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Summer time Fe depletion in the Antarctic mesopause region

T.P. Viehl [a,*], J. Höffner [a], F.-J. Lübken [a], J.M.C. Plane [b], B. Kaifler [a,c], R.J. Morris [d]

[a] Leibniz-Institute of Atmospheric Physics (IAP) at the University of Rostock, Schloßstr. 6, 18225 Kühlungsborn, Germany
[b] School of Chemistry, University of Leeds, Leeds LS2 9JT, United Kingdom
[c] German Aerospace Centre (DLR), Institute of Physics of the Atmosphere, Münchner Str. 20, 82234 Wessling, Germany
[d] Australian Antarctic Division (AAD), 203 Channel Hwy, Kingston, Tasmania 7050, Australia

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ABSTRACT

We report common volume measurements of Fe densities, temperatures and ice particle occurrence in the mesopause region at Davis Station, Antarctica (69°S) in the years 2011–2012. Our observations show a strong correlation of the Fe-layer summer time depletion with temperature, but no clear causal relation with the onset or occurrence of ice particles measured as noctilucent clouds (NLC) or polar mesosphere summer echoes (PMSE). The combination of these measurements indicates that the strong summer depletion can be explained by gas-phase chemistry alone and does not require heterogeneous removal of Fe and its compounds on ice particles.

1. Introduction

When meteors enter the Earth's atmosphere they predominantly ablate in an altitude region between 75 and 115 km. Ablated meteoric metal atoms form layers of neutral, ionised and molecular bound species, the latter mainly in the form of oxides and hydroxides (Self and Plane, 2003). The seasonal change in metal abundance is largely determined by the seasonal variation in global circulation and temperature dependent chemistry (Plane et al., 2015). In a recent study Feng et al. (2013) compare the seasonal variation at several sites (including measurements at Davis, Antarctica) with model calculations and list comprehensive references.

Another phenomenon characteristic to the MLT altitude range is the summer time occurrence of ice particles at polar latitudes. These ice particles can be detected by satellites, lidar instruments or the human eye when they have reached sufficient size (with radii typically larger than 20 nm) through condensation growth. In the case of satellite observations the ice particles are known as polar mesospheric clouds (PMC), in the case of ground based observations as noctilucent clouds (NLC), e.g. Baumgarten et al. (2012), DeLand et al. (2006), Russell et al. (2009), and Lübken et al. (2009). Visibly observable ice particles as well as smaller, subvisible ice particles can lead to polar mesosphere summer echoes (PMSE), which are strong radar echoes caused by small scale structures in electron densities (Rapp and Lübken, 2004; Lübken, 2013). These structures on the order of the radar Bragg wavelength rely on the combined effect of neutral air turbulence and charged ice particles. It is important to note that PMC and NLC require 'large' ice particles whereas PMSE can also be caused by smaller ice particles ($r \leq 20$ nm). Consequently, PMC/NLC appear at the lower edge of the super-saturated region (approximately 82–84 km) whereas PMSE extend to higher altitudes (up to 94 km).

Observations by Plane et al. (2004) and Lübken and Höffner (2004) and subsequent studies investigated the uptake of metal atoms, in particular of Fe (iron) and K (potassium), on ice particles. These authors report singular events of metal atom depletions with simultaneous occurrence of PMSE as well as NLC in the case of K, and NLC in the case of Fe. She et al. (2006) and Thayer and Pan (2006) found similar anti-correlations for Na (sodium). These studies suggest that the depletion is largely caused by an uptake of metal atoms on the ice particle surface. For K, this was reproduced in a model by Raizada et al. (2007). Northern hemispheric K densities were shown to fall nearly instantaneously at the beginning of the PMSE and NLC season. K densities remained low and steady for the period of ice particle occurrence. Similar to the beginning of the season, densities increased markedly at the end of the PMSE season, i.e. when no further ice particles were observed.

The hypothesis of metal atom adsorption on ice particles was developed further to explain the summer time behaviour of the

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* Corresponding author.
E-mail address: viehl@iap-kborn.de (T.P. Viehl).

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seasonal Fe cycle in the MLT region of the Southern Hemisphere. Gardner et al. (2011) compared observations performed at Rothera, Antarctica (Chu et al., 2006) and the South Pole (Gardner et al., 2005). Both Rothera and the South Pole show significant Fe depletion at around 80–92 km during the summer months and in particular during a period of about ± 40 days around summer solstice when NLC are observed. Differences in metal layer abundance, height and width between these two stations were attributed to differences in NLC altitude, brightness and occurrence frequency. Spatial and temporal mismatches between the presence of NLC particles and Fe depletion were noted, observable mostly above 87 km altitude and in the month prior to the first NLC detection. Common volume comparisons of Fe densities with PMSE were so far not available. In analogy to results from other metals in the Northern Hemisphere and due to promising modelling efforts, these gaps were attributed to smaller, sub-visible particles.

Gardner et al. (2011) found a high positive correlation of Fe densities with temperature as expected from calculations by Plane (2003) and others and discuss various influences on the seasonal variation of the metal layer. The authors concluded that the peak of the Fe layer was pushed to well above 90 km because persistent ice clouds at lower altitudes removed the Fe atoms in vicinity.

Hence, according to all those studies cited above it seems that the summer time Fe depletion in the Antarctic mesopause region is largely influenced by the uptake of metal atoms on ice particles. We present observations which challenge this hypothesis.

2. Instrumentation

The mobile Fe-Lidar operated by the Leibniz-Institute of Atmospheric Physics (IAP) was commissioned at Davis, Antarctica (68.6°S, 78.0°E) in the early summer season 2010–2011 (Lübken et al., 2011; Morris et al., 2012). It was in operation for more than two consecutive years until the end of the summer season 2012–2013 in early January 2013. The lidar is a two-wavelength system based on a frequency-doubled alexandrite laser (von Zahn and Höffner, 1996; Höffner and Lautenbach, 2009). It is capable of determining mesospheric temperatures and Fe densities in full daylight by scanning the Doppler broadened Fe resonance line at 386 nm. High solar background as well as low Fe densities are the conditions giving the largest possible measurement uncertainty. Typical uncertainties for temperatures are 5 K for 1 h integration and 1 km altitude range in summer time during noon conditions and annual low Fe density. Uncertainties for daily means are on the order of 1 K and less than 1% for temperature and Fe density, respectively. Variations in uncertainties depend on tropospheric weather, absolute Fe densities and observation period. NLC are simultaneously detected by an independent analysis of the retrieved residual infrared laser wavelength at 772 nm. As the system is capable of nearly background free single photon detection during full daylight, NLC are detectable within an integration time as short as 2 min. The complete dataset obtained by the mobile Fe-Lidar at Davis includes 2900 h of lidar measurements nearly equally distributed throughout the year and all hours of the day. During the austral summer months September 2011 to March 2012 a total of 1151 h of temperature and density measurements with at least 1 h duration were obtained on 94 days. The average length of the measurements considered is 12 h 14 min per day.

Another instrument operated at Davis is the 55 MHz Mesosphere–Stratosphere–Troposphere (MST) radar of the Australian Antarctic Division (AAD) which was put into operation in the summer season of 2002–2003 (Morris et al., 2004). This system has been detecting PMSE on a regular basis since the summer season 2003–2004. The AAD MST radar was in operation during all times when the IAP Fe-Lidar was in operation. As both instruments are located at Davis, common volume measurements of Fe densities, temperatures and ice particles (detected as NLC and PMSE) are available and allow a unique combined analysis of these atmospheric features.

3. Observations of Fe density, temperature and ice particles

3.1. Fe density and temperature in the 2011/2012 summer

Fig. 1 shows Fe densities and temperatures in the mesopause region from spring to autumn. Fe densities are cut off at 100 cm^{-3}. In general, densities and temperatures during the summer months are at their annual low with daily mean temperatures between 87 and 95 km lower than 145 K and densities lower than 10,000 cm^{-3} except for higher densities in the peak layer from mid-February onwards.

Contrary to model results (Feng et al., 2013) and previous observations (Gardner et al., 2011) for this Antarctic latitude, the upper boundary of the Fe layer at Davis as shown in Fig. 1 is generally higher during the summer months than during spring and autumn. (See, e.g., the 2,000 cm^{-3} contour line.) High densities at high altitudes in late March are caused by sporadic layers. The centroid altitude rises towards summer solstice and falls thereafter, as the whole Fe layer is shifted upwards. The whole layer thins out throughout all altitudes towards solstice. The figure also shows a very strong short term depletion in Fe densities of about 2 weeks duration around solstice between 87 and 95 km altitude. Simultaneously, record low daily average temperatures below 135 K are shown in the exact same altitude and time region. Some of these temperatures as well as singular short term profiles

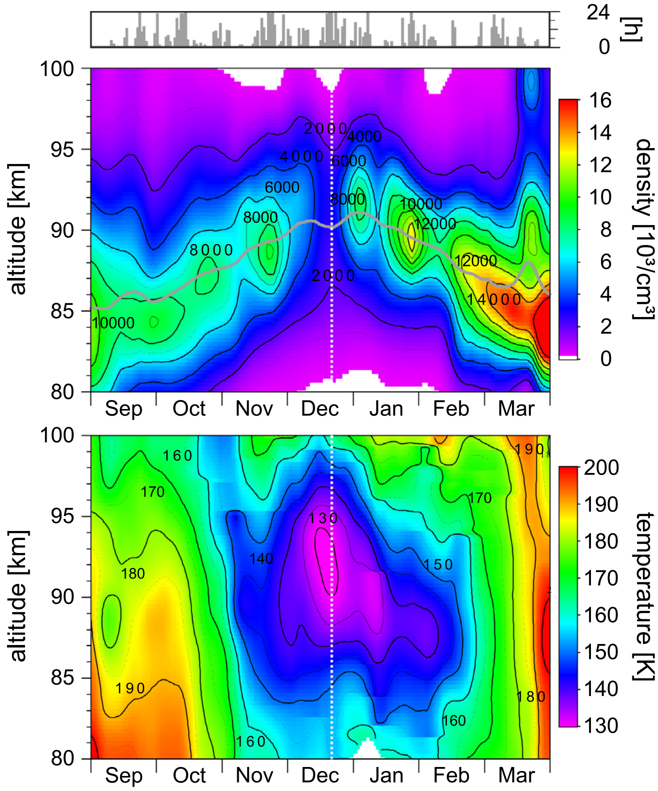

Fig. 1. Fe densities (upper panel) and temperatures (lower panel) September 2011 to March 2012. Lidar measurement periods are displayed as histogram for 0–24 h per day on the very top. The Fe layer's upper boundary and centroid altitude (grey line) are elevated around summer solstice (white dotted line). Very low densities around solstice coincide with very low temperatures.