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14. ABSTRACT

The SABER instrument was launched onboard the TIMED satellite in December 2001. Vertical profiles of kinetic temperature (Tk) are derived from broadband measurements of CO_2 15 μm limb emission, in combination with measurements of CO_2 4.3 μm limb emission used to derive CO_2 volume mixing ratio (vmr). Infrared emission from the CO_2 ro-vibrational bands are in non-local thermodynamic equilibrium (non-LTE) in the mesosphere and lower thermosphere (MLT), requiring new radiation transfer and retrieval methods. In this paper we focus on Tk and show some of the first SABER observations of MLT Tk and compare SABER Tk profiles with rocket falling sphere (FS) measurements taken during the 2002 summer MaCWAVE campaign at Andoya, Norway (69°N, 16°E). The comparisons are very encouraging and demonstrate a significant advance in satellite remote sensing of MLT limb emission and the ability to retrieve Tk under extreme non-LTE conditions.

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SABER observations of mesospheric temperatures and comparisons with falling sphere measurements taken during the 2002 summer MaCWAVE campaign

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[1] The SABER instrument was launched onboard the TIMED satellite in December 2001. Vertical profiles of kinetic temperature (Tk) are derived from broadband measurements of CO_2 15 μm limb emission, in combination with measurements of CO_2 4.3 μm limb emission used to derive CO_2 volume mixing ratio (vmr). Infrared emission from the CO_2 ro-vibrational bands are in non-local thermodynamic equilibrium (non-LTE) in the mesosphere and lower thermosphere (MLT), requiring new radiation transfer and retrieval methods. In this paper we focus on Tk and show some of the first SABER observations of MLT Tk and compare SABER Tk profiles with rocket falling sphere (FS) measurements taken during the 2002 summer MaCWAVE campaign at Andøya, Norway (69°N, 16°E). The comparisons are very encouraging and demonstrate a significant advance in satellite remote sensing of MLT limb emission and the ability to retrieve Tk under extreme non-LTE conditions. *INDEX TERMS:* 0340 Atmospheric Composition and Structure: Middle atmosphere—composition and chemistry; 0350 Atmospheric Composition and Structure: Pressure, density, and temperature; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Mertens, C. J., et al. (2004), SABER observations of mesospheric temperatures and comparisons with falling sphere measurements taken during the 2002 summer MaCWAVE campaign, *Geophys. Res. Lett.*, *31*, L03105, doi:10.1029/2003GL018605.

1. Introduction

[2] The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment is one of four instruments launched on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite December 7, 2001 [*Russell et al.*, 1999]. SABER scans the horizon and observes limb emission in 10 broadband spectral channels ranging from 1.27 μm to 17 μm. The observed limb emission profiles are analyzed to provide vertical profiles of the key data products, with approximately 2 km vertical resolution. Specific to this paper, kinetic temperature (Tk) is retrieved from CO_2 15 μm limb emission measurements. During the daytime, measurements from the CO_2 15 μm and CO_2 4.3 μm channels are combined to retrieve Tk/CO_2 simultaneously.

[3] In this paper we focus only on SABER Tk in the mesosphere and lower thermosphere (MLT), with SABER-derived CO_2 profiles the subject of a future letter. Here we show some of the first MLT Tk results from the non-LTE retrieval algorithm. The ability to retrieve Tk in an extreme non-LTE environment is demonstrated by comparing SABER results with rocket falling sphere (FS) measurements taken during the 1–5 July 2002 summer MaCWAVE campaign at Andøya, Norway (69°N, 16°E). The polar summer thermal structure with its cold mesopause and steep temperature gradients, both below and above the mesopause, produce the largest non-LTE effects in the CO_2 15 μm emission [*López-Puertas et al.*, 1992; *Wintersteiner et al.*, 1992].

2. Data Analysis

[4] *Mertens et al.* [2001] presented a non-LTE Tk retrieval algorithm based on observations of CO_2 15 μm broadband limb emission measurements, assuming CO_2 abundance was known. Recently, this algorithm was expanded and updated to enable simultaneous non-LTE retrieval of Tk and CO_2 by combining measurements of CO_2 15 μm and CO_2 4.3 μm limb emission, respectively. This algorithm forms the basis of the operational algorithm that will process global fields of Tk and CO_2 abundance on a routine basis. The salient features of the coupled non-LTE Tk/CO_2 retrieval algorithm are outlined by *Mertens et al.* [2002]. This algorithm is used to analyze SABER radiance measurements and produce the Tk profiles presented in this paper.

[5] The SABER mesospheric Tk shown here are first-look, preliminary results. There are a number of additional atmospheric parameters required as input into the non-LTE CO_2 model used in the retrieval algorithm: O_2, N_2, $O(^3P)$, and $O(^1D)$. These parameters were obtained from a TIME-GCM model climatology [*Roble*, 1995]. During daytime scans, Tk and CO_2 are both retrieved; at night, Tk is retrieved using CO_2 profiles from the TIME-GCM clima-

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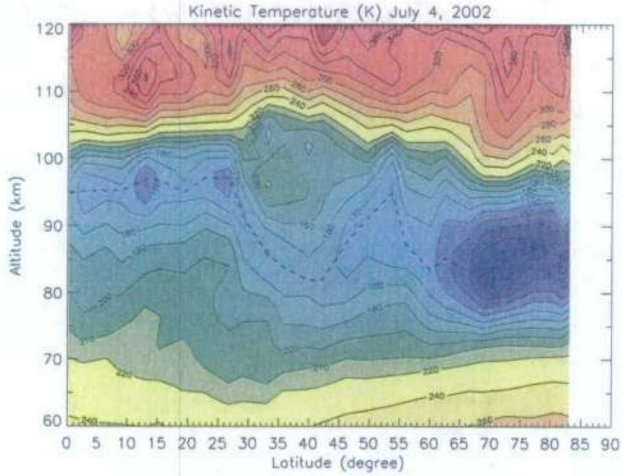

Figure 1. Latitude-altitude cross section of SABER temperatures (K) derived from the coupled non-LTE Tk/CO_2 retrieval algorithm on 4 July, 2002, from 15:48 UT to 16:14 UT (orbit 3094, daytime scans 25–51). The mesopause height is indicated by the dashed line.

tology. Version 1.02 SABER radiance data are used. In future updates, $O(^1D)$ and $O(^3P)$ will be derived from SABER 1.27 μm channel radiances in concert with retrieved O_3 and the $O_2(^1\Delta)$ model of *Mlynczak et al.* [1993]. In addition, CO_2 profiles retrieved during the day will be mapped and used in the nighttime Tk retrievals. Even though updates to SABER temperatures will occur in the future, the results below clearly demonstrate the overall quality of the CO_2 channel radiances and the accuracy of the non-LTE retrieval algorithm.

[6] The NASA 2002 summer Mountain and Convective Wave Ascending Vertically (MaCWAVE) campaign coordinated measurements of middle atmospheric temperature and winds from FS measurements at the Andøya rocket range (69°N, 16°E), and ion gauge measurements (CONE) and the network of ground-based lidars and radars from the ALOMAR observatory. In this paper we compare SABER mesospheric Tk with the MaCWAVE FS measurements [*Schmidlin et al.*, 1991]. The broader objective of Tk validation is ongoing and will include comparisons with many ground-based and in-situ measurements taken at various locations and seasons.

[7] The FS is a 1-meter diameter mylar balloon deployed near 115 km. After deployment the sphere is inflated and its trajectory is tracked by high precision radar. Position information and the sphere's drag coefficient are used to solve the equations of motion and calculate density and wind. Initial processing of the position data occurs at about 103–105 km. Calculation of ambient Tk requires (1) the sphere to experience deceleration and (2) the assumption of an initial Tk. This scenario is nominally reached at an altitude of z(o) which falls between 93 and 95 km. The calculated Tk converges to the true atmospheric Tk within one to two scale heights below z(o). Accuracy of the derived Tk is approximately 8–12 K at 90 km, 5–8 K at 85 km, and 1–3 K at 70 km. Vertical resolution is roughly between 2–5 km below 80 km, approaching 5–10 km near 80 km, and increasing to 10–12 km above 80 km.

3. Results and Discussion

[8] Figure 1 shows a slice of the global Tk field, composed of 26 scans during orbit 3094, on 4 July, 2002. One of the most striking features in Figure 1 is evidence of the worldwide two-level character of the mesopause altitude, a surprising and unexpected concept supported both by long-term ground-based measurements [*von Zahn et al.*, 1996; *She and von Zahn*, 1998; and references therein] and model simulations [*Berger and von Zahn*, 1999]. The two-level structure of the mesopause is characterized by two modes, or most likely values, for the global distribution of mesopause altitudes: a winter (or upper) altitude of 100 ± 3 km and a summer (or lower) altitude of 86 ± 3 km. During their field mission from late April to early July 1996, *von Zahn et al.* [1996] found that the winter (upper) mesopause height extended from the southern hemisphere to 23°N. Figure 1 shows a similar feature in the SABER data. The mesopause height is 96 ± 1 km from 0 to 27°N. The winter to summer transition occurs between 27°N and 36°N with a mesopause height of 91 km and 86 km in the transition region at 29°N and 33°N, respectively. The mesopause altitude between 36°N and 83°N is 86 ± 3 km, consistent with previous mid-latitude observations referenced above. The two-level mesopause structure is not observed in the corresponding LTE Tk of Figure 1 (not shown).

[9] The ability to derive accurate mesospheric Tk from limb emission measurements for polar summer conditions is one of the most stringent tests of the non-LTE retrieval algorithm. On 2 and 4 July 2002, FS measurements made during the MaCWAVE campaign were timed to coincide with SABER overpasses and provide validation data for the non-LTE algorithm. In Figure 2 we show comparisons of

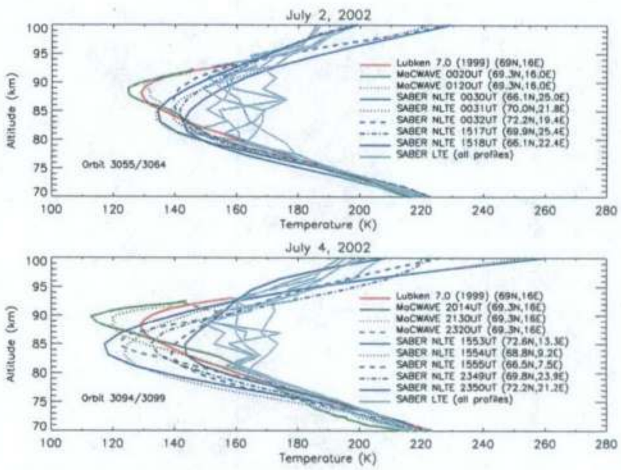

Figure 2. Comparison of SABER-FS temperature profiles. Also shown is the Lübken climatological profile for early July. Green lines are the FS profiles; dark blue lines are SABER Tk profiles from the non-LTE retrieval algorithm; light blue lines are SABER Tk profiles from the LTE retrieval algorithm; and the red line is the climatological profile.

Table 1. Uncertainties in SABER-Retrieved Kinetic Temperature (K) at 79 km and at the Mesopause Altitude for the 4 July, 2002 MaCWAVE Coincidence Scans Due to Key Non-LTE Input Parameters: CO_2 Concentration ([CO_2]), Atomic Oxygen Concentration ([O]), and the Rate of $CO_2(\nu_2)$ State Quenching by Atomic Oxygen (k_o)

	Retrieval Uncertainty (K): July 4, 2002					
	[CO_2][a]		[O](+50%)[b]		k_o[c]	
(Lat/Lon)	79 km	Z(Tmin)[d]	79 km	Z(Tmin)[d]	79 km	Z(Tmin)[d]
(72.6N/13.2E)	2	6	0	3	−2	−5
(68.8N,09.2E)	4	6	0	4	−8	−10
(66.5N,07.5E)	2	4	−5	−8	−5	−11
(69.8N,23.9E)	2	3	0	−4	−5	−5
(72.2N,21.2E)	5	9	1	6	0	0

[a]Perturb nominal CO_2 vmr profiles by decreasing CO_2 1%/km up to 17%, starting at 70 km.
[b]Perturb nominal atomic oxygen vmr profiles by +50%.
[c]Nominal rate: *Sharma and Wintersteiner* [1990]. Retrieved using 0.25*nominal rate.
[d]Temperature uncertainty at the mesopause altitude.

SABER-FS Tk profiles. All SABER overpasses within approximately ±5° of 69°N and 16°E are shown on these two days. Also shown is the Tk profile from the weekly climatology of *Lübken* [1999] for early July. SABER Tk profiles are generally in quite good agreement with the FS measurements below about 85 km and are always substantially in better agreement than the corresponding LTE Tk profiles in the mesopause region. The differences between LTE and non-LTE mesopause temperatures range from ~15–37 K on 2 July and from ~36–46 K on 4 July. This fact underscores the major objective of this letter: the first-look SABER mesospheric Tk results demonstrate an advance in satellite remote sensing of mesospheric limb emission, the knowledge of CO_2 non-LTE processes, and the ability to retrieve Tk under extreme non-LTE conditions.

[10] Detailed SABER-FS Tk comparisons for the closest time coincidences on 2 July are in excellent agreement at 85 km and below. FS Tk at 00:20 UT are 154 K and 138 K at 80 km and 85 km, respectively. At these same altitudes, SABER Tk at 00:31 UT are 152 K and 139 K, respectively, with differences no more than 2 K between the two profiles. SABER-FS Tk differences with respect to the FS 00:20 UT profile at 80 km and 85 km are no more than 2 K for the SABER 00:32 UT profile and no more than 6 K for the SABER 00:30 UT profile. These differences are well within the measurement uncertainty (see previous section for FS Tk uncertainty and Table 1 for SABER Tk uncertainty).

[11] Above 85 km SABER Tk profiles are significantly different than the FS Tk profiles. The Tk differences between the three SABER profiles centered around 00:31 UT and the FS profile at 00:20 UT are between 15 K and 30 K at 90 km. Furthermore, the mesopause altitude for the FS profile at 00:20 UT is 88 km, corresponding to the mesopause altitude of the climatological profile, while the SABER mesopause altitudes are 83 km, 85 km, and 87 km at 00:30 UT, 00:31 UT, and 00:32 UT, respectively.

[12] SABER-FS Tk differences for the closest time coincidences on 4 July are in excellent agreement at 80 km and below, but are substantially larger at 85 km as compared to the 2 July coincidence comparisons. At 80 km the FS Tk is 155 K at 23:20 UT. SABER Tk at 80 km are 150 K and 156 K at 23:49 UT and 23:50 UT, respectively. These differences are no more than 5 K and are within measurement uncertainty. However, at 85 km the SABER-FS Tk differences are between 10 K and 20 K, which is outside the measurement uncertainty. The FS Tk at 85 km is 123 K at 23:20 UT, while the SABER Tk profiles at 85 km are 132 K and 144 K at 23:49 UT and 23:50 UT, respectively. In contrast to the 2 July coincidence comparisons, however, both SABER and FS measurements agree on a 85 km mesopause altitude for the 4 July closest time coincidence comparison.

[13] We assessed the impact of uncertainty in the key non-LTE input parameters on SABER-retrieved Tk. We focused on the 4 July scans. Table 1 summarizes this sensitivity study. Clearly, these uncertainties cannot explain the SABER-FS Tk differences in the upper mesosphere. Nor do these uncertainties significantly alter the location of the mesopause. We have not, at this point, included the impact of horizontal Tk gradients, which seem quite large at high latitudes from Figure 1. Moreover, there may be biases in the SABER radiances that we do not fully understand yet.

[14] The SABER-FS Tk profile differences in Figure 2 fall into two categories: (1) difference in Tk (magnitude), and (2) difference in mesopause altitude. At this time measurement uncertainty doesn't appear to explain these differences. However, SABER and FS data indicate a highly variable mesosphere in both time and space, complicating single profile comparisons above about 80 km. Moreover, the vertical resolution of the FS measurements above 80 km,

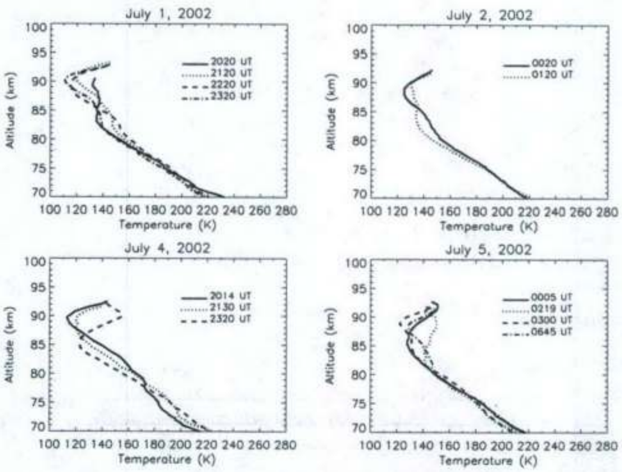

Figure 3. All FS measurements during summer MaCWAVE with rocket apogee sufficient to derive Tk above the mesopause.

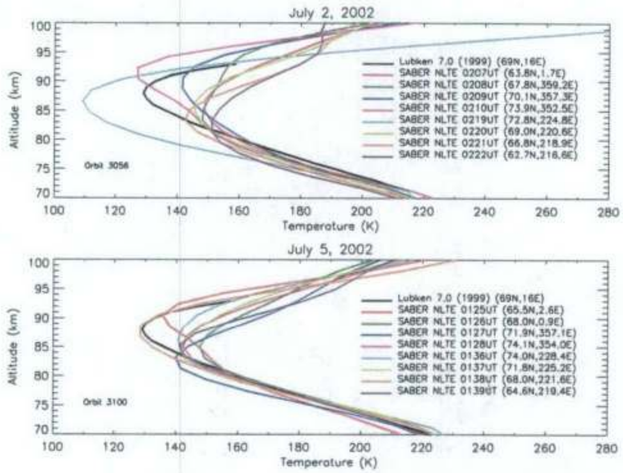

Figure 4. SABER Tk profiles in the latitude band between 63–74°N for the orbits just after the orbits of closest time coincidence shown in Figure 2.

where the natural variability of the thermal structure becomes increasingly large, is on the order of 10–12 km, roughly a factor of 5–6 less than the SABER measurements. Satellite versus in-situ or ground-based measurements are further complicated by the fact that the satellite tangent measurement is averaged over a 300 km horizontal path along the limb line-of-sight.

[15] Figure 3 shows all the FS measurements taken from 1 July through 5 July with rocket apogees sufficient to derive Tk profiles above the mesopause. The FS profiles show large variability above 80 km over time scales on the order of 3 hours. The variability occurs in both Tk (magnitude) and the mesopause altitude. For example, the mesopause Tk ranges from 111 K to 141 K, and the mesopause altitude ranges from 82 km to 90 km.

[16] Time variability in FS Tk profiles suggests that spacial variability in Tk must be present. This is evident in the SABER data in Figure 1 which shows wave-like fluctuations in the mesopause altitude about the winter and summer climatological means. For example, the mesopause altitude is 87 km at 56°N, 83 km at 69°N, and returns to 87 km at 77°N. Time and spacial variability in the SABER mesospheric Tk data is further illustrated in Figure 4. This shows Tk profiles in the 63-74° latitude band for the orbit just after the orbit of closest time coincidence on 2 and 4 July shown in Figure 2. On 2 July the mesopause Tk varies from 109 K to 151 K, and the mesopause altitude varies from 81 km to 92 km. On 5 July the mesopause Tk varies from 128 K to 150 K and the mesopause altitude varies from 83 km to 89 km.

4. Summary

[17] We have shown first-look SABER mesospheric Tk in early July from the equator to high latitudes in the northern hemisphere. The SABER Tk were derived from a coupled non-LTE Tk/CO_2 retrieval algorithm. SABER results corroborate the proposed worldwide two-level character of the mesopause altitude. SABER-FS Tk comparisons are in excellent agreement at 80 km and below and up to 85 km in some cases. Large SABER-FS Tk differences in single profile comparisons above 80 km are likely attributed to the highly variable state of the upper mesospheric thermal structure, combined with the factor of 5–6 less vertical resolution in the FS measurements relative to the SABER measurements in the region of high thermal variability (i.e., above 80 km), and the difficulty of obtaining exact time and air volume sampling between satellite and in-situ (and ground-based) measurements. More processing of SABER non-LTE Tk data is required to diagnose any systematic differences in the climatological state of the upper mesospheric thermal structure between SABER and correlative measurements. On the other hand, the SABER-FS comparisons clearly demonstrate an improvement in limb emission satellite remote sensing of the MLT region. That is, on average, the non-LTE retrieval algorithm improves retrieved Tk over LTE results by roughly 35 K in the mesopause region under polar summer conditions. Moreover, the two-level mesopause structure is not observed in the retrieved LTE Tk. The demonstrated quality of SABER CO_2 radiance measurements combined with the ability to retrieve Tk under non-LTE conditions bolsters confidence in SABER's potential to contribute to our understanding of the many intriguing and unanswered questions concerning the thermal structure of the MLT, as well as the energetics and dynamics of that region.

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