Variability and trends of water vapor and methane above the Zugspitze

Ralf Sussmann, Petra Hausmann, Andreas Ostler, Andreas Reichert, Markus Rettinger, Hannes Vogelmann, Thomas Trickl

Outline

• instruments & historical highlights
• $\text{H}_2\text{O}, \text{CH}_4$: knowns & science questions
• results $\text{CH}_4$ (trend, seasonality)
• results $\text{H}_2\text{O}$ (trends, spatio-temporal variability)
• summary
• future work
KIT Garmisch Group

“Atmospheric Variability and Trends“

Ralf Sussmann
Stefan Biggel
Petra Hausmann
Andreas Ostler
Matthias Perfahl
Andreas Reichert
Markus Rettinger
Thomas Trickl
Hannes Vogelmann

Variability & Trends, Transport, Sources & Sinks, …
Verification of Montreal Protocol, Post-Kyoto Process
Model Validation (ACTM, NIES TM, …)
Satellite Validation (ENVISAT, GOSAT, OCO-II, …)
Improving Radiation Codes (RRTM, …) in Climate Models (ECHAM, …)

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Garmisch NDACC & TCCON site: 47.5 °N, 11.1 °E, 743 m a.s.l.
Garmisch NDACC aerosol lidar

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Garmisch aerosol lidar: first understanding of contrail cross sections

≈50 s behind B-747 („Jumbo“)

Sussmann, JGR, 1999
Sussmann and Gierens, JGR, 1999
Sussmann and Gierens, JGR, 2001

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Garmisch trop. O$_3$ lidar: **long range transport, stratospheric intrusions**

May 28 and 29, 1997


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Garmisch TCCON FTIR system (since 2007)

Funding: State Government of Bavaria

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Garmisch TCCON FTIR: precision $<0.3\%$ (!)
NDACC site Zugspitze summit (47.4 °N, 11.0 °E, 2962 m a.s.l.)
NDACC FTIR at Zugspitze summit (since 1995)
Zugspitze NDACC FTIR: first detection of midlat. seas. cycle of meso. CO


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Schneefernerhaus

Funding: State government of Bavaria

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Differential absorption lidar for tropospheric water vapor (DIAL)

Some knowns: $\text{H}_2\text{O}$ and $\text{CH}_4$ are strong greenhouse gases

**water vapor**
- is the most important ghg
- accounts for about 60% of the natural greenhouse effect for clear skies

**$\text{CH}_4$**
- is the second most important anthropogenic ghg
- global warming potential (100 yr) of 25
Some knowns: life times, sources & sinks

water vapor $\approx 9.5$ days (⇒ high variability)

fast processes: evaporation and removal by condensation/precipitation

CH$_4$ $\approx 12$ years (⇒ well mixed, low variability)

Sources: anaerobic processes (natural wetlands, rice cultivation, livestock breeding), biomass burning, usage of fossil fuels

Sinks: 90 % of the loss by OH. Rest: uptake by soils, reaction with chlorine radicals
Science questions: ⇒ “spawning area”

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this happened only \( \approx 55 \) million years ago twice*:

- melting of methane clathrates in the north Atlantic
- release of \( \approx 3 \times 10^{18} \) t carbon, mostly \( \text{CH}_4 \) (remember industrialization: \( 500 \times 10^9 \) t)
- 6 K temperature increase within 1000 yr
- two events within 20 000 yr
- alligators/palms at the poles, deserts at mid latitudes, no life in the upper oceans

what about today**:

- potentially permafrost melting within next 100 yr
- will start at \( \Delta T > +2 \) K?
- e.g., in Siberia are 70 Gt frozen \( \text{CH}_4 \)
- remember ghg potential of \( \text{CH}_4 \) is 25

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Renewed methane increase for five years (2007–2011) observed by solar FTIR spectrometry

Update of: Sussmann, Forster, Rettinger, Bousquet, Atmos. Chem. Phys., 2012

How can we detect and quantify sources and sinks on regional to continental scale?

**Tentative explanation:**

- 1999-2006 near-zero increase: global anthropogenic emissions increased but wetland emissions decreased due to long-lasting drier conditions in various regions of the Northern Hemisphere
- after 2006 continuous renewed increase because wetland emissions have risen back to a normal level
Answer: by inverse modeling of global methane measurements

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Global column measurements of CH$_4$ (or CO$_2$): requirements

- high atmospheric background columns of CH$_4$ (or CO$_2$)
- strongest sources and sinks induce (only) $\approx 1\%$ relative changes in columns

$\Rightarrow$ requirement for CH$_4$ (or CO$_2$) column measurements:
- relative seasonal and latitudinal accuracy $<< 1\%$
  target: 3 per mille
Sussmann, Stremme, Buchwitz, de Beek, Atmos. Chem. Phys., 2005

SCIAMACHY: Channel 8, icing issue
Algorithm version WFMD v0.4
WFMD v0.41

Zugspitze FTIR

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Later in 2005: **Solution to icing problem ⇒ use of channel 6 (1.66 µm)**


SCIAMACHY – TM3

⇒ strong tropical methane enhancements !(?)

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The problem is severe because of the high variability of H$_2$O and the low variability of CH$_4$.

\[
\hat{t} - t = (A_{tt} - I)(t - t_a) + A_{tv1}(v_1 - v_{1a}) + A_{tv2}(v_2 - v_{2a}) + \ldots + \varepsilon_t \]

...smoothing error

...interference error

We call $A_{tv1}$, $A_{tv2}$, ... interference kernel matrices.
2008: SCIAMACHY tropical methane enhancements too high


≈ 3 % CH₄ errors related to the H₂O column
⇒ tropics are humid ⇒ erroneous tropical CH₄ enhancements!

errors gone with improved H₂O spectroscopy

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Validation 2009: But still seasonality riddle SCIA versus g.-b. FTIR

Zugspitze 2003 IMAP-DOAS v49

"frown" 😞

"smiley" 😊

SCIAMACHY

NDACC FTIR - Zugspitze
Validation 2009: seasonality riddle at many sites

Question: Who is right?
2010: identify and quantify $\text{H}_2\text{O-CH}_4$-interference problem of g.-b. FTIR

Sussmann, Forster, Rettinger, Jones, Atmos. Meas. Tech., 2011

Ralf Sussmann et al.: Variability and trends of water vapor and methane above the Zugspitze
2011: eliminate H₂O-CH₄-interference problem of g.-b. FTIR

Sussmann et al., Atmos. Meas. Tech., 2011:

- found that HITRAN 2008 has larger errors than old HITRAN 2000 (!)

⇒ use HITRAN 2000 and removed spectral windows 2 and 4 from retrieval

... finally SCIAMACHY people used CO₂ from carbon tracker with wrong seasonality for calculating the dry-air column reference for XCH₄ ...

⇒ new carbon tracker version eliminates this SCIA problem
Validation 2011: NDACC-SCIAMACHY – XCH4 seasonality riddle solved!

Sussmann, Forster, Rettinger, Jones, AMT, 2011: H₂O-CH₄ interference eliminated
Schneising et al., 2011; Frankenberg et al., 2011: new carbon tracker version

Sussmann et al., AMT, 2013; Ostler, Sussmann et al., 2014: seasonality also agrees with new TCCON network

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**Column water vapor – variability & trend studied with FTIR & Lidar: Why?**

- evidence for long-term changes in IWV is limited by the availability and quality of measurements (Trenberth et al., IPCC 2007)
- trend studies of IWV have mainly been based on radiosondes (e.g., Ross and Elliott, 2001)
- homogeneity of the radiosonde records was affected by changes in instrumentation and reduction of sounding activities (Elliott et al., 2002; Miloshevich et al., 2006)
- statistically significant, long-term trends in climate variables are difficult to derive from satellite data because of problems with satellite intercalibration and sensor drift (Hurrel and Trenberth, 1997; 1998; Christy et al., 1998; Wenz and Schabel, 1998; Trenberth et al., 2007).
- first reliable, satellite based IWV trend studies via ERS-2/GOME and ENVISAT/SCIAMACHY data were reported only recently (Wagner et al., 2006; Mieruch et al., 2008).

**Potential for:**
- NDACC-FTIR data – hitherto unused for water vapor
- Lidar: new developments
Science question: **water vapor feedback**

Wagner, Beierle, Grzegorski, Platt, JGR, 2006 (GOME satellite data)
Mieruch, Noel, Bovensmann, Burrows, ACP, 2008 (SCIAMACHY satellite data)

Investigate: can NDACC confirm non-thermodynamic behavior above land?

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FTIR water vapor retrieval: spectral micro windows

010-010
R10, R14
water lines,
1 solar OH line

Sussmann, Borsdorff, Rettinger, Camy-Peyret, Demoulin, Duchatelet, Mahieu, and Servais, Atmos. Chem. Phys., 2009

Kämpfer (ed.): “Monitoring atmospheric water vapor“, Springer 2013

010-010
R11
water line

010-010
R10, R13, R16
water lines

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FTIR water vapor retrieval: matching to radiosonde response

\[ \alpha = 10^7 \]
\[ \alpha = 890 \]
\[ \alpha = 183 \]
\[ \alpha = 62 \]
\[ \alpha = 43 \]

\[ \alpha = \alpha_{opt} = 183 \]
\[ \text{dofs} = \text{dofs}_{opt} = 1.84 \]

impact of regularization strength \( \alpha \) of FTIR retrieval

\( \alpha \): strength of Tikhonov first-derivative regularization

\( R = 0.99 \)
\( N = 25 \)

slope = 1.00 \( \pm \) 0.03
intercept = 0.015 mm \( \pm \) 0.121 mm
bias = 0.015 mm \( \pm \) 0.054 mm
stdv = 0.27 mm

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Water vapor column trends: Zugspitze and Jungfraujoch FTIRs

Update of Sussmann, Borsdorff, Rettinger, Camy-Peyret, Demoulin, Duchatelet, Mahieu, and Servais, Atmos. Chem. Phys., 2009

• weakly positive (insignificant) IWV trends above Zugspitze and Jungfraujoch
• agrees with Bern microwave trend (Hocke, Kämpfer et al., Int. J. Remote Sens., 2011)
Water vapor soundings with FTIR and lidar at the Zugspitze

FTIR, 2964m

2675m

Schneefernerhaus

Sonnalpin
Water vapor variability from combined lidar & FTIR: setup & geometry

locations of vertical center of gravity of FTIR H₂O slant columns
Variability of integrated water vapor from lidar & FTIR: spatial variability

σ of differences (lidar-FTIR) as a function of spatial mismatch

Δt < 30 min (summer data)

Implication:

- most sensor intercomparison studies suffered from too loose spatial matching criteria, e.g. Δx < 100 km
- Δx should be < 2 km
σ of the differences (lidar-FTIR) as a function of temporal mismatch

Implication:

• most sensor intercomparison studies suffered from too loose temporal matching criteria, e.g. Δt < 1 day
• Δt should be < 10 min
Variability of integrated water vapor from lidar & FTIR: seasonality

σ of differences (lidar-FTIR) as a function of season

(Δt < 20 min)
Water vapor variability from lidar profiles: *vertical short term variability*

example of long-range transport of humid air from a remote boundary layer

![Graph showing water vapor density vs. altitude]

- Orig.: subarctic UT
- Orig.: Pacific PBL
- Orig.: subtr. North Atl. PBL
- Orig.: subtr. North Atl. PBL
Water vapor variability from lidar profiles: *vertical short term variability*

example of a stratospheric intrusion: 3 extremely dry layers (RH < 1 %)

water vapor density \((10^{21} \text{ m}^{-3})\)

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Water vapor variability from lidar profiles: **vertical short term variability**

Variability reflects horizontal and vertical transport up to >100 m/s in the jet stream.

Zugspitze NCEP reanalysis

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Summary

• CH$_4$ columns trend well measured: 5 years renewed CH$_4$ increase
• CH$_4$ columns seasonality riddle solved (Odyssey 2004-2014)
• H$_2$O columns trend weak, difficult to derive due to variability
• H$_2$O columns & profile variability  
  - first steps towards quantitative understanding of spatio-temporal variability  
  - most H$_2$O sensor intercomparisons suffered from too loose matching criteria

Outlook (Bavarian Project “Virtual Alpine Observatory VAO-II“)

• radiative closure experiment to improve water vapor absorption parameters in climate models  
• investigate water vapor trends (serval stations, columns, UTLS, link to CH$_4$)  
• Issue Funding of Partners: Prof. Niklaus Kämpfer (Microwave, Uni Bern) & Dr. Emmanuel Mahieu (Jungfraujoch FTIR, Uni Liège)

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