AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078501

First Observed Temporal Development of a Noctilucent Cloud Ice Void

Linda Megner[1], Jacek Stegman[1], Pierre-Dominique Pautet[2], and Michael J. Taylor[2]

[1]Department of Meteorology, Stockholm University, Stockholm, Sweden, [2]Center for Atmospheric and Space Science, Utah State University, Logan, UT, USA

Key Points:
- First observation of a complete development of a so-called noctilucent cloud ice void
- The time scales with which the ice void appears and disappears suggest that the cause of the void is not a cooling followed by sedimentation of large particles, but rather a warming, causing particles to sublimate
- The void was remarkably stable and unaffected by the local prevailing wind, indicating that the origin of the void is of localized and stationary character

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Movie S1

Correspondence to:
L. Megner,
linda.megner@misu.su

Citation:
Megner, L., Stegman, J., Pautet, P.-D., & Taylor, M. J. (2018). First observed temporal development of a noctilucent cloud ice void. *Geophysical Research Letters*, *45*. https://doi.org/10.1029/2018GL078501

Received 15 MAY 2018
Accepted 14 AUG 2018
Accepted article online 28 AUG 2018

Abstract Noctilucent clouds are thin ice clouds that appear around the summer polar mesopause. Recently, the Cloud Imaging and Particle Size instrument on the AIM satellite discovered nearly circular ice free regions within the clouds—denoted as "ice voids." The origin of these ice voids is not known. Their existence has so far only been reported by Cloud Imaging and Particle Size, which only can give very limited information of the time scales involved. On 4 July 2010, such an ice void was registered by our ground-based camera taking images with 30-s time interval. We thus here present the first full temporal development of an ice void. Surprisingly, the void did not drift with the prevailing wind as cloud features around it, but instead remained notably stationary for its entire existence of approximately 1 hr. This indicates that that the origin is of stationary character, rather than a rapid change of the local atmosphere.

Plain Language Summary Noctilucent clouds are ice clouds that appear high in the atmosphere, about 80 km above the summer pole. By observing them we have learned a lot about the remote and inaccessible region where they form. Recently, a satellite borne instrument discovered nearly circular ice-free regions within the clouds, denoted as "ice voids." The origin of these voids is a mystery—we do not know what causes the clouds to disappear in large circular areas. So far these voids have only been observed from satellites, which only can take pictures of the clouds when they pass above once every 1.5 hr—longer than most ice voids exist. This means that until now we completely lack observations of the development and disappearance of the voids. Here we therefore present the first full temporal development of a void, as observed by our ground-based camera taking images every 30 s. Surprisingly, the void did not drift with the wind as cloud features around it, but it remained notably stationary for approximately 1 hr. These observations give important clues to help us solve the mystery of the origin of these voids—they suggest a steady local heating of the atmosphere as the cause.

1. Introduction

Noctilucent clouds (NLCs), also known as polar mesospheric clouds, have been extensively observed and characterized from the ground since their first identification in 1885 (Leslie, 1885). It has been argued that NLCs first appeared just around this time and that they are important indicators for atmospheric changes and variability (Thomas, 1996). More recently, it has also been demonstrated that NLC properties and occurrence frequency are intimately related to the dynamic coupling processes on global scale (Karlsson et al., 2007). Noctilucent clouds were first detected from space by an instrument on the OGO-6 satellite in 1972. It was also discovered that a permanent scattering layer exists over the polar cup during the summer (Donahue et al., 1972).

NLCs consist of scattering submicron ice particles, and the displays are typically very dynamical and structured; a large variety of different wave-like forms on scales varying from a few to hundreds of kilometers have been observed. These structures develop on time scales of minutes to hours and are clearly influenced by the wind prevailing in the layer where the cloud resides. Many of the observed structures may be attributed to gravity wave propagation through the layer, some of the waves generated locally and some of them propagating up from sources below. In fact, the characteristics of gravity waves in this altitude region have been retrieved from images of NLCs (e.g., Taylor et al., 2011; Witt, 1962). The wave patterns observed in NLC displays resemble the wave patterns that can be detected in airglow, particularly the OH airglow (e.g., Taylor et al., 1997, 2011). However, the mechanisms responsible for "visualization" of the passing gravity waves are completely different in the airglow layers as they are due to photochemical emissions rather than light scattering on particles, which results in different time constants and a much broader altitude range where the waves can be observed. On some occasions, the wave patterns observed in airglow could also be related to tropospheric sources—a strong thunderstorm activity (Taylor & Hapgood, 1988) or a tropospheric front (Brown et al., 2004; Giongo et al., 2018).

More recently NLCs have been extensively studied by a number of satellite missions, such as the SBUV satellite series (DeLand et al., 2003), the Odin satellite launched in 2001 (Llewellyn et al., 2004), and the AIM satellite (Russell et al., 2009), launched in 2007. The latter is entirely dedicated to research on NLC/polar mesospheric clouds. AIM carries the Cloud Imaging and Particle Size (CIPS) experiment, a wide-angle (120° along track by 80° across track) imager consisting of four identical cameras arranged in a cross pattern. CIPS is the first spaceborne instrument to take images of polar mesospheric clouds with a high spatial resolution (25 km^2) and was therefore the first instrument to discover "ice voids"—large dark circular regions described as "virtually ice-free" (Rusch et al., 2009). Later it has been pointed out that these regions may in fact not be ice free but simply populated by particles smaller than the detection limit of CIPS (Thurairajah, Bailey, Nielsen, et al., 2013; Thurairajah, Bailey, Siskind, et al., 2013). It should be stressed that "holes" in NLCs have been remarked on earlier (Dalin et al., 2010; Witt, 1962)—but it is unclear if these smaller structures are of the same origin as the larger observed by CIPS and presented in this article.

In the CIPS images ice voids appear as oval-shaped dark spots with diameters varying from tens to hundreds of kilometers but typically about 300 km. The cause of these ice voids is not known. Rusch et al. (2009) hypothesize that they "could be caused by energy deposition (heating) through gravity wave breaking, but they may also occur due to turbulent mixing from vertically displaced air (either by convective instability or also gravity wave breaking)." Thurairajah, Bailey, Siskind, et al. (2013) suggests that these voids could form in a shock wave, for instance caused by a meteorite, which cools the air so that the ice particles grow large and fall out, in a similar way that tropospheric "hole-punch" clouds are believed to originate from the passage of an aircraft (Heymsfield et al., 2011). Thurairajah, Bailey, Nielsen, et al. (2013) performed a case study of a void identified by CIPS using the NOGAPS-ALPHA model (Siskind et al., 2011). Their analysis indicates that the time and place of that void was characterized by higher temperatures and lower water mixing ratios.

These ice voids have so far only been observed by the CIPS instrument. Given that AIM is a polar orbiting satellite, the highest possible time resolution is about 90 min (the orbit time of the satellite). This means that until now only very limited information on the dynamical behavior on the relevant time scales of these features is available. Here we therefore, for the first time, present the detailed temporal and spatial development of an ice void, as registered by a ground-based camera in a noctilucent cloud display north of Stockholm, Sweden on 4 July 2010 (see Figure 1).

2. Data Analysis

Since the summer 2004 until the summer 2013, photographs of noctilucent clouds were taken from the top floor window of the Arrhenius Laboratory at the University Campus in Stockholm, Sweden (59.37°N, 18.06°E). Our digital camera took images of the twilight sky at a rate of one to two pictures per minute.

The molecular Rayleigh scattering background dominating in our photographs changes dramatically between the lower and the upper parts of the images due to changing solar depression angle. In order to remove this background and enhance the NLC structures we subtract a photograph taken on a (tropospheric) cloud- and NLC-free night at a corresponding solar zenith angle from a photograph with NLCs present. The resulting image with subtracted Rayleigh background can be much easier treated to enhance the contrast.

When observed and photographed from the ground, NLCs are distorted by the geometry of the observation. The spherical shape of the atmospheric layer where NLCs reside and the refraction modify the shape and size of features in the clouds as well as the speed of motion of these features. In order to correctly represent movements and actual spatial scales we use a technique to reproject these images onto a horizontal plane (Pautet et al., 2010). The observed star field is used to calibrate the FOV of the camera, and the layer altitude is assumed to be at an altitude of 82.5 km. Refraction that amounts to about 10 arc min at 5° elevation and rapidly decreasing with elevation is taken into account. In the reprojected images, the NLC layer appears as seen from above on a horizontal geolocated plane and is represented with a linear scale. The reprojected image is approximately 500 km at its broadest in both latitudinal and longitudinal directions.

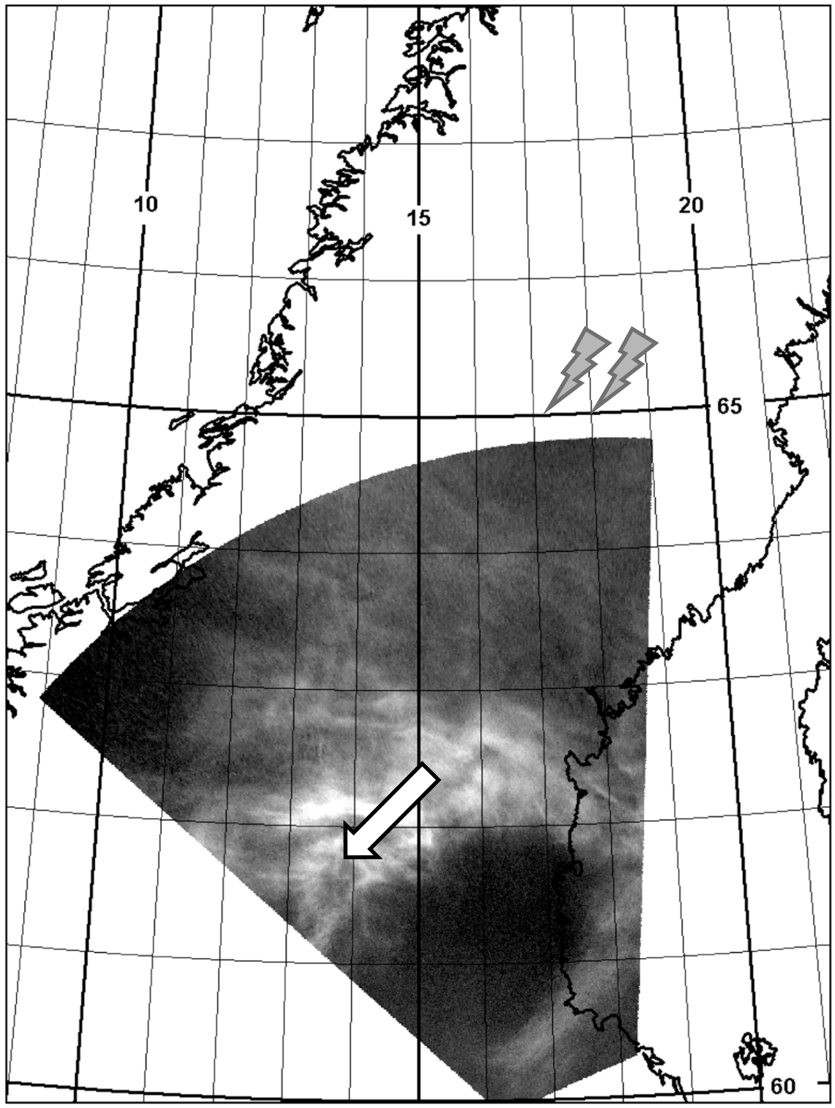

Figure 1. Reprojected, geolocated image of the void at 23:02 UT. The position of thunderstorm (lightning) activity is marked (see section 4), and the wind vector is given by the white arrow.

3. Results

An ice void appeared over central Sweden on 4 July 2010. Its development and motion can be seen in Figure 2, with a 10-min interval between the images. The left-hand panel shows the raw photographs, the middle panel shows the images with the atmospheric Rayleigh background subtracted, and the right-hand panel shows the corresponding reprojected geolocated images. In the supporting information, pictures with 30-s time separation can be viewed as a time-lapse movie that particularly well reveals the dynamical character of the clouds. The observed feature is centered around 61°N, 15°E and has an oval shape of approximately 200 × 300 km. It would thus be classified as a large void II structure according to the classification in Thurairajah, Bailey, Siskind, et al. (2013). Before the formation of the void, there is an extensive NLC cloud cover in the entire upper part of the field of view (N). The void is not formed from the center, or as a thinning of the present cloud layer. Instead, it is formed by clouds moving in from NE toward SW (from the upper right-hand to the lower left-hand in the reprojected picture series) but disappearing in the region of the void, so that the NLC cloud cover slowly extends to entirely enclose the cloud-free region. The void remained stable for about an hour, but eventually began to fill in with the new NLCs continuously floating in from NE and not dissolving any longer. From the surrounding cloud

10.1029/2018GL078501

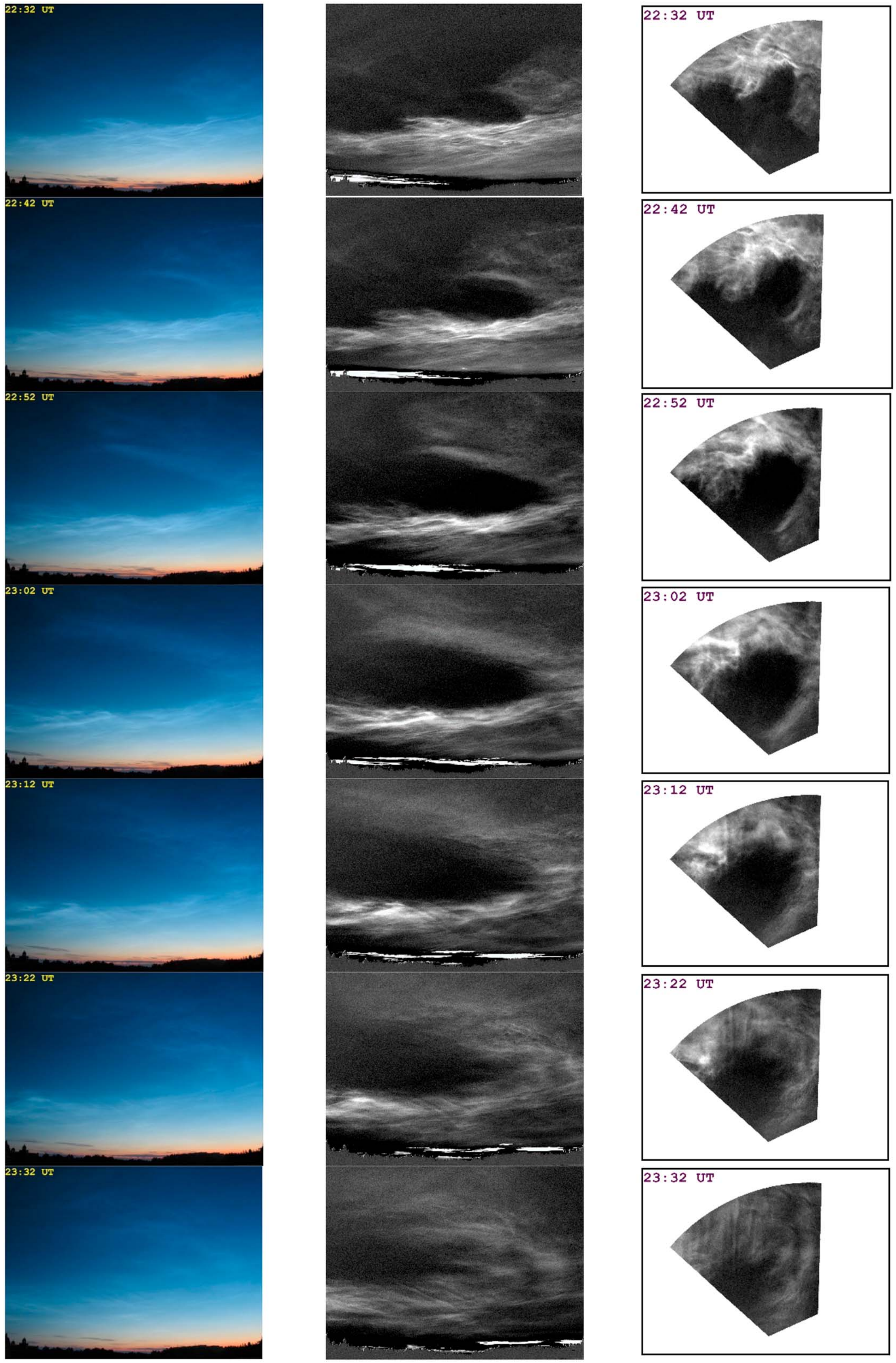

Figure 2. (left) Series of raw images between 22:32 and 23:32 UT with 10-min interval. (middle) Corresponding images with the Rayleigh background subtracted. (right) Corresponding reprojected, geolocated images. For the scale, compare with Figure 1.

structures, one can estimate that the general wind is toward SW and approximately 110 m/s. As opposed to most other structures typically observed in the cloud, the void was not influenced by the local prevailing wind and remained remarkably stable for about an hour until it finally slowly filled with weak NLCs. Outside the void, waves with an approximate horizontal wavelength of 30 km can be observed propagating toward the east with a horizontal velocity of approximately 50 m/s. These waves can obviously not be observed in the void, since there are no clouds there to visualize them. However, once the void starts weakening, the wave ridges present outside the void seem to extend further and further into the region of the void and become visible as the void is filled with clouds.

Once only a similar event was observed during the nine NLC seasons that the Stockholm camera has been operated. On 16 July 2005, not a complete void, but a strong "front" appeared in a very well developed NLC display. The cloud structures seemed to remain strong on one side of this front but vanished on the other side. The front remained stable for more than 90 min, from the time it started to appear, to the sunrise when the diminishing contrast no longer allowed continuing observation. This structure may well have been a part of a larger void extending to the north.

4. Discussion

The void was remarkably stable during an entire hour, and did not drift with the local prevailing wind as the NLC cloud features around it. This stability gives us surprising and important clues about the formation process. It indicates that the origin of the void is of localized character and persistent in time—a continuous source that keeps impacting the region for the entire hour—rather than a rapid single event. If something had passed through the local environment and temporally affected it for example by changing the temperature, the whole void would have drifted with the local wind field along with the other, identifiable features of the cloud. This, obviously, is not the case here, and contrasts with the findings of Thurairajah, Bailey, Nielsen, et al. (2013), who conducted a case study of a void and inferred temperatures from the NOGAPS-ALPHA model (Siskind et al., 2011). Their analysis suggests that the time and place of that void was characterized by higher temperatures and lower water mixing ratios than the surrounding air and that a poleward flow of warm air could be the reason for the higher temperatures. The explanation of poleward flow of warmer air does not seem to hold for the void observed here.

The void reported here is revealed by cloud features moving in, to enclose the void, rather than a weakening of the already present cloud layer. This indicates that ice growth and sedimentation of large particles is probably not the formation process. Instead, it appears that the cloud layer that is moving in is prevented from existing in the void region, most likely because of warm temperatures within the void; that is, the ice particles sublimate as soon as they move into the region of the void. This finding thus speaks against the speculations that voids could origin from shock waves, for instance caused by meteorites, which cool the air so that the ice particles grow large and sediment out, in a similar way that tropospheric "hole-punch" clouds are believed to origin from the passage of an aircraft (Thurairajah, Bailey, Siskind, et al., 2013).

The time scale of the formation and disappearance also gives important information about the formation process. Especially the fast disappearance of the void seems to suggest that ice growth followed by sublimation is not a feasible formation process. Particle ice growth in the lower part of the NLC (where the fastest growth happens) is typically around 10–20 nm/hr (Christensen et al., 2016; Megner et al., 2016). Obviously, this is dependent on the temperature and the water vapor in the surrounding air. Hence, if the region has been depleted of water vapor by a preceding fallout of sedimenting ice particles, then the growth will be significantly slower. The time needed for the ice particles to grow to a visible size would therefore be at a minimum a few hours, that is, significantly longer than the 15 min it took for the void to refill. Again, this indicates that the cause of void is a localized heating rather than cooling.

It is of course interesting to try to understand what the cause of the void could be. As earlier mentioned wave patterns observed in airglow can, on occasion, be linked to a strong thunderstorm activity. Most recently, mesospheric fronts have been observed in OH airglow and have been shown to, on some occasions, be related to tropospheric sources like cyclonic activity and large convective cloud cells (Giongo et al., 2018). In fact, for the present study, a strong thunderstorm was registered north of the observed region, at 65.1°N, 16.8°E (about 500 km NE from the centrum of the void), at 21:50 UT, 40 min before the appearance of the void, as marked in Figure 1 (the lightning record unfortunately does not extend to the time of our

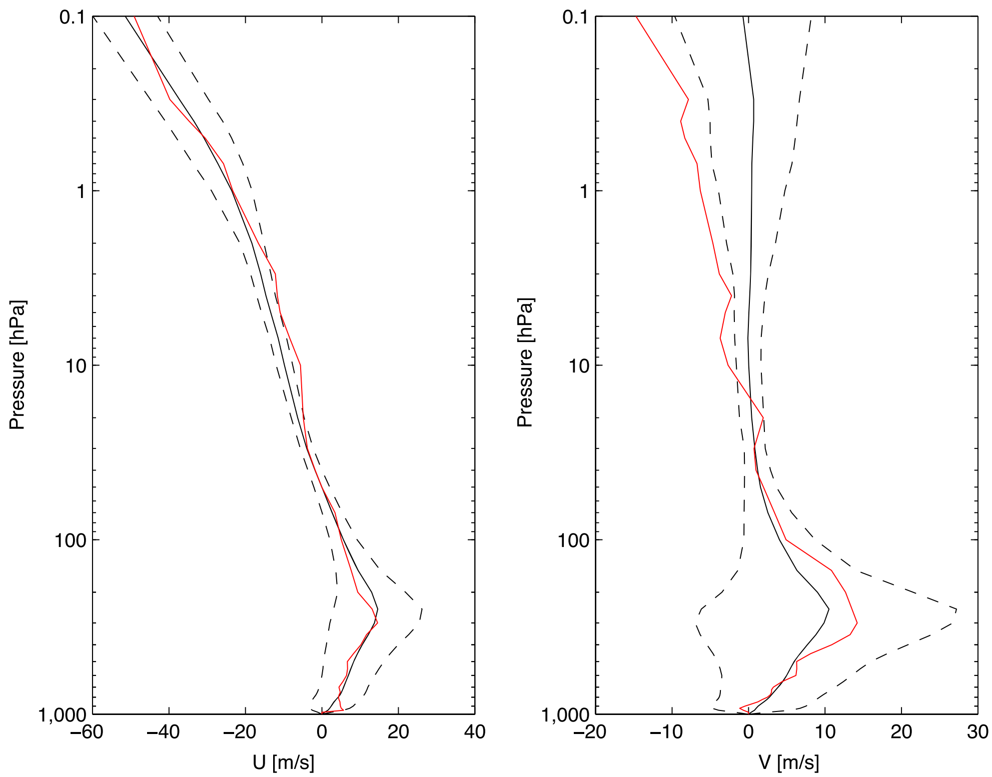

Figure 3. MERRA 2 (left-hand panel) zonal and (right-hand panel) meridional wind fields at the location of the void (15°E, 61°N). The red lines show the winds as close as possible to the time of the void (4 July 2010 at 24.00), the black lines show the average winds for the summer (4 June to 4 August), and the dashed lines show the 1-sigma standard deviation of the winds. The data have been obtained from the global modeling and assimilation office (Global Modeling and Assimilation Office, 2015).

observation). However, thunderstorms of similar strength are observed much more frequently than voids—in nine NLC seasons, our cameras have recorded only one void and one case of extensive strong and similarly stable "front" that could, potentially, have been a part of a much larger void. We would expect voids to happen much more often if they were initiated by thunderstorm activity unless certain other criteria also need to be satisfied. The most natural idea of such a criterion is the background wind field, which filters the gravity waves as they progress upward to the mesopause region. Since a wave cannot propagate through a layer where its phase speed matches the wind speed, the most efficient filtering occurs when the underlying wind field spans a wide range of velocities, that is, reaches from large positive to large negative values. If, on the other hand, the underlying winds are only in one direction, or if the winds are very weak, then fewer gravity waves would be filtered out, more would propagate up to the mesopause, and we would expect tropospheric disturbances to have a stronger effect on the mesopause region. Using MERRA2 analysis we have investigated the local wind field from 1,000 to 0.1 hPa at the position and time of the event (see Figure 3). The winds span positive and negative velocities and are not weaker than on average for the summer months. Instead, we note that the westward meridional winds between 10 and 0.1 h Pa are stronger than generally, although not extreme. According to simple linear theory, such a wind field would filter out more gravity waves than on average, and we would in fact expect even less impact of tropospheric events.

At the model top of 0.1 h Pa, roughly equivalent of 64-km altitude, the wind is directed toward WSW (253°) with a magnitude of 51 m/s. This can be compared to the general wind field inferred from the clouds around the void, approximately 20 km higher, of 120 m/s in the direction of SW.

It is not clear what had happened in the region of the void before the NLCs floated in; the heated region could have existed there for some time before being revealed by the incoming NLCs. A weather map of Europe (supplied as supporting information) shows a front related to the thunderstorm activity over northern Scandinavia, but without more information on the local atmosphere, it is impossible to say if waves initiated by the tropospheric storm activity were the true cause of the void.

5. Conclusions

We here report for the first time the full evolution of a so-called ice void in NLC. The void appeared over central Sweden on 4 July 2010 at about 22:30 UT and was captured by our ground-based camera on the roof the Arrhenius laboratory at Stockholm University. The observed feature is of oval shape and spans about 200 km in the east-west direction and 300 km in the north-south direction. The ice void development was followed, with 30-s time interval, from when it appeared, until it was filled with first weak, and then stronger NLC, about 1 hr later. The fast disappearance of the void (approximately 15 min) and the fact that it did not follow the general wind pattern suggest that it was formed by a localized warming lasting for at least an hour. The fact that the warming was unconnected to the general wind field indicates that the origin is of stationary character—a source that impacts the region for an extended time period—and not a rapid single event change of the local atmosphere, as one would expect for instance from a meteor shock wave.

Acknowledgments
Two anonymous reviewers are acknowledged for their helpful comments. L.M. is supported by the Swedish Research Council under contract 621-2012-1648. The data are available as supporting information.

References

Brown, L. B., Gerrard, A. J., Meriwether, J. W., & Makela, J. J. (2004). All-sky imaging observations of mesospheric fronts in OI 557.7 nm and broadband OH airglow emissions: Analysis of frontal structure, atmospheric background conditions, and potential sourcing mechanisms. *Journal of Geophysical Research*, *109*, D19104. https://doi.org/10.1029/2003JD004223

Christensen, O.-M., Benze, S., Eriksson, P., Gumbel, J., Megner, L., & Murtagh, D. (2016). The relationship between polar mesospheric clouds and their background atmosphere as observed by Odin-SMR and Odin-OSIRIS. *Atmospheric Chemistry and Physics*, *16*(19), 12,587–12,600. https://doi.org/10.5194/acp-16-12587-2016

Dalin, P., Pertsev, N., Frandsen, S., Hansen, O., Andersen, H., Dubietis, A., & Balciunas, R. (2010). A case study of the evolution of Kevin-Helmholtz wave and turbulence in noctilucent clouds. *Journal of Atmospheric and Solar - Terrestrial Physics*, *72*(14–15), 1129–1138. https://doi.org/10.1016/j.jastp.2010.06.0

DeLand, M. T., Shettle, E. P., Thomas, G. E., & Olivero, J. J. (2003). Solar backscattered ultraviolet (SBUV) observations of polar mesospheric clouds (PMCs) over two solar cycles. *Journal of Geophysical Research*, *108*(D8), 8445. https://doi.org/10.1029/2002JD00239811

Donahue, T. M., Guenther, B., & Blamont, J. E. (1972). Noctilucent clouds in daytime: Circumpolar particulate layers near the summer mesopause. *Journal of the Atmospheric Sciences*, *30*, 515–517.

Giongo, G. A., Bageston, J. V., Batista, P. P., Wrasse, C. M., Bittencourt, G. D., Paulino, I., et al. (2018). Mesospheric front observations by the OH airglow imager carried out at Ferraz Station on King George Island, Antarctic peninsula, in 2011. *Annales de Geophysique*, *36*(1), 253–264. https://doi.org/10.5194/angeo-36-253-2018

Global Modeling and Assimilation Office (2015). MERRA-2 inst6_3d_ana_Np: 3d, 6-hourly, instantaneous, pressure-level, analysis, analyzed meteorological fields v5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed [13072010] 10.5067/A7S6XP56VZWS.

Heymsfield, A. J., Thompson, G., Morrison, H., Bansemer, A., Rasmussen, R. M., Minnis, P., et al. (2011). Formation and spread of aircraft-induced holes in clouds. *Science*, *333*(6038), 77–81. https://doi.org/10.1126/science.1202851

Karlsson, B., Körnich, H., & Gumbel, J. (2007). Evidence for interhemispheric stratosphere-mesosphere coupling derived from noctilucent cloud properties. *Geophysical Research Letters*, *34*, L16806. https://doi.org/10.1029/2007GL030282

Leslie, R. (1885). Sky glows. *Nature*, *34*(264), 21885.

Llewellyn, E. J., Lloyd, N. D., Degenstein, D. A., Gattinger, R. L., Petelina, S. V., Bourassa, A. E., et al. (2004). The OSIRIS instrument on the Odin spacecraft. *Canadian Journal of Physics*, *82*, 411–422.

Megner, L., Christensen, O. M., Karlsson, B., Benze, S., & Fomichev, V. I. (2016). Comparison of retrieved noctilucent cloud particle properties from Odin tomography scans and model simulations. *Atmospheric Chemistry and Physics*, *16*(23), 15,135–15,146. https://doi.org/10.5194/acp-16-15135-2016

Pautet, P.-D., Stegman, J., Wrasse, C. M., Nielson, K., Takahashi, H., Taylor, M. J., et al. (2010). Analysis of gravity waves structures visible in noctilucent cloud images. *Journal of Atmospheric and Solar - Terrestrial Physics*, *73*(14-15), 2082–2090. https://doi.org/10.1016/j.jastp.2010.06.001

Rusch, D. W., Thomas, G. E., McClintock, W., Merkel, A. W., Bailey, S. M., Russell, J. M. III, et al. (2009). The cloud imaging and particle size experiment on the aeronomy of ice in the mesosphere mission: Cloud morphology for the northern 2007 season. *Journal of Atmospheric and Solar - Terrestrial Physics*, *71*(3-4), 356–364. https://doi.org/10.1016/j.jastp.2008.11.005

Russell, J. M., Bailey, S. M., Gordley, L. L., Rusch, D. W., Horányi, M., Hervig, M. E., et al. (2009). Aeronomy of ice in the mesosphere (AIM): Overview and early science results. *Journal of Atmospheric and Solar - Terrestrial Physics*, *71*(3-4), 289–299. https://doi.org/10.1016/j.jastp.2008.08.011

Siskind, D. E., Stevens, M. H., Hervig, M., Sassi, F., Hoppel, K., Englert, C. R., & Kochenash, A. J. (2011). Consequences of recent southern hemisphere winter variability on polar mesospheric clouds. *Journal of Atmospheric and Solar-Terrestrial Physics*, *73*(13), 2013–2021. https://doi.org/10.1016/j.jastp.2011.06.014

Taylor, M. J., & Hapgood, M. A. (1988). Identification of a thunderstorm as a source of short period gravity waves in the upper atmospheric nightglow emissions. *Planetary and Space Science*, *36*(10), 975–985. https://doi.org/10.1016/0032-0633(88)90035-9

Taylor, M. J., Pautet, P.-D., Zhao, Y., Randall, C. E., Lumpe, J., Bailey, S. M., et al. (2011). High-latitude gravity wave measurements in noctilucent clouds and polar mesospheric clouds. *IAGA Special Sopron Book Series 2*(1), 93–105. https://doi.org/10.1007/978-94-007-0326-1_7

Taylor, M. J., Pendelton, W. R. Jr., Clark, S., Takahashi, H., Gobbi, D., & Goldberg, R. A. (1997). Image measurements of short-period gravity waves at equatorial latitudes. *Journal of Geophysical Research*, *102*(D22), 26,283–26,299.

Thomas, G. E. (1996). Is the polar mesosphere the miner's canary of global change? *Advances in Space Research*, *18*(3), 149–158. https://doi.org/10.1016/0273-1177(95)00855-9
Thurairajah, B., Bailey, S. M., Nielsen, K., Randall, C. E., Lumpe, J., Taylor, M. J., & Russell, J. M. III (2013). Morphology of polar mesospheric clouds as seen from space. *Journal of Atmospheric and Solar - Terrestrial Physics*, *104*, 234–243. https://doi.org/10.1016/j.jastp.2012.09.009
Thurairajah, B., Bailey, S. M., Siskind, D. E., Randall, C. E., Taylor, M. J., & Russell, J. M. III (2013). Case study of an ice void structure in polar mesospheric clouds. *Journal of Atmospheric and Solar - Terrestrial Physics*, *104*, 224–233. https://doi.org/10.1016/j.jastp.2013.02.001
Witt, G. (1962). Height, structure and displacements of noctilucent clouds. *Tellus*, *14*, 1–18.