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Analysis of gravity waves structures visible in noctilucent cloud images

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A B S T R A C T

The noctilucent clouds (NLC) are high-altitude bright cloud formations visible under certain conditions from high-latitude places during the summer months. Even if the exact nature of these clouds still remains a mystery, they are an efficient tracer of the dynamic processes at their level, particularly the gravity waves propagating from the stratosphere through the mesopause layer. In this paper, we describe a technique developed to analyze the structures visible in the NLC images taken every summer night since 2004 from Stockholm, Sweden (59.4°N). The parameters of 30 short-period gravity wave events have been measured and compared with older datasets obtained mostly from low and mid-latitude sites, using airglow imaging techniques. The horizontal wavelengths are in good agreement with previous results while the observed horizontal phase speeds exhibit smaller values than for other sites. The directionality of the waves presents strong poleward preference, traditionally observed during the summer season. This anisotropy and the difference in the phase speed distribution cannot be explained by the filtering due to the background wind field but more probably by the position of the gravity waves sources, located to the south of the observation site.

1. Introduction

Noctilucent clouds (NLCs) are thought to be composed of small ice particles but their process of formation is still a hot research topic. They occur in the upper mesosphere, between 80 and 85 km, with a mean altitude of 82.9 km (Gadsden and Schröder, 1989), and are most frequently observed from the ground between 50° and 65° of latitude. Their appearance is very similar to cirrostratus clouds, which are also composed of ice but develop in the troposphere; however, their color is generally silvery blue (Fig. 1). Each NLC may be composed of different forms, classified in four major types: veil (Type I), bands (Type II), billows or waves (Type III) and whirls (Type IV). These four major types are then separated in several subdivisions (Gadsden and Parviainen, 1995). NLCs were first reported in 1884 (Leslie, 1884; Jesse, 1889), but their occurrence and brightness are claimed to be increasing, especially during the last 30 years (Gadsden, 2002; Klostermeyer, 2002; Deland et al., 2003). Furthermore, sightings from unusual mid-latitude sites have more often been reported (Taylor et al., 2002; Wickwar et al., 2002; Nielsen et al., this issue). Following these observations, it has been suggested that the occurrence of NLCs may be a very sensitive indicator of the changes in the atmosphere composition and dynamics, and possibly of the Earth global change.

Besides the study of their own properties (Witt, 1962; Fogle and Haurwitz, 1966), NLCs are also an interesting tool for analyzing the dynamics of the upper atmosphere. In fact, they work as a tracer of the coherent structures forming or propagating at their level (e.g., Fritts et al., 1993; Chandran et al., 2009). Optical studies of similar phenomena have already been done using the mesopause region airglow emissions as markers of the waves (e.g., Taylor et al., 1997; Pautet et al., 2005; Nielsen et al., 2009). Since the NLC layer is significantly thinner than a typical airglow layer (2–3 km compared to 8–9 km) (She and Lowe, 1998), the observed wave signatures should appear much more clearly in NLC images and thus could be studied in much better detail. Also, the airglow imaging technique requires conditions that are not always encountered at high-latitudes because of the persistent twilight in the summer months and the possible auroral contamination of these faint emissions throughout the year. Hence, imaging NLCs provide a method to perform summer-time observations, and in conjunction with airglow observations, complete a full seasonal study of wave structures.

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Fig. 1. Noctilucent cloud image taken from Frescati, Sweden (59.4°N), on July 16th, 2005, at 22:30 UT (0:30 LT).

Several types of structures, with different origins, may be analyzed using the patterns visible in the NLC images (Haurwitz, 1961), like the short-period (< 1 h) gravity waves (or bands) and the ripples (or billows). The background wind might also be determined (Fogle and Haurwitz, 1966; Fritts et al., 1993).

The small-scale waves, termed ripples or billows, are short-lived (typically few tens of minutes) structures due to localized regions of convective or shear instabilities, generated in-situ at mesospheric altitudes (Taylor and Hapgood, 1990; Fritts et al., 1993, 1994). They may also be the result of the breaking of a freely propagating gravity wave (Horinouchi et al., 2002).

Gravity waves are the oscillations of air parcels by the lifting force of buoyancy and the restoring force of gravity (Hines, 1960). They can be generated by several sources: in the troposphere by thunderstorm updrafts, frontal systems or airflow over mountains, but also by interaction with the polar jet stream, geostrophic adjustments, wave–wave interactions or wave breaking. These waves propagate vertically and horizontally and may be observed during several hours. Their horizontal wavelength may vary from 10 to more than 100 km. They play an essential role in affecting the dynamics and structures of the middle and upper atmosphere and participate in driving the thermal structure and setting up large-scale meridional circulation in the mesosphere and lower thermosphere (MLT) region (altitude ~60–100 km). Freely propagating gravity waves actively transport energy and momentum from the troposphere into the MLT region, where they deposit their energy and transfer their momentum to the mean flow when breaking in the more rarefied air (Lindzen, 1981; Fritts and Alexander, 2003). They also have direct effects on the noctilucent clouds: horizontal variations in cloud particle concentration, decrease of ice crystal size and average cloud albedo for short-period (less than a few hours) gravity waves, inhibition of the NLC formation due to temperature perturbations (Jensen and Thomas, 1994; Rapp et al., 2002).

When seen from the ground, all these waves are distorted by the geometry of the observation. The spherical shape of the atmospheric layer where NLCs reside and the refraction due to propagation through the atmospheric medium, modify the shape, the size and the observed speed of the waves. All these parameters are necessary to understand the gravity waves properties; thus, it is important to work with geographically-oriented, linear-scaled images to permit the accurate measurement of these values.

In this paper, we will describe a technique developed to analyze short-period gravity wave structures observed in NLC images. Following a detailed description of the problem geometry, the original images will be projected onto a linear geographic grid in a process known as "unwarping". These new images will be similar to satellite-type pictures: the NLC layer as seen from the top, looking downward, oriented due to the geographic north, and represented with a linear scale. The second part of this paper presents an analysis of the short-period gravity waves observed during 5 NLC seasons, between 2004 and 2008, from the Stockholm University campus (59.4°N). Their characteristics are compared with previous low and mid-latitude and recent high-latitude measurements obtained using airglow data.

2. Observations

NLCs may be seen at mid and high-latitudes due to the scattering of sunlight from a very thin layer of tiny ice particles (~50 nm), which can form and grow in the very cold conditions (~120–140 K) of the high-latitude mesopause region during the summer months. In this specific latitudinal zone, when the sun lies between 6° and 12° below the horizon (nautical twilight), an observer staying in the darkness will be able to see NLCs that are still in the direct sunlight because to their high altitude. Under these conditions, the sunlight scattering from the atmosphere occurs only at higher altitudes (above at least 40–50 km) and the sky is dark enough to observe NLCs that are seen within the twilight arch as it moves in azimuth with the sun (Fogle and Haurwitz, 1966).

Since summer 2004, pictures of NLCs have been taken from the top floor window of the Arrhenius Laboratory at the university campus in Frescati, Stockholm, Sweden (59.4°N, 18.1°E). A digital camera (Canon PowerShot G5), operating in interval time shooting mode, takes every night hundreds of pictures of the twilight sky at the rate of 1 (2004 and 2005) or 2 (since 2006) pictures per minute, with exposure times varying from 0.5 to 6 s, depending on the darkness of the sky. The images are stored on a computer in a digital format. Fig. 1 shows an example of NLCs photographed during the night of 16–17 July, 2005, at 22:30 UT. Many structures with various shapes and sizes are clearly visible in the twilight arch. At the upper edge of the image, above the twilight arch, the NLCs are not visible as they are not illuminated by the sunlight, and in the lower part of the image, below the twilight arch, because the sky is too bright as the sunlight reaches lower atmospheric layers. It is possible to see short-period gravity waves in the center right half of the image, at mid-height, but also ripples structures at the same elevation, close to the right edge. Although other structures are present in the image we will restrict our analysis to these two groups of structures. Due to the perspective, it is difficult to determine the parameters of these waves, i.e. their wavelength seems to decrease when they are located further from the observer. The final processed images will permit to make these measurements using any well-known computational technique, such as a Fast Fourier Transform.

3. Processing technique

Before processing an NLC image, it is necessary to know the observation parameters of the imaging system. The determination of the horizontal and vertical fields of view (FOV_X and FOV_Y) and the azimuth α_{Cam}, elevation β_{Cam} and rotation Rot_{Cam} of the optical axis of the camera is done with a well-proven star calibration method (Garcia et al., 1997). Knowing the exact geographical position of the observer and the exact time of observation, it is possible to identify the stars visible in a "calibration" image acquired when the sky is dark enough, usually at the beginning or at the end of the NLC season. The imager parameters can then be extracted by applying a least-square algorithm as the exact star locations are known.