Report from the NDACC meeting on atmospheric water vapour measurement

Bern, Switzerland, 5-7 July 2006

Edited by Geir Braathen, 6 September 2006

Introduction

Water vapour in the atmosphere is the key trace gas controlling weather and climate. It also plays a central role in atmospheric chemistry, influencing the heterogeneous chemical reactions that destroy stratospheric ozone. The effects of water vapour are large in the upper troposphere and lower stratosphere, but there are few measurements of water vapour concentrations and its long-term variation in this altitude region.

Balloon-borne water vapour measurements at Boulder, Colorado, for the period 1980-2005 show a significant increase of 5-10% per decade over altitudes of 15-28 km. Global water vapour measurements from the Halogen Occultation Experiment (HALOE) satellite instrument for 1991-2005 do not show a corresponding positive lower stratospheric trend. Interannual water vapour changes derived from HALOE data exhibit quantitative agreement with temperature variations near the tropical tropopause. In contrast, the long-term increases inferred from the Boulder data are larger than can be explained by observed tropopause temperature changes or past increases in tropospheric methane. The difference between the Boulder measurements and the results from HALOE is shown in Figure 1.

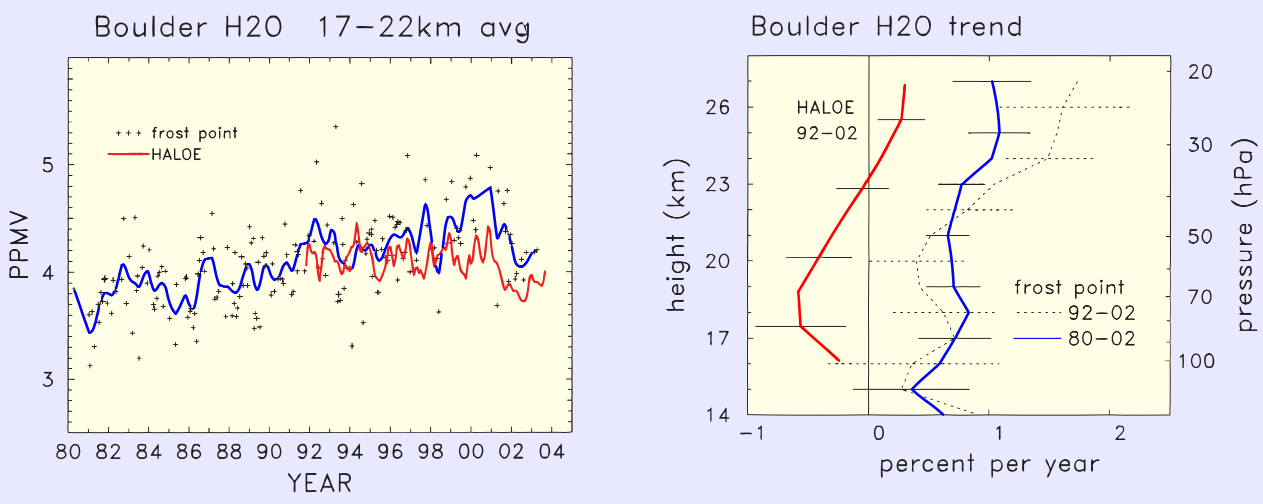


Figure 1. ***Left panel:*** *Data points show time series of water vapour averaged over 17–22 km at Boulder, Colorado, from frost-point hygrometer measurements covering 1980–2002. The blue line shows a smooth fit through the data points using a running Gaussian window with a half-width of three months. The red line shows HALOE satellite water vapour data during 1992–2002 for the same altitude region, using measurements near Boulder (over latitudes 35°–45°N and longitudes 80°–130°W).* ***Right panel:*** *Vertical profile of linear trends in water vapour derived from the Boulder frost-point hygrometer data (blue and dashed lines, shown for two time periods 1980–2002 and 1992–2002), and HALOE data for 1992–2002 (red line). The HALOE trends are based on measurements near Boulder (35°–45°N and 80°–130°W); very similar results are found for zonal means over 35°–45°N. Error bars show the statistical uncertainties of the linear trend fits. Adapted from Randel et al. J. Atm. Sciences, Sept. 2004.*

These unanswered questions on the distribution and trends of water vapour increases the importance of NDACC water vapour measurements and leads to a need for coordination, harmonisation and expansion of water vapour measurements and data interpretation within NDACC.

At the 2005 NDACC Steering Committee meeting it was therefore agreed that a meeting to discuss water vapour measurements within NDACC ought to be arranged before the next Steering Committee meeting in September 2006. A workshop, organized and hosted by Prof. Niklaus Kämpfer, Institute of Applied Physics, University of Bern, was held from 5-7 July 2006 with participants representing a variety of measurement techniques. The workshop was cosponsored by Commission on Atmospheric Chemistry and Physics of the Swiss Academy of Sciences.

This report summarises the presentations and discussions that took place at the workshop in Bern.

Water vapour measurements with balloon borne instruments

Rapporteur: Esko Kyrö

Presentation by Esko Kyrö:

Radiosondes: Intercomparison results from two recent campaigns

LAUTLOS , January-February, 2004

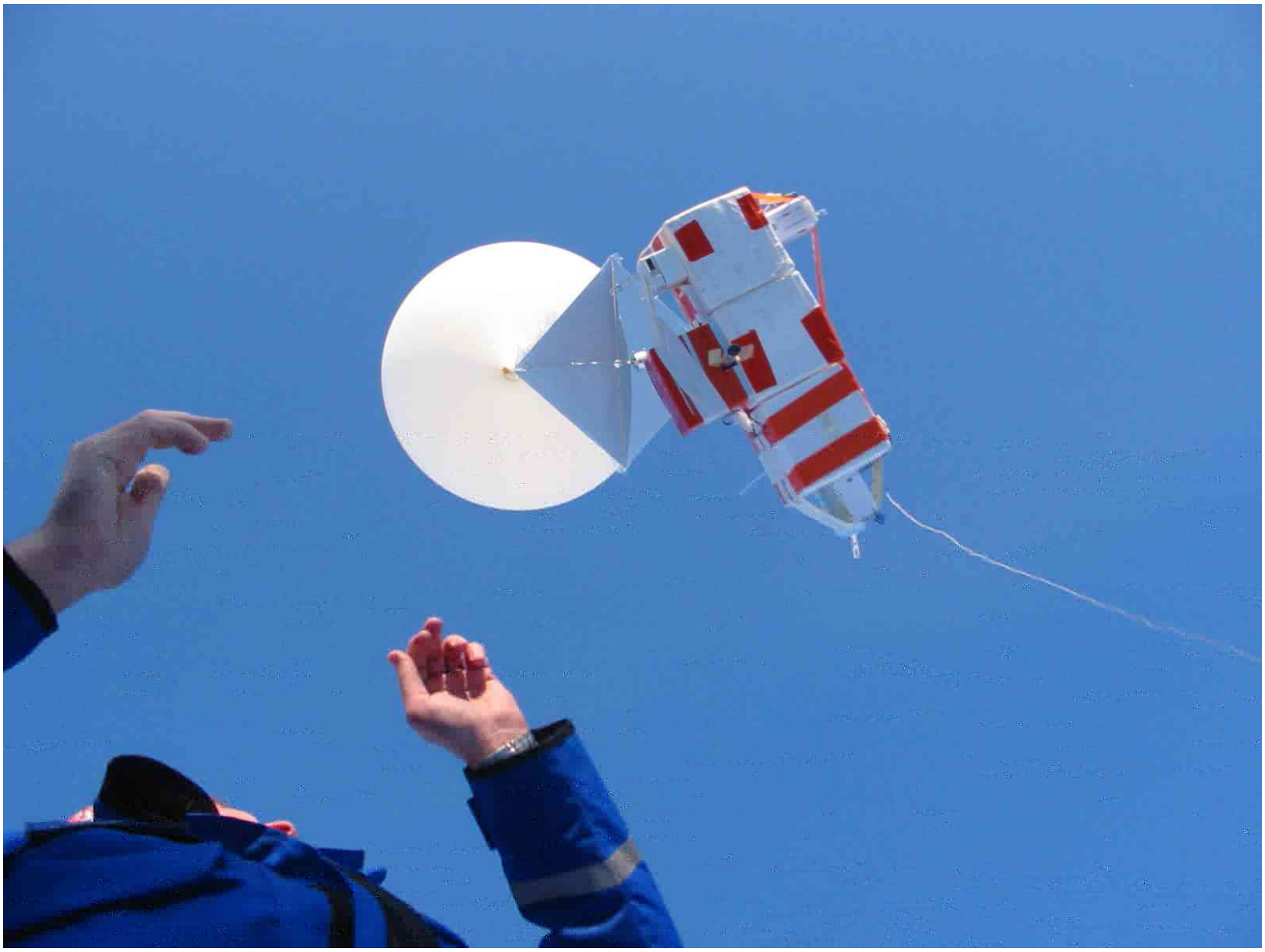
Motivation: Decadal radiosonde time series have discontinuities in them as the sonde type changes, and these discontinuities have to be corrected. The differences between the sonde generations are largest in the upper troposphere.

Participating radiosondes at the LAUTLOS campaign included 4 generations of Vaisala Humicap products (RS80A, RS80H, RS90, RS92), Meteolabor Peltier cooled frost point (FP) mirror hygrometer Snow White and FN sonde (a modification of the RS90 developed at the Lindenberg observatory). Additionally, as a reference for radiosondes in the UTLS region, two hygrometers of proven ppm-level capability participated: The FLASH Lyman-α sensor developed at Central Aerological Observatory, Moscow and the NOOA/ESRL cryogen cooled FP mirror hygrometer.

Key results of the LAUTLOS campaign were: The comparison with ppm-grade scientific hygrometers shows that radiosondes are good only in the troposphere up to the altitudes where the temperature reaches -55 °C to -60 °C. In colder temperatures and for stratospheric water vapour mixing ratios radiosondes did not observe the humidity variation detected by scientific hygrometers, not even with delay, i.e. with the time lag correction applied. Another prominent feature is the fairly large dry bias of the RS80A-type Humicap in the upper troposphere and a smaller bias for the RS80H, which in turn has a long response time. The newer Humicaps RS90 and RS92 agree well with the scientific hygrometers down to -55°C to -60°C temperatures in the Arctic winter atmosphere. Due to FLASH straylight limitations scientific payloads were only flown in night conditions.

Biases between various generations of Humicaps from about 1980 onwards can nowadays be accounted for due to the results from LAUTLOS and from other intercomparison experiments that have been performed at lower latitudes. For older sonde types the corrections are difficult if not impossible to obtain afterwards. Present day digital radiosondes are frequently intercompared in WMO radiosonde campaigns.

Panoramic view (360°) of the Sodankylä Observatory, Northern Finland. Photo: Holger Vömel.



Launch of a frost-point hygrometer payload during the LAUTLOS campaign in Sodankylä, Finland, in January-February 2004. Photo: Holger Vömel.

Validation data for the best radiosondes are also obtained as a by-product of scientific hygrometer soundings because hygrometer teams use radiosondes for telemetry purposes.

WMO Intercomparison of High Quality Radiosonde Systems Vacoas, Mauritius, 2-25 February 2005

Based on the report by: J. Nash, R. Smout, T. Oakley, Met Office, Exeter, UK B. Pathack Mauritius Meteorological Services, Vacoas

Table 1. Types of sensor for the radiosondes tested in the WMO intercomparison of high quality radiosonde systems

Type	Temperature sensor	Humidity sensor	Pressure sensor	GPS height	Wind
Graw DFM-97 (Germany)	Aluminised bead thermistor	External thin film capacitance	Yes	Yes	GPS code correlating
Meisei RS-01G (Japan)	Aluminised bead thermistor	External thin film capacitance	No	Yes	GPS code correlating
Meteolabor SRDS-C34 (Switzerland)	Thermocouple	Chilled mirror. Hygrometer (Snow White)	Hypsometer (boiling point of water)	No	Not submitted
MODEM M2K2 (France)	White bead thermistor	External thin film capacitance	No	Yes	GPS code correlating
Sippican LMS-5 (USA)	Aluminised chip thermistor	Internal thin film capacitance	No	Yes	GPS code correlating

Type	Temperature sensor	Humidity sensor	Pressure sensor	GPS height	Wind
Sippican multithermistor (USA)	3 aluminised chips, one black and one white	Not submitted	Not submitted	Not submitted	Not submitted
Vaisala RS-92-SGP (Finland)	Aluminised capacitance	Dual external thin film capacitance	Yes	Yes	GPS code correlating

Key results of RH comparison: In night time measurements Vaisala and Snow White were generally within 4 per cent of the reference at all heights up to 14 km, but were not in close agreement at heights above 15 km (the average of the three best sondes from Vaisala, Snow White and Sippican was used as a reference). The temperature at 15 km was about -70°C. Snow White showed much lower relative humidity than Vaisala at temperatures near -80°C. Sippican measurements at night were generally within 5 percent of the reference at heights up to 11 km, i.e. down to a temperature of -40°C, but the values reported in clouds at heights around 13 km were low by at least 15 percent relative to Snow White and Vaisala. Vaisala relative humidity measurements were around 10 percent higher than saturation with respect to ice in the highest clouds. Thus, it is possible that both Snow White (possible evaporation of ice crystals from the cloud by heating in the sample chamber) and Vaisala (contamination in cloud) were reporting relative humidity that was too high (but referring to later talk by Herman Smit about MOZAIC results it is possible that this is a genuine supersaturation and not a measurement error). However, in the drier regions at 16 km, Sippican relative humidity measurements were at least 20 percent too high. Improved calibration of this new sensor at temperatures below -40°C is now being addressed by the manufacturer. It is also worth noting that as a result of the comparison Vaisala is now applying pulse heating of its Humicap sensors down to -60°C instead of the earlier -40°C. This was actually done, at the request of the IOC chairman, in the middle of the Mauritius campaign when it turned out that the regular production model practice to stop heating at -40°C produced poor agreement with Snow White in the colder temperatures.

In daytime measurements there was an additional dry bias in RH measurements of radiosondes caused by the humidity sensor observing at a higher temperature than the reported temperature. Software corrections or direct measurement of the humidity sensor temperature is recommended as a result. The full conclusions of all the intercomparison campaign results and all participating radiosondes are available at: http://www.wmo.ch/web/www/IMOP/reports/2003-2007/RSO-IC-2005_Final_Report.pdf

Presentation by Sergey Khaikin:

Fluorescent Lyman-α Stratospheric Hygrometer FLASH.

Sergey Khaikin described the working principle and applications of the FLASH hygrometer sonde. FLASH has been developed at the Central Aerological Observatory by the team led by Vladimir Yushkov. In addition to the sonde version, there is also an aeroplane version flown on several stratospheric missions on board the M-55 Geophysica.

A co-axial optics design makes FLASH small and light-weight (less than 1 kg). FLASH is a very fast sensor with a large dynamic range. It is fairly insensitive to clouds.

FLASH is calibrated against a reference hygrometer (Leybold MBW 373L) in a vacuum chamber simulating atmospheric conditions with the pressure ranging from 3 to 1100 hPa, the temperature ranging from -80°C to +20°C and the water vapour mixing ratio ranging from 1 to 1000 ppmV.

The parachute descent profiles in the payload configuration where FLASH looks down are the best for the instrument because of the out-gassing from the balloon and the rest of the payload. According to the LAUTLOS comparison there is excellent agreement between FLASH and the NOAA CFH (Cryogen cooleded Frostpoint Hygrometer) from about mid-troposphere to the burst altitude (about 27 km). In the lower troposphere the FLASH instrument is affected by an interfering fluorescence signal from oxygen.

After the LAUTLOS campaign several teams became interested in the FLASH sonde and more experience has been obtained in making FLASH soundings “quasi-operationally”. Consequently, the production of sondes has increased. Currently quasi-operational use is ongoing in Ny-Ålesund and Sodankylä and is planned for Lindenberg. More opportunities are foreseen in the future (e.g. AMMA and STRATEOLE campaigns).

About 50 soundings have been made thus far using FLASH.

Presentation by Holger Vömel:

Water vapour observations in the upper troposphere and lower stratosphere (presented by Niklaus Kämpfer in absence of H. Vömel)

The University of Colorado has recently developed a new version of the classical NOAA/ESRL/GMD hygrometer sonde, which has been named Cryogen cooled Frostpoint Hygrometer, CFH. An early version of CFH already participated in LAUTLOS but with limited success due to interfacing problems when attaching the ozonesonde to the payload. Later on nearly 200 soundings with CFH's have been done in Boulder, Sodankylä and some tropical sites. Microprocessor control makes soundings easier for non-expert users and the recalibration of CFH after possible recovery is comparatively straightforward.

The problem is (as was also the case in the old NOOA instrument) that after passing through wet clouds the measurements may fail completely. On the other hand, CFH is currently the only small balloon borne instrument that can measure water vapour from the surface all the way to the middle stratosphere.

Some experience on the intercomparison with the European instruments (FISH on the Geophysica and on the large balloons, FLASH on both platforms and the Ovarlaez frostpoint instrument) have been obtained, generally with good results, but more cross Atlantic cooperation is needed. In the U.S more divergence between the instruments is seen: The WB57 instruments from Harvard and JPL do not always give consistent data and show a strong difference with NOAA FP and CFH observations. The recent Costa Rica campaign illuminated this problem once again. The differences are between 50 % and 100 % in the tropical tropopause layer, which makes it hard to do good science with any of the data.

When comparing CFH with radiosondes the upper troposphere seems to be a difficult region. Some sondes, like the Snow White, do a reasonable job, but too many failures occur. The Vaisala RS92 seems to do a good job at night and is very reliable, but daytime RH shows a dry bias. The other radiosonde manufacturers also struggle in the UT and do not quite as well as the Vaisala RS92. In case of the commercial radiosondes, the company secrets make it difficult to trace instrument and calibration changes.

The main focus of the CFH measurements has been in the tropics. More observations from the tropics are needed for two reasons: One is that stratospheric water vapour is largely controlled by what happens in the tropics and we are still a little in the dark on the details. This means that we need in situ water vapour observations preferably combined with either lidar or in situ particle observations. The other is that in a warming climate the water vapour feedback may be strongest in the upper tropical troposphere. This is exactly the region where we have the least number of observations. So we need both an instrument and several sites for long term routine observations in the tropics which can address both issues.

Status of a few better H_2O instruments according to Holger Vömel:

	Claimed accuracy	Calibration	Limitations	Dynamic range	History	Cost	Ease of use	Engi-neering status
CFH	0.5°C DP/FP (4-9%)	++	No "wet" clouds	++	+	- (o)	o	research/small series
Snow White	0.1°C DP/FP	+	Some clouds RH > 3-6% No stratosphere	o	+	o	++	production small series
Lyman-α (FLASH)	9% (20% below 2 ppmv)	+	Night time only. Descent only. No lower troposphere	+	o	--	+	research / small series

TDL (MayComm)	5% (0.5 ppmv)	o	?	+	-	--	(++)	Proof of concept
Polymer (Vaisala RS92)	1% RH	-	No stratosphere Large radiation error Chemical contamination Very hard to trace sensor/ calibration changes	-	+	++	+ (++)	Large scale production

Presentation by Jean-Pierre Pommereau:

Summary of sondes and experiments in France

The ELHYSA frostpoint hygrometer of J. Ovarlez (now transferred to G.Berthet, LPCE) is fully operational but requires the full CNES telemetry system and weighs about 80 kg. It is not suitable for operational service, but it remains a campaign instrument.

The case is similar case with the balloon-borne SAOZ spectrometer (J.-P. Pommereau), which has been flown during several campaigns.

The tunable diode laser system Micro-SDLA is being developed to a smaller sonde version, Pico-SDLA, which will weigh only 2 kg and hence could be used on small balloons. The PI is G. Durry (CNRS-SA/ Reims University). The first flight with Pico-SDLA is planned for October 2006.

Summary of sonde experiments:

- Test of Surface Acoustic wave (SAW) instrument of the University of Cambridge. R.L. Jones. Fine in UT, not enough sensitivity yet in LS.
- Comparison of sonde instrumentation: SAW, Snow White, RS-80, RS-90. PI are R. L. Jones and L. Eden: Best results for RS90, but there are still no reliable measurements above 15 km.

Summary of discussion on balloon borne measurements

High vertical resolution of sonde instruments is of importance in several applications:

- UTLS research: UT/LS exchange (atmospheric dynamics), Climate studies (data for radiative forcing calculations), hydroxyl chemistry (ozone chemistry)
- A priori profiles for remote sensing instruments, FTIR, MW, satellites.
- Raman lidar calibration constant
- Validation of remote sensing instruments (satellite/ground based)

Radiosondes are limited to tropospheric humidities and temperatures. FLASH and CHF are good also in the tropopause region and the stratosphere. For complete profiles we need a combination of the best radiosondes and research hygrometers. Both FLASH and CFH have the same problem that they are currently interfaced to RS-80 whose production has stopped. In the future more modern sondes are needed for tropospheric RH and telemetry. Discussion with Vaisala on interfacing stratospheric hygrometers to RS92 is ongoing but may be delayed because the company does not see the market opportunities that would endorse a rapid development project. Other sonde manufactures are also possible, e.g. in case of FLASH interfacing to Snow White has been considered.

From a scientific point of view more operational sites are needed (currently Sodankylä and Ny-Ålesund are “quasi-operative” in the frame of the European project SCOUT-O3). A considerable limitation for an extensive use of the hygrometers that are capable of measuring in the UTLS range is the high price of FLASH and CFH (in the range of USD 3000). Both CFH and FLASH are reusable which can significantly reduce the cost. The recalibration of CFH is in principle straightforward (thermistor calibration). In the case of FLASH, the lack of a simple field calibration system (check up at site before flight or recalibration after possible recovery) is a problem considering operational use at regular sonde sites. Recovered sondes are presently sent for re-calibration to the CAO calibration lab in Dolgoprudny.

Report on discussion of H_2O measurements with the FTIR technique

Rapporteur: Ralf Sussmann

Justus Notholt showed H_2O and HDO total column retrievals performed at the Ny-Ålesund NDACC site as well as during the last (Oct./Nov. 2005) Polarstern cruise. A set of micro-windows in the wave number range between 2400 – 3000 cm^{-1} was used that were determined by an automatic line-finding-program developed by the group in Bremen. A good correlation between the surface temperature and HDO was found. Tests with profile retrievals have been started by the Bremen group using a "modified Tikhonov" regularisation approach.

Ralf Sussmann presented H_2O column and profile retrievals from the Zugspitze NDACC mountain site (2964 m asl). Four micro-windows around 850 cm^{-1} with a total of 9 weak to strong lines were selected, showing a smoothing error as a function of altitude which is independent on the absolute column level. The micro-windows are free of absorptions from interfering species. The total column retrievals are showing high accuracy (<0.1 mm) and precision, which is due to the improvements achieved between HITRAN versions 1996 and 2000. For profiles, an optimal estimation retrieval was set up using a climatological a priori covariance constructed from 360 radio soundings launched on site during a 3 months (AIRS validation) campaign. The retrieval shows 3 degrees of freedom of signal and the resulting partial columns were compared to the coincident sondes, showing good agreement. The Zugspitze FTIR will be synergistically combined with the nearby Garmisch FTIR (734 m asl) and the Zugspitze water vapour lidar (2650 m asl., profile range onset at FTIR altitude). R. Sussmann is PI of an ESA-EUMETSAT EPS-MetOp water vapour validation project, comprising all Zugspitze (2 FTIR, 1 lidar, 2 GPS) activities.

Matthias Schneider showed results on H_2O optimal-estimation profile retrievals from the Izaña NDACC station and its validation via soundings launched 15 km apart from the site. A set of 6 micro-windows with 7 different water lines with different strengths was used. There are interferences of O_3, CO_2, N_2O and CH_4, whose impact is minimized via simultaneous fitting. From the available sounding data set at Izaña, a log-normal distribution of water vapour was found, therefore the retrieval was performed on a logarithmic scale. By an extensive error estimation and continuous comparisons to sondes it was concluded that upper tropospheric H_2O amounts can be retrieved, even for a moderately humid lower troposphere. A seven year record (1999-2006) of lower, middle and upper tropospheric H_2O amounts at the Izaña site was shown.

In addition, a seven year record of HDO/H_2O isotopologue ratios has been presented. The results are based on a novel retrieval approach which takes inter-species correlations properly into account, thereby allowing for the first time optimal estimation retrievals of isotopic ratios from ground-based FTIR [Schneider et al. ACPD, 6, 5269-5327, 2006].

Discussion results were that, independently from the site, approximately 3 degrees of freedom of signal can be achieved by FTIR, and the accurate knowledge of the instrumental line shape does not play a major role due to the broad water absorption features. As to the retrievals T. Trickl and R. Sussmann pointed to the caveat that it is an intrinsic property of a logarithmic retrieval to introduce a positive bias for small signals, as it is the case for the water vapour absorptions occurring close to the upper limit of the attainable altitude range. F. Hase argued that this well-known argument is only applicable for weak absorbers (line center absorption in the order of noise level). Since in the case of H_2O the SNR for the total line area is high and since the ensemble values are better approximated by a log-normal PDF, the log-retrieval allows for a superior reconstruction of the true state, as proven in a recent peer-reviewed publication [Schneider et al. ACP, 6, 811-830, 2006].

For the attainable altitude range of the retrievals it seems that the lower altitude sites can reach altitudes up to 8-10 km on a routine basis, and higher altitudes are reached only for very dry conditions, while the high-mountain sites like the Zugspitze are showing always nearly the same altitude range, i.e., up to 13 km both for dry and wet days. Some discussion on best selection of a priori profiles showed up, which turned out to be similar to the ongoing discussions within the microwave group (A. Haefele's talk): Using one profile gives a stand-alone retrieval while using some actual best estimate profile (e.g., nearby radio sonde) results in a combined sounding system. The way to go is a question of philosophy and the advantage of a more realistic actual profile should only show up in altitude ranges with a significant a priori contribution.

Summary of discussion on water vapour measurements with the lidar technique

Rapporteur: Thomas Trickl

The lidar technique has reached some maturity in providing tropospheric water-vapour measurements with high vertical and temporal resolution and with errors below 5 % in most of the operating range. This is mandatory for an investigation of the transport processes underlying the free-tropospheric layering and variability as well as for trend studies. It is highly desirable to extend the lidar operation to the lower stratosphere in order to make possible accurate ground-based observations in a region in which the use of other instrumentation is still problematic. Balloon-borne sensors do not provide reliable data above 8 km, FTIR has not yet been demonstrated to yield information on altitudes above the hygropause and the useful range of microwave sensors currently starts above 15 km. An important goal would also be the validation of satellite sensors which are most reliable in the stratosphere.

Two methods are used, the Raman lidar and the differential-absorption lidar (DIAL). The Raman method has the great advantage of not requiring sophisticated laser systems. As a consequence, an automatic operation of these systems can be achieved. Therefore, the Raman approach is preferred at most stations of the NDACC. On the other hand, Raman backscattering is more than three orders of magnitude less efficient than Rayleigh backscattering. Thus, due to the strong solar background Raman lidar measurements during daytime require very narrow spectral filtering and are mostly limited to altitudes below 5 km above the ground, which may be exceeded under conditions of high humidity. During night-time an operating range up to the "hygropause" region has been demonstrated. For instance at Table Mountain measurements up to 15 km have been possible with a 355 nm laser emitting about 7 W of average power (700 mJ/pulse). Measurements of mixing ratios as low as 0.01 g/kg, up to 13-14 km, with a 20 minutes integration time, are possible with the Raman system of Rome (Tor Vergata), using about 4 W of average power at 355 nm.

The DIAL method used at the NDACC station Garmisch-Partenkirchen is substantially more sensitive within the troposphere, in particular during daytime. However, traditionally lasers with near-infrared pulse energies well below 100 mJ have been used. The new lidar is designed for energies around 0.7 J (currently achieved: 250 mJ) within the 815 nm band system and has a 0.65 m-diameter telescope. In this way the system specifications become comparable with those of Raman lidars and measurements to the upper troposphere become possible. For routine operation up to the hygropause the lidar is installed at the Schneefernerhaus research station at 2674 m asl, thus avoiding light losses by absorption in the moist boundary layer. During daytime the operating range is reduced by just a few hundred metres which allows water-vapour sounding to be carried out around the clock. In this way atmospheric layers of interest may be studied during the full length of their overpass. The current disadvantage of DIAL measurements is the considerable time spent for laser alignment. A major effort will be needed to achieve a quasi-automatic mode of operation.

Ground based DIAL measurements are mostly restricted to the troposphere since absorption measurements in the stratosphere require a laser operation in the stronger 935 nm band system of H_2O. Measurements within this band system are possible up to more than 25 km if the humidity remains at just a few per cent below 7.5 km which occasionally occurs during the cold season. This may be used at least for some satellite validation.

Ground-based routine measurements in the stratosphere require a Raman lidar with a high-power ultraviolet laser. In contrast to the situation for the DIAL an increase of the laser power helps to improve the signal-to-noise ratio since Raman scattering is a so-called zero-background method. XeCl lasers (308 nm) with an average power of 300 W are available and must be modified for the atmospheric application. We anticipate that such an upgraded Raman system, operated with a 1.5 m diameter receiver, is capable of performing night-time measurements to at least 25 km with an accuracy of the order of 5 %.

Calibration is not a great issue for the DIAL technique since it is based on very accurately known spectroscopic data (absorption cross sections, line-shape parameters). However, the system constant of a Raman lidar must be calibrated. This is normally achieved with radiosonde data which are sufficiently accurate in the lower troposphere. In the boundary layer the influence of light backscattering by aerosols must be considered. Other possibilities are intercomparisons with microwave and FTIR systems. Here, problems with incomplete range overlap may exist. Also, an intercomparison with a DIAL may yield an accurate calibration. A synergy through the use of several instruments at a single site is advantageous.

The calibration of a Raman lidar must be repeated at least several times per year to verify its stability. For the daily performance control an ultraviolet lamp with stable output characteristics may be used.

In summary, no strict procedure was recommended at the end of the discussion.

Summary of discussion on water vapour measurements with microwave instruments

Rapporteur: Gerald Nedoluha

A total of nine presentations was devoted to measurements of water vapor profiles by microwave radiometry. Microwave instruments are thus far the only ones to cover the altitude range from approx. 20 – 70 km. Several of these instruments are operated within NDACC so far. A talk by Alexander Haefele showed how profiles from balloons and microwave instruments can be combined in an optimal way to obtain a merged profile from the ground to the mesosphere.

In the discussion an issue that came up was the accuracy of spectral line information. Joachim Urban thinks it is actually pretty good, especially compared with some of the problems encountered at sub-mm wavelengths. Bertrand Calpini asked about the importance of temperature to the measurements. Gerald Nedoluha pointed out that the errors in temperature were usually fractionally much smaller than the errors in the species measurements, but that under some circumstances they could be important. As far as trend studies temperature errors are certainly more important than spectral line errors, but again, the fractional temperature trend is likely to be small.

There was also a discussion on forward models and retrieval schemes. In general different groups use their own schemes, but several groups do use the forward model and retrieval software ARTS/QPACK developed at Bremen and Gothenburg. There was also a short discussion of baseline issues. Alexander Haefele mentioned that the baseline can be affected by wet reference loads.

A discussion about validation ensued. Unlike the FTIR group, which does side-by-side and exchange gas cells, nothing like this makes sense for microwave instruments. Microwave instruments use black bodies for calibration. Sondes are of some use for validation at the lowest altitudes measured. Validation against satellites is generally done, but there are certainly issues because of the differences in vertical resolution. Having a mobile instrument for inter comparison would be useful, but Niklaus Kämpfer and Gerald Nedoluha both agreed that moving an instrument that performs regular measurements in the frame of NDACC will probably make that instrument useless for long-term trend measurements. Niklaus Kämpfer mentioned that the IAP plans to build a compact version of the MIAWARA type of instrument that could be used as a kind of travelling standard in the future.

There was a short discussion of whether additional microwave instruments should be deployed at TMO in October 2006 during the Lidar campaign. Gerald Nedoluha hopes that the WVMS instrument would be ready by then, but it does not make useful measurements below ~40 km. There is some discussion of the possibility of such a campaign again in 2007. Niklaus Kämpfer pointed out that people need a very long lead time if they are to participate in such a campaign. Geir Braathen thinks we should have more of these meetings between different instrument groups, a feeling that was shared by all.

Summary at end of workshop

Geir Braathen made a concluding presentation at the end of the workshop. The main points were:

Sondes

- Vaisala RS 80 has a dry bias. RS 92 is virtually without bias.
- Snow White measures higher than RS 92, but Peltier cooling is not enough for stratospheric meas.
- LAUTLOS: NOAA CFH and FLASH compare very well down to 5 km.
- WMO intercomparison in Mauritius in February 2005.
  - ✓ Vaisala, Snow White and Sippican. Is report out?
  - ✓ GCOS: Move towards a new and better radiosonde
- CFH may fail in thick liquid clouds.
- Sondes (Flash, CFH) are probably the best solution for the UTLS region due to the good vertical resolution.
- Flash can be reused.
- We should have stations with a suite of water vapour instruments.
  - ✓ Bern/Payerne is one possibility.
  - ✓ We also need stations in the tropics

FT-IR

- Hitran 2000 gives much better water vapour profiles than Hitran 96.
- Approx. 3 independent layers.
- Very accurate H_2O columns
- Improved retrieval of UT H_2O by combining strong lines and moderately strong lines.
- FT-IR well suited for middle troposphere. More difficult in the UT.
- One should think about a reanalysis of old data from e.g. Kitt Peak.

Lidars

- Two different techniques:
  - ✓ Raman lidar. Altitude range: surface – 15 km (hygropause) at night time. Up to 8 km at daytime.
  - ✓ DIAL (needs to break world records in laser technology). Altitude range: surface-13 km (hygropause) above ground any time. Valid for high altitude site. From a dry site there is the potential to go to 25-30 km
- Raman lidar needs calibration. One point along the profile suffices.
- DIAL is absolutely calibrated

Microwave

- Altitude range: 20-80 km
- How well do we know the spectroscopic parameters?
- How much does the temperature profile influence the water vapour profile?
- Europeans and Americans are using different forward models.
- QPACK retrieval code used by some, but not all.
- Should the MW working group have a travelling standard like for the FT-IR and lidar WGs?
- Is it possible for some MW instruments to participate at the Table Mountain intercomparison in October 2006?

Combining MW and other techniques

- Cross validation of satellites by a ground-based station
- Cross validation of GB stations by a satellite
- ”Assimilating” various other measurements in the MW retrieval can give a continuous ”smooth” H_2O profile from the ground to the mesopause. More work is needed to develop the technique.
- One should identify sites that has several measurment techniques. Bern/Payerne is one possibility.

Next steps

- Workshop report.
  - ✓ Rapporteurs send their ”clean” notes to Geir. ”Clean” = Good English with complete sentences. No telegram style. Deadline 15.7.2006.
  - ✓ Geir makes draft report that is circulated to the participants. 21.7.2006.
  - ✓ Feedback on draft report by 8.9.2006.
  - ✓ Final report by mid Sept. based on feedback.
  - ✓ Presentation of report at SC meeting at OHP late Sept.
- Make an inventory of existing H_2O measurements within NDACC. Send info that you might have on existing H_2O measurements.
- Identify stations that would be suitable/desirable for Flash or CFH measurements. Coordinate with satellite overpasses.
- It was agreed that a follow-up meeting should be arranged about a year from now.
- It was discussed whether one should try to establish an atmospheric water vapour session at the EGU General Assembly of 2008.

Appendices

Agenda

Wednesday, July 5th

14.00 - 14.20	Welcome, Aim of Workshop	N. Kämpfer, G. Braathen
14.20 - 14.40	Radiosondes	Esko Kyrö
14.40 - 15.00	Water vapor observations in the upper troposphere and lower stratosphere	Niklaus Kämpfer for Holger Vömel
15.00 - 15.20	Flash sondes	Sergey Khaykin
15.20 - 15.40	SAOZ, French activities	Jean-Pierre Pommereau
15.40 - 16.20	Discussion: Balloon soundings	Esko Kyrö
16.20 - 16.50	Break	
16.50 - 17.10	FTIR Bremen	Justus Notholt
17.10 - 17.30	Water vapor partial columns retrieval from Zugspitze plus Garmisch FTIR measurements	Ralf Süssmann
17.30 - 17.45	Water vapour profiles by ground-based	

	FTIR Spectroscopy: Study for an optimised retrieval and its validation	M. Schneider, F. Hase, and T. Blumenstock
17.45 - 18.00	Ground-based FTIR remote sensing of tropospheric HDO/H2O ratio profiles	M. Schneider, F. Hase, and T. Blumenstock
18.00 - 18.30	Discussion FTIR	Justus Notholt
20.00	Dinner in Restaurant Casino, Bern, Herrengasse 25, Casinoplatz	

Thursday, July 6th

08.30 - 08.50	Lidar at table mountain	Thierry Leblanc
08.50 - 09.10	Lidar activities at Rome - Tor Vergata	Fernando Congeduti
09.10 - 09.30	Lidar at Zugspitze	Thomas Trickl
09.30 - 09.50	Lidar at MeteoSwiss	Bertrand Calpini
09.50 - 10.20	Break	
10.20 - 11.00	Discussion: Lidar	Thierry Leblanc
11.00 - 11.20	Microwave activities at table mountain, Lauder and Mauna Loa	Gerald Nedoluha
11.20 - 11.40	Microwave activities at Bern (ground based)	Alexander Haefele
11.40 - 12.00	Microwave activities at Bern (aircraft)	Stefan Müller
	Lunch	
14.00 - 15.00	Visit of instruments on roof	IAP Team
15.05 - 15.20	Microwave activities at Toulouse	Erwan Motte
15.20 - 15.40	Microwave activities at Bremen	Sven Golchert
15.40 - 16.00	Microwave activities at Merida	Gerd Hochschild
16.00 - 16.15	Microwave activities at Kiruna	Gerhard Kopp
16.15 - 16.45	Break	
16.45 - 17.30	Discussion: Microwave sensors	Niklaus Kämpfer

Friday, July 7th

08.30 - 08.50	Comparison Microwave with Satellites	Klemens Hocke
08.50 - 09.10	Comparison Microwave with Balloon	Alexander Haefele
09.10 - 09.30	MOZAIC	Herman Smit
09.30 - 09.50	Satellite measurements ODIN	Joachim Urban
09.50 - 10.20	Break	
10.20 - 11.00	Discussion: Satellites	Gerald Nedoluha
11.00 - 12.00	Summary, end of workshop	Geir Braathen, All

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