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NOCTILUCENT CLOUD OVERVIEW

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ABSTRACT

The goal of this paper is to summarize primary features of the properties and processes of the summer mesopause. The historical data on the properties of noctilucent clouds (NLCs) has relied primarily upon rocket probes, however in recent years remote sensing activities with lidars and radars have added significantly to our understanding of the spatial and temporal variations, and the relationships between NLC and PMSE displays. Models and simulations have provided insight for understanding many of the processes contributing to the formation of the NLCs. However, the details of the processes of particle formation, and the possible connections to climate, dynamics, and transport in the middle atmosphere are very intriguing to the scientific community. Key measurements of the properties and processes reported from prior investigations are summarized as a reference for developing our current understanding of the summer polar mesopause region.

1. INTRODUCTION

The purpose of this paper is to summarize the key elements of our understanding of the summer mesopause region, and provide some insights from the first major campaigns to investigate, and attempt to understand this region during the early 1980's. This short paper cannot provide a summary of all that has been accomplished during the several intensive studies of the summer mesopause over the past 25-years, only the general properties and key results for understanding the environment which controls NLC formation are briefly described. An emphasis is placed upon our original high resolution measurements of the structure and dynamics of the summer mesopause region from the CAMP and STATE campaigns in 1982 and 1983. Our initial understanding of NLC properties was based on early ground observations and the rocket programs conducted in the early 1980s. The activity since the 1990s has greatly expanded a focus on the scientific issues of the summer polar atmosphere using several new rocket payload instruments and ground based remote sensing with lidar and radar techniques.

2. INVESTIGATIONS OF NLCs

During the past 25-years, the developments of instrumented rocket payloads and the advances in radar and lidar have provided tools to study the region and to answer many questions about the summer polar mesosphere. However, many of those answers generated additional questions regarding the properties, and the physical and chemical process in this interesting region of the atmosphere.

2.1. Early Measurements

Optical scattering characteristics of noctilucent clouds (NLC) have been documented by many scientific observers at high latitudes [1-7]. The ground based measurements have characterized the height, season, geographical distribution, wave structures, wavelength dependence of scattered radiation, and polarization properties of the visible particles. The earliest satellite measurements of NLCs from the OGO-6 in 1969 were reported by Donahue et.al. [8]. Major steps in our knowledge about the polar atmosphere and the NLC particles came from the early instrumented rocket payloads that made *in situ* measurements in the summer mesopause region. Early rocket measurements of Witt and colleagues from 1960s used photometers to measure the optical scattering properties to study the NLC layer, which had been observed from the ground during prior decades [9].

Using ten acoustic grenade payloads at Kronograd Sweden and Barrow Alaska during the summers of 1963-1965, Theon and colleagues first measured the atmospheric structure and showed that the summer mesopause was quite cold. They reported that the expected concentrations of water vapor at the temperatures measured in the mesosphere (below 150°K) provided the necessary but not a sufficient condition for NLC ice cloud formation [10]. They reported based on their wind measurements, that NLC occurrence may be associated with low wind velocities in the mesosphere [11].

During the period 1979-1983, Balsley and Ecklund conducted the first high latitude measurements of the

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summer echoes in the middle atmosphere with the MST Radar at Poker Flats Alaska [12, 13]. These VHF radar measurements provided the initial descriptions of the Polar Mesosphere Summer Echoes (PMSE).

The Cold Artic Mesopause Program (CAMP) in 1982 at ESRANGE was the first major coordinated rocket campaign to investigate the summer polar mesopause with a focus on understanding the noctilucent cloud phenomenology [14]. This campaign provided the first measurements of several important properties with near simultaneous launches of several instrumented payloads. Tab. 1 lists the measurements conducted; these included structure, dynamics, optical scattering, ion density and composition, and neutral chemistry (NO and O_3) [15-17]. In 1983, we conducted another high latitude summer campaign, Structure and Atmospheric Turbulence Environment (STATE), to obtain the first *in situ* rocket payload measurements when a PMSE was simultaneously measured by the MST Radar at PFRR Alaska [18-21].

Table 1. Measurements in 1982 CAMP campaign

Rocket	Instrument	Parameter	Date	Time	Researcher
	EISCAT	Vertical Wind	Aug 2	23.00	F. Bertin
CAMP-P	Mass Spectrometer	Positive Ion Composition	Aug 3	23.32	E. Kopp
CAMP-P	Ion Probes	Positive Charge, Aerosol	Aug 3	23.32	L.G. Björn
SOAP 1	Photometer Lyman-α	NLC-height Temperature	Aug 3	23.49	G. Witt
SOAP 1	Resonance Fluorescence	Atomic Oxygen	Aug 3	23.49	P.H.G. Dickinson G. Witt
F235X	Resonance Fluorescence	Atomic Oxygen	Aug 4	00.05	P.H.G. Dickinson
TAD	Active Falling Sphere	Temperature, Density, Wind Velocity, Turbulence, Waves	Aug 4	00.16	C.R. Philbrick
SU-LO	Thermistor	Temperature	Aug 4	00.31	C.R. Philbrick

During the period 1981-1985, additional satellite observations of NLCs were obtained with the SME [22-24]. SME and several other satellites have now provided extensive sets of observations from space (including observations from manned flights) that provide a better representation of the distribution and occurrence of NLCs [25, 26].

2.2. Research of the Last Decade

Major advances have been made in our ability to detect and monitor the evolution of NLCs at ARR, with the ALOMAR facility, and at other high latitude lidar sites, PFRR and ESRANGE [27-29]. These sites provide new opportunities for studying NLCs using lidar and radar. The ability to continuously monitor NLCs and PMSEs, and launch instruments into them has rapidly increased our knowledge of the properties and process involved; key results are summarized in several publications [30-36].

2.3 General Characteristics of NLC

The general processes active in controlling the conditions for formation of NLC and PMSE are becoming understood. The essential qualities of global circulation driven by the thermal tides and momentum coupling from tidal and gravity waves provide the velocity and moisture fields which result in producing the cold polar mesopause [37, 38]. Wave breaking turbulence acts to transfer momentum that causes adiabatic cooling of the mesopause, while providing added moisture to the region. The summer polar mesopause is typically less than 130 K (70-90 K colder that winter mesosphere), and has been observed to be as cold as 110°K at the minima of the superimposed tidal and/or gravity wave features [15]. Although many models for the region have been developed over the years, the essential large scale features were obtained by combining the dynamical processes of seasonal variation in wave breaking suggested by Lindzen [37] into the chemical model in 1985 by Garcia and Solomon [38], and a later improved version [39]. The model shows the effects of gravity wave drag above 65 km, reversal of the zonal wind, meridional velocities (~10 m/s), vertical velocities (~2 cm/s), and shows the temperature of summer mesopause is expected to be < 140° K.

The summer mesopause temperature was shown to be cold enough to freeze the water content in the mesopause about 40 years ago [10]. NLCs typically occur about 84±4 km, while the PMSE radar signatures cover this region and extend upward to 90 km. The NLC ice particles range 20 to 80 nm in size when they are observed from the ground [32, 33], during a period of about 6 weeks centered about 2 weeks after solstice [26]. The ice particles appear as an oblate shape (axial ratio about 5 [34]), and they grow out of a larger population of small ice particles that are observed as PMSE in VHF radar signatures [31, 36, 40-42]. The mass spectrometers flown through NLC layers have observed hydrated ions with higher masses than detected when no NLCs are present [16, 17, 35]. Essentially all electron profiles measured through an NLC layer show a 'bite out' where a substantial fraction of the electrons are attached to the ice particles, and in a few cases, showing small increases in the total positive ion density (cf. [16, 17]). The increase likely results from a reduction in the ion-electron recombination loss. However, in one case the charge was taken by ice particles and water cluster ions disappeared in the layer [35]. It is unclear if the NLC nucleation center is due to positive water-cluster ions, or the smoke particles from meteoric debris; since plausible arguments are made for both [30, 42].

3. RESULTS FROM EARLY CAMPAIGNS

The CAMP and STATE campaigns provided important data for interpretation for the summer mesopause environment and properties. These campaigns included the piezoelectric accelerometer instrument to measure the density, temperature and wind through the mesosphere and into the lower thermosphere. Between the late-1970s and the mid-1980s, ten successful flights of the instrument provided a unique set of data on the atmospheric structure and dynamics. Fig. 1 shows the instrument components; included are the three tungsten proof masses with a common center of gravity that were attached by a sandwiched piezoelectric bimorph within a stainless steel housing (~8x10x5 cm). The proof masses were clamped until the sphere, in which the sensor was housed, was released from the spinning payload. The 25-cm sphere's moments of inertia were carefully adjusted using a rotation pendulum. The instrument was very sensitive and measured accelerations down to approximately 10^{-8} m/s^2 (~10^{-9} g), to provide density, temperature and wind velocity between 50 and 150 km. With proper care in design and calibration to balance the sphere, adjust the moments of inertia, and determine the sensitivity of each axis, the accuracy of the measurements is unmatched. The drag coefficients for the Mach and Reynolds numbers of this flow regime are well known.

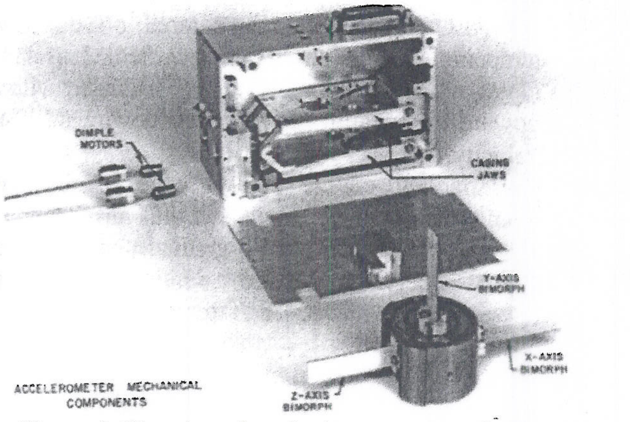

Figure 1. The piezoelectric three-axis accelerometer experiment components are shown with housing.

3.1. The CAMP Campaign

The CAMP launches from ESRANGE occurred on the night of 3/4 August 1982 (see Tab. 1). Several papers have described the measurements [15-17], and the results from the structure measurements of the density, temperature and wind are presented in Figs. 2 and 3. The vertical resolution in these plots is 250 meters. The density compared with the global average of the USSA76 model shows the dynamic response of the polar region and the large gradient in density associated with the momentum deposition from turbulence causing adiabatic cooling of the summer mesopause.

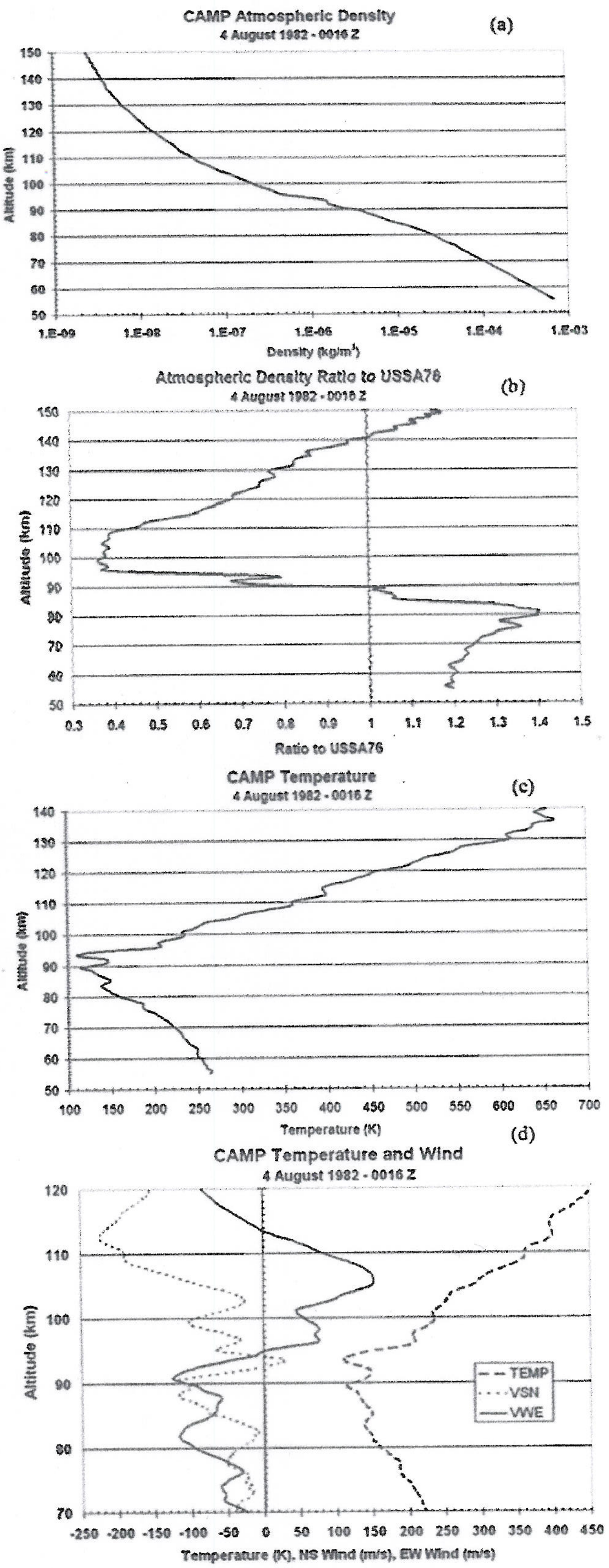

Figure 2. Accelerometer measurements show the structure and dynamics during an NLC event. The wind measurement is plotted as vector direction (north and east are positive).

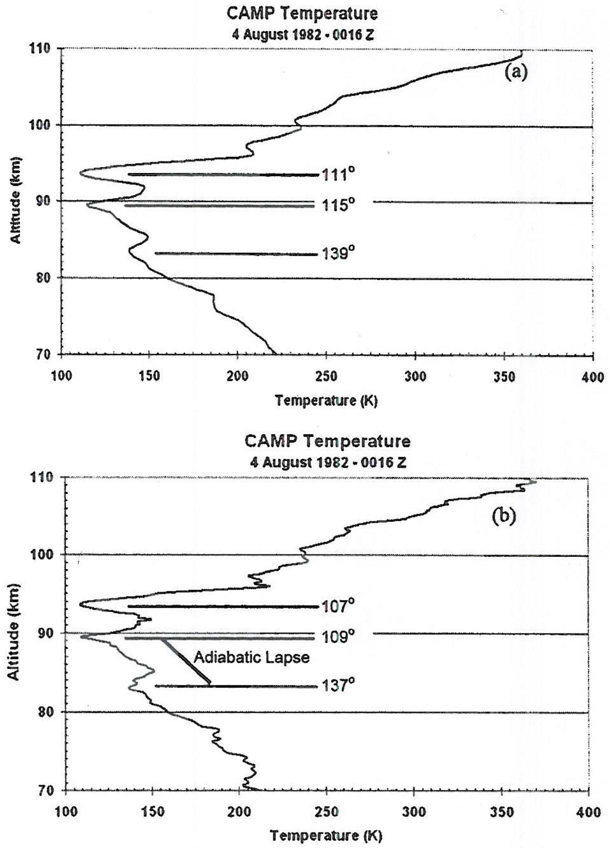

Figure 3. Temperature measurements during the CAMP project; (a) 250 m, (b) 100 m resolution.

The results shown in Figure 2 and Fig. 3(a) are all processed as independent segments of accelerometer data over 250 m height ranges. Unique data can be obtained at the rate of a half-spin cycle of either the x-axis or y-axis data, thus the highest useful resolution corresponds to one-quarter of a 6-Hz spin period; corresponding to about 50 m where the velocity is 1.2 km/s (~75 km altitude). Fig. 3(b) shows the same measurements, but is processed at the 100 m resolution. As expected, the temperatures at the minima are slightly lower in the case of the higher resolution data processing. Fig. 3(b) also contains a line showing the adiabatic lapse rate of the temperature, and demonstrates that the lower side of the temperature minima experience turbulent mixing, including the thick layer between 85 and 99.5 km.

The NLC was located at the altitude of the lower temperature minimum, which is also where the largest number of high mass hydrated ions are located, as shown in Figure 4. The water cluster ions, $H^+(H_2O)_n$, are present over a much larger altitude range than the NLC layer, but the NLC layer is located where the higher mass ions are found. It is interesting to note that at the temperature minimum, the contribution of the 3rd hydrate (n=3) decreases where the NLC layer, as well as the 5th, 6th, and 7th hydrate peak. A layer of meteoric ions between 90 and 100 km is also present, so the relative contributions of meteoric smoke and cluster ions are not clarified in this case.

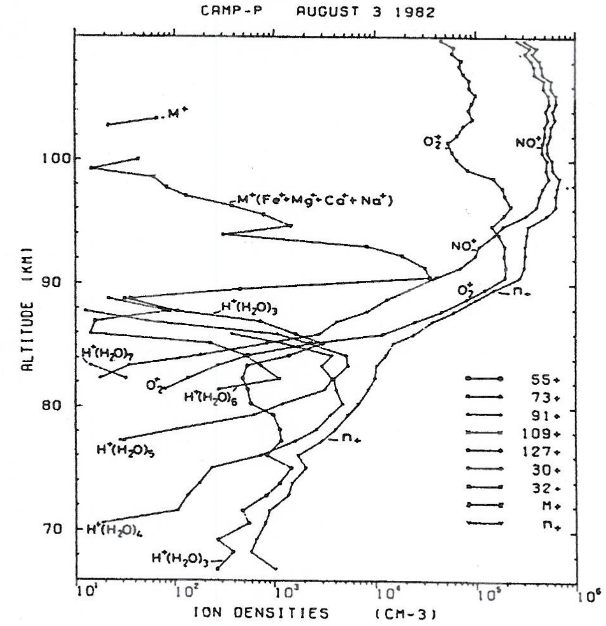

Figure 4. The positive ion composition measured the Bern University mass spectrometer, Kopp [16].

The following points are useful to consider:

(1) NLC appears to be centered on the lower temperature minimum in the wave field,
(2) Wave structure observed is associated with an upward propagating wave, and a downward phase velocity,
(3) Gradient of the bottom edge of the wave structure is super-adiabatic, and thus turbulent,
(4) Wave turbulence will gradually move super-cooled nuclei downward, while mixing water upward from bottom side of the turbulent layer.

3.2. The STATE Campaign

We conducted the STATE experiment at PFRR to provide *in situ* measurements together with the MST radar for the purpose of investigating the strong summer radar echoes that had been observed for several summer seasons [18]. The measurements were made on three days with PMSE conditions present and these results have been reported [18-21]. Fig. 5 shows the accelerometer measurements of structure. A temperature minimum of 122° K was observed at 90 km on this day with strong PMSE present [18].

4. DISCUSSION AND CONCLUSIONS

The dynamics and meteorological structure of the summer polar mesopause are the keys in the processes governing the formation ice particles that are

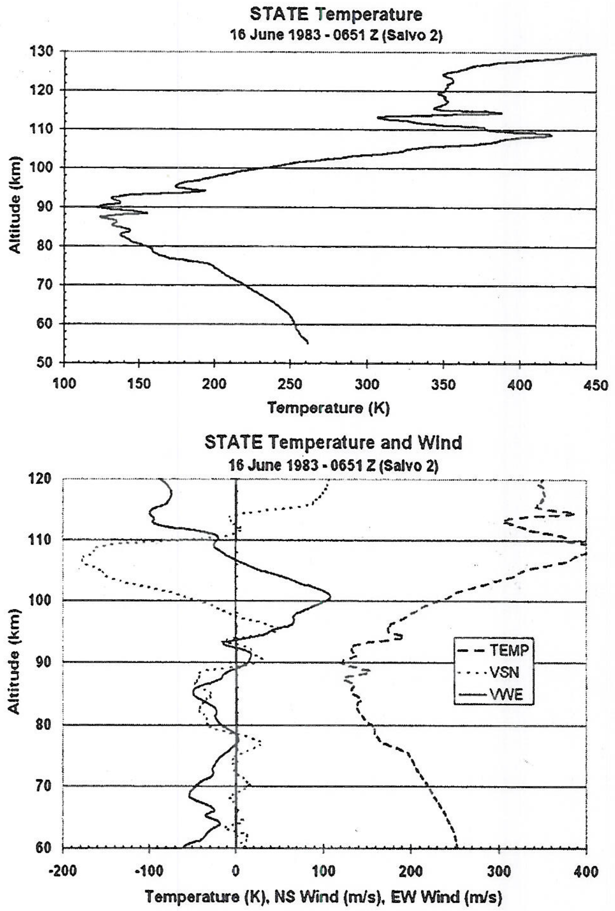

Figure 5. The temperature and wind profiles measured during the STATE campaign at PFRR during a period of PMSE.

observed as noctilucent clouds and PMSE radar signatures. The ties that connect the small charged-aerosol/cluster-ion particles with the signatures from scattered light and radio waves are becoming clearer. The large difference between the classical turbulence inner scale and the scale of 3-meter scattering has been long recognized [21], however it is apparent that processes causing the PMSE are strongly dependent upon turbulence structure in the region. High resolution measurements of the density, temperature, and wind point to the importance of the downward motion of waves that provide intense mixing layers in the mesopause region. These turbulent layers serve to both transport super cooled nuclei and small particles down through the region, while moistening the few kilometers thick layer with water from below. Positive water cluster ions are found present through the PMSE and NLC region, and the highest masses of these ions are correlated with the NLC location [16, 35]. The large and highly structured 'bite out' from the electron density profiles occurs in the region where NLCs are located, and indicate that the larger particles (> ~10 nm) are effective in collecting a significant fraction of the electron charge in those layers. These results lead to the suggestion that the PMSEs are associated with the presence of large numbers of small positive charged ice particles that are caught up in the motion of turbulent layers and lead to a change the local permittivity in the region. When these small charged particles coalesce into larger ones, they may appear as an NLC, however this is after growing to sizes greater than about 20 nm. The optical scattering dependence on the six power of the radius requires about 20 nm particles (~10^6 water molecules), which is probably the size needed for a visible NLC.

Satellite data should advance our understanding of interesting questions about distribution and frequency of occurrence; however we must continue to rely on *in situ* rocket probes to answer the fundamental physics of the process in formation of NLCs and the details of the relationships between the radar scatter signals from PMSEs and the optical signatures of NLCs observed. Particularly important are detailed measurements of the structure and dynamics (temperature, wind, waves), ion density and composition (positive and negative), properties of the nuclei (dust or ion), and size/shape/charge distributions of particles. Capabilities for continuous monitoring the mesosphere with lidar and radar are important for understanding the evolution of properties and processes governing the development of the PMSE/NLC features in the mesopause region. The AIM (Aeronomy of Ice in the Mesosphere) satellite, which was launched 25 April 2007, should further improve our understanding of this region, particularly refining the location and variations in the NLC layer, particularly long-term changes.

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As with most researchers, my knowledge on this subject is built upon the accomplishments of colleagues, their explanations of experiments, and my attempts to add new things that I learn during my research. It has been a privilege to know, work together with, and learn from most of the major contributors to this field, and I am appreciative to each of them. I am most appreciative of the many opportunities for collaborations with Ulf vonZahn, Ernest Kopp, Georg Witt, Eivind Thrane, and Dirk Offermann. The ALOMAR facility scientists and the Leibniz Institute for Atmospheric Physics (IAP) are providing a most valuable set of data for the investigations in this field. The contributions of Georg Witt and researchers of the Meteorological Institute of Stockholm University (MISU) provided the foundation, and continue to enrich this field of research.

Our development of the piezoelectric accelerometer experiment was accomplished because of the engineering expertise of Don Fryklund. Working with the PSU undergraduate students on the ESPRIT project caused me to go back and review the many reports of a host of colleagues reporting their work during the 20 years, since I was active in

this field. Interactions with students each day stimulate us to seek answers, think about diverse topics, and develop new ways to try to contribute to our understanding of the nature of this world. Many thanks go to them.

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