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Microphysical properties of mesospheric aerosols: an overview of in situ-results from the ECOMA project

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Abstract Six sounding rockets were launched within the ECOMA (='Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere') project to study the characteristics of meteoric smoke particles (MSPs) and mesospheric ice particles, as well as their possible microphysical relation. The launches were conducted during three campaigns from the Andøya Rocket Range (69^{o}N, 16^{o}E), one in September 2006, and the other two in the summers of 2007 and 2008. This article provides an overview of these observations and presents the corresponding geophysical results with special emphasis on our understanding of the micropyhsics of mesospheric ice particles. Most notably, we are able to confirm the existence of MSPs at all altitudes between 60 - 85 km in September, and a seasonal variation that is consistent with previous model studies in which MSP-variability is mainly driven by the global circulation. Together with these model studies as well as recent satellite observations of MSPs our results hence cast some doubt on a standard assumption of state-of-the-art microphysical models of mesospheric ice clouds, namely that ice nucleation mainly occurs heterogeneously on MSPs.

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1 Introduction

The mesosphere is host to several aerosol species which are involved in a large variety of processes. Among these aerosol types, the most prominent ones are ice particles which nucleate and develop in the environment of the extremely low temperatures of the polar summer mesopause and are observed as noctilucent clouds/polar mesospheric clouds (NLC/PMC) or as polar mesosphere summer echoes (PMSE) [28, 21]. Scientific interest in these ice clouds has intensified in recent years since it has been speculated that their properties should be severely modified by minute changes of background temperatures and water vapor such that they might be sensitive indicators for changes of the background mesospheric state [29]. While the most recent analyses of satellite PMC observations do indeed show trends of both PMC brightness as well as occurrence frequency [2, 26], the underlying causes for these changes are yet to be fully understood [12, 15].

Hence, it appears to be obvious that experimental efforts need to be targeted at unraveling the microphysical properties of these ice clouds, where one of the most important uncertainties is the issue of their actual nucleation mechanism [25]. For the latter, the heterogeneous nucleation on another mesospheric aerosol species, namely meteoric smoke particles (MSP) [9], has been the favored nucleation pathway in most previous studies of mesospheric ice microphysics even though solid experimental evidence for this or any other proposed nucleation mechanism has so far been elusive [25, and references therein].

Motivated by the obvious need to gain a deeper understanding of mesospheric aerosol properties and related processes, the German-Norwegian-led ECOMA (='Existence and Charge state Of Meteoric smoke particles in the middle Atmosphere') project focussed on in situ observations of MSPs and mesospheric ice particles as well as their potential relation.

The current paper provides an initial overview of the results obtained during the first three out of a total of four major field campaigns involving the launching of a total of 9 sounding rockets and a multitude of ground based observations. In Section 2 we describe the instrumentation of the ECOMA-payloads and give an overview of the first three field campaigns. Turning to the scientific results, we then describe the results of our initial MSP-observations in September 2006, i.e., after the polar summer (Section 3.1), followed by several aspects of ice charge density measurements during the ECOMA summer flights (Sections 3.2 and 3.3), to finally focus on aspects of simultaneous observations of MSP and ice particle properties and corresponding implications for ice particle nucleation (Section 3.4). Finally, the most important results will be summarized in Section 4 including a short outlook regarding the final planned ECOMA campaign which is to be conducted in winter 2010.

2 The ECOMA project: Payload description and campaigns

The concept of the ECOMA-payload is to gather a suite of instruments which allows simultaneous and common volume observations of mesospheric aerosol particles along with their most important ambient parameters such as electron and positive ion number densities, neutral densities, temperatures, turbulence parameters, and information about the charging state of the ECOMA vehicle with respect to the ambient plasma. A photo of the front deck of the ECOMA-payload as it was launched during flights ECOMA04 and ECOMA06 (see Table 1) is shown in Figure 1. This

Fig. 1 Photo of the main instruments of the ECOMA payload located on the front deck of the 14 inch payload. Note that these instruments are located under the split-nosecone which is ejected at ∼55 km on the rocket ascent. See text for more details regarding these instruments and corresponding acronyms.

Table 1 Dates, times, solar zenith angles, and launch conditions of the ECOMA sounding rocket flights. Note that during flight ECOMA02 there appeared a malfunction of the ECOMA particle detector.

Label	Date	Time [UT]	solar zenith angle [^{o}]	launch condition
ECOMA01	08 Sept. 2006	22:17	114.5	moderate ionosphere (ios)
(ECOMA02)	17 Sept. 2006	21:07	112.0	disturbed ios
ECOMA03	03 Aug. 2007	23:22	93.2	NLC and PMSE
ECOMA04	30 Jun. 2008	13:22	50.8	NLC and PMSE
ECOMA05	07 Jul. 2008	21:24	86.6	NLC, but no PMSE; quiet ios
ECOMA06	12 Jul. 2008	10:46	47.5	NLC and PMSE, disturbed ios

picture shows the ECOMA particle detector (PD) to measure the charge number density of mesospheric aerosols (by means of the classical Faraday cup technique) along with the total particle volume density (by means of the newly developed active photoionization/photodetachment technique, see [22, 23] for details) in the center, surrounded by two fixed biased Langmuir probes on deployable booms (the electron probe, EP, and the positive ion probe, PIP) to measure relative altitude profiles of electrons and positive ions [1]. Further instruments on this deck are the MAGIC particle sampler to collect particles during the flight and return them to the ground for further laboratory analysis [5], the receiving antennas of the wave propagation experiment to obtain absolute electron number densities [3], and two more Faraday cups to collect particle charge number densities, i.e., the charged dust detector (CDD) from Tromsø University [7], and the Dartmouth dust detector (DDD) from Dartmouth College [14]. Note that these two additional Faraday cups were replaced by simple Pirani gauges during all flights except ECOMA04 and ECOMA06 to obtain altitude profiles of neutral number densities and temperatures. In the rear, each ECOMA payload was equipped with a CONE (combined sensor for neutrals and electrons) ionization gauge for measuring neutral parameters and (relative) electron densities [4], as well as with two cold plasma probes (CPP) to measure the payload potential along with electron temperature [27]. Finally, a mid-section of the payload contained a photometer during all summer flights to detect and characterize mesospheric ice particles during NLC-passages of the payload [18].

So far, six ECOMA payloads have been launched using a two stage vehicle consisting of a Nike-Improved Orion motor combination reaching typical apogees of about 130 km. All launches were made from the Andøya Rocket Range (69^oN, 16^oE) in the frame of three field campaigns in September 2006, and in the summers 2007 and 2008. Table 1 gives an overview of the basic dates of these rocket launches along with some short information about the situations in which the rockets were launched.

3 Scientific results

3.1 MSP properties during September 2006

Figure 2 summarizes the most important results of the first successful measurements with the ECOMA-PD during flight ECOMA01 in September 2006. This figure shows MSP volume densities derived from the flash current measurements (originating from photoelectrons emitted from the particles; see [22] and [23] for details including an in-depth discussion of cross-sensitivity to species other than MSPs) with the ECOMA-PD revealing evidence for the existence of MSPs in the entire altitude range from 60 - 85 km in September in satisfactory agreement with state-of-the-art MSP-models [23].

In contrast, the direct collection of charged particles with the Faraday-cup part of the instrument reveals a narrow layer of negatively charged particles between 82 and 90 km. As shown in detail in [27] this apparent layering is caused by the aerodynamical properties of the instrument and does not reflect the true altitude distribution of MSPs. Note that similar sensitivity restrictions apply to all previous Faraday cup measurements of MSPs.

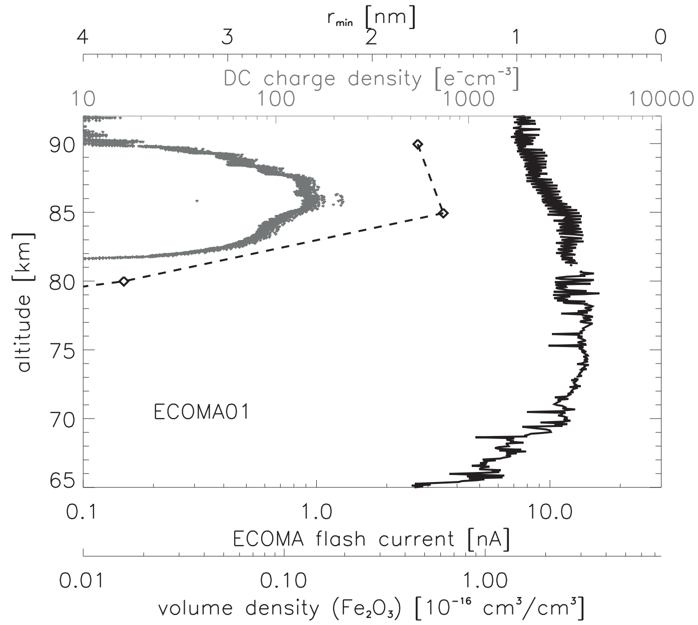

Fig. 2 Overview of the main results obtained with the ECOMA-PD from flight ECOMA01. The thick black line shows the altitude profile of peak photoelectron currents (denoted as ECOMA flash current) recorded by the instrument. The lowermost abscissa converts these currents to MSP volume densities assuming a Fe_2O_3-composition (see [23] for a detailed discussion on the composition of MSPs and corresponding implications). The grey solid line shows charge number densities of particles which penetrated into the ECOMA Faraday cup (denoted as DC charge density). Note that the limited altitude extent of this layer is determined by the aerodynamics-limited detection efficiency of Faraday-cup-type instruments as indicated by the altitude profile of minimum detectable MSP radius (dashed line, uppermost abscissa).

3.2 Ice particle charge densities in PMSE

Figure 3 shows an overview plot of all summertime particle charge number densities measured with the Faraday cup channel of the ECOMA-PD. This figure reveals that during all flights with PMSE detected by the ALWIN radar [11], the ECOMA-PD observed net-negatively charged particles in the same altitude range where the radar received strongly enhanced backscatter. The exception to this is flight ECOMA05, where the rocket was launched into a situation with confirmed absence of PMSE.

In spite of this lack of radar backscatter, the onboard photometer clearly revealed the presence of an NLC layer when the rocket passed through an altitude range from $\sim$ 80 - 86 km. Interestingly, the Faraday cup channel of the ECOMA-PD recorded apparently positively charged aerosol particles in this altitude range with charge number densities of the order of just a few hundreds of positive elementary charges /cm^3. Whether or not these positive charge signatures are truly caused by positive particles or rather hint at secondary charge production as suggested by

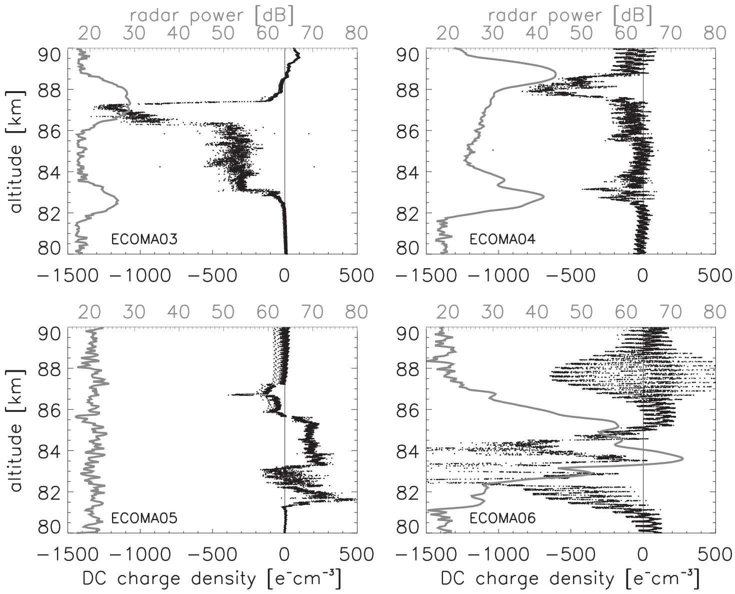

Fig. 3 Overview of all ECOMA-PD Faraday cup-measurements of particle charge number densities (black dots) during the summer flights of the ECOMA project. The grey solid lines show corresponding radar power profiles of PMSE averaged over 10 min around the rocket launches. Note that the strong modulation of the charge densities observed during flight ECOMA06 is likely caused by photoemission from the instrument walls, and that the feature above 86 km is probably caused by rocket coning and is not geophysical.

[6] is hard to judge from our data alone, but we note that current understanding of mesospheric particle charging cannot explain positive charges on pure ice particles [30, 23]. While the definitive cause for this extraordinary particle charge signature is currently not understood, we still find it worthy to point out that the electron density during this rocket flight was exceptionally low as compared to all other ECOMA summer flights (see Figure 6). This might on the one hand explain the absence of radar backscatter which has previously been shown to require a minimum electron number density of a few hundred electrons cm^{-3} [20], and on the other hand this might indicate that in this low electron density plasma the charging and/or secondary charging properties of mesospheric aerosol particle are substantially different from ‘normal’ situations with larger electron densities.

3.3 A three instrument consistency comparison

As noted before, the payloads ECOMA04 and ECOMA06 carried three instruments which are (at least partly) based on a Faraday cup design such that the corresponding measurements provide an ideal data set for intercomparison and investigation of effects like detection sensitivity and/or secondary charge production. Figure 4 compares altitude profiles of (negative) particle charge densities derived from observations with the ECOMA-PD, the CDD and the DDD from flight ECOMA04. This comparison reveals several interesting features: First of all note that the very

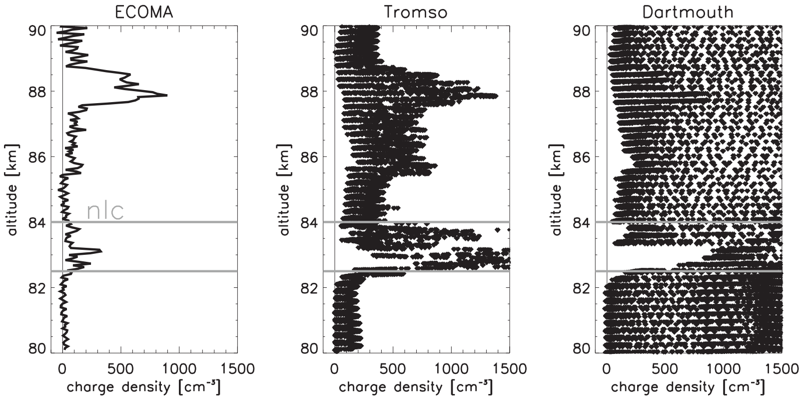

Fig. 4 Comparison of profiles of particle charge number densities measured during flight ECOMA04 with the ECOMA-particle detector (left panel), the charged dust probe of Tromsø University (middle panel), and the dust detector of Dartmouth College (right panel).

large spin modulation of the CDD and DDD-data is likely from photoelectrons from sunlight which are modulated as the instruments go in and out of the shadow of the ECOMA-PD (see Figure 1). For comparison to the ECOMA-PD-results one should hence concentrate on the inner envelope of the data instead of individual data points. Secondly, it is evident that all three instruments observe similar features with a double layer of negatively charged particles located at around 83 and 88 km. However, when looking into greater detail, it is striking that the ECOMA-PD charge densities are larger than the others in the upper layer while they are smaller in the lower layer.

In an initial attempt to understand these differences we set up a full three-dimensional Direct Monte Carlo Simulation (DSMC) of the aerodynamical environment of these instruments using a freely available software package developed by G. A. Bird (www.gab.com.au) and used in many previous studies of the aerodynamics of sounding rocket measurements [10, and references therein].

Figure 5 shows the relative density field (relative to its free-flow value) around the top deck of the ECOMA04 payload in a plane intersecting the three particle detectors for flight conditions at an altitude of 85 km. This simulation reveals that the density enhancement within the foremost ECOMA-PD is much larger than the enhancement in the CDD and DDD. This happens, because the CDD and DDD are behind the shock wave of the ECOMA instrument structure, i.e., behind this shock wave the flow is strongly decelerated from its free flow value of 1000 m/s to less than the speed of sound, i.e., ∼300 m/s. While particle trajectory calculations within this density field are yet to be done, this implies that particles in the upper layer (which

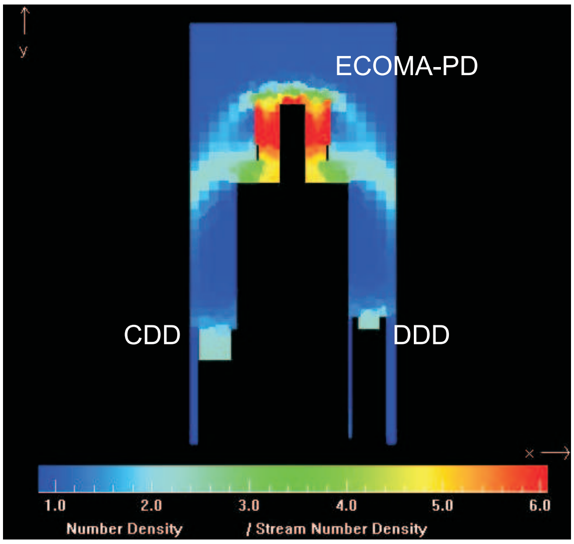

Fig. 5 Relative density field around the ECOMA04-payload for a background number density of $2\times10^{14}cm^{-3}$, a background temperature of 142 K, and a rocket velocity of 1000 m/s.

are smaller than particles in the lower layer as confirmed by onboard photometer measurements which detected NLC only in the lower layer) are so small that they are deflected by the shock wave extending from the edges of the ECOMA-PD such that only the largest of them can make it into the downstream CDD and DDD.

In the lower layer, however, particles are larger and presumably have such large inertia that they penetrate the above mentioned shock wave and reach the CDD and DDD. But how can this possibly explain that ECOMA-PD-densities are even smaller than the CDD and DDD-densities? Here we consider two possible scenarios: on the one hand it is at least conceivable that due to the strongly enhanced density and temperature at this altitude particles sublimate in the ECOMA-PD and are hence not detected.

On the other hand, it is also possible that the charge densities recorded by the CDD and DDD are actually dominated by secondary charges produced by particles which collided with the walls of the ECOMA-PD structure upstream of the CDD and DDD under grazing incidence. Such secondary impact effects have earlier been observed with a dust probe [6] similar to the CDD but placed centrally in the front of the payload. An analysis based on the observed currents to a probe grid and the currents to a collector plate directly under the grid, show that electrons are rubbed off the grid during impacts and that the negatively charged collision fragments thereafter hit the collector plate and contribute to the currents to it. This analysis indicates that fragments of the large NLC particles can rub off some 50 elementary charges per impact thereby producing strong positive currents to the grid while the collector plate shows negative currents. [6] suggested that a possible consequence of this is that the NLC particles may contain a substantial amount of meteoric smoke particles which survive the collision and are charged during the impact process. It could then

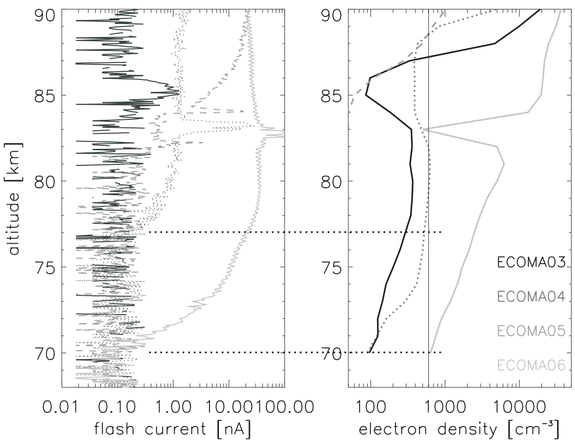

Fig. 6 Comparison of altitude profiles of flash currents measured during the ECOMA sounding rocket flights in summer (left panel) and corresponding electron densities from the wave propagation experiment. Dotted horizontal lines indicate altitudes with electron densities of 600 cm^{-3} (vertical black line) for flights ECOMA04 and ECOMA06. Grey shading indicates the altitude range with ice particles. Updated from [23], copyright by the AGU.

have been these charge fragments which were recorded by the CDD and DDD and not the primary charge density of the mesospheric ice particles.

Whether one or the other scenario is correct cannot be judged based on the current state of analysis but will require more work in the future.

3.4 MSP and ice particle properties under polar summer conditions

Finally, Figure 6 summarizes all summertime flash current-profiles measured by the ECOMA-PD and compares them to corresponding electron densities derived from the wave propagation, PIP, and EP experiment. First of all, we note that the flash current peaks seen during all summer flights in the 80 - 85 km range have been shown to be direct evidence for NLC-layers by comparison to photometer observations and can actually be used to derive ice particle volume densities [24, 23]. Secondly, we note the very different altitude extent of the flash current profiles. As shown in detail in [23], this is caused by the corresponding different background electron density-profiles. For example, detailed calculations of the charging of MSPs show that under sunlit conditions a minimum electron density of about 1000 cm^{-3} is required to turn a significant fraction of the MSPs from an average positive charge to an average neutral charge state. Outside the ice region, altitudes where the electron density reaches a value close to this limit, the flash current appears out of the background noise of the ECOMA-PD. This happens because the threshold energy for photoemission is increased by a positive particle charge owing to the additional Coulomb attraction of the photoelectron by this positive charge [31]. See Figure 9 and corresponding discussion in [23] for more details. These results shed new light on the issue of MSP charging and imply that MSPs are either positively charged or neutral under sunlit conditions (i.e., in polar summer) and negatively charged in darkness. Finally, [23] have shown that the comparison of ECOMA-flights in September and during the summer months is consistent with model calculations of the seasonal variation of MSPs and hence reinforces earlier model results that MSP seasonal variation is mainly driven by the variation of the global circulation [17]. Importantly, these model results are also largely supported by the first global observations of MSPs with the SOFIE instrument on AIM [8].

Taking all these results together, this implies a minimum of MSP number densities during polar summer and hence casts some doubt on the feasibility of mesospheric ice nucleation on MSPs [17].

Future work on mesospheric ice nucleation should hence also consider alternative nucleation mechanisms such as heterogeneous nucleation on charged MSPs [16], homogeneous nucleation under conditions of extreme temperature variations owing to gravity waves [13, 19], and other proposals as summarized and discussed in [25].

4 Summary

In summary, the main results of the ECOMA project are to date:

- Successful demonstration of the active photoemission/photodetachment technique for the detection of mesospheric particles.
- Proof of MSP existence in the entire altitude range from 60 - 85 km in September 2006 at 69^oN, 16^oE.
- Particle volume densities can be derived from the photoionisation measurements.
- Limitation of previous MSP observations by Faraday cup-type instruments are due to aerodynamics.
- Comparison of three Faraday cups on the same payload begins to validate aerodynamic models of how these detectors work and underlines the potential importance of secondary effects. Clearly though, more work is needed to understand Faraday cup detector function.
- Close correspondence between negatively charged ice particles and PMSE is confirmed.
- Observation of apparently positively charged particles under conditions of very low plasma densities and in the confirmed presence of NLC, likely influenced by secondary charging effects.
- MSP charging is influenced by photodetachment/photoionization processes. MSPs are likely positively charged or neutral under sunlit conditions and negatively charged during darkness.
- MSP observations in September and June/July/August imply MSP variability consistent with global scale model predictions. Taking all now available evidence from models, satellite observations and the here presented results together casts some doubt on the feasibility of predominant mesospheric ice nucleation on MSPs.

At this stage the final ECOMA campaign is scheduled for December 2010 to study the influence of the Geminid meteor shower on the properties of MSPs. It is planned to launch one ECOMA payload each before, during, and after the peak activity of the shower - hopefully allowing insight into the time scales of MSP formation and microphysics.

Acknowledgments

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References

1. A. Brattli, O. Lie-Svendsen, K. Svenes, U.-P. Hoppe, I. Strelnikova, M. Rapp, R. Latteck, and M. Friedrich. The ECOMA 2007 campaign: rocket observations and numerical modelling of aerosol particle charging and plasma depletion in a PMSE/NLC layer. *Ann. Geophys.*, 27(2):781–796, 2009.
2. M. T. DeLand, E. P. Shettle, G. E. Thomas, and J. J. Olivero. Latitude-dependent long-term variations in polar mesospheric clouds from SBUV version 3 PMC data. *J. Geophys. Res.*, 112, D10315, doi:10.1029/2006JD007857, 2007.
3. M. Friedrich, K. M. Torkar, W. Singer, I. Strelnikova, M. Rapp, and S. Robertson. Signatures of mesospheric particles in ionospheric data. *Ann. Geophys.*, 27(2):823–829, 2009.
4. J. Giebeler, F.-J. Lübken, and M. Nägele. CONE - a new sensor for in-situ observations of neutral and plasma density fluctuations. *Proceedings of the 11th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Montreux, Switzerland (ESA SP)*, pages 311 – 318, 1993.
5. J. Gumbel, T. Waldemarsson, F. Giovane, M. Khaplanov, J. Hedin, B. Karlsson, S. Lossow, L. Megner, J. Stegman, K. H. Fricke, U. Blum, P. Voelger, S. Kirkwood, P. Dalin, Z. Sternovsky, S. Robertson, M. Horányi, R. Stroud, D. E. Siskind, R. R. Meier, J. Blum, M. Summers, J. M. C. Plane, N. J. Mitchell, and M. Rapp. The MAGIC rocket campaign: an overview. *Proceedings of the 17th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sandefjord, Norway (ESA SP–590)*, pages 139–144, 2005.
6. O. Havnes and L. I. Næsheim. On the secondary charging effects and structure of mesospheric dust particles impacting on rocket probes. *Ann. Geophys.*, 25:623–637, 2007.
7. O. Havnes, J. Trøim, T. Blix, W. Mortensen, L. I. Næsheim, E. Thrane, and T. Tønnesen. First detection of charged dust particles in the Earth's mesosphere. *J. Geophys. Res.*, 101:10839–10847, 1996.
8. M. E. Hervig, L. L. Gordley, L. E. Deaver, D. E. Siskind, M. H. Stevens, J. M. R. III, S. M. Bailey, L. Megner, and C. G. Bardeen. First satellite observations of meteoric smoke in the upper atmosphere. *Geophys. Res. Lett.*, 113, 2009.
9. D. M. Hunten, R. P. Turco, and O. B. Toon. Smoke and dust particles of meteoric origin in the mesosphere and stratosphere. *J. Atmos. Sci.*, 37:1342–1357, 1980.
10. S. Knappmiller, S. Robertson, Z. Sternovsky, and M. Friedrich. A rocket-borne mass analyzer for charged aerosols in the mesosphere. *Rev. Sci. Instrum.*, 79, 2008.
11. R. Latteck, W. Singer, and H. Bardey. The ALWIN MST radar: technical design and performance. *Proceedings of the 14th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Potsdam, Germany (ESA SP–437)*, pages 179 – 184, 1999.

12. F.-J. Lübken, U. Berger, and G. Baumgarten. Stratospheric and solar cycle effects on long-term variability of mesospheric ice clouds. *J. Geophys. Res.*, 114, 2009.
13. F.-J. Lübken, J. Lautenbach, J. Höffner, M. Rapp, and M. Zecha. First continuous temperature measurements within polar mesosphere summer echoes. *J. Atmos. Sol. Terr. Phys.*, 71:453–463, 2009.
14. K. A. Lynch, L. J. Gelinas, M. C. Kelley, R. L. Collins, M. Widholm, D. Rau, E. MacDonald, Y. Liu, J. Ulwick, and P. Mace. Multiple sounding rocket observations of charged dust in the polar winter mesosphere. *J. Geophys. Res.*, 110, A03302, doi:10.1029/2004JA010502, 2005.
15. D. Marsh and A. Merkel. 30-year PMC variability modeled by WACCM. *Eos. Trans. AGU, Spring Meet. Suppl.*, pages Abstract SA33B–08, 2009.
16. L. Megner and J. Gumbel. Charged meteoritic particles as ice nuclei in the mesosphere: Part 2 - a feasibility study. *J. Atmos. Sol. Terr. Phys.*, 71:1236 – 1244, 2009.
17. L. Megner, J. Gumbel, M. Rapp, and D. Siskind. Reduced meteoric smoke particle density at the summer pole implications for mesospheric ice particle nucleation. *Adv. Space Res.*, 41:41–49, 2008.
18. L. Megner, M. Khaplanov, G. Baumgarten, J. Gumbel, J. Stegman, B. Strelnikov, and S. Robertson. Large mesospheric ice particles at exceptionally high altitudes. *Ann. Geophys.*, 27(3):943–951, 2009.
19. B. J. Murray and E. J. Jensen. Homogeneous nucleation of amorphous solid water particles in the upper mesosphere. *J. Atmos. Sol. Terr. Phys.*, 72:51 – 61, 2010.
20. M. Rapp, J. Gumbel, F.-J. Lübken, and R. Latteck. D-region electron number density limits for the existence of polar mesosphere summer echoes. *J. Geophys. Res.*, 107(D14), doi:10.1029/2001JD001323, 2002.
21. M. Rapp and F.-J. Lübken. Polar mesosphere summer echoes (PMSE): Review of observations and current understanding. *Atmos. Chem. Phys.*, 4:2601–2633, 2004.
22. M. Rapp and I. Strelnikova. Measurements of meteor smoke particles during the ECOMA-2006 campaign: 1. particle detection by active photoionization. *J. Atmos. Sol. Terr. Phys.*, 71:477485, 2009.
23. M. Rapp, I. Strelnikova, B. Strelnikov, P. Hoffmann, M. Friedrich, J. Gumbel, L. Megner, U.-P. Hoppe, S. Robertson, S. Knappmiller, M. Wolff, and D. R. Marsh. Rocket-borne in-situ measurements of meteor smoke: charging properties and implications for seasonal variation. *J. Geophys. Res.*, doi=10.1029/2009JD012725, in press, 2010.
24. M. Rapp, I. Strelnikova, B. Strelnikov, R. Latteck, G. Baumgarten, Q. Li, L. Megner, J. Gumbel, M. Friedrich, U.-P. Hoppe, and S. Robertson. First in situ measurement of the vertical distribution of ice volume in a mesospheric ice cloud during the ecoma/mass rocket-campaign. *Ann. Geophys.*, 27(2):755–766, 2009.
25. M. Rapp and G. E. Thomas. Modeling the microphysics of mesospheric ice particles: Assessment of current capabilities and basic sensitivities. *J. Atmos. Sol. Terr. Phys.*, 68:715–744, 2006.
26. E. P. Shettle, M. T. DeLand, G. E. Thomas, and J. J. Olivero. Long term variations in the frequency of polar mesospheric clouds in the northern hemisphere from SBUV. *Geophys. Res. Lett.*, 36, L02803, doi:10.1029/2008GL036048, 2009.
27. I. Strelnikova, M. Rapp, B. Strelnikov, G. Baumgarten, A. Brattli, K. Svenes, U.-P. Hoppe, M. Friedrich, J. Gumbel, and B. P.Williams. Measurements of meteor smoke particles during the ECOMA-2006 campaign: 2. results. *J. Atmos. Sol. Terr. Phys.*, 71:486–496, 2009.
28. G. E. Thomas. Mesopheric clouds and the physics of the mesopause region. *Rev. Geophys*, 29:553–575, 1991.
29. G. E. Thomas, J. J. Olivero, E. J. Jensen, W. Schröder, and O. B. Toon. Relation between increasing methane and the presence of ice clouds at the mesopause. *Nature*, 338:490–492, 1989.
30. T. Vondrak, J. M. C. Plane, and S. R. Meech. Influence of submonolayer adsorption on the photoemission of the Cu(111)/water ice surface. 125, 2006.
31. D. M. Wood. Classical size dependence of the work function of small metallic spheres. *Phys. Rev. Lett.*, 46:749, 1981.