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# Simultaneous observation of sodium atoms, NLC and PMSE in the summer mesopause region above ALOMAR, Norway (69°N, 12°E)

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## Abstract

Based on simultaneous observations of Na density, polar mesosphere summer echoes (PMSE) and noctilucent cloud (NLC) at ALOMAR, Norway (69°N) during the summers of 2001 and 2002, we report the strong anti-correlation of sodium atoms with NLC, suggesting that in the presence of large ice particles Na is always absent, and a weaker anti-correlation of sodium atoms with PMSE, suggesting that a population of sub-visible particles also deplete Na to a varied degree. This conclusion is in general agreement with recent reports on iron and potassium atom-ice particle anti-correlation. For this study, we use data taken with the Weber Na lidar, the ALWIN VHF radar, and the RMR lidar on 8 specific days in 2001 and 4 days in 2002 plus half-monthly average variation over the summer 2001 based on all 17 days of coincident measurements.

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**Keywords:** Mesopause sodium layer; Polar mesospheric summer echoes; Noctilucent cloud; Heterogeneous chemistry and wave activities

## 1. Introduction

The first lidar detection of a noctilucent cloud (NLC) was made in August 1989 at the Andøya rocket range, Norway (69°N, 16°E) by a ground-based, excimer-pumped narrowband dye laser operated at 589 nm (Hansen et al., 1989). Despite the fact that a Na-NLC vertical separation was noted, implicating that lidar cannot measure tem-

perature at the NLC altitudes, there existed a desire in the fluorescence lidar community for concurrent temperature measurement, in the hope to investigate the atmospheric background in which the NLC ice particles form, grow and decay. This turned out to be a difficult proposition, since the early Na lidar (Kurzawa and von Zahn, 1990) was unable to make temperature measurements under sunlit conditions in the summer Arctic where NLCs reside. The size distribution of NLC particles was determined later by 3-color observations by the Rayleigh-Mie-Raman (RMR) lidar (von Cossart et al., 1999) at the Arctic Lidar Observatory for Middle Atmosphere

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1 Research (ALOMAR), Norway (69°N, 16°E); un- 53  
 2 fortunately, due to the poor signal-to-noise ratio 54  
 3 (SNR) of Rayleigh scattering at high altitudes, the 55  
 4 RMR lidar cannot make temperature measurements 56  
 5 at the NLC altitudes (82–85 km) in summer. In this 57  
 6 special issue, Thayer and Pan (2005) reported 58  
 7 several years simultaneous observation of Na atoms 59  
 8 and NLC, respectively, by a broadband Na 60  
 9 resonance lidar and a Rayleigh lidar. They found 61  
 10 on the average a 20% reduction of Na atoms below 62  
 11 the Na peak altitude, when NLCs were detected. 63  
 12 Though very strong radar echoes, termed “polar 64  
 13 mesosphere summer echoes (PMSE)”, were first 65  
 14 observed at frequencies of ~50 MHz (Czechowsky 66  
 15 et al., 1979; Ecklund and Balsley, 1981) about 10 67  
 16 years before lidar observation of NLC, the nature of 68  
 17 PMSE has become clear only in recent years (Cho 69  
 18 and Rottger, 1997; Rapp and Lübken, 2003). PMSE 70  
 19 are believed to be related to small charged ice 71  
 20 particles and therefore indicated the presence of ice 72  
 21 particles; they also affect plasma diffusion and 73  
 22 extend the scale of turbulent structures to that 74  
 23 observable by a VHF radar. 75

24 The ALOMAR Weber sodium lidar is capable of 76  
 25 measuring temperatures and winds under sunlit 77  
 26 conditions near the mesopause. It was deployed in 78  
 27 August 2000 and made one observation period 79  
 28 lasting barely 24 h that first summer (She et al., 80  
 29 2002). The power per beam (0.5 W) was too weak to 81  
 30 detect typical NLCs. The Weber lidar conducted 82  
 31 temperature measurements of greater than 2 h 83  
 32 duration on 17 days during the summer of 2001. 84  
 33 These data when combined with the collocated 85  
 34 VHF ALWIN radar, which is capable of investigat- 86  
 35 ing PMSE (Bremer et al., 2003), and the RMR lidar, 87  
 36 which is capable of detecting the backscatter from 88  
 37 NLC, will be used in this paper to investigate the 89  
 38 anti-correlation between ice particles and sodium 90  
 39 atoms in the polar summer mesopause. 91

40 There have been previous studies of ice particle 92  
 41 removal of metals such as iron and potassium. Iron 93  
 42 Boltzmann lidar observations at the South Pole 94  
 43 (Plane et al., 2004) revealed a severe reduction of 95  
 44 iron atoms at the altitudes of NLC. There were 96  
 45 rather limited PMSE observations in the Antarctic, 97  
 46 thus it was difficult to experimentally evaluate metal 98  
 47 atoms and small ice particle anti-correlation. The 99  
 48 question of ice particle–metal atoms interaction is 100  
 49 much more complicated. This is because low 101  
 50 temperatures favor both ice particle formation and 102  
 51 lower metal density due to chemistry. Also the 103  
 52 extent of metal depletion depends on the surface

53 area and on the time that the ice particles have 54  
 55 existed. A numerical model, such as Plane et al. 56  
 57 (2004), that includes these elements, is required for 58  
 59 the understanding of ice particle–metal atoms 60  
 61 interaction. The IAP group recently presented 62  
 63 experimental evidence for ice particle interaction 64  
 65 with potassium atoms, conducting lidar observa- 66  
 67 tions in three summers between 2001 and 2003 in 68  
 69 Spitzbergen (78°N). Lübken and Höffner (2004) 70  
 71 concluded that the NLC (larger ice particles with 72  
 73 radius greater than 10 nm) removed all available K 74  
 75 atoms, while the PMSE (smaller particles with 76  
 77 radius between 3 and 10 nm) reduced the number 78  
 79 of K atoms. Since co-located observations of Na 80  
 81 density, NLC and PMSE are still rare, a report on 82  
 83 the observation of sub-visual ice particle–Na atom 84  
 85 anti-correlation is timely, even if the existing data at 86  
 87 this point do not permit a study of Na–ice 88  
 89 interaction as extensive as that of Lübken and 90  
 91 Höffner (2004) on K–ice particle interaction. 92

93 Sodium and potassium are both alkali metals and 94  
 95 one might expect a very similar (if not identical) 96  
 97 effect, with anti-correlation between ice particles 98  
 99 and Na atoms. In a closer examination, the 100  
 101 anticipated lack of difference between the interac- 102  
 103 tion of Na and K atoms with ice particles was 104  
 104 merely a conjecture, since the seasonal dependences 105  
 105 in Na and K abundance in the mesopause region are 106  
 106 well known, and they are very different. The fact 107  
 107 that the K abundance is 2–3 times higher in summer 108  
 108 than in winter, while the Na seasonal abundance 109  
 109 variation is reversed, was experimentally established 110  
 110 even in the first simultaneous lidar observation 111  
 111 (Megie et al., 1978). This difference in both the 112  
 112 seasonal variation of abundance and total abun- 113  
 113 dance between Na and K is still not well understood 114  
 114 (see Plane (2003) for a review of meteoric metal 115  
 115 chemistry). 116

117 In the past, the ALOMAR RMR lidar and the 118  
 119 VHF radar at Andenes have been used for the first 119  
 120 simultaneous observations of PMSE and NLC 120  
 121 (Nussbaumer et al., 1996), showing that the NLC 121  
 122 is usually located at the lower edge of PMSE (von 122  
 123 Zahn and Bremer, 1999). In this paper we extend 123  
 124 these investigations and present data-sets with 124  
 125 simultaneous, collocated Na density, PMSE and 125  
 126 NLC observations taken in 2001 and 2002 at 126  
 127 ALOMAR, in combination pointing to the effect 127  
 128 of Na atom–ice particle anti-correlation. 128  
 129 101  
 130 103

1 **2. Instrument and observation**

3 The main instruments used were the Weber Na  
 4 lidar, the RMR lidar and ALWIN VHF radar, all  
 5 located at ALOMAR, close to the Andøya rocket  
 6 range, Norway. We briefly describe the capability of  
 7 these measurements under typical summer polar  
 8 sunlit conditions. The Weber Na lidar is capable of  
 9 measuring Na density, mesopause-region tempera-  
 10 ture and horizontal wind. The minimum detectable  
 11 Na signal of this lidar is  $\sim 3$  photons in 75 m and  
 12 1 min. The temperature and wind measurement  
 13 errors depend on the observed SNR, requiring a  
 14 minimum signal level of  $\sim 15$  photons in 75 m and  
 15 1 min for meaningful measurements at a resolution  
 16 of 0.5 km and 1 h. An overview of the ALOMAR  
 17 RMR lidar was given by von Zahn et al. (2000) and  
 18 due to the fidelity of the instrument even weak NLC  
 19 can be detected at noon under the highest sunlight  
 20 conditions (Fiedler et al., 2003). The data used in  
 21 this analysis are 6 min mean values with a vertical  
 22 resolution of  $\sim 0.5$  km. The telescopes used by both  
 23 lidars were pointed at the zenith for most of 2001  
 24 and at  $20^\circ$  to the east and west of zenith for most of  
 25 the 2002 observations. Details of the ALWIN VHF  
 26 radar (53.5 MHz) can be found in Latteck et al.  
 27 (1999). For the description of the PMSE in this  
 28 paper we use 5 min mean values of the SNR derived  
 29 from the backscattered echo power with the  
 30 vertically directed beam. The data are sampled with  
 31 a vertical resolution of 300 m. Though dynamics in

the summer polar mesopause region is not the main  
 topic for this paper, we will mention the extreme  
 temperature gradient that was observed in 2002. In  
 this instance, both the ground-based Weber lidar  
 and an ionization gauge-based, Combined Observa-  
 tion of Neutral and Electrons, or CONE sensor  
 (Rapp et al., 2001) on board a rocket captured the  
 same temperature gradient.

3 **3. Results and discussion**

We present simultaneous observation of Na  
 density, PMSE and NLC during the summer  
 MaCWAVE (Mountain and Convective Waves  
 Ascending Vertically) campaign (Goldberg et al.,  
 2004) in July 2002, and regular summer observa-  
 tion between June and August 2001. The MaCWAVE  
 campaign is a multiple instrument rocket campaign,  
 focused on wave dynamics and interactions con-  
 tributing to polar summer mesopause structure and  
 variability. On July 02, 2002, a moderately high  
 mesopause at 89 km altitude was observed with a  
 temperature below 120 K. Accompanying this me-  
 sopause formation, a dramatic anti-correlation of  
 Na atoms and ice particles was observed. We  
 present hourly mean and bi-hourly mean profiles  
 centered at 1.83 UT, when a sounding rocket was  
 launched. Shown in Fig. 1(a) are background  
 removed hourly mean profiles of Na lidar signal,  
 centered at 1.83 UT, July 02, 2002, taken by the west  
 (solid) and east (dashed) lidar beams in the units of

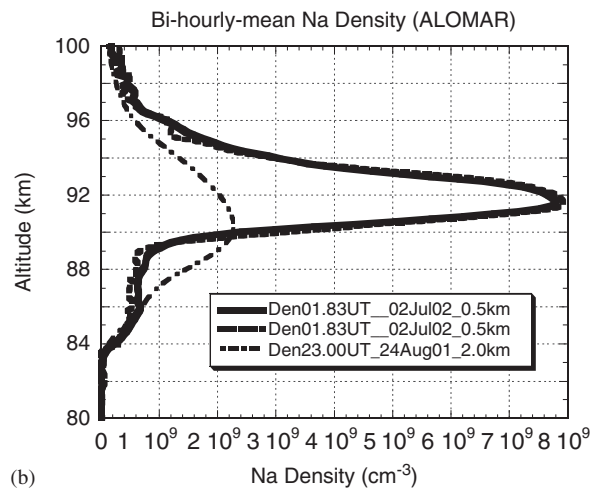
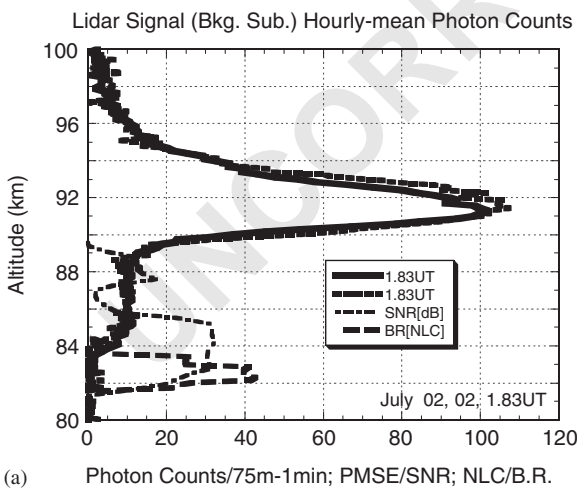


Fig. 1. (a) Photon counts for two sodium lidar beams (solid, dashed), PMSE SNR (dash-dot), and NLC BSR (long dashed) for 02 July 2001 at 1.83 UT. (b) Two-hour-mean sodium density showing the agreement between two beams separated by 60 km at 88 km altitude. Also shown in the figure, for comparison, is an hourly mean density profile taken on 24 August 2001 (dash-dot), representing a more typical profile when neither PMSE nor NLC present.

photons per 75 m bin and 1 min integration. These profiles are shown with the concurrent hourly mean PMSE (dash-dot) profiles in SNR (db) and NLC (long dashed) profiles in backscatter ratio (BR). A dramatic 10-fold signal decrease is observed at the altitudes where PMSE (small ice particle, radius thought to be less than 10 nm) resides, and the signal disappeared all together at altitudes (81–84 km in this case) where NLCs (ice particles thought to be larger than ~20 nm) were observed. The accompanying Na density was retrieved from photon count profile by our standard data analysis procedure (She et al., 2000). The Na density change as a function of altitude for this day is shown in Fig. 1(b), where bi-hourly mean Na density profiles center at 1.83 UT, July 02, 2002 observed by west (solid) and east (dashed) beams are shown. Due to the sharp density gradient at ~90 km, the spatial resolution used was 0.5 km. That the solid and dashed profiles in both Figs. 1(a) and (b) are nearly the same is expected, although the two observation values were ~60 km apart. As can be seen in Figs. 1(a) and (b), the sharp gradient near the mesopause existed for both bi-hourly mean and hourly mean. In fact, this condition lasted about 4 h. The “plateau” and very sharp gradient in sodium density were unique to this day—they did not occur on the 17 days of observation during 2001. We believe that these unusual features were due to enhanced wave breaking, leading to the associated large temperature gradient as discussed in Fritts et al. (2004). The evidence of strong ice particle and

sodium atom anti-correlation clearly displayed below the very cold mesopause as shown in Fig. 1(a). To illustrate that the Na density profile at the absence of PSME and NLC is different and that the Na layer of July 02 is unusual, we also show in Fig. 1(b) a 2-h mean density (dash-dot) centered in 23.0 UT, August 24, 2001 for comparison. This profile varies smoothly between 83 and 105 km with a peak density at 90.5 km, without sharp gradient. The abundance of this day is more typical for summer, while the 02 July profile is not only narrower but also with much higher abundance.

The accompanying temperature profiles (resolution 2 h and 0.5 km) measured by both lidar beams were averaged and the CONE-sensed temperature profile at 1.83 UT on board the MIDAS rocket are both shown in Fig. 2(a) with a dramatic 40 K change over less than 1 km near the mesopause. To further appreciate the situation, we show the mean zonal wind profile in Fig. 2(b). The dynamics in this occasion is interesting and complex; the causes for the extreme temperature gradient, 40 K/km and wind gradient exceeding 100 m/s/km, and its implication have been investigated in a recent paper (Fritts et al., 2004). According to lidar data, this “extreme” gradient in fact exists for about 4 h. Though the extreme gradients were degraded somewhat in the 2-beam and 2-h mean, they were still clearly present. The temperature profile shows heating above mesopause between 89 and 93 km. The heating may be the result of gravity wave breaking in the summer mesopause depositing

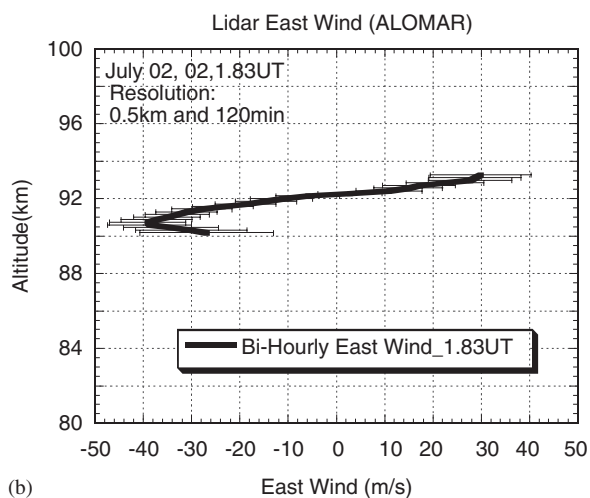
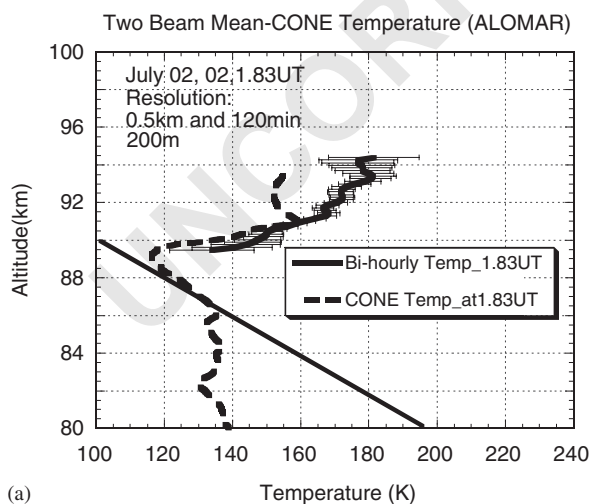
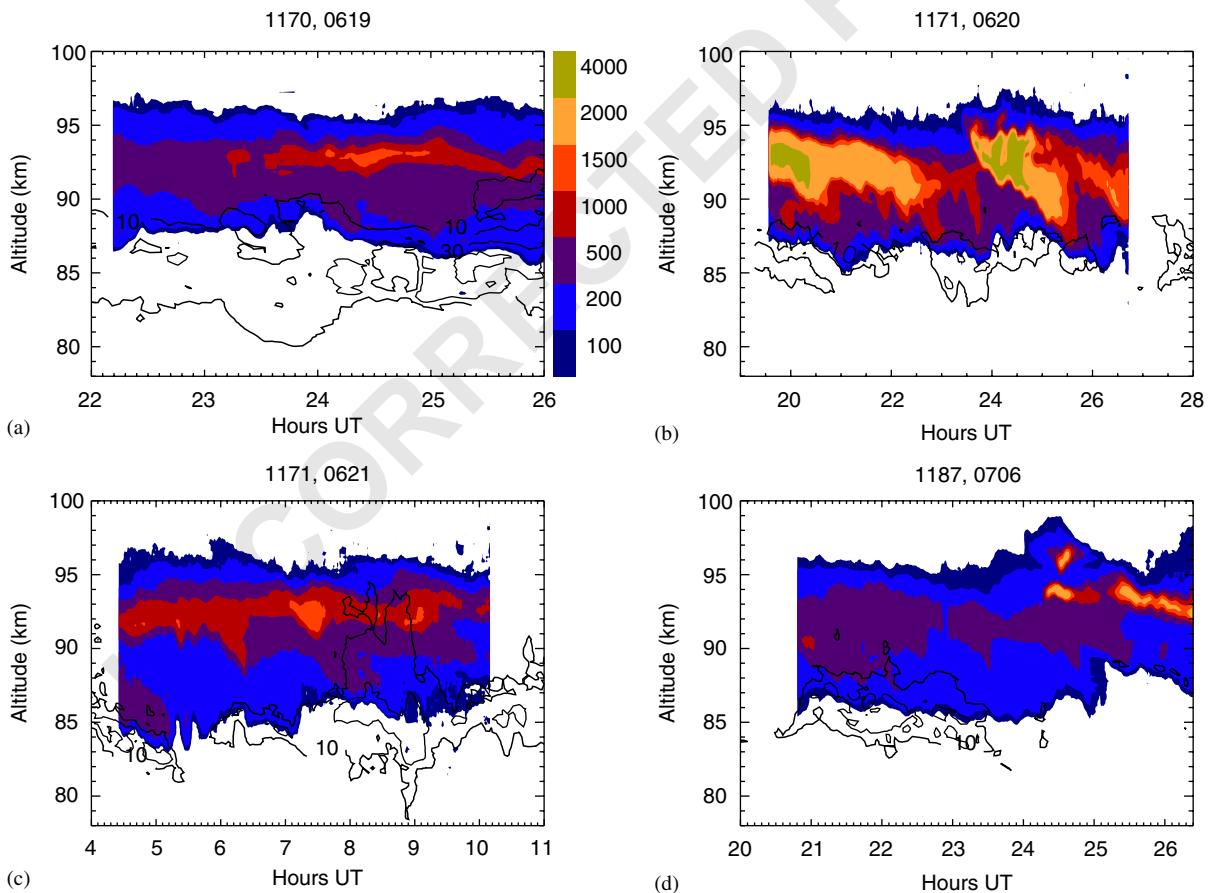


Fig. 2. (a). Temperatures from the sodium lidar (solid) and the MIDAS CONE instrument (dashed) for 02 July 2001 centered at 1.83 UT. (b). Two-hour-mean zonal wind showing the large gradient.

1 eastward momentum on the westward mean wind  
2 that decelerates it. The lidar observed mean wind  
3 from the two lidar beams shown in Fig. 2(b) appears  
4 to be consistent with this scenario.

5 The reduction of Na density in the presence of  
6 PMSE occurs frequently with or without the  
7 concurrence of sharp temperature and wind gradi-  
8 ents. In summer 2001, the two beams of the Weber  
9 lidar pointed vertically, measuring Na density and  
10 mesopause region temperatures. The ALWIN radar  
11 also observed concurrently detecting the presence of  
12 PMSE with SNR greater than 15 on 48 h during the  
13 95 h with Na lidar observations distributed over 17  
14 days in 2001. PMSE were present during 15 of the  
15 17 days with lidar observations and the only  
16 observing periods with no PMSE were at the end  
17 of the season on August 24 and 25, 2001. The  
18 occurrence rate (% of time with PMSE) for PMSE  
19 during the lidar observing periods was 65% for  
20 June, 82% for July, and 24% for August. Shown in  
21

22 Fig. 3 are eight panels with the best coverage of  
23 simultaneous Na density and PMSE observations as  
24 a function of UT hours during summer 2001 (June  
25 19, 20 and 21, July 06, 13, 23 and 25 and August  
26 20). In each case, the lower edge of the Na density  
27 profiles overlaps and tracks the upper half (often  
28 near peak) of the PMSE profiles in altitude. The  
29 sodium densities in this figure and the figures below  
30 were determined from raw 1-min profiles normal-  
31 ized to the Rayleigh signal at 40 km and then scaled,  
32 so the peak value agrees with the full hourly average  
33 profile from our standard data analysis procedure.  
34 The sodium density is usually below  $100/\text{cm}^3$  by the  
35 midpoint of the PMSE profile. The  $50\text{--}100/\text{cm}^3$   
36 sodium contour often tracks the peak of the PMSE  
37 layer. Depending on atmospheric conditions, so-  
38 dium density and PMSE often move vertically  
39 together in response to atmospheric vertical moti-  
40 ons. The last 2–3 h in the panel of July 06 shows up  
41 and down motions, while in the panel of August 20  
42



43 Fig. 3. Na density in  $\text{cm}^{-3}$  (blue–red–yellow contours) and PMSE SNR (black contour lines) for 8 days in 2001: 19, 20, 21 June, 6, 13, 23, 25 July, and 20 August. The numbers at the top of each plot in Figs. 3–5 give the day of year (YDOY) and the date (mmdd).

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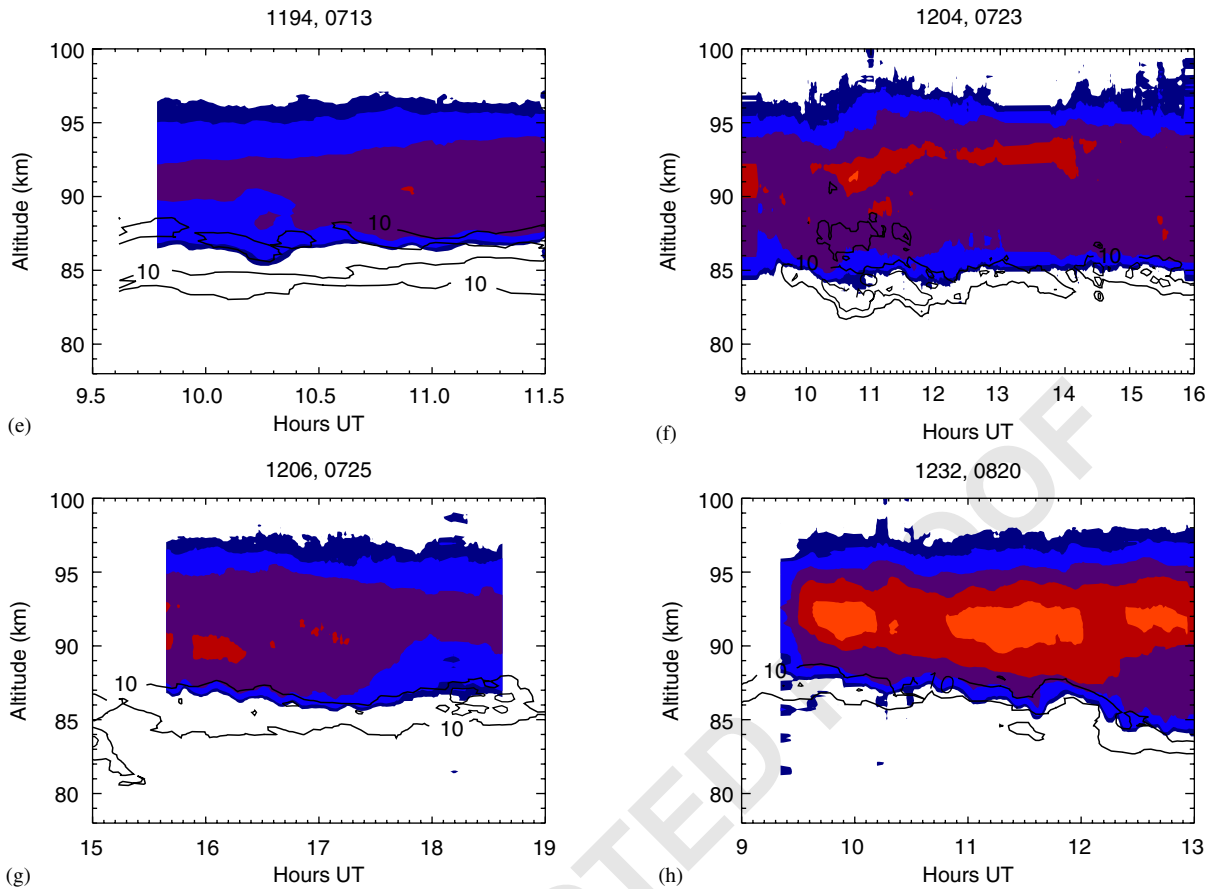


Fig. 3. (Continued)

shows descending motion of both Na density and PMSE. The PMSE signal strength (and also the width of the layer when displayed as SNR) is also affected by atmospheric turbulence and its coupling to the  $\sim 3$  m scale irregularities that are actually observed by the radar, not just the amount of small ice particles (Rapp and Lübken, 2004). So it is not surprising that the width of the PMSE layer sometimes changes without any corresponding changes in the sodium or NLC signal. A good example of this was on 21 June, 2001 at 9 UT when the width of the PMSE layer increased from  $\sim 2$  km to  $\sim 10$  km, without any significant change in the altitudes of the peak of the PMSE layer or the bottom edge of the sodium layer.

Unfortunately, during these 17 days of lidar observations in 2001, we were unlucky and the only day with a significant NLC present was July 06/07, 2001 and for some minutes on August 06, 2001 while during the other days there was clearly no NLC present. The Na, NLC and PMSE signals for

July 06/07 are shown in detail in Fig. 4(a). This was a very active and interesting day with multiple layered structures. The sporadic sodium layers at 96 km at 24.5 UT and 93 km at 24.5–26.5 UT were likely due to sporadic ion layers and are unrelated to the NLC and PMSE layers lower down that are likely due to ice particles. The sporadic layers do show the presence of short-period gravity waves quite well, indicating that the day is rather active dynamically. The PMSE layer peak and the  $50/\text{cm}^3$  Na contour both descend from 87 km at 21 UT to 86 km at 23 UT, while the NLC layer forms at 22 UT within the bottom half of the PMSE layer. The PMSE layer dies out at 23.5 UT and the NLC layer strengthens to a maximum at 25 UT. The time series of temperatures at 87 km and 90 km, Fig. 4(b), show variation in general support of the temporal development of PMSE and NLC layers. The peak of PMSE and the lower ledge of Na descended vertically between 21 and 22.5 UT, and we see the temperature at 87 km increased during this period.

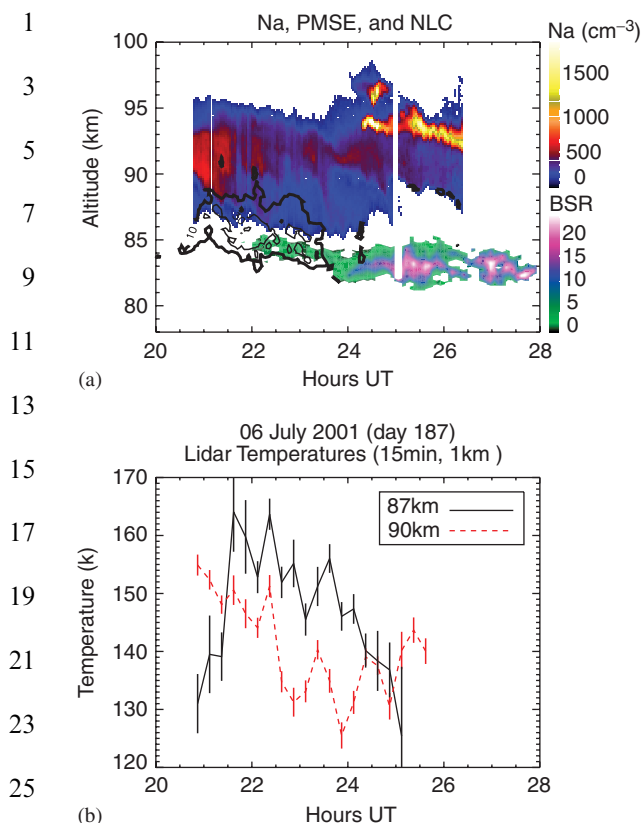


Fig. 4. (a). Detailed view of sodium density (blue–red–yellow contours), PMSE SNR (black contour lines: thick = 10, thin = 30), and NLC BSR (green–pink contours) on 06–07 July 2001. The  $x$ -axis is given as hours since midnight on 06 July. (b) Temporal evolution of temperatures (15-min and 1-km resolution) at 87 km and 90 km, accompanying PMSE dynamics.

The reason for lack of PMSE around 23.7 UT is not clear. However, at 87 km we do see a 10 K warming between 23.0 and 23.7 UT and immediately cooled back to the same temperature at 24.2 UT with the altitude of lower ledge of Na unchanged. It is possibly that the warming evaporated the smaller ice particles in PMSE and the cooling that followed enlarged the left-over ice particle in PMSE, and these joined growing NLC due to sedimentation. Modeling of ice particle growth and decay would be needed to confirm these qualitative statements. Between 24 and 25.2 UT, the lower ledge of Na ascended vertically while the Na peak descended vertically, and during the same period, temperature at 87 km cooled by  $\sim 25$  K, and warmed by  $\sim 15$  K at 90 km. At the end of this period, the bottom of the sodium layer moved upward, and it jumped up almost to 90 km, and the NLC layer intensified. At

the same time, a small radar echo formed at 89 km and they both descended to 87 km by 26.5 UT. This apparent jump may not correspond to true vertical motion of air parcels. Rather, it may just correspond to the next phase front of a gravity wave. The NLC did not show this dramatic change in altitude.

In 2002, 3 days had coincident Na-PMSE observations (Fig. 5). During these days, the lower edge of the Na layer overlaps the PMSE as expected, while it appears to track the upper edge of PMSE between 25 and 30 UT on 01 July. Two of those days (01 and 11 July) also had significant NLC layers, while the other day (25 June) showed some minor NLC signals that were only slightly above the noise level. The strongest day, 01–02 July, which was discussed earlier in the paper, is an excellent case showing the anti-correlation of NLC and Na atoms. These plots again show anti-correlation between the Na and NLC, and the overlap of the upper half of the PMSE layer and bottom edge of the Na layer. Due to the nature of the observations, we have discussed variations in the layers in terms of temporal and altitude changes. We note that they could also be caused by horizontal variations in the layers drifting overhead. This is more of a problem for the 2002 data, as the PMSE profiles are separated by  $\sim 30$  km horizontally from the NLC and sodium profiles.

In 2001, we use the sodium observations on 17 days to calculate half monthly average sodium density profiles. We also calculate the half monthly average PMSE signal, sampled at the same time as the sodium observations. This is shown in Fig. 6. Again the  $50/\text{cm}^3$  sodium contour follows the peak of the PMSE profile. The PMSE SNR was waning by mid-August while the sodium peak density was increasing. We do not have enough NLC coincidences to do this calculation for the NLC signal, but the 1997–2003 climatology at ALOMAR was consistent with our case studies, showing the NLC's starting a week into June and ending by mid-August with altitudes ranging from 80 to 86 km (Fiedler et al., 2004).

#### 4. Conclusion

Based on the simultaneous observation of Na density and ice particles, i.e., PMSE (smaller sizes, with radius even below 10 nm) and NLC (larger sizes, with radius larger than  $\sim 20$  nm) at ALOMAR, Norway during summers of 2001 and 2002, we found that in the presence of NLC, Na is always

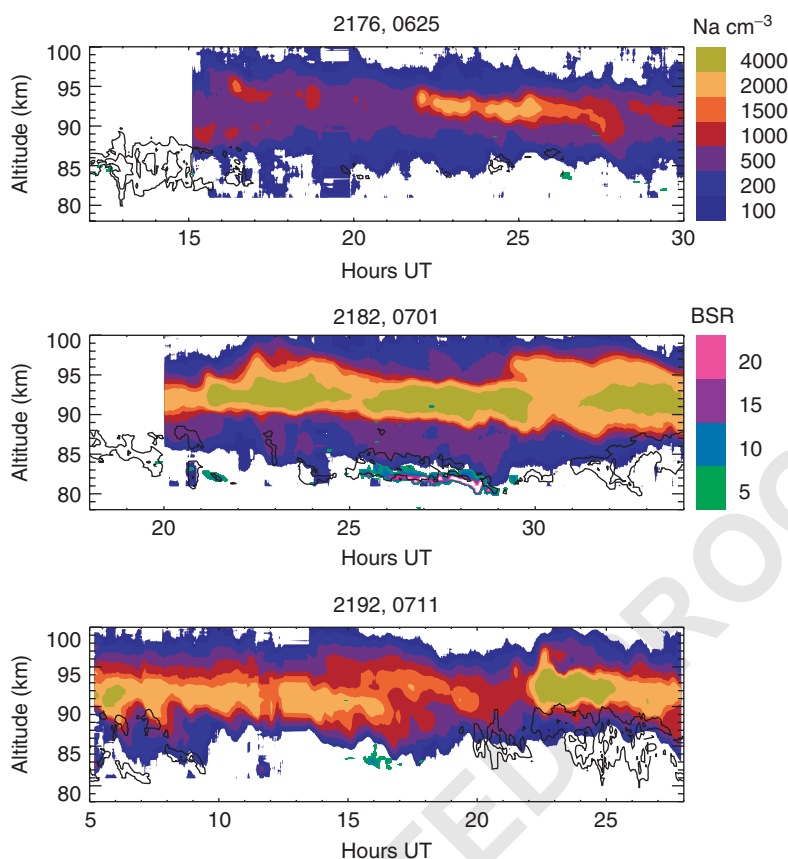


Fig. 5. Sodium density (blue–red–yellow contours), PMSE SNR (black contour lines: thick = 10, thin = 30), and NLC BSR (green–pink contours) for 3 days in 2002: 25 June and 1 and 11 July.

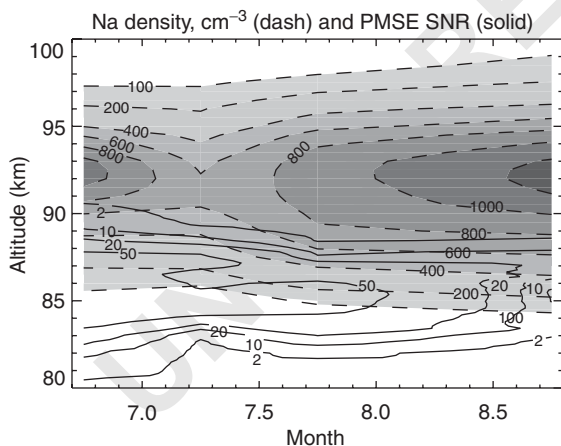


Fig. 6. Variation over the summer of sodium density (dashed contours, shaded) and PMSE SNR (solid contours) using half-monthly averages from mid June to late August.

absent at the same altitudes, and when PMSE is present, the lower edge of the Na layer most often than not overlap the peak of PMSE layer. This is in

general agreement with recent reports on iron and potassium atom–ice particle anti-correlation. This was not clear a priori, because although sodium and potassium are both alkali metals, the total abundances and the seasonal variation of the abundances of mesopause-region sodium and potassium are quite different, a difference still not understood (Plane, 2003).

Our observation clearly demonstrated the anti-correlation between Na atoms and NLC and PMSE. There were cases showing less anti-correlation between Na density and PSME SNR, as observed coexistence of PMSE and high Na density at  $\sim 90$  km for more than an hour's duration on 21 June 2001 indicated. Whether this high PSME signal is resulting from enhanced radar backscatter or from not enough time for ice particle to scavenge Na atoms cannot be determined from lidar observation alone. A comprehensive model study (Plane et al., 2004) would be required. We also observed the correlated vertical motion of both Na

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1 density and PMSE due to waves. These are topics of  
 3 scientific interests in their own right. They should be  
 5 studied as continued observations take us to a more  
 7 complete understanding of interactions between Na  
 9 atoms and PMSE.

## 7 Acknowledgments

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