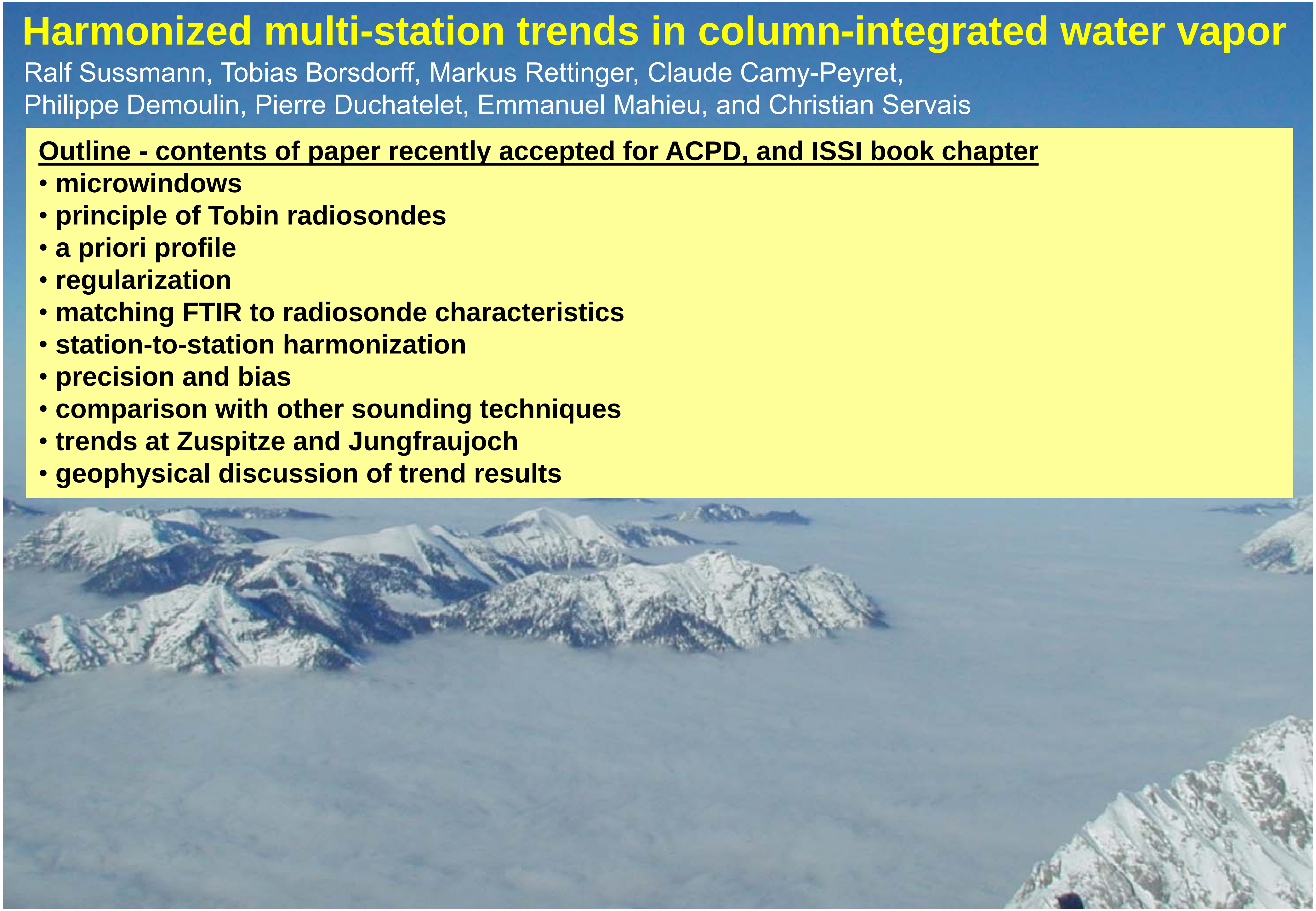
Harmonized multi-station trends in column-integrated water vapor

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

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).



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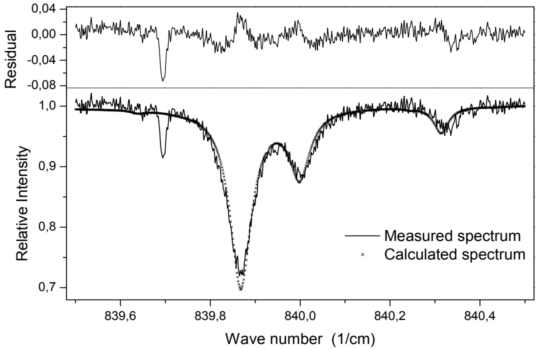
Outline - contents of paper recently accepted for ACPD, and ISSI book chapter

- **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**

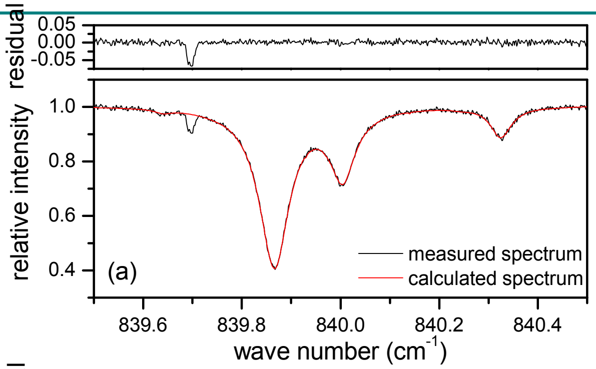
Water vapor retrieval: Interference-free micro windows, Toth update

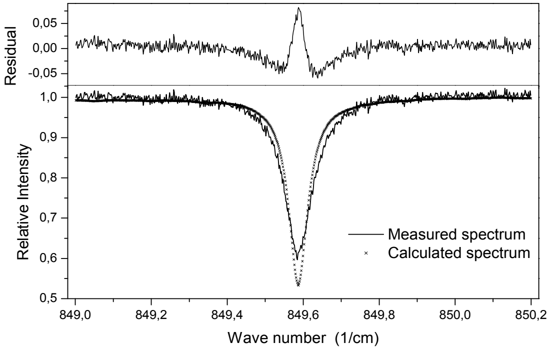
HITRAN1996

HITRAN2000

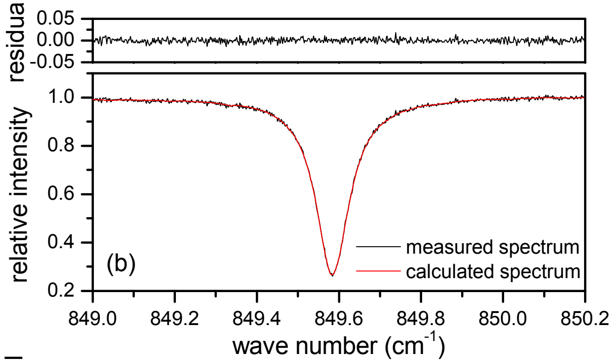


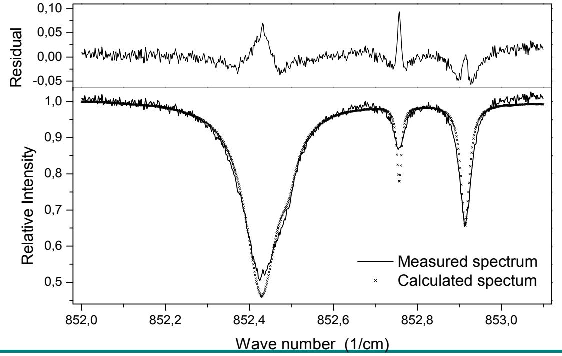
010-010
R10, R14
water lines,
1 solar OH line: deweighted in $\mathbf{S}_e$



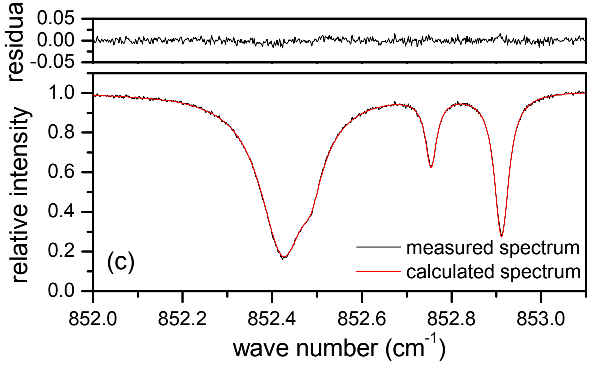


010-010
R11
water line





010-010
R10, R13, R16
water lines



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

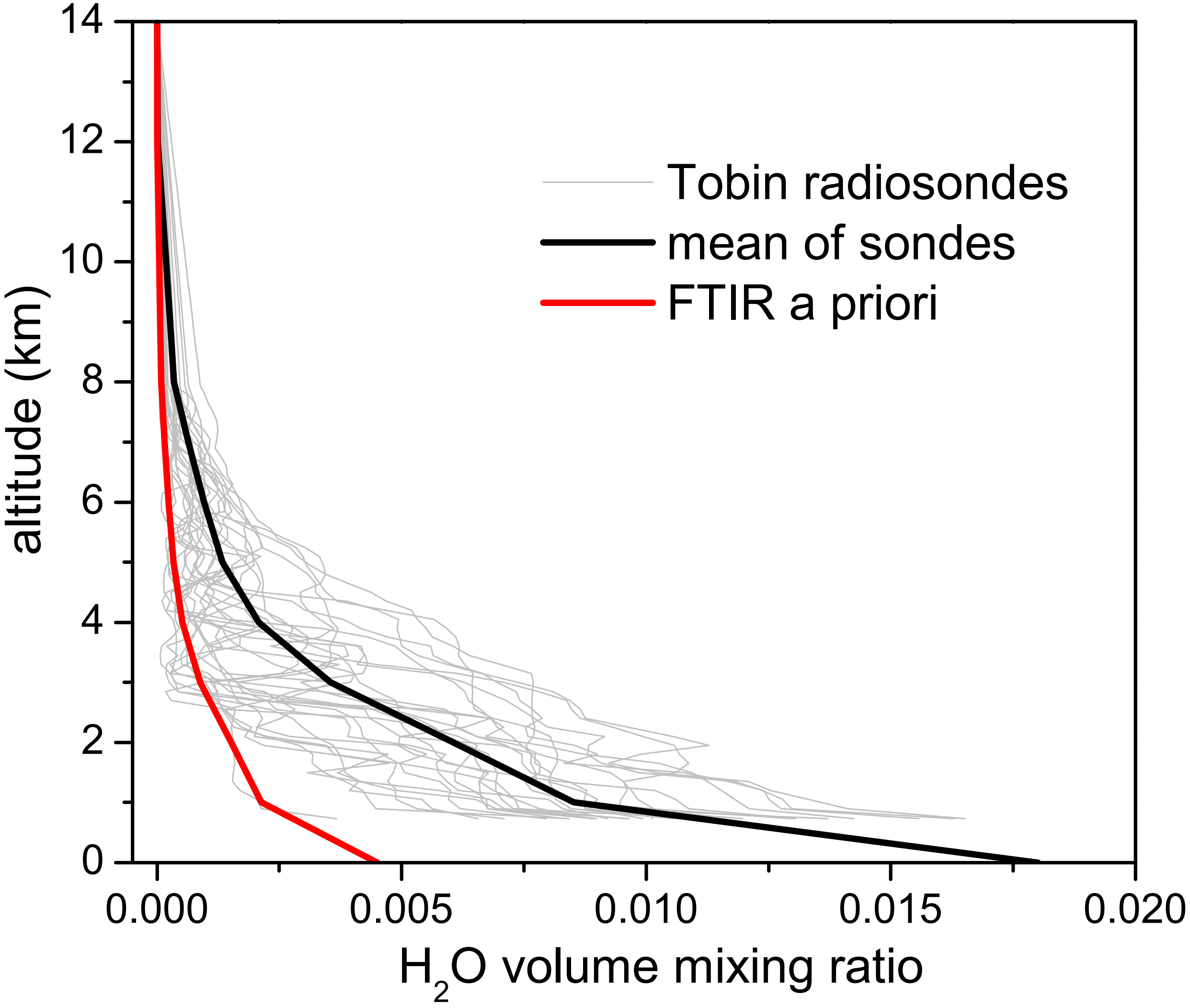
Vaisala RS 80-30 G sondes
TOTEX-800-g balloons
2 x Digicora III (Marvin 21, SPS220G)

TOBIN-Inter-/Extrapolation between both soundings:

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

Tobin, D., W. Feltz, B. Knuteson, H. Revercomb, *“ARM T/q Best Estimate Profiles for AIRS validation”,* 1 March 2000

Water vapor retrieval: A priori profile



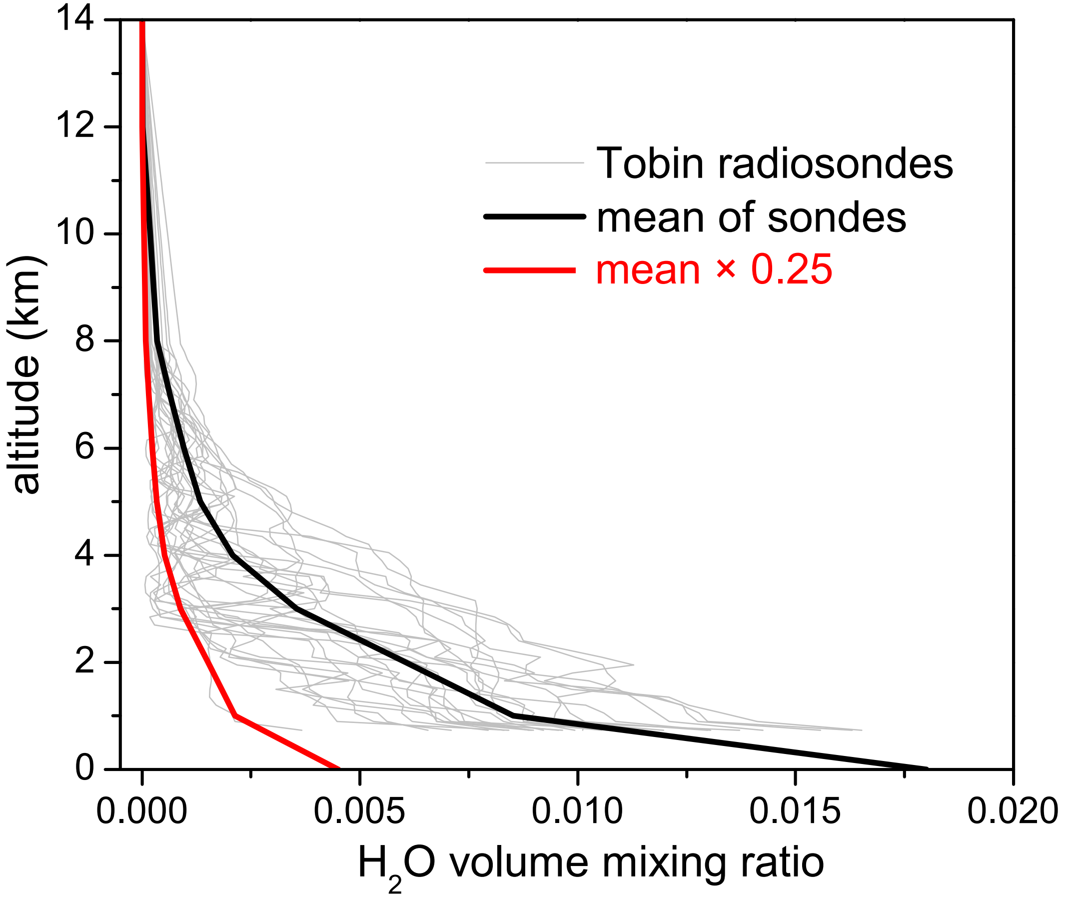
Water vapor retrieval: Regularization approach

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-L_1 on the %-VMR scale

$$\mathbf{R} = \alpha\, \mathbf{L}_1{}^T \mathbf{L}_1 = \quad \alpha \times \begin{pmatrix} 1 & -1 & 0 & \cdots & 0 \\ -1 & 2 & \ddots & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & 2 & -1 \\ 0 & \cdots & 0 & -1 & 1 \end{pmatrix} \in \Re^{n \times n}$$

with regularization strength α.

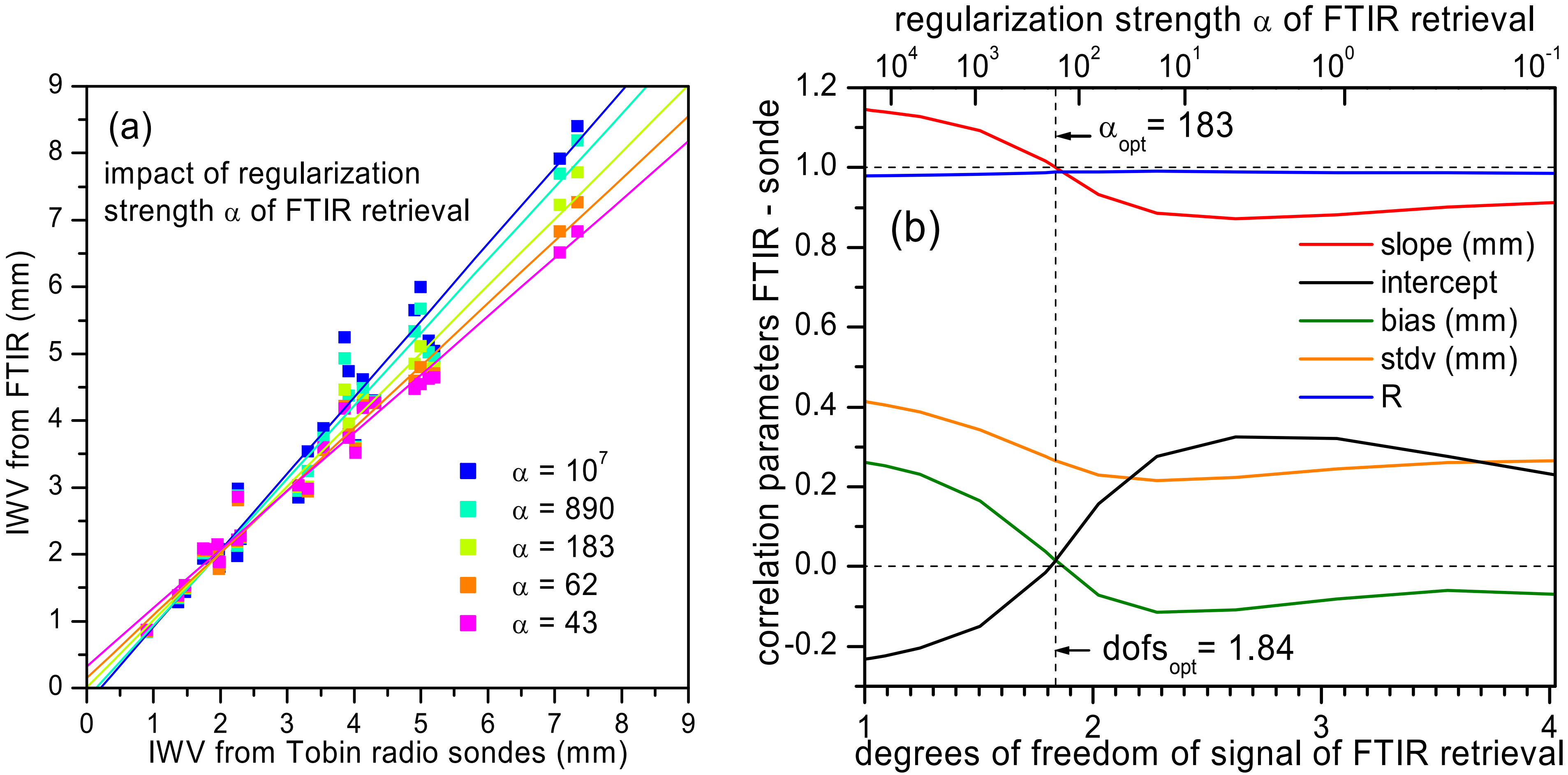
Case $\alpha \to \infty$ any change in profile shape totally is forbidden, any altitude constant change fully allowed: $dofs \to 1$.
Case $\alpha \to 0$ is a totally unconstrained profile retrieval with $dofs \to n$ = number of model layers (oscillations)

👍L_1 constrains only the profile shape and any altitude constant change is fully allowed

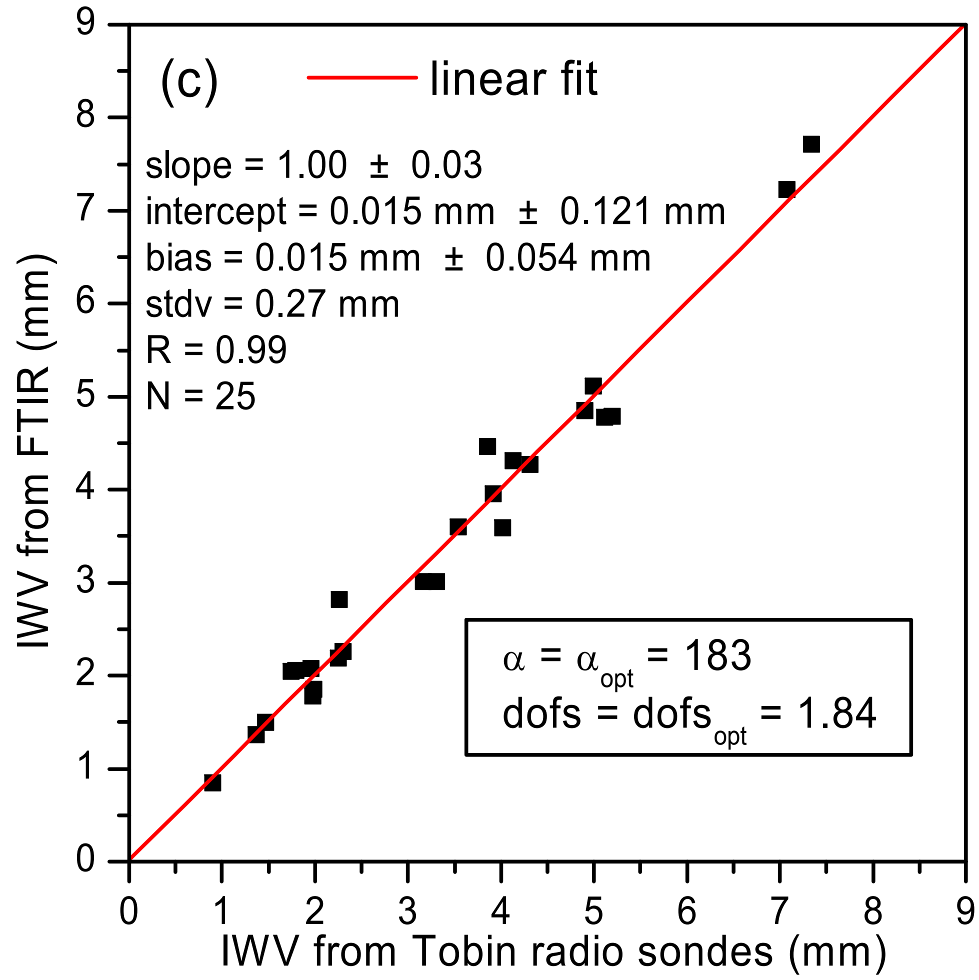
⇒ profile oscillations are avoided

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

Which regularization strenght α to use? : Tune α for matching to radiosondes

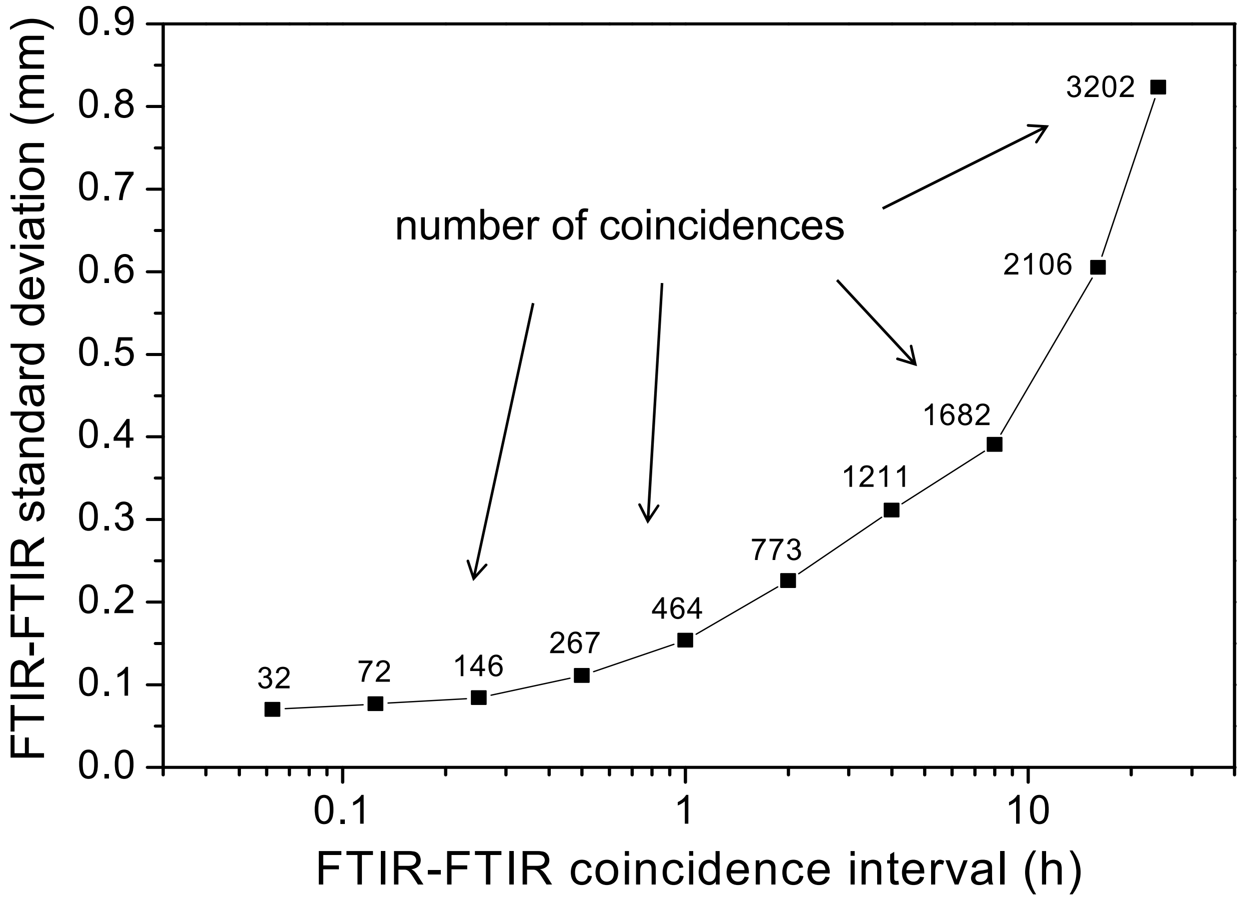


Tune α for matching to radiosondes: The optimum-α result



Water vapor FTIR-FTIR side-by-side intercomparison: Variability & coincidence

stdv of differences of coincident columns



- 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

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.

precision[1] (mm)	precision[1] (% of mean IWV)	bias (mm)	bias (% of mean IWV)
0.05	2.2	0.02(1)	0.96(52)

[1] for ≈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.

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

[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).

Harmonized station-to-station transfer of retrieval : point spacing

Effective regularization strength depends linearly on spectral point spacing *p*. Therefore, possible station-to-station differences in *p* should be compensated for by correcting *α* :

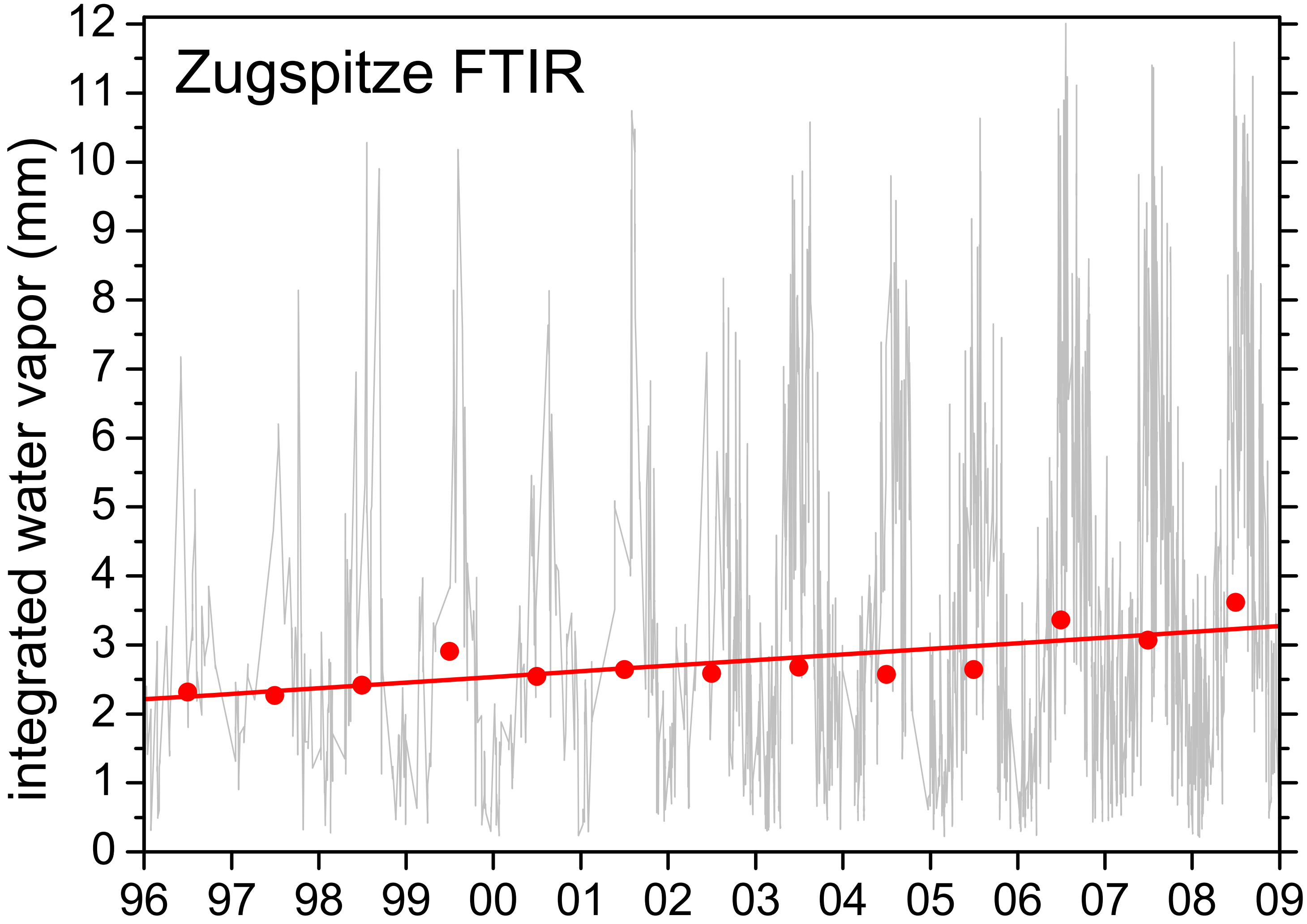
$$\alpha_{\text{station}} / \alpha_{\text{Zugspitze}} = p_{\text{Zugspitze}} / p_{\text{station}},$$

with $\alpha_{\text{Zugspitze}} = 183$ and $p_{\text{Zugspitze}} = 0.0015\ \text{cm}^{-1}$ as reference.

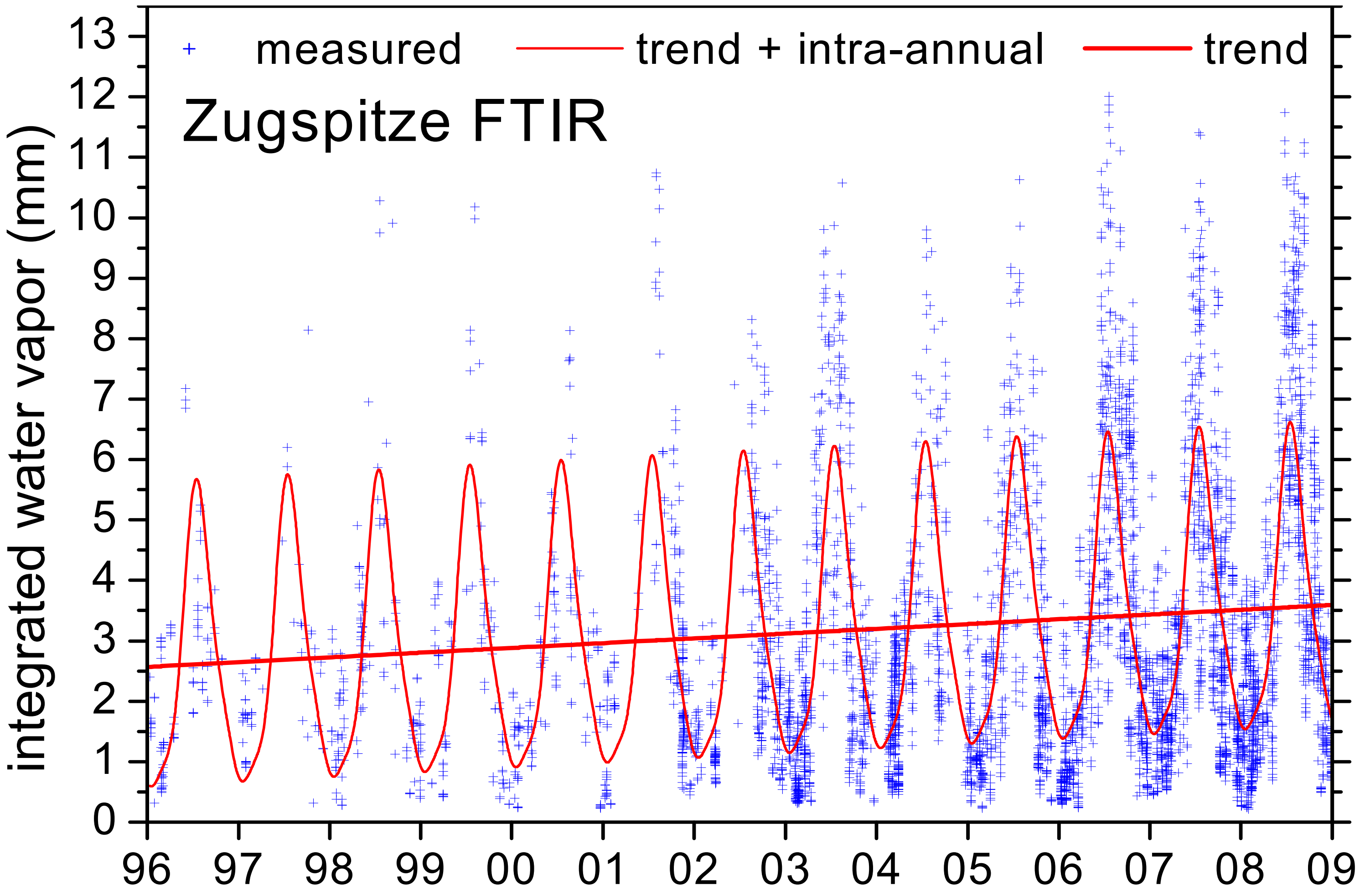
Harmonized station-to-station transfer of retrieval : quality selection

- 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 ≈5 % highest-rms retrievals were excluded

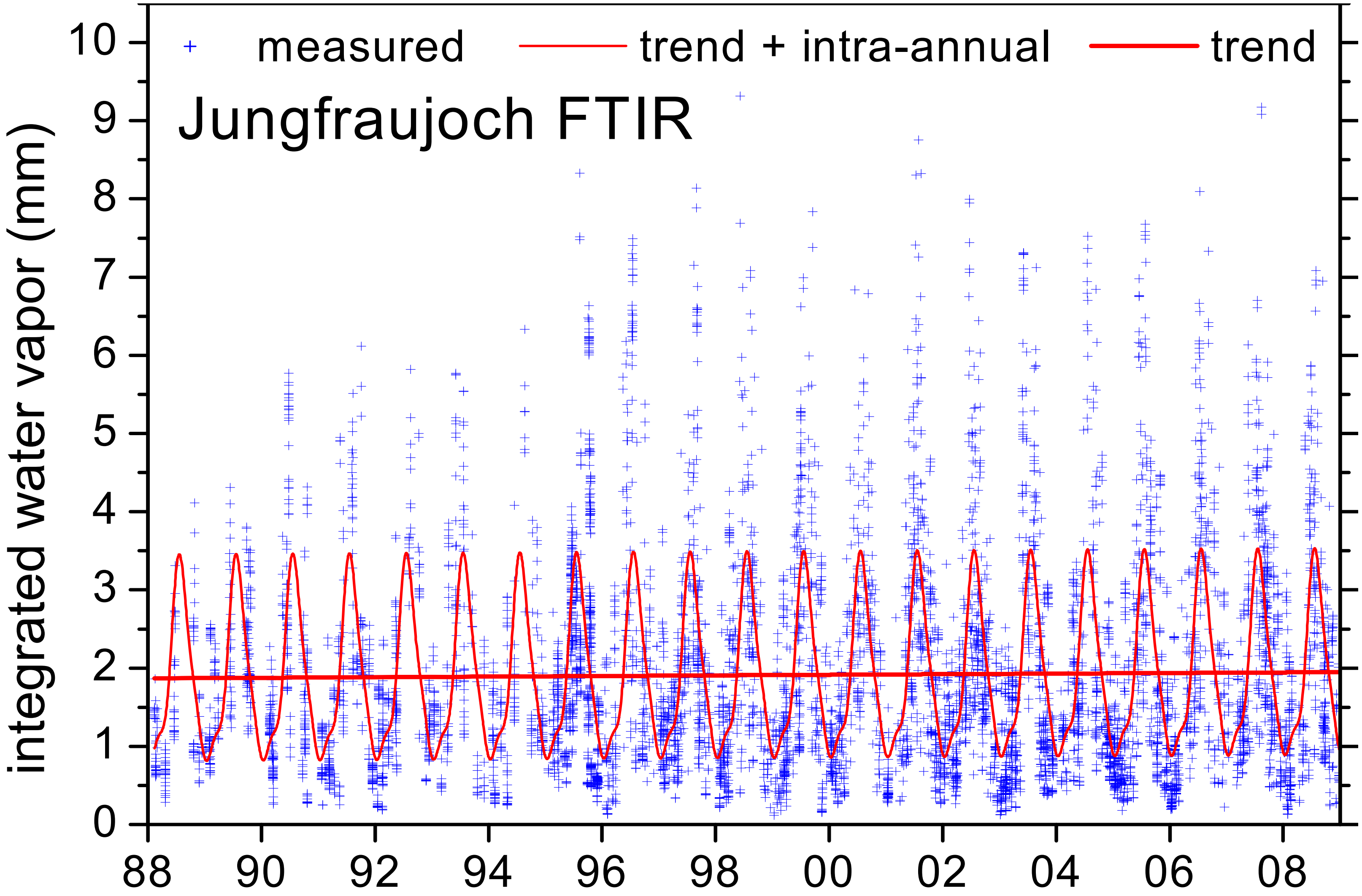
Optimum water columns retrieval: time series and trends



Optimum water columns retrieval: time series and trends



Optimum water columns retrieval: time series and trends



Zugspitze & Jungfraujoch water trends: bootstrap analysis of trend existence

	trend (mm/decade)	uncertainty interval [2.5th percentile, 97.5th percentile][1] (mm/decade)	significant non-zero trend? (95 % confidence)
Zugspitze [1996 – 2008]	**0.79**	**[0.65, 0.92]**	**yes**
Zugspitze [1996 – 2002]	**0.63**	**[0.20, 1.06]**	**yes**
Zugspitze [2003 – 2008]	**1.41**	**[1.14, 1.69]**	**yes**
Jungfraujoch [1996 - 2008]	0.08	[-0.01, 0.17]	no
Jungfraujoch [1996 - 2002]	-0.04	[-0.27, 0.19]	no
Jungfraujoch [2003 - 2008]	0.05	[-0.18, 0.28]	no
Jungfraujoch [1988 - 2008]	0.04	[-0.01, 0.10]	no

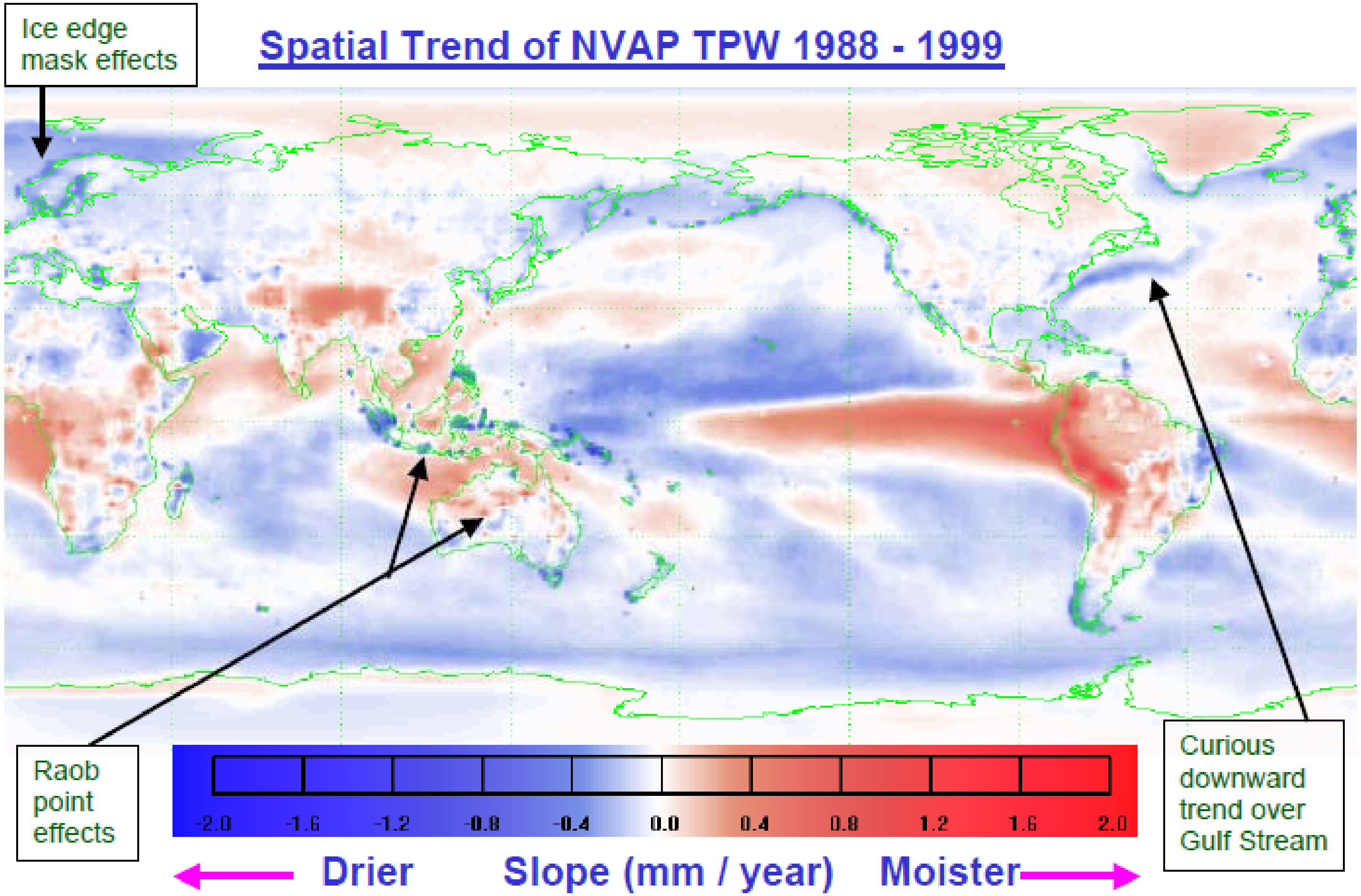
Differing Zugspitze & Jungfraujoch water trends: geophysical discussion

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



Spatial Trend of NVAP TPW 1988 - 1999

Ice edge mask effects

Raob point effects

Curious downward trend over Gulf Stream

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

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

Vonder Haar, T. H., Forsythe, J. M., Juo, J., Randel, D. L., and Woo, S.: Water vapor trends and variability from the global NVAP dataset, 16th Symposium on Global Change and Climate Variations, 9-13 January 2005, San Diego, California, American Meteorological Society, P5.16, 2005.

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:

Wagner, T., Beirle, S., Grzegorski, M., and Platt, U.: Global trends (1996–2003) of total column precipitable water observed by Global Ozone Monitoring Experiment (GOME) on ERS-2 and their relation to near-surface temperature, J. Geophys. Res., 111, D12102, doi:10.1029/2005JD006523, 2006.

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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ISSI book chapter 2009/10
Sussmann and Camy-Peyret, 2002, http://www.imk-ifu.kit.edu/downloads/AIRSVAL_Phase_I_Report.pdf
Susmann and Camy-Peyret, 2003, http://www.imk-ifu.kit.edu/downloads/AIRSVAL_Phase_II_Report.pdf