**Why a FTIR retrieval specially optimized to column-integrated water vapor?**

- IWV accounts for about 60% of the natural greenhouse effect for clear skies and provides the largest positive feedback in model projections of climate change.
- 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).
Harmonized multi-station trends in column-integrated water vapor

Ralf Sussmann, Tobias Borsdorff, Markus Rettinger, Claude Camy-Peyret, Philippe Demoulin, Pierre Duchatelet, Emmanuel Mahieu, and Christian Servais

Outline - contents of paper recently accepted for ACPD, and ISSI book chapter

- microwindows
- principle of Tobin radiosondes
- a priori profile
- regularization
- matching FTIR to radiosonde characteristics
- station-to-station harmonization
- precision and bias
- comparison with other sounding techniques
- trends at Zuspitze and Jungfraujoch
- geophysical discussion of trend results
Water vapor retrieval: Interference-free micro windows, Toth update

HITRAN1996

HITRAN2000

010-010
R10, R14
water lines,
1 solar OH line: deweighted in $S_e$

010-010
R11
water line

010-010
R10, R13, R16
water lines

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Harmonized multi-station trends in column-integrated water vapor
Construct FTIR a priori profile & FTIR-radiosonde coincidences: “Tobin” principle

Sonde 1 launched 1h before overpass
Sonde 2 launched 5 min before overpass

AIRS validation campaign
19 Aug 2002 - 17 Nov 2002

Vaisala RS 80-30 G sondes
TOTEX-800-g balloons
2 x Digicora III (Marvin 21, SPS220G)

TOBIN-Inter-/Extrapolation between both soundings:

\[ q_{Tobin}(z, t_{op}) = q_{sonde}(z, t_0) + (dq(z)/dt) (t_{op} - t_0) \]


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Harmonized multi-station trends in column-integrated water vapor
Water vapor retrieval: A priori profile

Harmonized multi-station trends in column-integrated water vapor
Findings from the radiosondes:

- Profile variability is on average well approximated by a simple VMR-profile scaling = altitude constant changes on the %-VMR scale.
- Columns variability is very high.

Search for a regularization that:

1. Constrains to some extent the profile shape (to avoid oscillations).
2. Does not at all constrain altitude-constant changes on the %-VMR scale (⇒ “free scaling”).
Regularization for water vapor retrieval: **Use Tikhonov-L₁ on the %-VMR scale**

\[
R = \alpha L_1^T L_1 = \alpha \times \begin{pmatrix}
1 & -1 & 0 & \cdots & 0 \\
-1 & 2 & \ddots & \ddots & \vdots \\
0 & \ddots & \ddots & \ddots & 0 \\
\vdots & \ddots & \ddots & 2 & -1 \\
0 & \cdots & 0 & -1 & 1
\end{pmatrix} \in \mathbb{R}^{n \times n}
\]

with regularization strength \( \alpha \).

Case \( \alpha \rightarrow \infty \) any change in profile shape totally is forbidden, any altitude constant change fully allowed: \( dofs \rightarrow 1 \).

Case \( \alpha \rightarrow 0 \) is a totally unconstrained profile retrieval with \( dofs \rightarrow n = \) number of model layers (oscillations)

\( L_1 \) constrains only the profile shape and any altitude constant change is fully allowed

\( \Rightarrow \) profile oscillations are avoided

\( \Rightarrow \) true columns variability is not damped (crucial for water vapor)

---

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**Harmonized multi-station trends in column-integrated water vapor**
Which regularization strength $\alpha$ to use? : Tune $\alpha$ for matching to radiosondes

(a) Impact of regularization strength $\alpha$ of FTIR retrieval

(b) Correlation parameters FTIR - sonde

regularization strength $\alpha$ of FTIR retrieval

degrees of freedom of signal of FTIR retrieval

IWV from Tobin radiosondes (mm)

IWV from FTIR (mm)

$\alpha = 10^7$
$\alpha = 890$
$\alpha = 183$
$\alpha = 62$
$\alpha = 43$

$\alpha_{opt} = 183$

dofs$_{opt} = 1.84$

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Harmonized multi-station trends in column-integrated water vapor
Tune $\alpha$ for matching to radiosondes: The optimum-$\alpha$ result

(c) linear fit

slope = 1.00 ± 0.03
intercept = 0.015 mm ± 0.121 mm
bias = 0.015 mm ± 0.054 mm
stdv = 0.27 mm
$R = 0.99$
$N = 25$

$\alpha = \alpha_{opt} = 183$
$dofs = dofs_{opt} = 1.84$
Water vapor FTIR-FTIR side-by-side intercomparison: Variability & coincidence

- side-by-side measurements with two FTIR systems at ISSJ between 1995 - 2001
- note that the exponential increase reflects an atmospheric property (water vapor variability) and is not due to the instruments

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Harmonized multi-station trends in column-integrated water vapor
Optimum FTIR water columns retrieval: **Precision and bias**

Precision (1 sigma) and bias of optimized FTIR IWV retrievals derived from a sideby-side intercomparison of two FTIR instruments at the Jungfraujoch.

<table>
<thead>
<tr>
<th>precision(^1) (mm)</th>
<th>precision(^1) (% of mean IWV)</th>
<th>bias (mm)</th>
<th>bias (% of mean IWV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>2.2</td>
<td>0.02(1)</td>
<td>0.96(52)</td>
</tr>
</tbody>
</table>

\(^1\) for \(\approx\)15 min FTIR integration

… sounds good but how does it compare to other techniques?
IWV correlation parameters from a FTIR side-by-side intercomparison and examples for comparisons of all different ground-based remote techniques versus radiosondes: FTIR, microwave (TROWARA, GBMS), GPS, sun photometer (PFR), and Raman lidar (BASIL). Errors are for 1 sigma confidence, N is the number of coincidences.

<table>
<thead>
<tr>
<th></th>
<th>( \Delta t )</th>
<th>( \Delta x^1 )</th>
<th>slope</th>
<th>intercept</th>
<th>bias</th>
<th>stdv</th>
<th>stdv (% of mean)</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTIR-FTIR(^2)</td>
<td>3.75</td>
<td>0</td>
<td>1.001(7)</td>
<td>0.02(2)</td>
<td>0.02(1)</td>
<td>0.07</td>
<td>3.1</td>
<td>0.999</td>
<td>32</td>
</tr>
<tr>
<td>FTIR-FTIR(^2)</td>
<td>30</td>
<td>0</td>
<td>1.008(4)</td>
<td>0.00(1)</td>
<td>0.02(1)</td>
<td>0.11</td>
<td>4.4</td>
<td>0.998</td>
<td>267</td>
</tr>
<tr>
<td>FTIR-FTIR(^2)</td>
<td>120</td>
<td>0</td>
<td>1.002(5)</td>
<td>0.03(2)</td>
<td>0.04(1)</td>
<td>0.23</td>
<td>8.0</td>
<td>0.998</td>
<td>773</td>
</tr>
<tr>
<td>FTIR-sonde(^3)</td>
<td>120</td>
<td>8</td>
<td>1.00(3)</td>
<td>0.02(12)</td>
<td>0.02(5)</td>
<td>0.27</td>
<td>7.9</td>
<td>0.99</td>
<td>25</td>
</tr>
<tr>
<td>TROWARA-sonde(^4)</td>
<td>120</td>
<td>40</td>
<td>0.88</td>
<td>1.36</td>
<td>0.36</td>
<td>2.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jungfraujoch GPS-sonde(^4)</td>
<td>30</td>
<td>80</td>
<td>1.12</td>
<td>0.39</td>
<td>0.53</td>
<td>1.39</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jungfraujoch PFR-sonde(^4)</td>
<td>30</td>
<td>80</td>
<td>0.76</td>
<td>0.52</td>
<td>0.08</td>
<td>1.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>FTIR-sonde(^5)</td>
<td>120</td>
<td>0</td>
<td>0.85(1)</td>
<td>0.66(9)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>136</td>
</tr>
<tr>
<td>BASIL-sonde(^6)</td>
<td>20</td>
<td>0</td>
<td>1.07(2)</td>
<td>-0.04(3)</td>
<td>0.09(2)</td>
<td>0.07</td>
<td>3.6</td>
<td>0.99</td>
<td>17</td>
</tr>
<tr>
<td>GBMS-sonde(^6)</td>
<td>20</td>
<td>0</td>
<td>0.98(4)</td>
<td>0.08(7)</td>
<td>0.05(3)</td>
<td>0.15</td>
<td>8.9</td>
<td>0.98</td>
<td>23</td>
</tr>
</tbody>
</table>

\(^1\) Distance between ground-based sounder and radiosonde launch site.
\(^2\) This work (individual measurements of 2 Jungfraujoch FTIRs).
\(^3\) This work (2 hr-Zugspitze FTIR versus Tobin radiosondes, see Fig. 3c).
\(^4\) Taken from Figs. 9 and 10 in Morland et al. (2006).
\(^5\) Taken from Palm et al. (2008), retrieval different than that in our work.
\(^6\) Computed from digitalization of data points of Figs. 6 and 7a in Fiorucci et al. (2008).
Effective regularization strength depends linearly on spectral point spacing $p$. Therefore, possible station-to-station differences in $p$ should be compensated for by correcting $\alpha$:

$$\frac{\alpha_{\text{station}}}{\alpha_{\text{Zugspitze}}} = \frac{p_{\text{Zugspitze}}}{p_{\text{station}}},$$

with $\alpha_{\text{Zugspitze}} = 183$ and $p_{\text{Zugspitze}} = 0.0015 \text{ cm}^{-1}$ as reference.
a threshold for the root-mean-square (rms) residuals of the spectral fit was used

a value for the threshold was derived by inspection of the probability distribution of all residuals of the Zugspitze time series. This distribution is right skewed with only 5 % of the retrievals showing exceptionally high-rms residuals. Therefore, the rms threshold was set to exclude these 5 %

we found similar behavior for the Jungfraujoch. Therefore, also for ISSJ the \( \approx 5 \% \) highest-rms retrievals were excluded
Optimum water columns retrieval: time series and trends

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Harmonized multi-station trends in column-integrated water vapor
Optimum water columns retrieval: time series and trends

Zugspitze FTIR measured trend + intra-annual trend

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Harmonized multi-station trends in column-integrated water vapor
Optimum water columns retrieval: time series and trends

Jungfraujoch FTIR

measured  trend + intra-annual  trend

Harmonized multi-station trends in column-integrated water vapor
### Zugspitze & Jungfraujoch water trends: bootstrap analysis of trend existence

<table>
<thead>
<tr>
<th>Period</th>
<th>Trend (mm/decade)</th>
<th>Uncertainty interval [2.5th percentile, 97.5th percentile] (mm/decade)</th>
<th>Significant non-zero trend? (95% confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zugspitze [1996 – 2008]</td>
<td>0.79</td>
<td>[0.65, 0.92]</td>
<td>yes</td>
</tr>
<tr>
<td>Zugspitze [1996 – 2002]</td>
<td>0.63</td>
<td>[0.20, 1.06]</td>
<td>yes</td>
</tr>
<tr>
<td>Jungfraujoch [1996 - 2008]</td>
<td>0.08</td>
<td>[-0.01, 0.17]</td>
<td>no</td>
</tr>
<tr>
<td>Jungfraujoch [1996 - 2002]</td>
<td>-0.04</td>
<td>[-0.27, 0.19]</td>
<td>no</td>
</tr>
<tr>
<td>Jungfraujoch [2003 - 2008]</td>
<td>0.05</td>
<td>[-0.18, 0.28]</td>
<td>no</td>
</tr>
<tr>
<td>Jungfraujoch [1988 - 2008]</td>
<td>0.04</td>
<td>[-0.01, 0.10]</td>
<td>no</td>
</tr>
</tbody>
</table>
Differing Zugspitze & Jungfraujoch water trends: geophysical discussion

Found a zero trend for Jungfraujoch but a significant positive trend for Zugspitze

⇒ the reason be due to the horizontal distance (∼250 km) and/or the altitude difference (3.58-2.96 km) of the two stations. This would imply either an altitude dependency with a significantly higher (positive) trend below 3.58 km than above and/or rather strong regional variations of IWV trends on the scale of 250 km.

⇒ is it geophysically possible that decadal IWV trends change sign on the horizontal scale of ∼250 km?
Differing Zugspitze & Jungfraujoch water trends: **geophysical discussion**

“absolute trends not trustable, but clear indication of higher spatial variability of IWV trends over land”

**Spatial Trend of NVAP TPW 1988 - 1999**

Figure 4: Slope of the TPW anomaly regression line for 1988 – 1999.

Differing Zugspitze & Jungfraujoch water trends: geophysical discussion

Is it geophysically possible that decadal IWV trends change sign on the horizontal scale of ≈250 km?

Yes:

**Above ocean** IWV trends correlate with SST

However, above **land** the positive ST-IWV correlation is often reversed by
- dried out (closed) earth-surfaces and
- intelligent plant behavior (anti-perspiration)

This leads to the fact that significant changes in IWV trends on the scale of ≈250 km are rather the rule than the exception.

Very recently confirmed by “good” satellite data:


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Harmonized multi-station trends in column-integrated water vapor
Summary
• interference-free micro-window set
• Tobin radiosondes: defined coincidences
• a priori profile: radiosondes
• regularization: Tikhonov-L$_1$ on %-VMR scale
• matching FTIR to radiosonde characteristics: via alpha
• station-to-station harmonization: point spacing, quality selection
• precision (<0.05 mm) and bias (≈0.02 mm)
• comparison with other sounding techniques: “FTIR comp. or better“
• decadal IWV trends at Zuspitze (positive) and Jungfraujoch (zero)
• geophysical interpretation: positive trend below 3.58 km and/or strong spatial variability of decadal IWV trends over land (no strict correlation between ST and IWV)

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REFERENCES:
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ISSI book chapter 2009/10

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Harmonized multi-station trends in column-integrated water vapor