area–perimeter relation for fractals is (Mandelbrot, 1991)

$$A \propto P^{2/D} \Leftrightarrow P \propto A^{D/2}. \tag{2}$$

Smooth perimeters with $D=1$ would lead from the latter equation to Eq. (1) and a perimeter with the highest degree of irregularity (meaning that it fills a plane) would result in $D=2$ and hence $P \propto A$.

In order to obtain D, it is common to examine objects with a scaling behaviour of $A(P)$ over at least two orders of magnitude. Then the dimension can be estimated from the slope of a fit to the data points in a double logarithmic plot (see Section 3.3).

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