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First in situ temperature measurements at the Antarctic summer mesopause

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Abstract. The Arctic summer mesopause at ~88 km is the coldest-known place (~130 K) in the terrestrial atmosphere and is ~60 K colder in summer than winter. Indirect evidence has suggested that the summer mesopause temperatures in the Antarctic are a few Kelvin warmer than in the Arctic. However, reliable measurements have not been available at southern high latitudes to verify this. We report the very first *in situ* temperature observations in the summer mesosphere from Antarctica based on rocket-borne falling spheres launched from Rothera (68°S, 68°W). The first of 24 successful launches, on 5 January 1998, showed a mesopause temperature of 129 K at 87 km, surprisingly close to northern hemisphere (NH) mean summer values. During January the mesospheric temperatures are similar to the northern summer, but the difference increases to several Kelvin in February.

Introduction

In summer, the temperature at the northern polar mesopause around 88 km altitude decreases by more than 60 K from its winter value to reach ~130 K, making it the lowest temperature on our planet [*Theon et al.*, 1967; *Lübken and von Zahn*, 1991]. These very low temperatures result in an optical phenomenon called 'noctilucent clouds' (NLC) which is observed from the ground since more than 100 years [*Gadsden and Schröder*, 1989]. The thermal structure in the high latitude summer mesosphere (HLSM) is contrary to first expectations considering that the atmosphere north of the polar circle is continually sunlit in mid summer, whereas sunlight is totally absent in mid winter. Modelling studies have suggested that adiabatic cooling and warming associated with vertical movements induced by dynamical processes such as gravity waves are the key parameters for the dramatic deviation of the thermal structure from radiative equilibrium [*Garcia*, 1989].

Even basic physical properties of this region, such as the variation of the thermal structure with altitude and with season, are not fully understood in terms of fundamental physical and chemical processes. A sensitive test of our understanding of the physical mechanisms is a comparison between the summer season at northern and southern polar latitudes. While the summer polar mesopause temperature profile has been measured in the NH for more than 3 decades, there have been no reliable measurements in the SH. Indirect evidence has suggested that the Antarctic summer mesopause is a few Kelvin warmer than its northern counterpart.

A hemispheric temperature difference is possible if gravity wave sources in the troposphere are weaker at southern latitudes (there is some speculation in the literature about smaller gravity wave excitation in the south due to different orography, however, no conclusive measurements are available yet). It would then be expected that summer mesosphere temperatures at austral latitudes should be larger, i.e., closer to radiative equilibrium, due to less dynamically-induced cooling. This speculation was supported both by the observation that polar mesosphere summer echoes (PMSE) detected by ground-based radar are absent, or at least much weaker, at southern polar latitudes [*Balsley et al.*, 1995; *Huaman and Balsley*, 1999] and by the reduced albedo of polar mesospheric cloud (PMC) observed by satellite over the southern pole compared to that over the northern pole [*Thomas et al.*, 1989].

From the observational point of view, rocket-borne techniques carrying *in situ* instrumentation provide, up until now, the most important method to explore the thermal structure of the mesosphere in summer at high latitudes because ground- and satellite-based optical measurements have difficulty providing reliable data since sunlit conditions prevail. In this paper we present the very first *in situ* measurements of the thermal structure in the Antarctic mesosphere which we performed in January and February 1998.

Experimental Method and Rocket Launches

Temperatures are deduced from *in situ* measurements of densities by the 'falling sphere' technique [*Schmidlin et al.*, 1991; *Lübken et al.*, 1994]. A small rocket transports a sphere, made of metalized mylar, to an altitude of typically 110 km altitude. After it is released the sphere inflates to 1-m diameter and passively falls through the atmosphere whereby it decelerates. A high-precision radar tracks the descent trajectory which is then used in the equations of motion to determine atmospheric density and horizontal winds. Temperatures are obtained by integrating the density profile assuming hydrostatic equilibrium. The height-dependent sphere reaction time-constant causes a smoothing of the density, temperature, and wind profiles. The smallest scales detectable are typically 8, 3, and 0.8 km at 85, 60, and 40 km, respectively. The uncertainty of the tempera-

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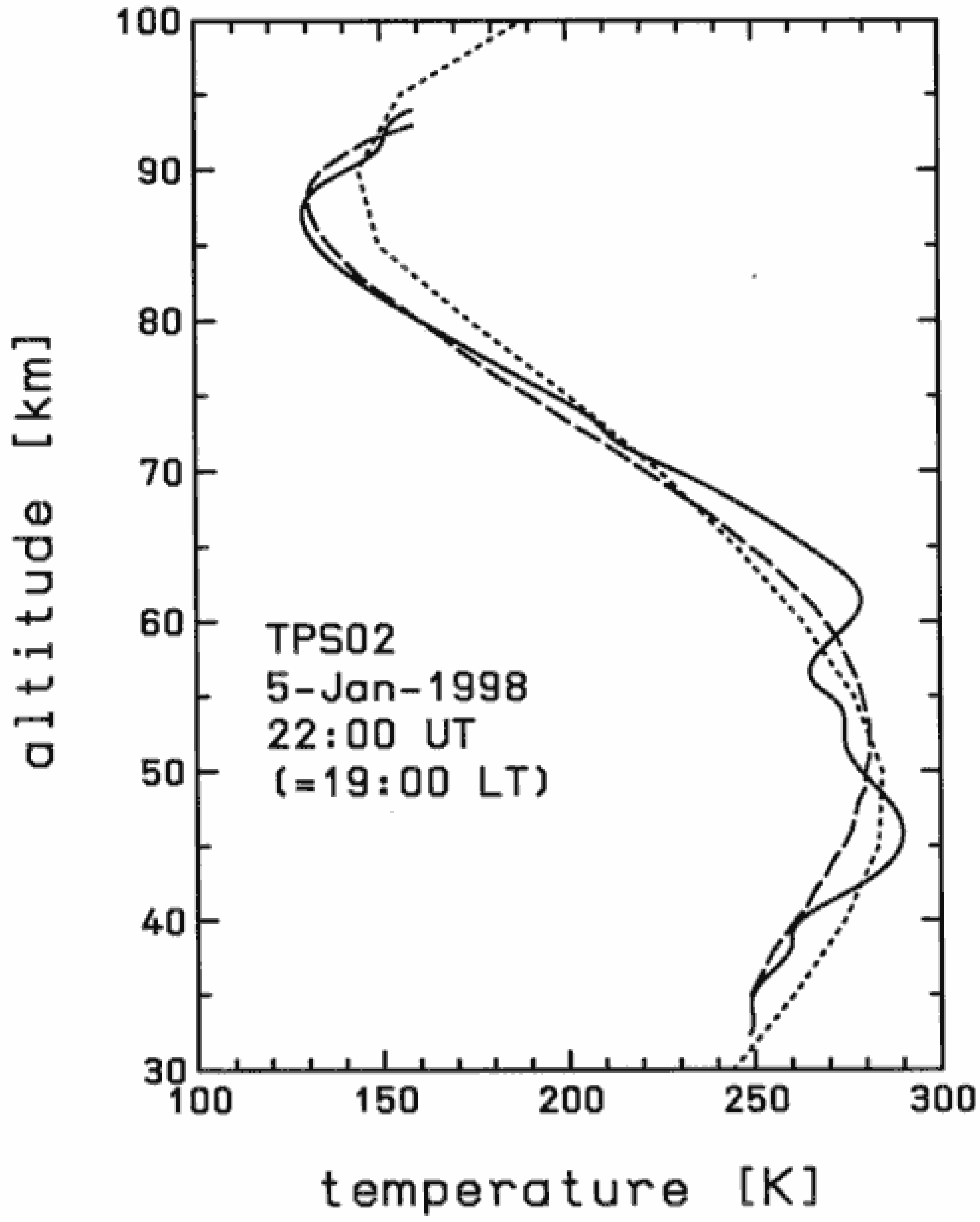

Figure 1. The very first temperature profile covering the entire mesosphere and the upper stratosphere obtained from *in situ* techniques at Antarctic latitudes (solid line). This falling sphere flight took place on January 5, 1998, at 19:10 UT. The northern hemisphere July profile (dashed line) from *Lübken* [1999], and the CIRA-1986 reference profile for 70°S, January, (dotted line) are shown for comparison.

ture data is typically 7, 3, and 1.5 K at 90, 80, and 70 km altitude, respectively [*Schmidlin et al.*, 1991].

A total of 26 meteorological rockets were launched from the British Antarctic Survey research station Rothera (67°34'S, 68°07'W) from January 4 to February 27, 1998. The spheres were successfully tracked in 24 out of 26 flights and atmospheric density, temperature, and horizontal wind profiles were derived. Most of the flights (17 out of 24) took place in the early afternoon (~16–19UT = 13–16LT), i.e. at fixed local time, in order to avoid tidal variations and to facilitate comparison with NH launches (nearly all flights in the NH were performed around noon or midnight ; see *Lübken*, 1999, for a discussion on the potential bias due to tides).

We first present the results and then compare them to falling sphere measurements performed at the Andøya Rocket Range in Northern Norway (69°N,16°E) which is located almost exactly at the colatitude of Rothera. We will also compare our results with the latest version of the COSPAR International Reference Atmosphere, CIRA-1986 [*Fleming et al.*, 1990], and the latest thermospheric model based on mass spectrometer and incoherent scatter data, MSIS [*Hedin*, 1991].

Results

The first successful launch in the campaign took place on January 5, 1998, at 22:00UT (19:00LT); the observed temperature profile is shown in Figure 1. As far as the upper mesosphere is concerned this is the first ever profile determined by in situ methods at Antarctic latitudes. The mesopause is located at 87 km and is as cold as 129 K. Contrary to expectations the temperatures in the upper mesosphere are not systematically larger than the Arctic summer mean. The second successful flight performed on January 8 gave a temperature profile which is even closer to the Arctic summer mean with differences typically smaller than ±(1–2) K.

A collection of all 11 flights performed in January is shown in Figure 2a. The mesopause is found between approximately 85 and 90 km with typical temperatures of 120–140 K. Except for the stratosphere and the uppermost mesosphere there is very little variability between the various profiles. The small 'bump' in temperatures at ~72 km is caused by an uncertainty in the sphere's drag coefficient when the sphere passes through Mach number 1. We will ignore the wavy structures below ~60 km since they may at least partly be caused by vertical winds acting on the sphere, but could also be a signature of temperature fluctuations due to gravity waves. We will instead concentrate on the upper mesosphere. One of the profiles (TPS06 launched on 14 January, 17:40 UT) shows comparatively large temperatures of ~185 K at ~91 km altitude. Since there is no obvious reason for this deviation in terms of launch time, sphere performance etc., we attribute this high value to natural variability. The RMS deviation from the mean profile is 16, 4.5, and 3.8 K at 90, 80, and 70 km, respectively.

A collection of all 13 flights performed in February is shown in Figure 2b. Compared to January the mean temperatures are higher in the upper mesosphere and the variability has increased. Most of the flights show temperatures above 130 K, except for flight TPS21 launched on February 17 at 13:34 UT where the mesopause is as cold as 114 K.

In order to demonstrate the seasonal variation of the thermal structure at typical NLC altitudes we have plotted in Figure 3 the temperatures at 82 km and a smoothed curve obtained from a polynomial fit to the data points. The mean temperature gradually increases with season from ~150 K in January up to more than 170 K at the end of February. The RMS variability of the data points around the smoothed curve is ~7 K.

The smoothing procedure demonstrated in Figure 3 was performed at all altitudes from 35 to 93 km at integer kilometers. This showed the mean summer mesopause to be located at approximately 88 km where the mean temperature is 133–135 K during January. Temperatures gradually increase with season and are larger than ~160 K in the entire stratosphere and mesosphere by the end of February. The stratopause is located at 50±3 km and is as warm as 270–285 K.

Discussion

Concentrating on the upper mesosphere, a comparison of the temperatures shown in Figures 1–3 with corresponding NH measurements [*Lübken*, 1999] shows no significant difference in January, but increasingly larger temperatures in the south as the season progresses. The smoothed fit of the mesopause temperature is only slightly warmer by 2–6 K in January compared to that of NH July, but this difference is smaller than the variabilities. At typical NLC and PMSE

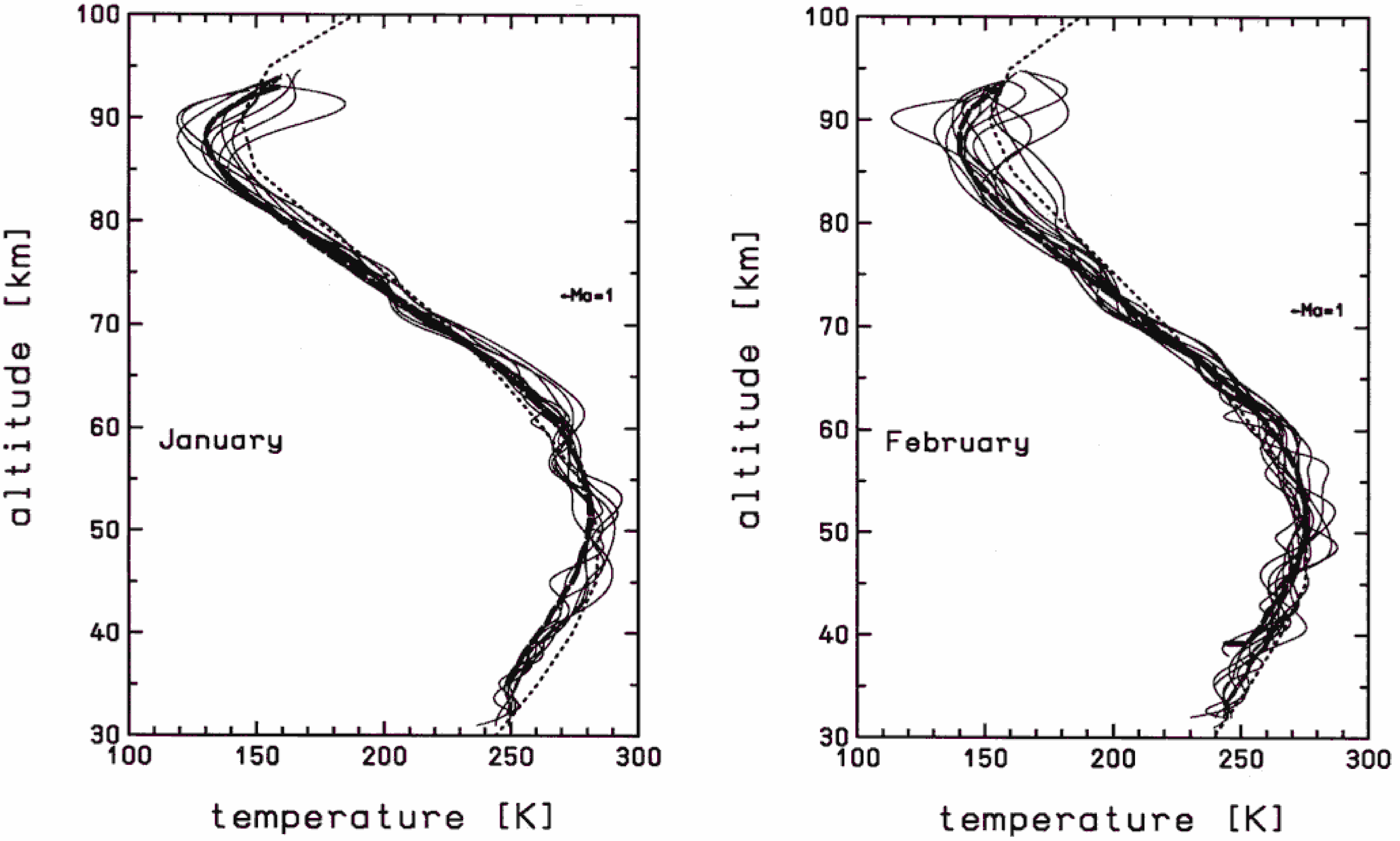

Figure 2. Temperature profiles obtained from Rothera from (a) 5–30 January 1998 (11 in total) and (b) 1–27 February 1998 (13 in total). The northern hemisphere July profile (dashed line) from *Lübken* [1999], and the CIRA-1986 reference profile for 70°S, January, (dotted line) are shown for comparison.

altitudes (82-85 km) the SH/NH difference of mean temperatures during January/July (Figure 3) is smaller than 2-3 K which is well within the RMS variabilities. However, at the end of February the southern upper mesosphere is warmer by approximately 7-8 K. Our temperatures are much lower by up to 15-20 K compared to the CIRA-1986 reference atmosphere, and also significantly lower compared to MSIS (see Figure 3). The difference to CIRA-1986 is practically independent of season, whereas the difference to MSIS is smaller at the beginning of January.

From models we expect typical water vapor mixing ratios of 1-4 ppmv [*Garcia*, 1989] which corresponds to frost-point temperatures T_f of 139-148 K in the 88–82 km altitude range. Since the actual mean temperatures are smaller than T_f ice particles can exist in the upper Antarctic mesosphere until approximately mid February. Indeed, PMSEs were observed during several of the FS flights in the beginning of February when a ship carrying a VHF radar was close to the Rothera station (R. Woodman, personal communication).

Considering individual profiles and assuming a water vapor mixing ratio of 1 ppmv independent of altitude we find $T<T_f$ in the 83-90 km height range in 12 out of 23 flights, 9/10 in January, and 3/13 in February (flight TPS10 on 23 January was not included in this statistics since it gave temperatures below ~80 km only). This suggests that the thermal structure at 68°S is indeed favorable for the existence of NLC and PMSE particles during January, but less so as the season progresses.

The obvious difference in PMSE and PMC occurrence has stimulated speculations about a north/south temperature difference in the HLSM [*Huaman and Balsley*, 1999]. Our results support model calculations which suggest that the hemispheric difference of PMC occurrence could be caused by a 3–5 K warmer mesopause [*Thomas et al.*, 1989]. On the other hand, the temperature variability at that altitude is much larger (11 K) than the model prediction (3.5 K). Detailed model calculations are necessary to find out whether

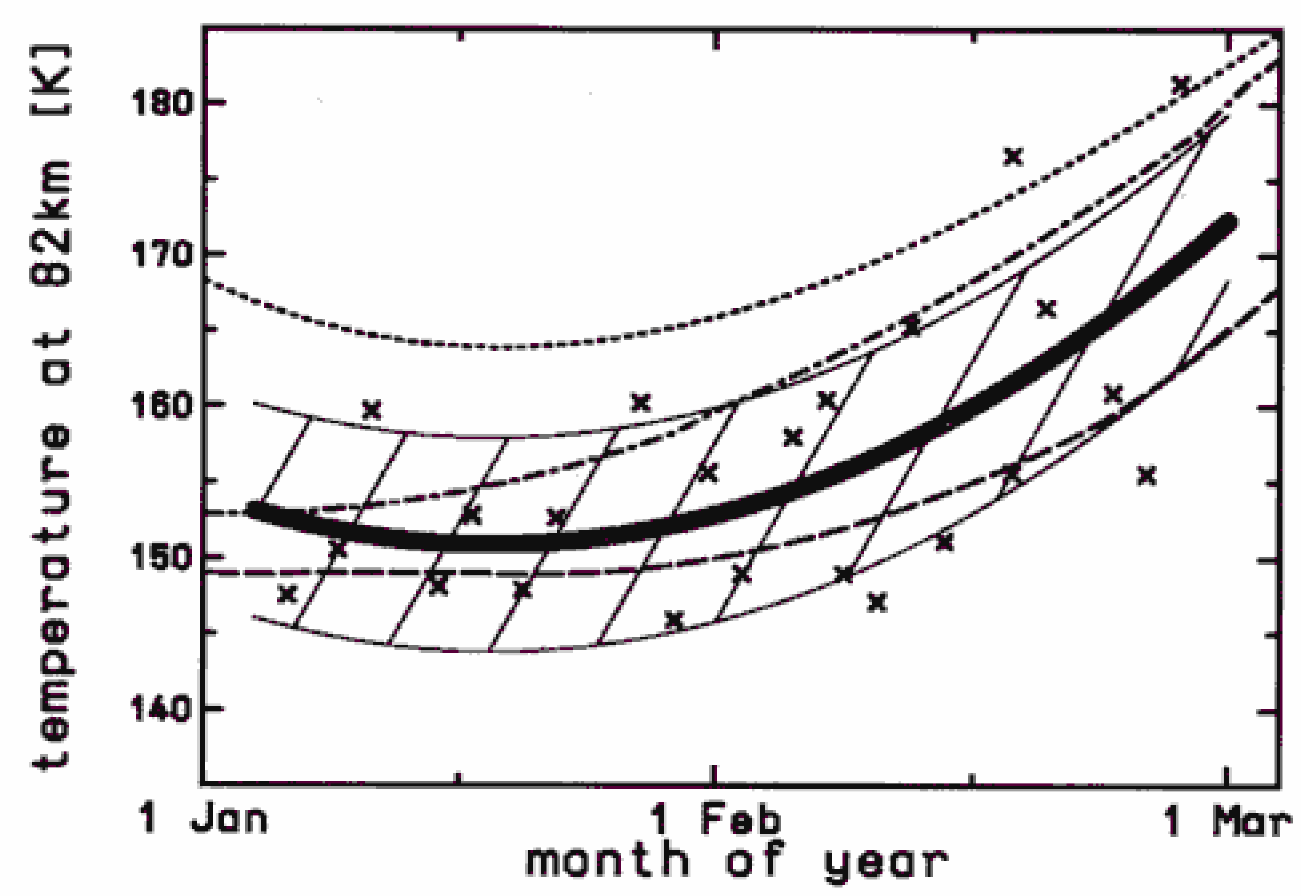

Figure 3. All individual temperature measurements from Rothera at an altitude of 82 km (crosses) and a polynomial fit of degree 2 through these points (thick solid line). The RMS deviation between the data and the fit is ~7 K (hatched range). For comparison the northern hemisphere mean FS profile (dashed line, from *Lübken*, 1999), the CIRA-1986 (dotted line) and the MSIS (dotted-dashed line) profiles for 70°S are shown.

the small north/south temperature difference is sufficient to explain the obvious north/south PMSE asymmetry or whether additional differences, for example in water vapor concentration, condensation nuclei abundance, and turbulence need to be assumed.

The close symmetry of the southern and northern thermal structure in the upper atmosphere during January/July implies that the main physical processes dominating the energy budget are similar. This is a surprising result considering the obvious difference in the land/ocean distribution which is expected to cause different gravity wave activity and different dynamical forcing in the upper atmosphere. Comparing the variability of our temperature profiles measured in January with those from the north (see Figure 7 in *Lübken*, 1999) there is no obvious indication of the effect of such a hemispheric difference in gravity wave activity.

We expect our experimental results to stimulate model calculations aimed at understanding the thermal structure in the summer upper mesosphere at Antarctic latitudes. Such models might also address the question as to whether a local tropospheric gravity wave source restricted to the Antarctic peninsula could determine the thermal structure above Rothera.

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