Foreword: Layered phenomena in the mesopause region

Jeffrey P. Thayer
SRI International, Menlo Park, California, USA

Gary E. Thomas
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA

Franz-Josef Lübken
Leibniz Institute of Atmospheric Physics, Kühlungsborn, Germany

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[1] Layered phenomena in the mesopause region is the subject of an international working group whose main focus concerns the physics and chemistry of the summertime mesosphere and the processes involved in forming polar mesospheric summertime echoes (PMSEs) and polar mesospheric clouds (PMCs)—the global equivalent to ground observer's noctilucent clouds (NLCs). PMCs are ice clouds that occur in the summer mesosphere at altitudes typically between 81 and 86 km, and poleward of 50 degrees latitude. PMSEs are strong backscattered signals from the summer mesosphere region, recorded largely, although not exclusively, by VHF radars, that occur most often poleward of 50 degrees latitude and at altitudes typically between 82 and 88 km. The major areas of research within this working group involve understanding and numerically modeling the dynamical, thermal, and chemical processes related to the summer mesosphere; microphysical modeling of MCs; determining the scattering, composition, and shape of mesospheric particles; resolving sources of condensation nuclei; performing laboratory experiments of relevant reactions and related constituents involved in PMC and PMSE behavior, and determining the properties and conditions of PMC, PMSE, and the summer mesosphere by making rocket, satellite, and ground-based radar and lidar measurements. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics

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1. Past

[2] The working group on layered phenomena in the mesopause region (LPMR) held a workshop at the Asilomar Conference Grounds in Pacific Grove, California, 10–12 October 2001. The workshop attracted researchers and students from all over the world engaged in LPMR research, with many of the results presented in this special issue. A web page summarizing the meeting can be found at http://isr.sri.com/nlc2001.

[3] The International Working Group on Layered Phenomena in the Mesopause Region is an official unit of the International Commission on the Middle Atmosphere (ICMA). This commission is one of ten that make up the International Association of Meteorology and Atmospheric Science (IAMAS). The umbrella organization for this association is the International Union of Geodosy and Geophysics (IUGG), which in turn is a scientific member of the International Council of Scientific Unions (ICSU). The LPMR working group is the oldest in IAMAS, having been formed in 1979 by Olev Avaste of the University of Turku, Estonia. Professor Gary Thomas was cochair with Avaste from 1985 until Dr. Avaste's death in 1991, at which time he became chair. Professor Franz-Josef Lübken has been cochair since 1995. Previous meetings of the working group have been held in Tallinn (1984), Boulder (1988), Tallinn (1988), Boulder (1995), and Kühlungsborn (1999).

2. Present

[4] Although significant details of LPMR research are put forth in this special issue, it is the duty of the working group to provide a position statement that addresses the current state of the field and its future direction. The LPMR field has benefited over the past decade from significant gains in measurement resources, new techniques, and improved numerical models. Two-dimensional maps of mesospheric

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clouds are now being constructed to observe large-scale features in the cloud field [see *Carbary et al.*, 2003]. Long-term ground-based measurements have also continued over this time period resulting in multidecadal studies of NLC behavior [see *Romejko et al.*, 2003]. In addition, the extended satellite missions measurements (especially the SBUV series) are becoming very important in revealing long-term trends in PMC behavior for both hemispheres [see *DeLand et al.*, 2003]. The solar cycle modulation of cloud occurrence (with fewer clouds occurring around solar maximum) is certainly recognizable in all the long-term data sets, but they indicate different phase lags between the solar cycle and MC occurrence that is not well understood (see *Kirkwood and Stebel* [2003] regarding planetary wave influences on PMCSs and their relation to the solar cycle). SAGE-II satellite observations have also indicated a definite brightening of PMCs through the 1980's and 1990's, and a consistent north/south asymmetry with the north having ~50% more clouds [*Shettle et al.*, 2002]. Satellites and ground-based microwave observations have also seen increases in middle atmosphere water vapor over the past ten years [*Nedoluha et al.*, 1998]. In addition, NLCs at latitudes as far south as 42N have been observed for the first time in the summer of 1999, and again in the subsequent two summers in the Rocky Mountain states of the US [*Taylor et al.*, 2002; *Wickwar et al.*, 2002]. The 1999 low-latitude NLC was also detected as a PMC by the NASA SNOE satellite. The connection of all these observations with the rise in greenhouse gases, particularly carbon dioxide and methane, is intriguing but certainly tenuous. Measurement programs and modeling studies must continue to help resolve this outstanding issue.

[5] The research advancements over the past decade have improved our general understanding of the summer mesosphere and have helped to better characterize NLC/PMC and PMSE phenomena. For instance, *Chu et al.* [2003], *Collins et al.* [2003], *Fiedler et al.* [2003], and *Thayer et al.* [2003] present events and statistical summaries of NLC characteristics and behavior as observed from four different lidar sites. In particular, they report on short-period gravity waves modifying PMC characteristics, south pole measurements of PMCs revealing intriguing differences from lower latitudes, and the occurrence of late season PMCs. A number of papers in this special issue report on PMSE observations and model studies to improve our understanding of PMSE formation. The database on PMSE has significantly increased in recent years and is used to systematically investigate seasonal, latitudinal, and long-term variations [*Bremer et al.*, 2003; *Zecha et al.*, 2003]. New observations from rockets and active remote techniques (''heating'') reveal details of the role of charged particles, their interaction with the background plasma, and their influence on electron diffusivity [*Smiley et al.*, 2003; *Blix et al.*, 2003; *Belova et al.*, 2003].

[6] It was proposed some time ago that the reduction of electron diffusivity by charged aerosols is the key factor for understanding the presence of very small-scale electron irregularities required to produce backscatter of electromagnetic waves at radar frequencies [*Kelley et al.*, 1987; *Cho et al.*, 1992; *Cho and Röttger*, 1997]. Based on several studies in the past [e.g., *Hill*, 1978], detailed theoretical analysis was recently performed to demonstrate the importance of the aerosol mass and radius in plasma diffusion, and to show that the lifetime of small-scale structures in the plasma is several hours if charged aerosols with radii larger than approximately 10 nm are present [*Rapp et al.*, 2003; *Lie-Svendsen*, 2003; *Rapp and Lübken*, 2003]. These results were combined to form a comprehensive theory of PMSE that explains, for the first time, the most important features of PMSE (e.g., the height distribution) in terms of neutral turbulence acting on aerosols, ions, and electrons [*Rapp and Lübken*, 2003]. This model also explains the apparent non-correlation between PMSE and turbulence in the lower part of PMSE and a better coincidence in the upper part as seen in observations [*Lübken et al.*, 2002].

[7] Large particles (radius larger than 10 to 20 nm) are present several kilometers below the mesopause and produce PMSEs and NLCs. For these large particles, plasma diffusion is slow (several hours) and an excitation by turbulence is necessary only occasionally. On the other hand, small particles (radius smaller than 5 to 10 nm) in the upper part of PMSE produce small plasma diffusion lifetimes of several minutes only and require a more frequent excitation. Several years of in situ turbulence measurements show stronger and more frequent turbulence around the mesopause compared with several kilometers below [*Lübken et al.*, 2002]. This height distribution of turbulence is expected from gravity waves propagating into the mesosphere and breaking preferentially around the mesopause. The study of PMSE therefore allows for the investigation of a combination of extreme thermal conditions (low enough temperatures to get charged aerosols) and dynamical processes (turbulence). Thus, PMSE provides a tracer of more fundamental processes (such as turbulence), but in a manner more complicated than originally anticipated. Details of our current understanding of PMSE will be tested and verified in the future by more in situ and ground-based observations, for example, by permanent monitoring of turbulence in the polar mesosphere by VHF and MF radars.

[8] NLC/PMC research and PMSE research present an interesting contrast: For NLC ground-based studies, it has been difficult until recently to obtain round-the-clock time series, yet the physical process of detection is straightforward (Mie scattering from submicron ice particles). In contrast, PMSE may be detected, even with completely overcast skies, as long as electron density fluctuations are present. Both phenomena appear to require supersaturated conditions, at least in the initial stages of their development, although the causes of these favorable conditions are far from certain, and the recent finding of strong mesospheric echoes in winter raises entirely new questions. The different stages of understanding lead to different levels of scientific inquiry, as illustrated by the PMSE papers presented in this issue.

[9] On the theoretical side, the following description captures most of the current thinking on NLCs/PMCs. The summer mesopause is dynamically driven to extremely low temperatures, almost certainly due to upward propagation and breaking of gravity waves. The upward moving air not only is cooled adiabatically, but also transports water vapor from the lower atmosphere into the mesopause region. Even small amounts (several parts per million) of water vapor can provide conditions favorable for ice formation and growth, provided there are adequate numbers of nucleating particles (either large water-cluster

ions or nanoparticles of meteoric origin [see *Thomas*, 1996]).

[10] Over most of the ice particle lifetime, the water vapor pressure will be much larger than the saturation vapor pressure over ice—that is, supersaturation—resulting in a continued particle growth rate and subsequent sedimentation. Because the saturated vapor pressure over ice depends exponentially on temperature, and only linearly with water concentration, the moving particle will be influenced primarily by the thermal environment in which it finds itself. The end of life of the ice particle is marked by its transition out of the supersaturated region, either through sedimentation or by horizontal transport into warmer unsaturated air. At that point it rapidly loses size as it sublimates, and hence its optical visibility precipitously declines (the visibility varies as the fifth to sixth power of its size). If the ice particle were nucleated by a dust particle, this ''bare'' particle might be levitated upward into the region of supersaturation, and a new cycle of nucleation and growth could ensue. *Berger and von Zahn* [2002] and *von Zahn and Berger* [2003] have recently modeled the growth and transport stages of ''icy particles'' from their birth in the polar regions to their demise at lower latitudes and heights. *Gumbel et al.* [2003] have addressed the influence the presence of ice particles may have on the ion chemistry in the polar summer mesosphere.

[11] A number of new opportunities are now available that will help advance LPMR research. New lidar measurements of PMC depolarization have enabled the shape of the cloud particles to be studied more regularly [*Baumgarten et al.*, 2002]. Coordinated PMSE measurements with active RF-induced electron heating experiments have tested the processes related to PMSE occurrence [*Belova et al.*, 2003]. Recent ground-based and rocket measurements from Spitzbergen (78N) are revealing new information on PMSE, NLC, and temperatures in the deep polar regions [*Lübken and Müllemann*, 2003]. New rocket data are available from the summer of 2002 MAC/WAVE campaign, designed to address the fine-scale structure in the plasma and neutral gases in the summer mesosphere. General circulation models have begun to incorporate ice microphysics into self-consistent, fully coupled simulations. Also, numerical models have, for the first time, combined PMSE and MC physics into one system and attempted to explain their behavior [*Berger and von Zahn*, 2002].

[12] Other rocket measurements to observe mesospheric temperature and dynamics will be continuing. Future rocket programs such as ECOMA (existence and charge state of meteoric dust in the middle atmosphere) and MAGIC (mesospheric aerosol-genesis, interaction and composition) aim at measuring the very small dust particles which are believed to be the major nuclei most crucial in the initial phase of MC generation.

[13] Laboratory experiments are presently being developed to determine the chemical role of ice crystals in the mesosphere. The NASA UARS, TIMED, and SNOE missions and the European Odin mission are all satellite programs currently in operation that will continue to provide much needed information on the composition and energy balance of the mesosphere, and the occurrence and behavior of MCs. An exciting future addition to these satellite programs is the recently selected NASA Small Explorer (SMEX) investigation called Aeronomy of Ice in the Mesosphere (AIM). This new mission is designed specifically to study PMCs and their atmospheric environment. AIM will also include an experiment to measure the influx of small cosmic dust believed to be at least partially responsible for nucleating ice particles.

3. Future

[14] As we have gained a better understanding of the layered phenomena of NLC, PMC, and PMSE, we have begun to question how their presence may help us learn more about the background atmosphere. Are they a harbinger of mesospheric change, or even climatic change? Do MC excursions to middle latitudes indicate a change in the dynamically driven cold summer mesosphere? How do atmospheric waves, on all scales, affect MC? Do they activate chemical paths not possible without the presence of small ice particles, such as the uptake of atomic oxygen by ice particles? How is water vapor cycled through the middle atmosphere, and how is it influenced by ice formation and transport? Can our current understanding of PMSE explain all observed features; for example, details of the height structure (multiple layers), the variation with season and latitude (north/south asymmetry), and the relationship to NLC and PMC? What are the most important initial condensation nuclei? We expect the multidisciplinary makeup of the LPMR working group to answer these and other questions in future studies. The progress will depend on the resources available as the questions asked involve a greater understanding of the middle atmosphere as a whole, and not just the layered phenomena alone. Thus, we must work to continually improve the accuracy of our research while advancing the precision of our tools. Rocket and laboratory research, for example, are important elements to LPMR research that must continue to advance if we are to fully resolve the possible sources and mechanisms involved in MC formation and PMSE backscatter. The collection of papers presented in this special issue represent the present state of LPMR research. Plans for the next LPMR conference are in preparation and will be hosted in the summer of 2004 in Cambridge, England by the British Antarctic Survey.

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F.-J. Lübken, Leibniz Institute of Atmospheric Physics, Kühlungsborn, Germany.

J. P. Thayer, SRI International, 333 Ravenswood Avenue, Menlo Park, CA 94025, USA. (thayer@sril.com)

G. E. Thomas, Laboratory for Atmospheric and Space Physics, University of Colorado, 1234 Innovation Drive, Boulder, CO 80303, USA.