Intercomparisons of Stratospheric Water Vapor Sensors: FLASH-B and NOAA/CMDL Frost-Point Hygrometer

H. VÖMEL

Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado

V. YUSHKOV, S. KHAYKIN, AND L. KORSHUNOV

Central Aerological Observatory, Dolgoprudny, Russia

E. KYRÖ AND R. KIVI

Finnish Meteorological Institute, Sodankylä, Finland

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ABSTRACT

Studies of global climate rely critically on accurate water vapor measurements. In this paper, a comparison of the NOAA/Climate Monitoring and Diagnostics Laboratory (CMDL) frost-point hygrometer and the Fluorescent Advanced Stratospheric Hygrometer for Balloon (FLASH-B) Lyman-alpha hygrometer is reported. Both instruments were part of a small balloon payload that was launched multiple times at Sodankylä, Finland. The comparison shows agreement well within the instrumental uncertainties between both sensors in the Arctic stratospheric vortex. The mean deviation between both instruments in the range between 15 and 25 km is −2.4% ± 3.1% (one standard deviation). The comparison identified some instrumental issues, such as a low mirror-temperature calibration correction for the NOAA/CMDL frost-point hygrometer as well as a time lag. It was found that the FLASH-B hygrometer measures water vapor reliably above 7 km in the polar atmosphere. Comparisons in the upper troposphere are affected by the gain change of the NOAA/CMDL hygrometer, causing a lag and a wet bias in the tropospheric low gain setting under the dry conditions in the upper troposphere.

1. Introduction

Upper-tropospheric and stratospheric water vapor plays an important role in the global climate system, yet there are few measurements of this trace gas in this altitude region. Global measurements can be obtained from satellite sensors but require in situ measurements for validation and often have limited vertical resolution, which is insufficient for process studies within the tropopause region.

Only a few instruments are capable of providing reliable in situ observations in this altitude region. These are deployed either on board high-flying aircraft [National Aeronautics and Space Administration (NASA) ER-2, NASA WB-57, or the Russian M-55 Geophysica] or on board high-altitude balloons. Despite careful calibration and instrument preparation, not all in situ sensors give the same results, and differences up to about 30% have been observed in comparison measurements (Kley et al. 2000). Which instrument to rely on is, therefore, a serious issue for climate studies as well as for validation purposes. Laboratory studies have so far been unable to resolve these differences, and relying on in situ intercomparisons of different sensors has so far been the only way to address this problem. The only in situ comparison between the balloon-borne Fast In Situ Stratospheric Hygrometer (FISH) Lyman-alpha hygrometer and the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL) frost-point hygrometer has shown excellent agreement between these two instruments (Schiller et al. 2002). However, the comparison between the Harvard Lyman-alpha hygrometer and

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Corresponding author address: Holger Vömel, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Campus Box 216, Boulder, CO 80309.
E-mail: holger.voemel@colorado.edu

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the NOAA/CMDL frost-point hygrometer has shown significant differences (Kley et al. 2000).

This paper focuses on the comparison between the Fluorescent Advanced Stratospheric Hygrometer for Balloon (FLASH-B) Lyman-alpha instrument and the NOAA/CMDL frost-point hygrometer, which are the only two lightweight balloon-borne instruments for stratospheric water vapor that have obtained sizeable observations in the past. The NOAA/CMDL frost-point hygrometer in particular has been flown since 1980 at Boulder, Colorado, and is the instrument with the longest record of stratospheric water vapor observations.

The data presented in this paper are a result of the Lapland Atmosphere–Biosphere Facility (LAPBIAT) Upper Troposphere Lower Stratosphere (LAUTLOS) Water Vapor Validation Project, which took place in January and February 2004 (http://fmiarc.fmi.fi/LAUTLOS_web/index_lautlos.html). During a 4-week period, balloons were launched 2 times per day, carrying up to five different radiosonde and water vapor sensors up to an altitude of around 25–26 km. Here we focus on the two main stratospheric instruments that participated in this experiment, the NOAA/CMDL frost-point hygrometer and the FLASH-B Lyman-alpha hygrometer. This paper discusses the level of agreement between the two instruments, the performance characteristics, and instrument-specific considerations that were identified in this experiment.

2. Instrumentation

a. The NOAA/CMDL hygrometer

The NOAA/CMDL frost-point hygrometer (Oltmans 1985; Vömel et al. 1995) is a chilled-mirror hygrometer that uses cryogenic cooling. It measures the temperature of a mirror, which is controlled to maintain a small and constant layer of frost coverage. Under these conditions the mirror temperature equals the frost-point temperature of the air passing through the sensor. The mirror temperature is measured by an individually calibrated thermistor embedded in the mirror disk. It is then used in a vapor pressure equation (Goff and Gratch 1946) to calculate the partial pressure of water vapor in the air. The instrument therefore indirectly measures the partial pressure of water vapor.

The frost or dew coverage on the mirror is detected by a phototransistor, which senses infrared light emitted by a light-emitting diode and reflected off the mirror. A feedback controller uses the photodiode signal to control the heater and maintain the mirror temperature at the ambient frost-point temperature. The feedback controller implemented in the NOAA/CMDL frost-point hygrometer is a simple proportional controller. It uses the deviation from the frost-coverage set point to drive the heater, which regulates the mirror temperature above the cryogen temperature. The heater current is proportional to the error signal, and the proportionality constant is called the feedback gain factor. A proportional controller has the advantage that it is easy to implement; however, the response characteristics limit this instrument to mid- to upper-tropospheric and stratospheric measurements. The water vapor partial pressure changes by about five orders of magnitude between the surface and the middle stratosphere. Because of this large range of values, a single gain factor is not sufficient to achieve stable control over the entire troposphere and in the stratosphere. The NOAA/CMDL frost-point hygrometer uses two different feedback gain values: a lower setting, which allows the instrument to measure tropospheric water vapor, and a higher setting, better suited for stratospheric measurements. The change from low to high gain is controlled by a pressure switch. During LAUTLOS the gain change occurred typically between 200 and 150 hPa, that is, generally in the lowermost stratosphere. This gain change caused some data loss in this region, which will be discussed later. In some cases the low gain setting was not appropriate for measurements in the lower troposphere, leading to extreme oscillations of the mirror temperature, since the feedback controller was unable to maintain a constant frost layer. Measurements made while the controller was unstable or during the period of gain change are flagged and ignored in the data analysis.

The controller stability is the largest source of uncertainty in frost-point measurements. The combined uncertainty of controller stability, mirror-temperature measurement, and electronic uncertainties amount to 0.5°C in frost-point measurement, which corresponds to about 10% of the measured mixing ratio in the polar stratosphere and upper troposphere (Vömel et al. 1995).

The NOAA/CMDL hygrometer is interfaced with the EnSci electrochemical concentration cell (ECC) ozonesonde, which uses a Vaisala RS80 radiosonde for data transmission and for the simultaneous measurement of pressure, temperature, and humidity. During LAUTLOS this instrument combination was installed in the center of the balloon payload with the stainless steel sampling tubes extending beyond the top and bottom of the instrument. Contamination through outgassing of water vapor from the balloon material and load line was significant and led to unreasonably high water vapor measurements by the trailing water vapor instruments on ascent. The descent observations by the now leading instruments are free of contamination.

b. FLASH-B

The FLASH-B instrument was developed at the Central Aerological Observatory, Russia, for balloon-borne water vapor observations in the upper troposphere and stratosphere (Yushkov et al. 1998, 2000). The instrument is based on the fluorescent method (Kley and Stone 1978; Bertaux and Dellanoy 1978), which uses the photodissociation of water vapor (H_2O) molecules at a wavelength $\lambda < 137$ nm, followed by the detection of the fluorescence of excited OH radicals. The source of Lyman-alpha radiation ($\lambda = 121.6$ nm) is a hydrogen glow-discharge lamp, while the detector of the OH fluorescence at 308–316 nm is a Hamamatsu R647-P photomultiplier run in photon-counting mode. The fluorescence spectral region is selected using a narrowband interference filter. The intensity of the fluorescent light detected by the photomultiplier is directly proportional to the water vapor mixing ratio under stratospheric conditions (30–150 hPa) with a small oxygen absorption (3% at 50 hPa).

The precursor of the FLASH-B instrument, the optical hygrometer (Khaplanov et al. 1992), designed for use on board both stratospheric balloons and rockets, had a weight of about 5 kg. It participated in the European Arctic Stratospheric Ozone Experiment (EASOE) field campaign in 1991/92 (Khattatov et al. 1994) as well as in an Arctic balloon field campaign in Russia.

The modified version of the optical hygrometer, named FLASH-B, has a significantly smaller size and lower weight. It was successfully used for water vapor measurements on board long- and short-duration balloons (Yushkov et al. 2001). Based on this experience, the recent version of the FLASH-B instrument has been developed for regular balloon soundings and was directly interfaced with a Vaisala RS-80 radiosonde.

The instrument uses the open layout described by Khaplanov et al. (1992), in which the optics unit looks directly into the outside air. This arrangement is suitable only for nighttime measurements with a solar zenith angle larger than 98°, at which sunlight no longer reaches the detector. The coaxial optical layout allows reducing the size of the instrument to 106 mm × 156 mm × 242 mm with a total weight of 0.980 kg, including batteries.

The accuracy of the FLASH-B instrument is determined by the calibration error, estimated as 4% in the range between 3 and 100 ppmv. The measurement precision is 5.5%, calculated for a 4-s integration time at stratospheric conditions. The total uncertainty of the measurement is less than 10% at stratospheric mixing ratios greater than 3 ppmv, increasing to about 20% at mixing ratios less than 3 ppmv.

The source of vacuum UV (VUV) radiation used in the FLASH-B instrument is a hydrogen glow-discharge lamp filled with a mixture of hydrogen and helium to a pressure of 10 hPa. Unlike the more sophisticated hygrometers based on the fluorescence technique, the FLASH-B does not use a VUV photon flux control. The hydrogen glow-discharge lamps used in the FLASH-B instrument have been shown to have a very stable Lyman-alpha emission intensity over both operation and storage time. Every lamp is subjected to rigorous laboratory tests for stability of the emission intensity, which is checked before every sounding. VUV light sources containing a mixture of hydrogen and helium are known to have stray helium line emissions, which may override the spectrum of the hydroxyl fluorescence and may cause spurious signals from the backscattering of this emission. The FLASH-B instrument uses a hydrogen lamp in which the 270–320-nm emission is suppressed using a special window filter. This window filter is made using monocrystalline magnesium fluoride with an absorbing layer vacuum-deposited on its inner surface. In this way, up to 50% transmission at the 121.6-nm line and selective absorption at 300 nm are achieved at the same time. In addition, the instrument uses a narrowband interference filter centered at 310 nm with 8-nm bandwidth and an out-of-band extinction of 10^{-5}, thus reducing the possible effect of the stray light backscattering.

The background signal in the absence of fluorescence light is detected using a lamp modulation with a 1-kHz square wave, 1/16 duty cycle, and synchronous demodulation of the received signal. The background signal is detected while the lamp is off and then subtracted from the fluorescence signal.

The FLASH-B hygrometer is not an absolute instrument for water vapor measurements. Every hygrometer has to be calibrated in the laboratory before flight. Laboratory studies have shown that the calibration coefficients do not change over time. The lamp intensity, which influences the calibration most strongly, is checked directly before every sounding.

A laboratory facility capable of simulating atmospheric conditions is used for the calibration. In particular, the large range of water vapor mixing ratios (1–1000 ppmv), pressure (1000–3 hPa), and temperature (down to 190 K) can be generated by the calibration setup.

The calibration procedure is performed as follows: after purging the system with dry air for 1–2 h, the airflow boosted by a compressor is dried passing a silica

TABLE 1. Listing of all soundings used in this evaluation.

Date	Time (UTC)	FLASH No.	NOAA No.	Comment
29 Jan 2004	1730:10	9498	0231	Questionable NOAA performance
30 Jan 2004	1635:07	1001	0109	Good NOAA and FLASH data
6 Feb 2004	1955:47	0491	0231	Good NOAA data up to 17 km
11 Feb 2004	1734:54	2050	0230	Good NOAA and FLASH data
16 Feb 2004	1757:24	1958	0210	Good NOAA and FLASH data
17 Feb 2004	1745:03	1868	0228	Good NOAA and FLASH data
18 Feb 2004	1744:27	2130	0229	Good NOAA and FLASH data
23 Feb 2004	1746:57	2007	0230	NOAA battery failure
24 Feb 2004	1735:00	2050	0229	Good NOAA and FLASH data
26 Feb 2004	1744:31	2050	0210	FLASH failure

gel dehumidifier and then divided into two branches, one of which is moistened in an H_2O bubbler. The airflows of both branches are mixed together via two flow controllers, producing variable H_2O mixing ratios.

The mixed airflow is then divided, with one branch flowing through a commercial reference dewpoint hygrometer (MBW 373L) to determine the H_2O mixing ratio, and the other branch entering a stainless steel chamber, which has been cooled down to 210 K in a low-temperature freezer. The fluorescence hygrometer is flanged to the chamber via vacuum caulking. The pressure in the chamber is reduced using a vacuum pump to 50 hPa. A calibration run starts at the lowest H_2O mixing ratio and increases the H_2O mixing ratio in steps. Every calibration level is measured for about 15 min.

The calibration fit function is linear in the pressure range 30–150 hPa and water vapor mixing range 1–300 ppmv. At higher pressures the VUV absorption by oxygen and water vapor is taken into account. A constant lamp stray light does not affect the calibration since the calibration coefficients are determined as the slope of the regression line.

The total uncertainty of the calibration is determined by the following factors: the uncertainty of the frost-point measurement (0.1 K), the uncertainty of the temperature dependence of the water vapor partial pressure, the uncertainty in the pressure determination, error accounting for inconsistency of the air sampled by the reference dewpoint hygrometer and the air inside the chamber, and instability of the VUV intensity of the lamp. The total relative error of the calibration amounts to 4%.

During LAUTLOS the FLASH-B instrument was installed on the balloon payload with the downward-looking optics. This caused significant self-contamination during ascent measurements in the stratosphere. During payload descent the instrument probes the undisturbed air, and these observations can be considered to be contamination free.

The telemetry system used for the FLASH-B is similar to that used for the NOAA/CMDL hygrometer. It is directly interfaced with a Vaisala RS80 radiosonde and transmits one data frame comprising 20 measurements of the fluorescence signal every 4 s, along with the pressure, temperature, and humidity measurements of the Vaisala radiosonde. The time of measurement of the Vaisala pressure, temperature, and humidity corresponds to the preceding FLASH-B measurement cycle, which leads to a 4-s shift between the humidity measurement of the FLASH-B and the humidity measurement of the Vaisala Humicap sensor. This telemetry lag has been corrected in the analysis.

3. Observations and discussion

The observations presented here are simultaneous measurements of water vapor by the FLASH-B hygrometer and the NOAA/CMDL frost-point hygrometer on board the nighttime LAUTLOS payload. The soundings analyzed here (listed in Table 1) give a direct comparison of these two sensors in the stratosphere and upper troposphere. There are a total of 10 simultaneous soundings of the two instruments; however, only 7 produced useful data. In two soundings, because of instrument failure, no useful data were produced for either the FLASH or the NOAA hygrometer. In the first sounding the NOAA hygrometer produced questionable data, which are likely to be attributed to an electronic malfunction of the NOAA hygrometer. A total of 6 different NOAA hygrometer instruments and 7 different FLASH-B instruments were used in the 10 soundings reported here.

a. NOAA/CMDL frost-point and FLASH comparison: Stratosphere

The seven good soundings listed in Table 1 are shown in Fig. 1. These soundings were used to calculate the mean deviation profile shown in Fig. 2. All simulta-

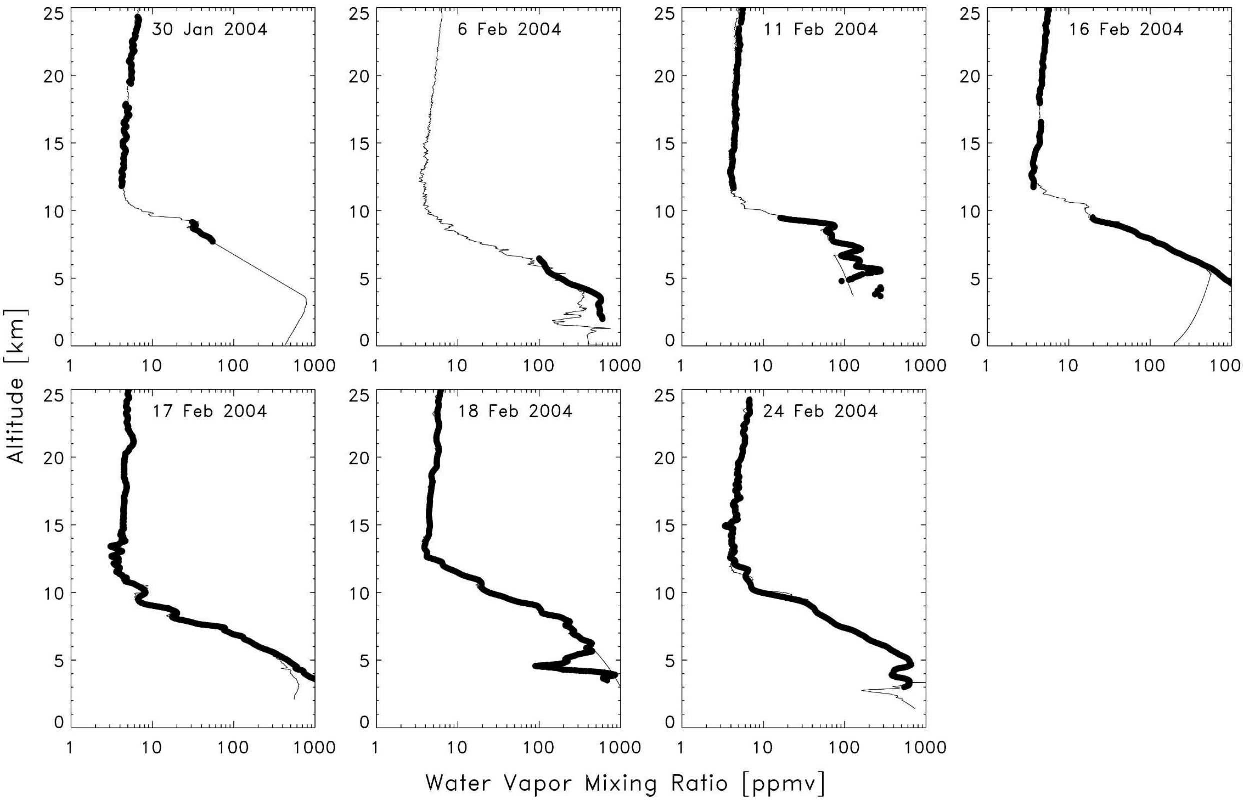

FIG. 1. Descent profiles of the FLASH-B (thin line) and NOAA/CMDL (thick line) water vapor soundings used for the comparison during LAUTLOS.

neous profiles have been carefully time synchronized. Small differences in the time stamps of the data files have been removed by matching the simultaneous temperature profiles between the two data streams on ascent. All NOAA/CMDL frost-point hygrometer profiles were smoothed using a 43-s running mean. The impact of this smoothing is described below. Only descent data are considered in this comparison, since contamination caused by balloon and payload outgassing was significant during ascent. With the exception of the altitude region between 8.8 and 11.8 km, the mean comparison shows a good agreement between the two instruments in the altitude region between 7 and 26 km, with a mean deviation of −2.4% ± 3.1% (one standard deviation) for data between 15 and 25 km. The balloon ceiling for these soundings was between 24.5 and 26.7 km, with the majority of the balloons bursting near 25.5 km. Figure 2 also indicates a ±10% uncertainty limit, which applies for the NOAA frost-point hygrometer.

The disagreement in the altitude region between 8.8 and 11.8 km is an artifact caused by the preprogrammed change in the feedback gain of the frost-point hygrometer. This gain change causes a disturbance of the feedback controller, which maintains a constant frost layer, and it takes some time for the instrument to regain full control. The recovery in the tropospheric setting can be anywhere from 0 to 10 min and depends strongly on the individual instrument as well as on the amount of water vapor at the time when this gain change happens. In general, the larger the amount of water vapor, the faster the controller regained good control.

b. *Calibration correction for the NOAA hygrometer*

Figure 2 indicates a small relative wet bias of the NOAA/CMDL hygrometer increasing with altitude above 20 km and reaching about 10% at 26 km. Part of this difference is related to the fit that is applied to the thermistor calibration. All thermistors are individually calibrated at the fixed calibration temperatures of 0°, −45°, and −79°C. A simple model (Layton 1961) based on these calibration points is used to translate the measured thermistor resistance into the corresponding temperature. As part of the development of the new University of Colorado cryogenic frost-point hygrometer, a set of 30 thermistors has been calibrated over the temperature range from −100° to +20°C. This extended calibration run was used to quantify the accuracy of the

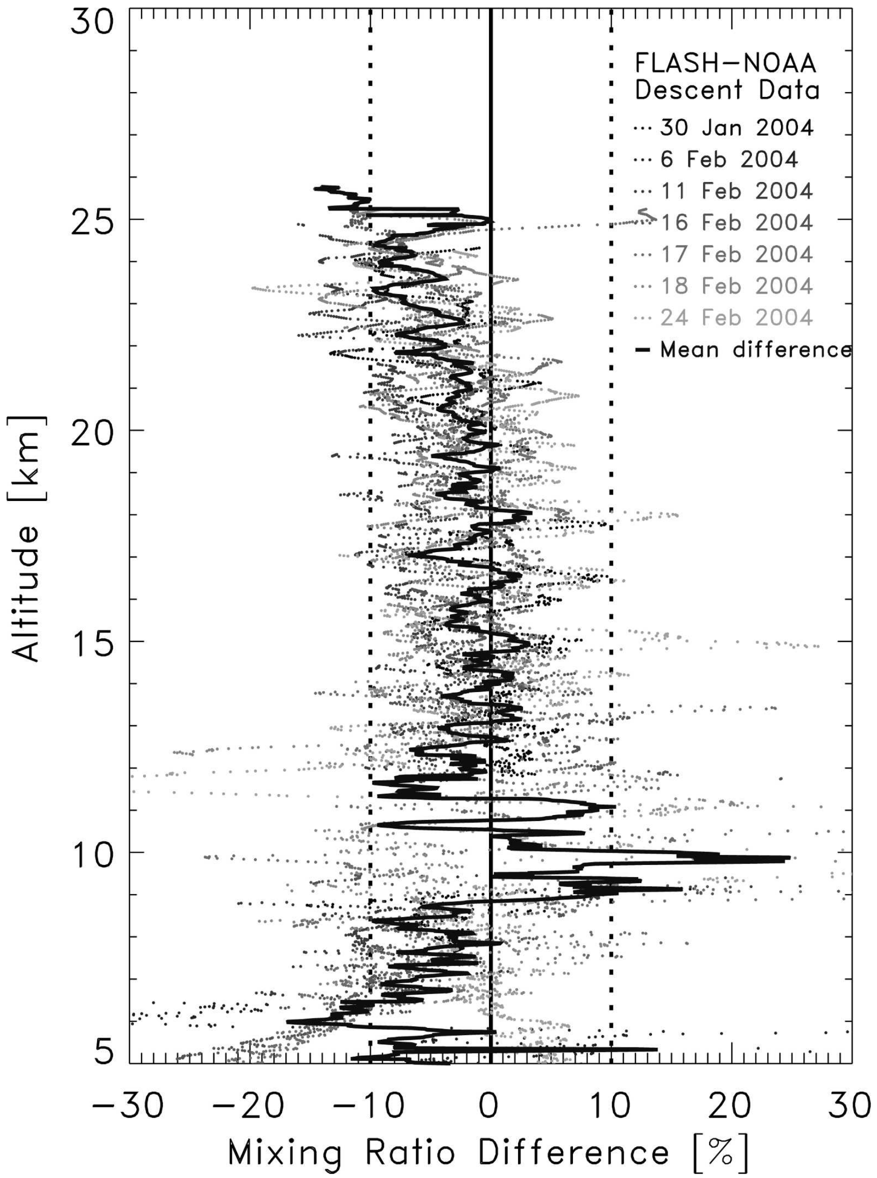

FIG. 2. Comparison of the FLASH-B and NOAA/CMDL water vapor observations during descent.

calibration model outside the standard calibration temperatures. The difference between the temperature derived from the thermistor model and the actual measured temperature of the calibration bath is shown in Fig. 3. By design of the calibration model the difference between the modeled temperature and the actual measured temperature is 0 at the calibration points. Between +10° and −85°C the difference between modeled temperature and measured temperature is less than 0.075°C. At the calibration temperature of −90°C, the difference reaches 0.16°C. This means that the mirror temperature reported using the three-point calibration model has an increasing warm bias up to 0.2°C at a frost-point temperature of −91.5°C. A simple correction, based on these extended calibrations, was introduced to the frost-point hygrometer dataset. The correction, shown as thick black line below −79°C in Fig. 3, has the form

$$T_{\mathrm{FP,corr}} = T_{\mathrm{FP}} - [-0.029(T_{\mathrm{FP}} + 79) + 0.083]^2|_{T_{\mathrm{FP}} \le -79}.$$

It is applied only at temperatures below −79°C. Figure 4 shows the effect of the calibration correction on

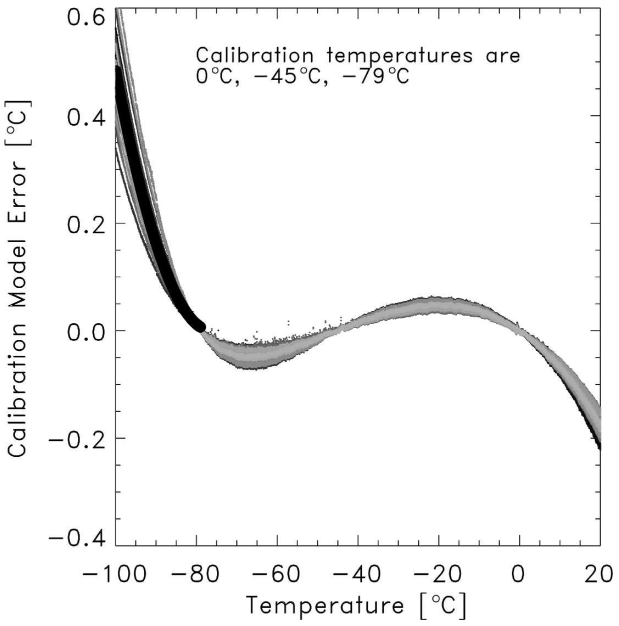

FIG. 3. Difference between the three-point calibration model and the actual measured temperature for 30 thermistors calibrated over the extended temperature range from −100° to +20°C. The thick black line indicates a simple quadratic correction that is applied for temperatures below −79°C.

the profiles. All soundings during LAUTLOS show a similar frost-point temperature profile, and therefore the correction is similar for all soundings. The peak correction is −2.3% at 25.3 km and removes some of the difference between the NOAA/CMDL frost-point hygrometer and FLASH-B.

c. NOAA/CMDL hygrometer instrument behavior

Having a second lightweight, fast-response instrument for stratospheric water vapor enabled us for the first time to asses the response characteristics of the NOAA/CMDL frost-point hygrometer under true atmospheric conditions.

The stratospheric water vapor profile above the hygropause usually contains very few features, and the response time of the instruments studied here is often not of significance. However, near the polar vortex edge and with a dehydrated polar vortex, sharp features may be observed in the vertical profile of water vapor, which can be used to characterize the response time of the hygrometer, in particular of the feedback controller, which regulates the mirror temperature to maintain a constant frost coverage.

The sounding on 18 February 2004 (Fig. 5) is the best example of sharp vertical features in the water vapor profile encountered near the polar vortex edge. The data cover the altitude region between roughly 26 and 20 km, immediately after the balloon burst on parachute descent. The ambient temperature is in the range from −64° to −74°C, and the frost-point temperature measured by the NOAA hygrometer is in the range from −90° to −85°C (Fig. 5, middle). The balloon burst occurred at 6048 s of flight time, which causes a large change in the air going through the NOAA/CMDL hygrometer, which takes a few tens of seconds to recover proper frost-layer control. The NOAA/CMDL hygrometer underestimates the minimum at 6065 s (25.5 km) and overestimates the maximum at 6090 s (24.8 km). After proper control has been regained, there is reasonable, although not perfect, agreement in the magnitude of the vertical features. While the temperature measurements by both instruments show almost perfect agreement, the water vapor mixing ratio profiles show a slight lag of the NOAA hygrometer. The NOAA frost-point hygrometer lags the FLASH-B measurements by about 5 s, which appears to be a result of the time lag of the feedback controller. Because of the fast descent rate of 22 m s^{-1} at 25 km, this time lag corresponds to a vertical shift of about 110 m. During ascent or valved descent the payload moves with a ver-

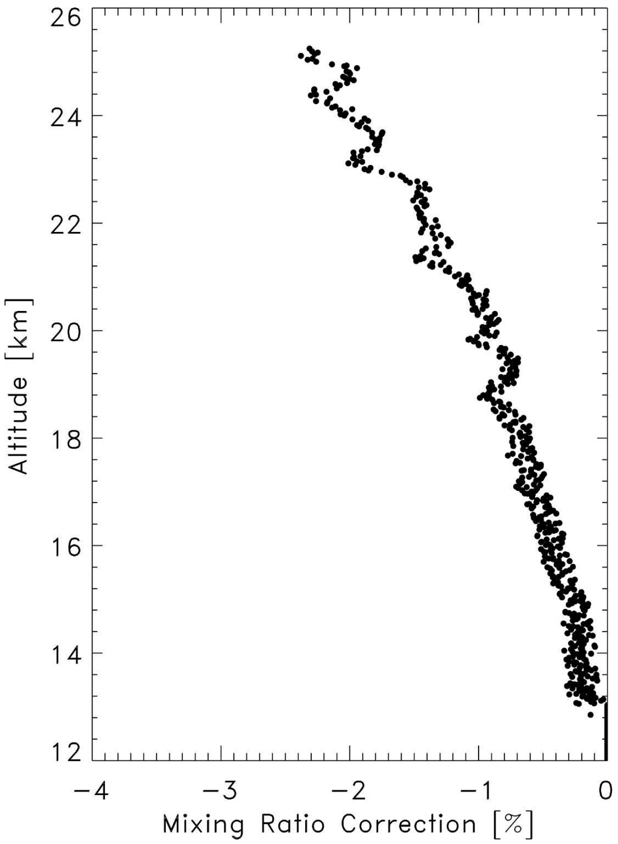

FIG. 4. Impact of the calibration correction on the mixing ratio profile based on the sounding on 18 Feb 2004.

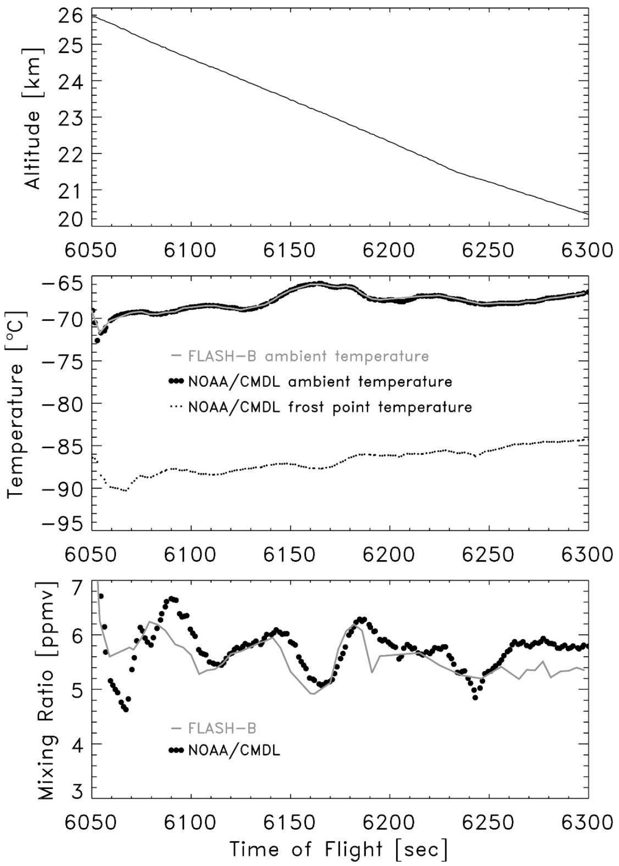

FIG. 5. (top) Altitude, (middle) temperature, and (bottom) mixing ratio measured by the FLASH-B hygrometer and by the NOAA/CMDL frost-point hygrometer during descent on 18 Feb 2004.

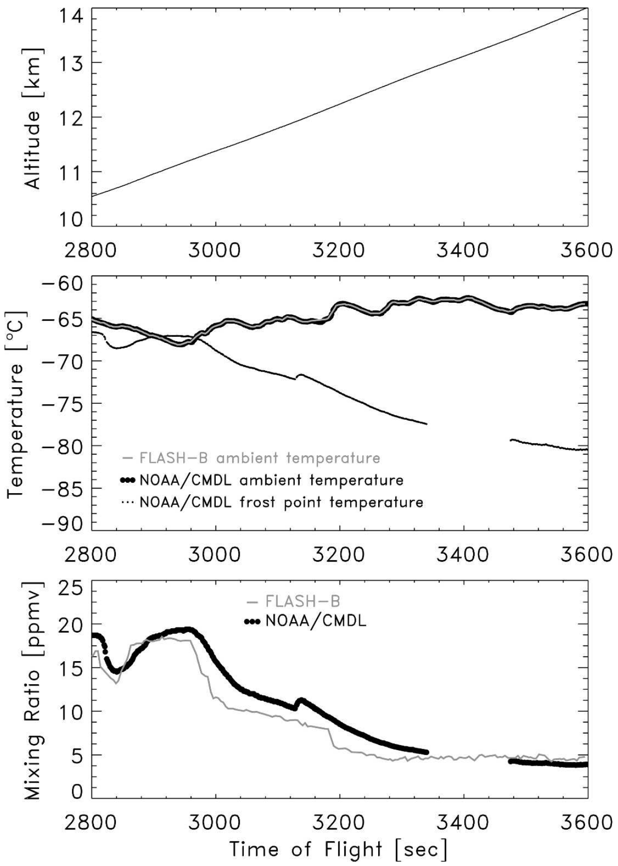

FIG. 6. (top) Altitude, (middle) temperature, and (bottom) mixing ratio measured by the FLASH-B hygrometer and by the NOAA/CMDL frost-point hygrometer during ascent in the lower stratosphere on 18 Feb 2004.

tical speed of about 5 m s^{-1}, which corresponds to a vertical shift of only 25 m.

This time lag depends on the controller response of the instrument, which is in turn a function of the rate of frost formation and frost evaporation. It also depends on the controller settings, which in this case is the higher gain used in stratospheric measurements. Therefore, this result applies only to measurements in the frost-point range below −85°C and for the stratospheric higher gain controller setting.

The low gain setting at a frost-point temperature between −30° and −40°C does not cause a time lag, and the instrument shows the same fast response time as the FLASH-B hygrometer. However, the NOAA hygrometer shows a significant time lag in the low gain setting and in the frost-point temperature range between −65° and −75°C (Fig. 6). The gain change is triggered at 3350 s, causing a data loss for about 1.5 min. The comparison with the FLASH-B hygrometer reveals a significant lag of the frost-point hygrometer in the low gain setting at this cold temperature. This frost-point hygrometer response improves significantly with the higher gain setting after 3440 s.

This slow response in the low gain setting under relatively dry conditions contributes significantly to the large disagreement between the two instruments in the 9–11-km region.

d. NOAA/CMDL hygrometer oscillations

In some instruments, the controller is not able to maintain a constant frost layer and oscillates around the set point. These oscillations may be symmetric or chaotic oscillations, depending on the individual instrument. In the case of small symmetric oscillations the observations are still useful, if a running mean is applied to smooth out these oscillations. In the sounding on 17 February 2004 (Fig. 7) the frost-point hygrometer oscillated in the stratosphere with a peak-to-peak amplitude of 4.5°C or 3 ppmv and a period of about 21.5 s. A running mean with a width of two oscillation periods, that is, 43 s, was able to reduce these oscillations by a

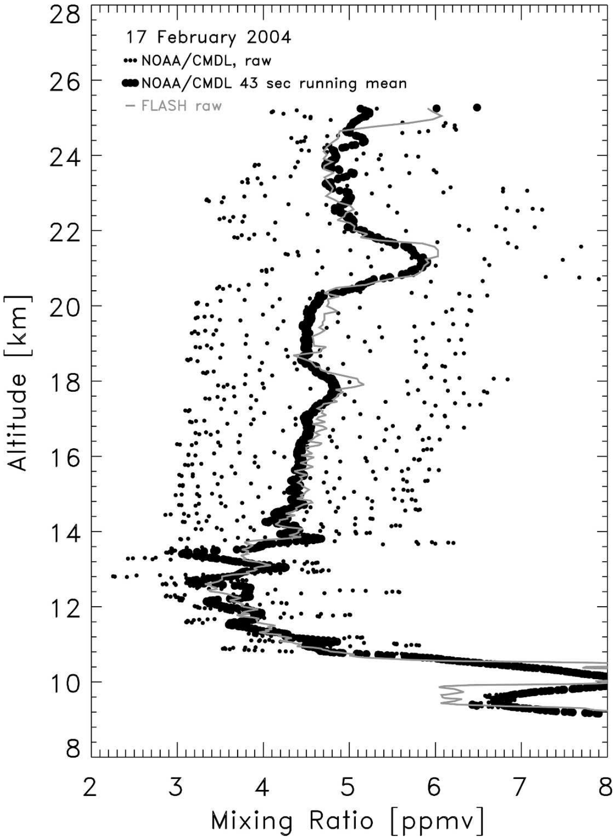

FIG. 7. Impact of smoothing on controller oscillations. A 43-s running mean was applied to the raw data as well as a 9-s time-lag correction.

factor of 15. Further, applying a correction for the 5-s lag leads to a very good agreement between both instruments.

Note that these are descent data and that the strong water vapor gradient at 14 km stimulates stronger oscillations below, which are not sufficiently smoothed out by this method. Note also that the running mean was applied to the mixing ratio and not to the measured mirror temperature. The nonlinearity of the Clausius–Clapeyron equation would lead to slightly lower mixing ratio values, if the running mean was applied to the frost-point temperature measurements and the mixing ratio was subsequently calculated from the smoothed frost-point temperature. Apparently, the asymmetry between heating and cooling, inherent to stratospheric frost-point hygrometers, leads to asymmetric oscillations around the ambient frost-point temperature. These are fortuitously compensated by the nonlinearity of the Clausius–Clapeyron equation, leading to largely symmetric oscillations around the ambient mixing ratio, which can be smoothed out with a simple running mean of the appropriate width.

e. Tropospheric behavior of FLASH-B

The frost-point hygrometer has no inherent lower altitude limit for water vapor measurements, although for the NOAA hygrometer, a lower limit is given by the stability of the controller. However, the FLASH-B has an inherent lower altitude limit, which is given by the amount of Lyman-alpha absorption by water vapor and oxygen. This occurs somewhere in the midtroposphere and depends strongly on the amount of water vapor. The comparison of NOAA frost-point hygrometer and FLASH-B measurements in the troposphere on descent show consistent agreement between 7 and 9 km in the polar troposphere (Fig. 8). The apparent disagreement between both instruments in the 9–11.5-km region is an artifact caused by the improper gain setting after the gain change of the frost-point hygrometer, which occurs in this altitude region. It can take the frost-point hygrometer up to 2 km in altitude to regain good control, and therefore the disagreement in this altitude region needs to be disregarded.

The tropospheric comparison between both instruments on ascent shows a different picture (Fig. 9). Between 5 and 12.5 km there is a systematic dry bias of the FLASH-B hygrometer of about 10%–20%. The stronger dry bias below is a result of the FLASH-B sensitivity, roughly in agreement with the descent data. The sudden change from dry bias to wet bias at 13 km is difficult to understand and is possibly a result of two separate factors. The stratospheric wet bias is largely meaningless, since both instruments show significant contamination, which apparently affects the FLASH-B more strongly than the NOAA frost-point hygrometer. Contamination does not play a role in the troposphere, and therefore the dry bias observed there is real. The tropopause was generally in the region between 9 and 11 km, and it can be expected that contamination begins to play a role above this region. The frost-point hygrometer gain change on ascent occurred typically between 11 and 13 km. Below this level, the data are influenced by the improper low gain setting, and it takes some short amount of time after the gain change for the instrument to regain control. Therefore, this region is highly influenced by the gain change and explained by the typical altitude at which the frost-point hygrometer regains control.

4. Summary and discussion

During the LAUTLOS campaign at Sodankylä, Finland, in January and February 2004, the NOAA/CMDL frost-point hygrometer and the FLASH-B Lyman-alpha hygrometer were compared in soundings on

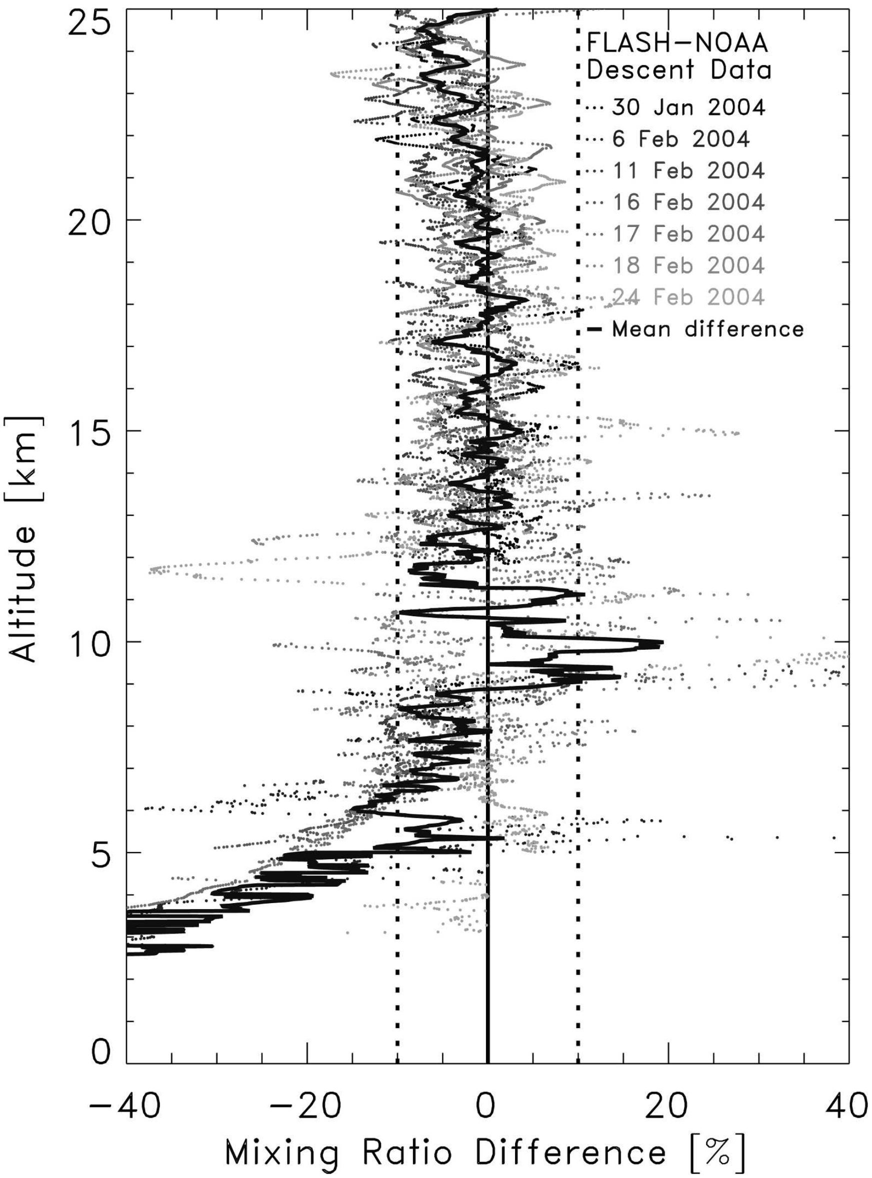

FIG. 8. Comparison of the FLASH-B and NOAA/CMDL water vapor observations during descent after time-lag and low-temperature calibration correction.

board the same balloon payload. The simultaneous measurements show good agreement between both instruments, with a mean deviation of −2.4% ± 3.1% (one standard deviation) for data between 15 and 25 km. The FLASH-B hygrometer is calibrated in the laboratory against a commercial reference frost-point hygrometer. This comparison indicates that there do not seem to be any intrinsic differences between frost-point hygrometer and Lyman-alpha water vapor measurements in the atmosphere.

A small wet bias of the NOAA/CMDL hygrometer, increasing with altitude as a result of the calibration fit inaccuracy at temperatures below −79°C, had previously not been considered. A low-temperature correction is based on the extended calibration of 30 thermistors to temperatures down to −100°C. The maximum correction based on this calibration fit correction is 2.3% at 25.3 km.

The comparison revealed a 5-s time lag of the hygrometer response in the stratosphere, which is most likely caused by the feedback controller. This time lag depends on the individual controller settings as well as on the altitude, that is, the amount of water vapor in the air. The value of 5 s was derived in the polar strato-

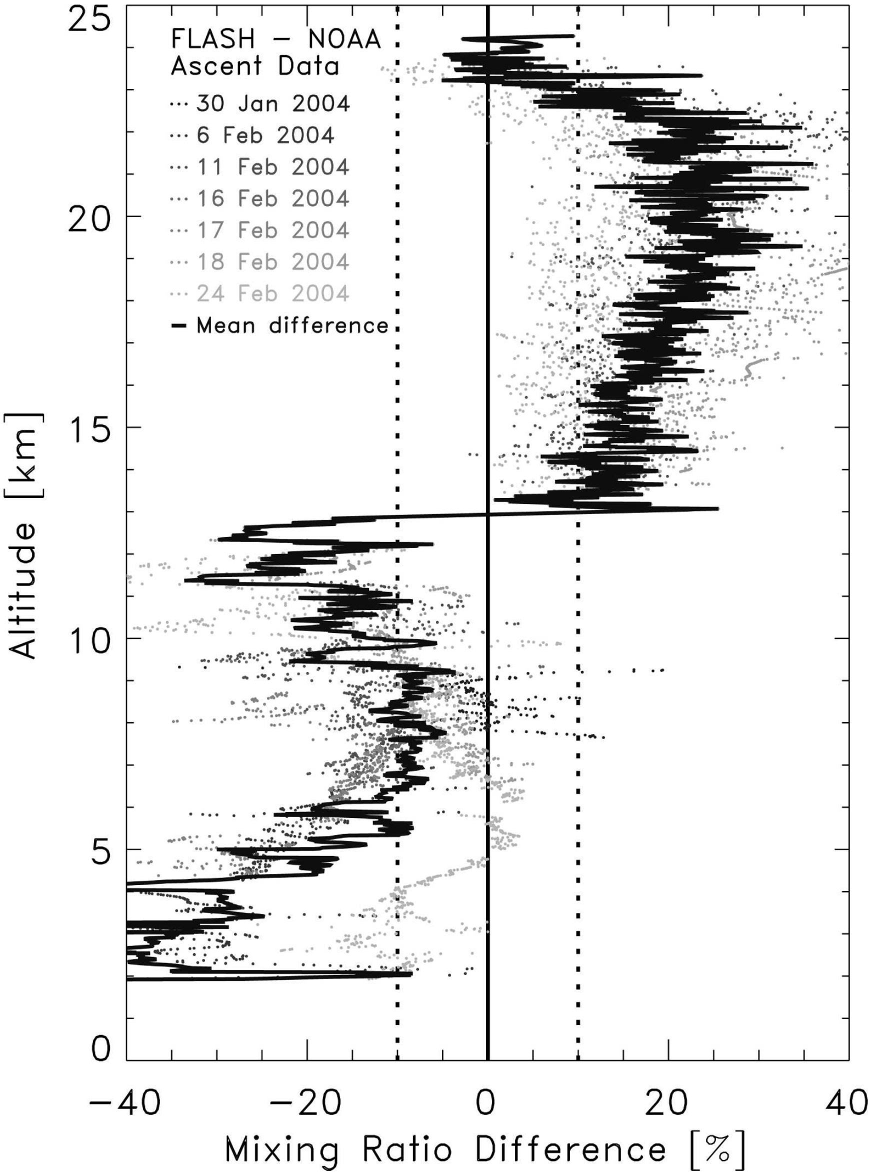

FIG. 9. Comparison of the FLASH-B and NOAA/CMDL water vapor observations during ascent.

spheric vortex in the region of 20–26 km and does not apply at lower altitudes or for soundings in which the controller is not stable. Below 20 km, the available water vapor is larger and thus the feedback controller response is faster. It also does not apply for different controller designs implemented in other frost-point hygrometers or for different controller settings of the NOAA/CMDL hygrometer.

The comparison between NOAA/CMDL and FLASH-B, including the low-temperature correction and a 5-s time-lag correction, gives a mean deviation of −1.3% ± 2.7% (one standard deviation) for data between 15 and 25 km. The FLASH-B Lyman-alpha hygrometer during LAUTLOS was found to measure water vapor reliably above 7 km. This lower altitude limit is determined by the absorption of Lyman-alpha radiation by oxygen and water vapor and can be lower in a dry atmosphere, which was seen in some profiles.

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