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Characterization of Precipitable Water Vapor at the TMT Candidate Sites in Northern Chile: The Importance of Surface Data

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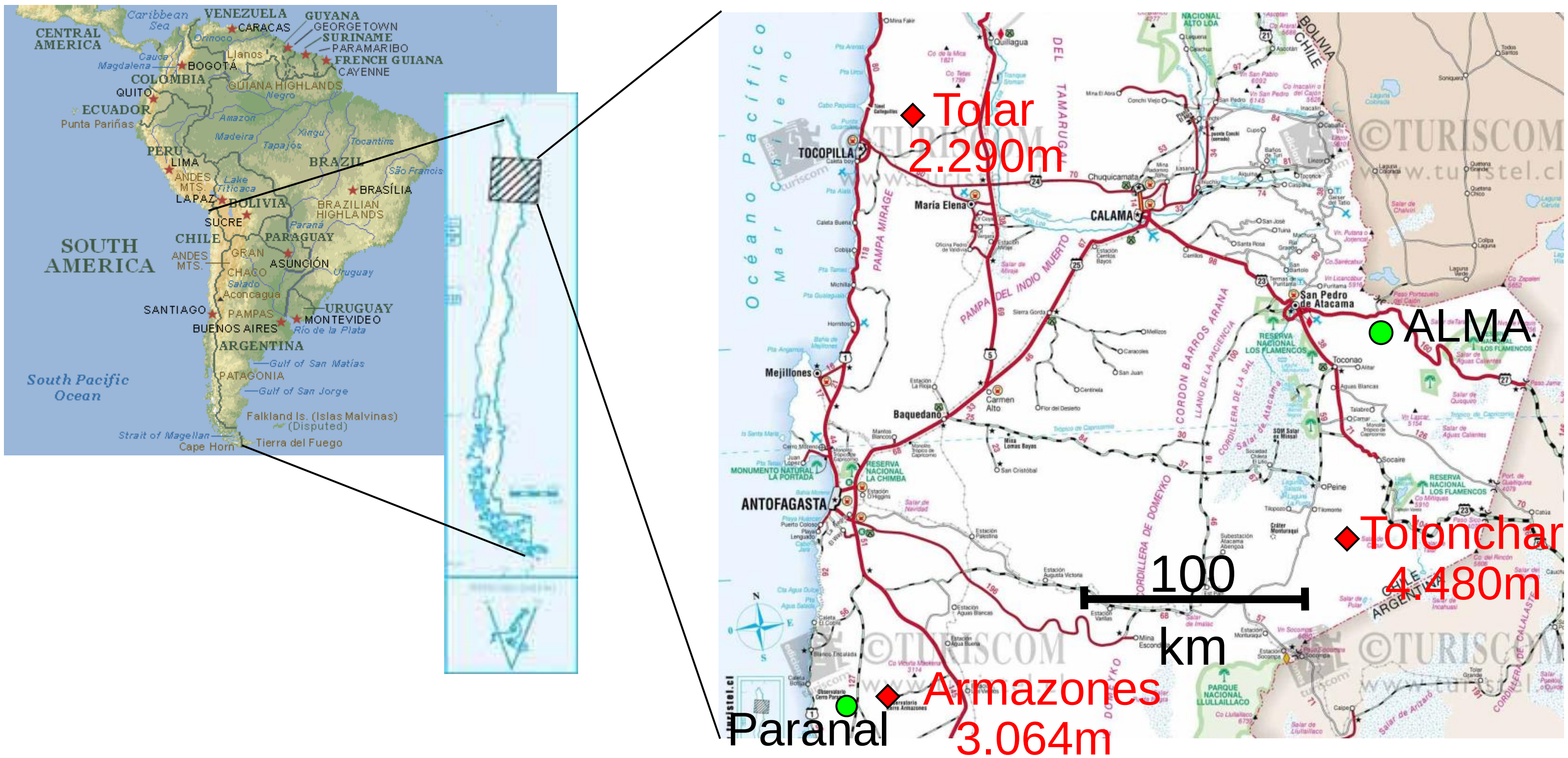
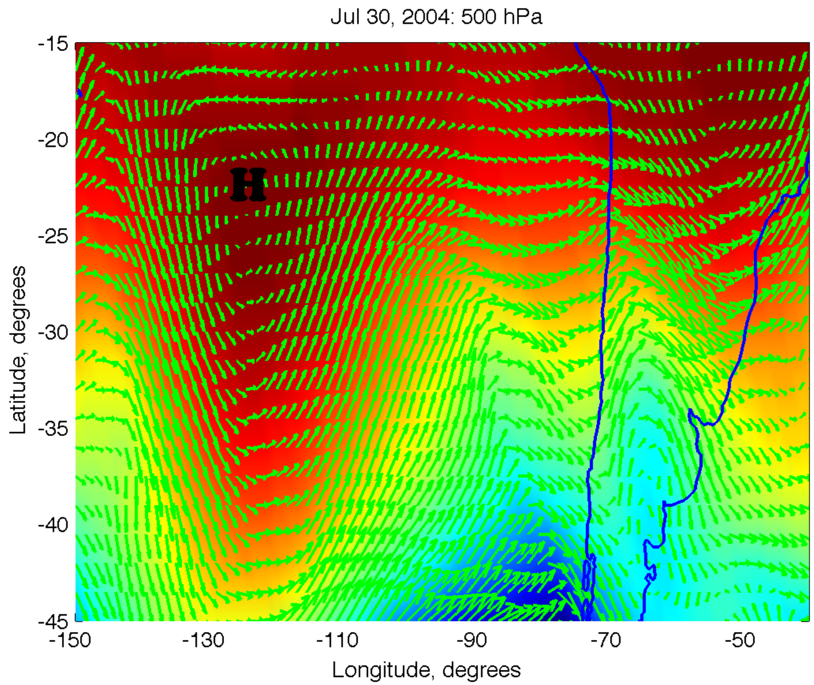
Outline

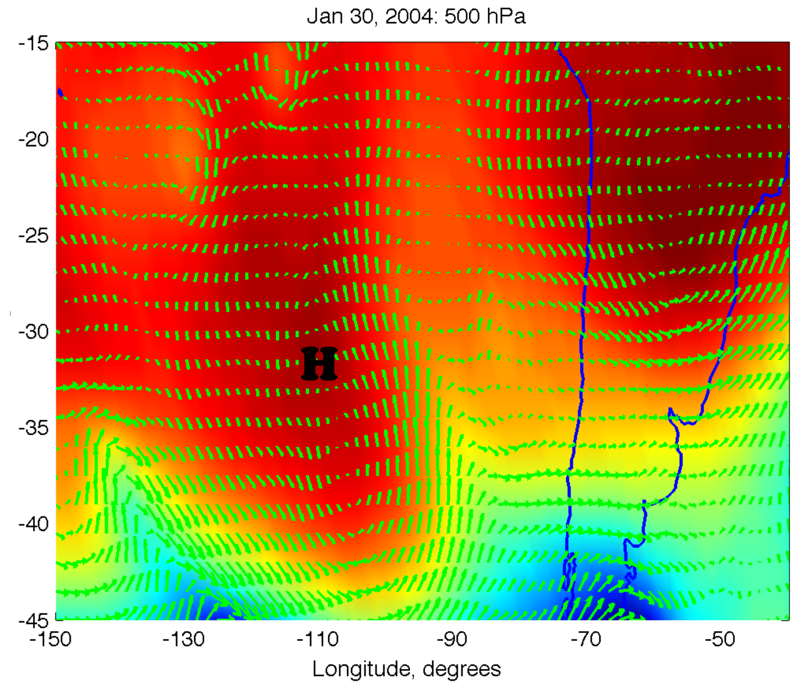
- Location of sites tested by TMT in northern Chile
- Synoptic-scale meteorological conditions
- Monitoring of PWV at the TMT candidate sites
  - Satellite studies: Andre Erasmus and collaborators
  - Infrared radiometers (20 μm)
  - Radiosonde soundings from the Antofagasta station
  - Surface weather data: assuming an underlying PWVvertical profile model
- Results
  - Overall, seasonal, PWV: night time results
- Final remarks
  - PWV from surface data & the water vapor scale height
  - Possible methods to infer the water vapor scale height

Location of the TMT candidate sites in northern Chile



Synoptic-scale meteorological conditions in northern Chile





[1] Downward phase of the Hadley Cell (relatively dry air)

[2] The High Pressure Center with subsidence of dry air, creates a temperature inversion layer over the Pacific

[3] The Andes mountain deflects the zonal mean flow northward and helps maintaining the south Pacific subtropical anticyclone

Monitoring of PWV at the TMT candidate sites

- Preliminary Studies (Erasmus & van Staden 2001, 2002, 2003)
  - Uses atmospheric emission at 6.7 μm observed from orbital platform (GOES-8)
- IRMA, Infrared Radiometry (data series too short)
  - Receivers designed and built by scientists at the University Of Lethbridge. 3rd generation of the IRMA receiver was supported by TMT
  - Detects atmospheric radiances at 20 μm from surface
  - Needs a Line-by-Line Radiative Transfer Model
  - Needs information on the atmospheric temperature lapse rate and water vapor scale height. Obtained from analysis of radiosonde data
- Weather station data (helpful for determination of long-term stats)
  - Uses atmospheric temperature and relative humidity at surface level
  - Needs information on water vapor scale height. Obtained from analysis of radiosonde data

Preliminary PWV studies
Erasmus & van Staden (2001, 2002, 2003)
PWV in range 300hPa-600hPa (10hPa increments)
Clear sky conditions only

Uses atmospheric radiances observed from NOAA's GOES-8 satellite in the 6.7 μm band.

$$R = \frac{(X-b)}{m}$$ ← True Radiance

$$T_{eff} = PlankFunction(R)$$ ← Brightness Temperature

$$T = b \cdot T_{eff} + a$$ ← Calibrated temperature

$$UTH = f(T,\theta)$$ ← Upper Troposphere Humidity

$$x = UTH \cdot x_s(AirTemperature)$$ ← Water vapor mixing ratio

$$PWV = \frac{1}{g} \cdot \int_0^p x \cdot dp$$ ← Integrated water vapor

Reference:

Soden & Bretherton (1993), JGR 96, 16669:16688

Soden & Bretherton (1996), JGR 101, 9333-9343

D. A. Erasmus and M. Sarazin, SPIE-4168 (2000)

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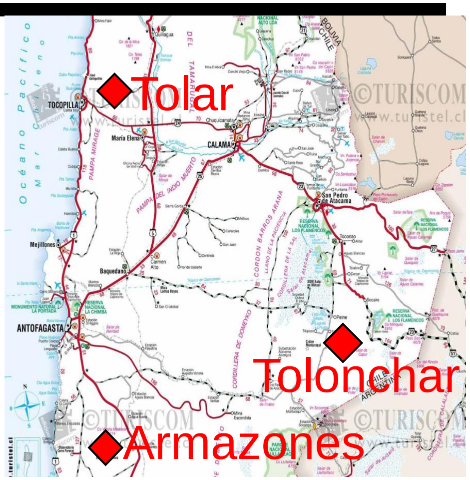
Results from the preliminary PWV studies of Erasmus & van Staden



Caveats:
[1] Satellite studies emphasize the 300hPa-600hPa region

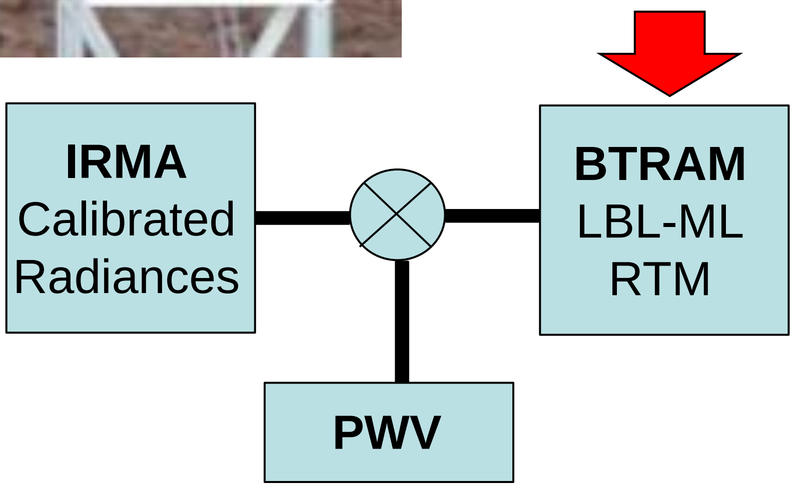
[2] The methodology produces sensible results for clear days; which might imply a bias towards relatively drier conditions.

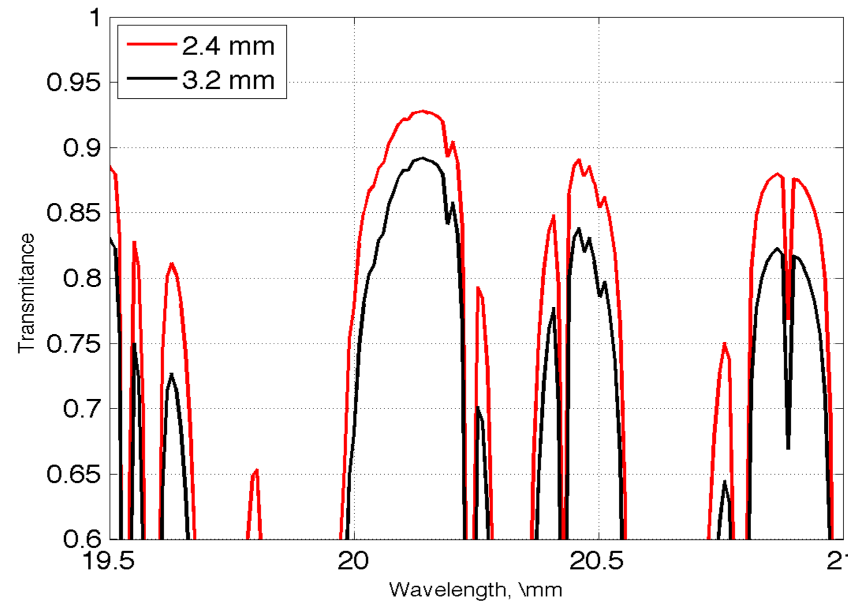
Site	Elevation (m)	PWV Median (mm)	PWV 10% (mm)
Cerro Tolar	2290	4.02	1.59
Cerro Armazones	3064	2.87	1.15
Cerro Tolonchar	4480	1.70	0.70
San Pedro Mártir	2830	2.63	1.06
Mauna Kea 13N	4050	1.86	0.72

IRMA (20 μm)

University Of Lethbridge and Herzberg Institute of Astrophysics

-Γ = 6.95 K/km
H = 1.4 km
Surface Press.
Surface Temp.





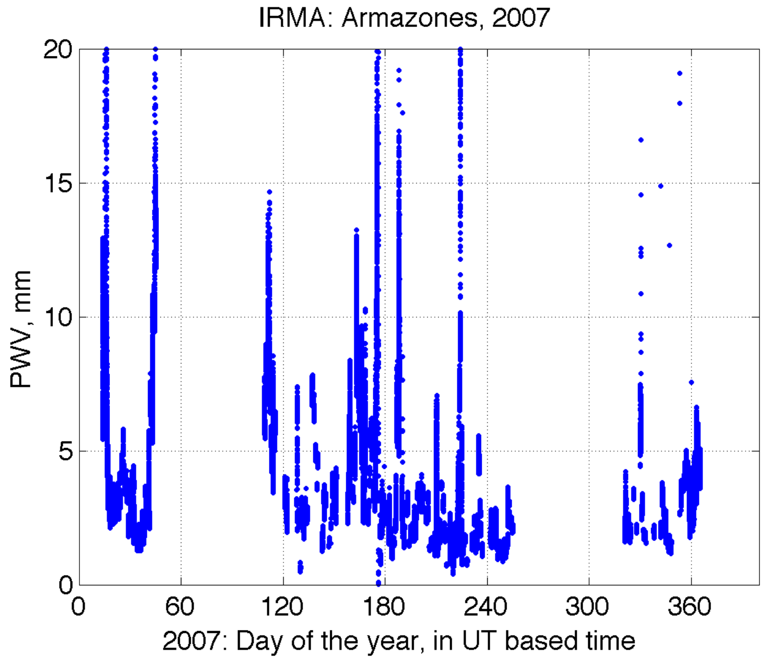
References:
G. J. Smith (2001), Master Thesis
I. Chapman (2003), Master Thesis
R. R. Querel (2007), Master Thesis
Chapman & Naylor (2005)

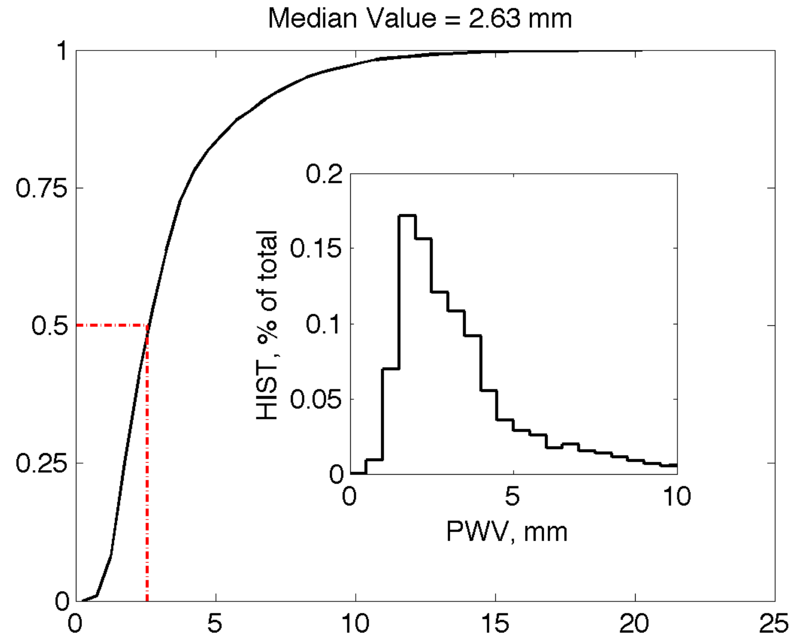
$\Delta T \pm 0.1\% \rightarrow \Delta PWV \pm 10\%$

$\Delta P \pm 0.1\% \rightarrow \Delta PWV \pm 1\%$

$\Delta H \pm 21\% \rightarrow \Delta PWV \pm 23\%$

The Use of Surface Weather Data to Infer PWV





Caveats:

[1] The IRMA radiometers produced limited data: 172 days only Armazones

[2] The observations missed a good fraction of the Fall and Spring seasons

Reason: The remoteness of the sites conspired against keeping track of the calibration of these radiometers and keeping them operating at all times.

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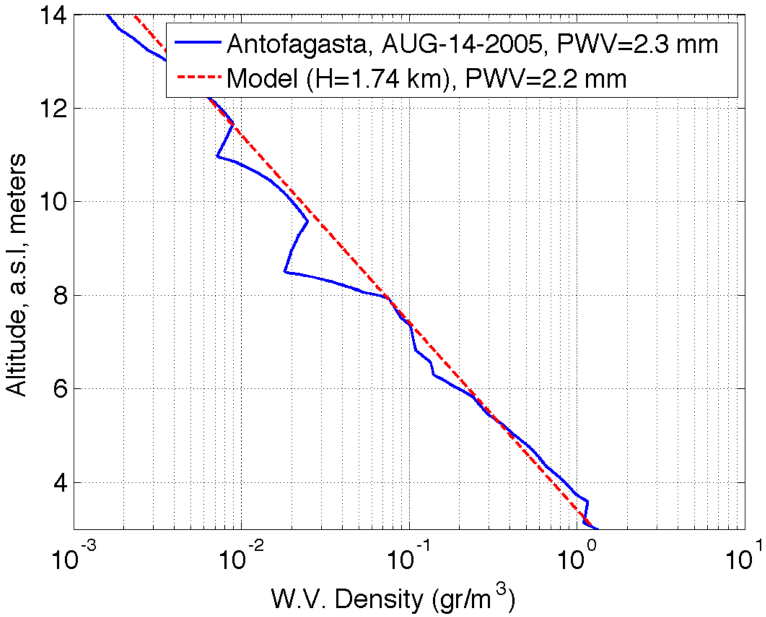
Use of surface weather data to infer PWV at the sites in Chile

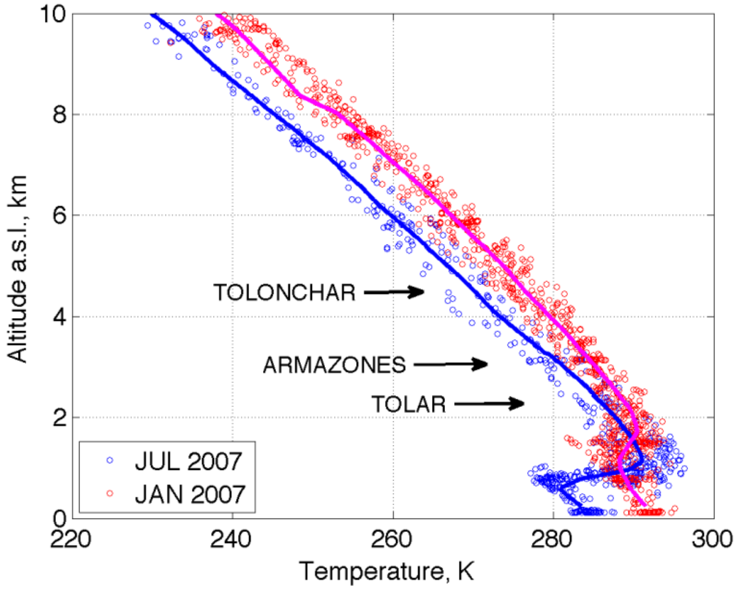
- The larger dataset that we could use to learn about PWV in the atmospheric column at each of the sites in northern Chile consists on surface measurements of Temperature and Relative Humidity
- The limited amount of IRMA data in 2007 could be used to compare and validate results
- It was considered appropriate derive PWV from radiosonde soundings from the Antofagasta station. This is located ~100 km from Armazones and from Tolar, but further away west from the Toloncher site.

How to use surface weather data to infer the PWV in the atmospheric column

- Assumptions:
  - In areas dominated by high pressure systems (such as the northern part of Chile), the weather is dominated by subduction of relatively dry air (the mean vertical profile of RH is ~20%). The vertical distribution of water vapor tends to decrease exponentially with a given scale height
  - The strongest temperature inversion layer induced by the subsiding air, forms at an altitude lower than that of the sites under study. Consequently, the surface water vapor at the sites is coupled with the higher levels of the troposphere

Verification of the Assumptions using Radiosonde data from Antofagasta

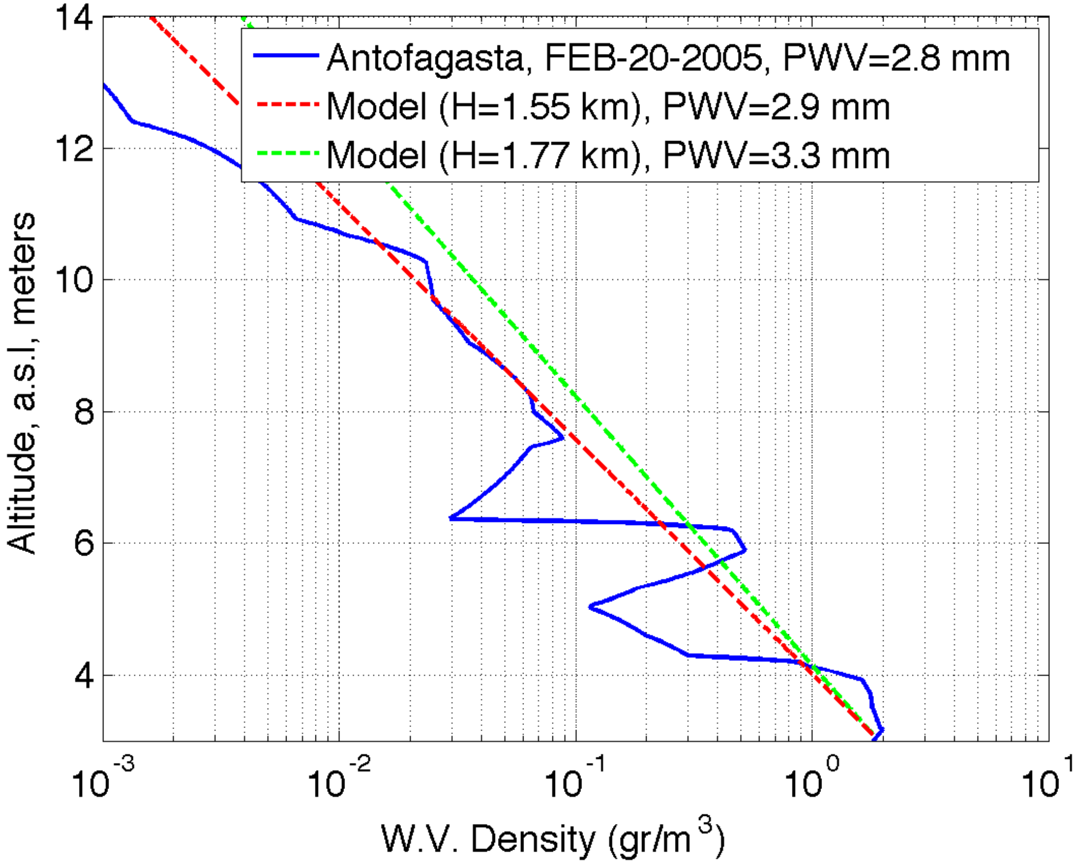




JULY (27 profiles) : Temperature Inversion is strong: 10 K
600 m thick, from 0.6 km to 1.2 km a.s.l.

JANUARY (30 profiles): Temperature Inversion is weaker: 2 K
600 m thick, from 1.0 km to 1.6 km a.s.l.

Verification of the Assumptions using Radiosonde data from Antofagasta



A Summer Case

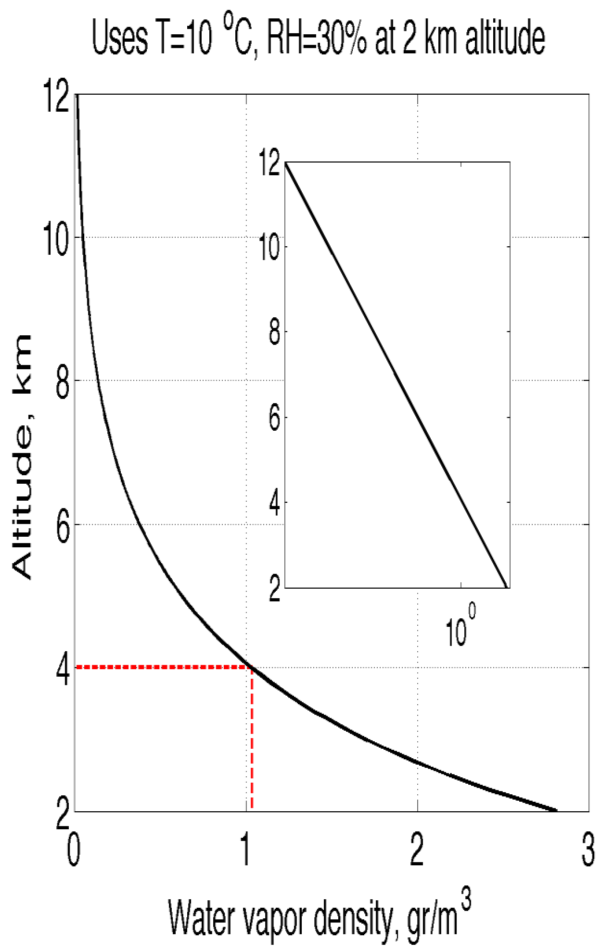
The real profile has plenty more structure (larger fluctuations)

The low-frequency decay is still exponential, and the scale height plays an important role.

Error% (H=1.55 km) ~ -4%
Error% (H=1.74 km) ~ +20%

Uncertainty in the scale height leads to over determination and under-determination of the PWV

Model for the vertical profile of water vapor density and PWV



$$wvp_0 = wvp_S \frac{RH}{100}$$

$$wpv_S = 611.21 \cdot e^{\left(18.678 - \frac{T[°C]}{234.5}\right)\left(\frac{T[°C]}{257.14 + T[°C]}\right)}$$

$$\rho_{v0} = \frac{wvp_0}{R_V \cdot T[K]}$$

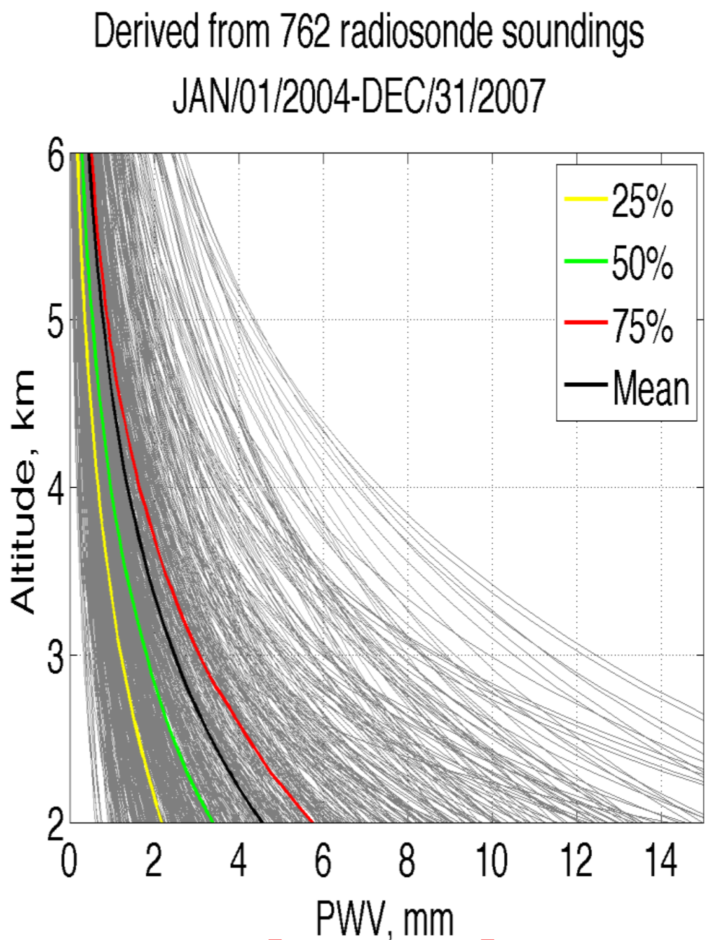
$$\rho_v(z) = \rho_{v0} \cdot e^{-\frac{(z-h_0)}{H}}$$

$$PWV(z_0) = \int_{z=z_0}^{z=z_{MAX}} \rho_v(z) \cdot dz$$

$$PWV(z_0) = \int_{z=z_0}^{z=z_{MAX}} \rho_{v0} \cdot e^{-\frac{(z-z_0)}{H}} \cdot dz$$

$$PWV(z_0) = \rho_{v0} \cdot H \cdot \left(1 - e^{\frac{(z_0 - z_{MAX})}{H}}\right)$$

The Water Vapor Scale Height (H)



Small ← H → Large

$\rho_{V_0} \Rightarrow PWV$

Tolar and Armazones:
H=1.55 km (median of summer)
H=1.74 km (median other seasons)
Radiosondes launched from Antofagasta

Tolonchar:
H=1.13 km
Radiosondes launched from Chajnantor
Giovanelli et al. (2001), PASP 113, 803

The TMT weather stations & data analysis procedure

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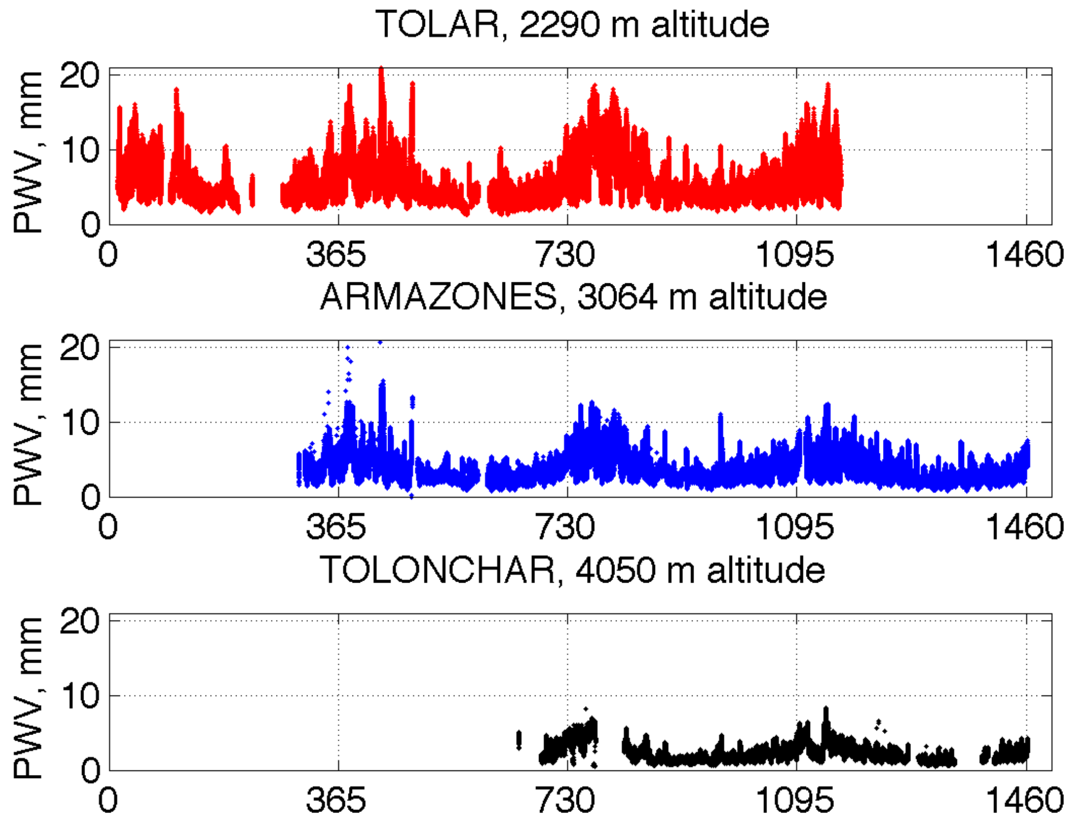
$$(T, RH)$$

$$\rho_{V_0}$$

$$PWV(z_0) = \rho_{v0} \cdot H \cdot \left(1 - e^{\frac{(z_0 - z_{MAX})}{H}}\right)$$



The PWV data series (with 2-minutes time resolution) was averaged in periods of 24 hours before used To compute the global statistics.

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Results: Overall & Seasonal

Site	Alt. (m)	PWV (mm) GOES	PWV (mm) Surf. D.	ΔPWV (mm)	ΔPWV (%)	PWV Night Time (mm)
Tolar	2290	4.02	4.73	+0.71	18%	4.2
Armazones	3064	2.87	3.19	+0.32	11%	2.9
Toloncha	4480	1.70	1.83	+0.13	8%	1.7

Otarola et al. (2010), PASP, 122, 470-484

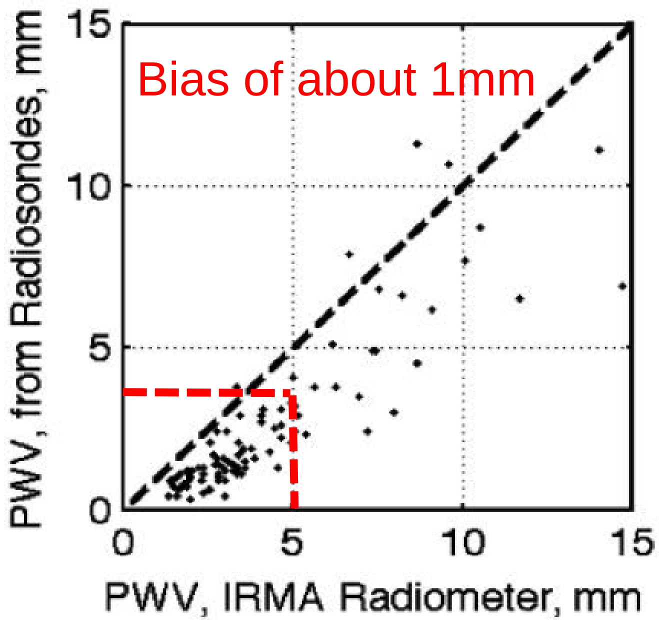
The global median values obtained from surface weather data agree within 20% with the results from the preliminary studies of Erasmus & van Staden

The difference decreases with altitude. This might be to the fact that the Satellite studies are more sensitive to the 300 hPa – 600 hPa region
300 hPa ~ 10 km a.s.l. and 600 hPa ~ 4 km a.s.l.

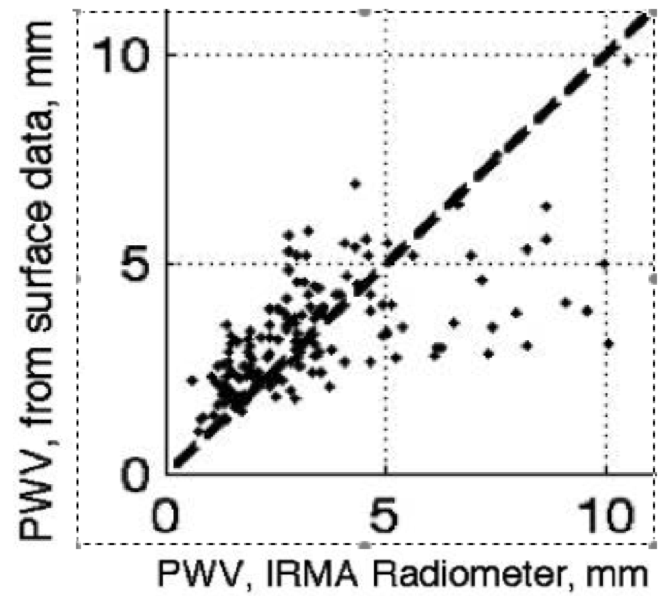
Comparison of PWV from Surface-data Radiosonde soundings and IRMA Radiometers

Florian Kerber
Results showed
No Bias
(Site-2010)

Reason:
He used In-situ
& night time
radiosondes



Obvious offset between
IRMA and Radiosondes (AFTA)

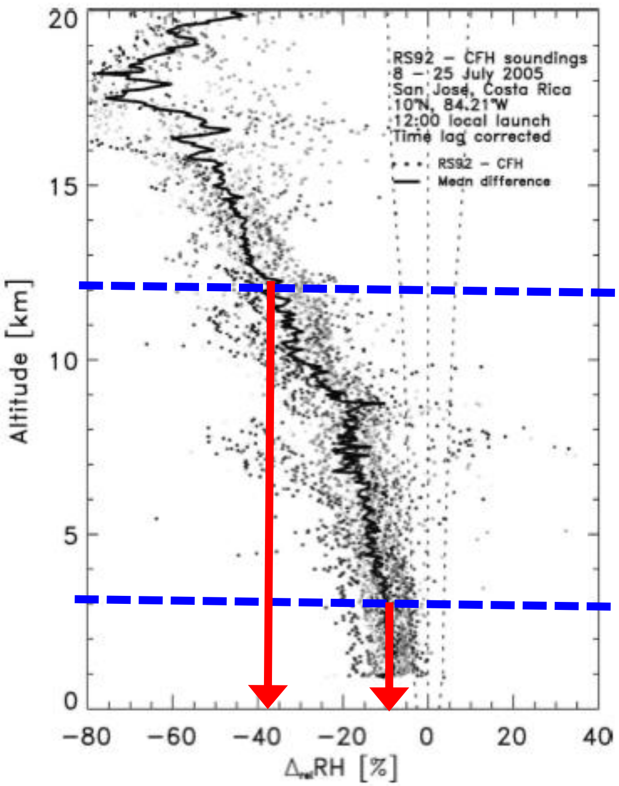


Less of an offset between
IRMA and PWV from surface data
But more scattering

Offset with radiosondes can be explained by a combination of factors:

1) There is a known dry bias in the radiosonde humidity sensors
2) Radiosondes are launched from about 100 km away from Armazones
3) Collocated data is very limited
4) Noise level in IRMA receivers ~ 0.25 – 0.5 mm

Radiosonde Humidity Bias



ΔRH, %
Vaisala RS-92 & Cryogenic Frost-point Hygrometer (CFH)
From Vömel et al. (2007)

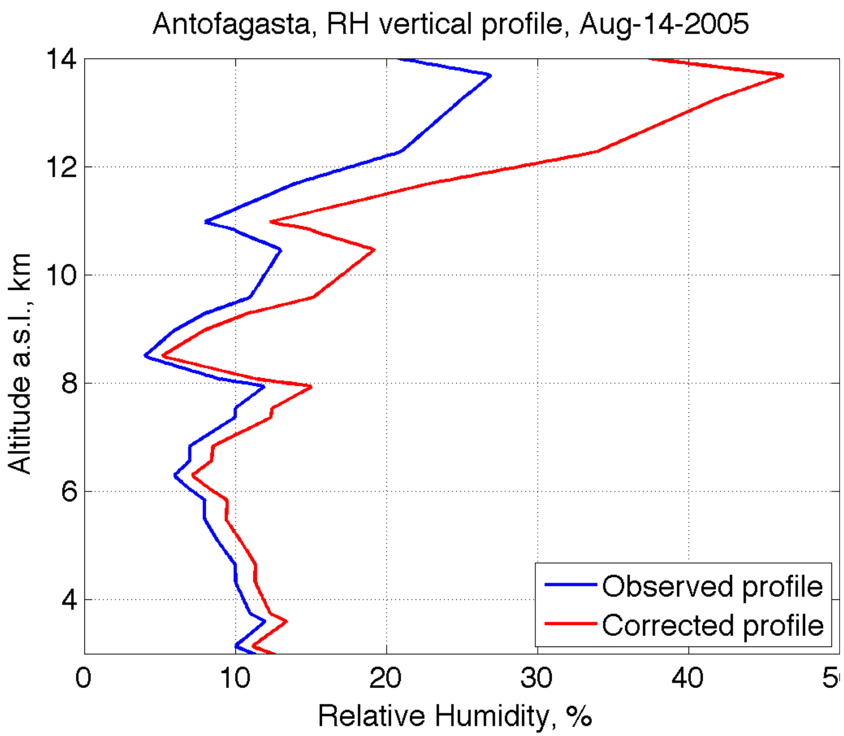
Comparison shows:

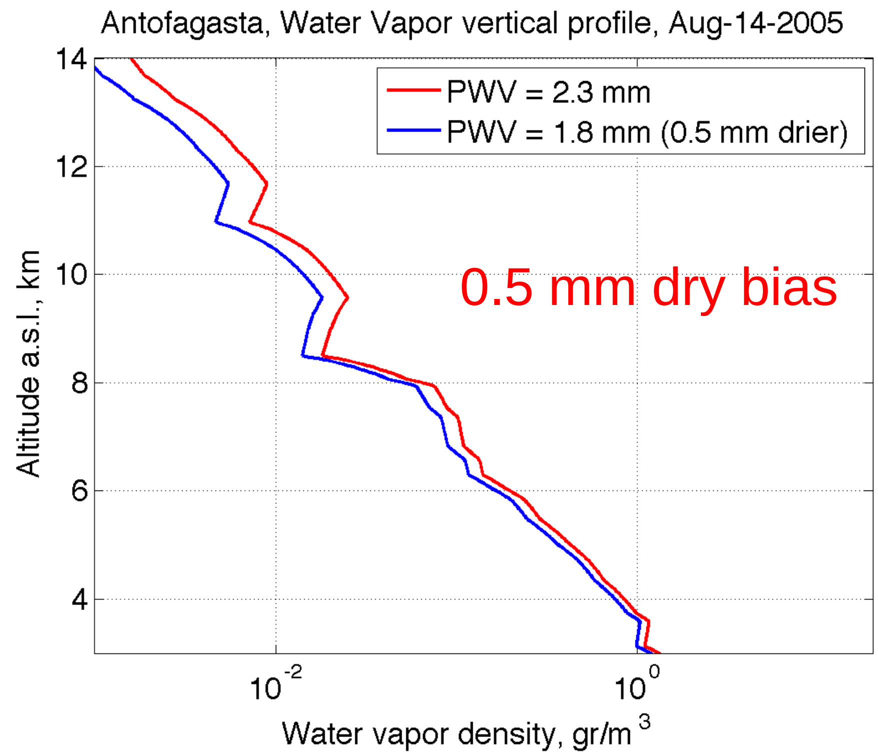
Dry bias in RS-92 humidity sensor
(9 % at surface level & 50% at 15 km altitude)
-Originates in a solar radiation illuminating the relative humidity sensor
A solution: protective caps, but they limit the sensor ventilation

A temperature-dependent calibration error
(bias-increasing with decreasing temperature)
-The response time of the sensor gets slower with lower temperature. This introduces a lag effect.

1-mm PWV bias → ~20% dry-bias
In Atacama Desert
RH ~20% absolute
Then bias is 4% of RH

Radiosonde Humidity Bias

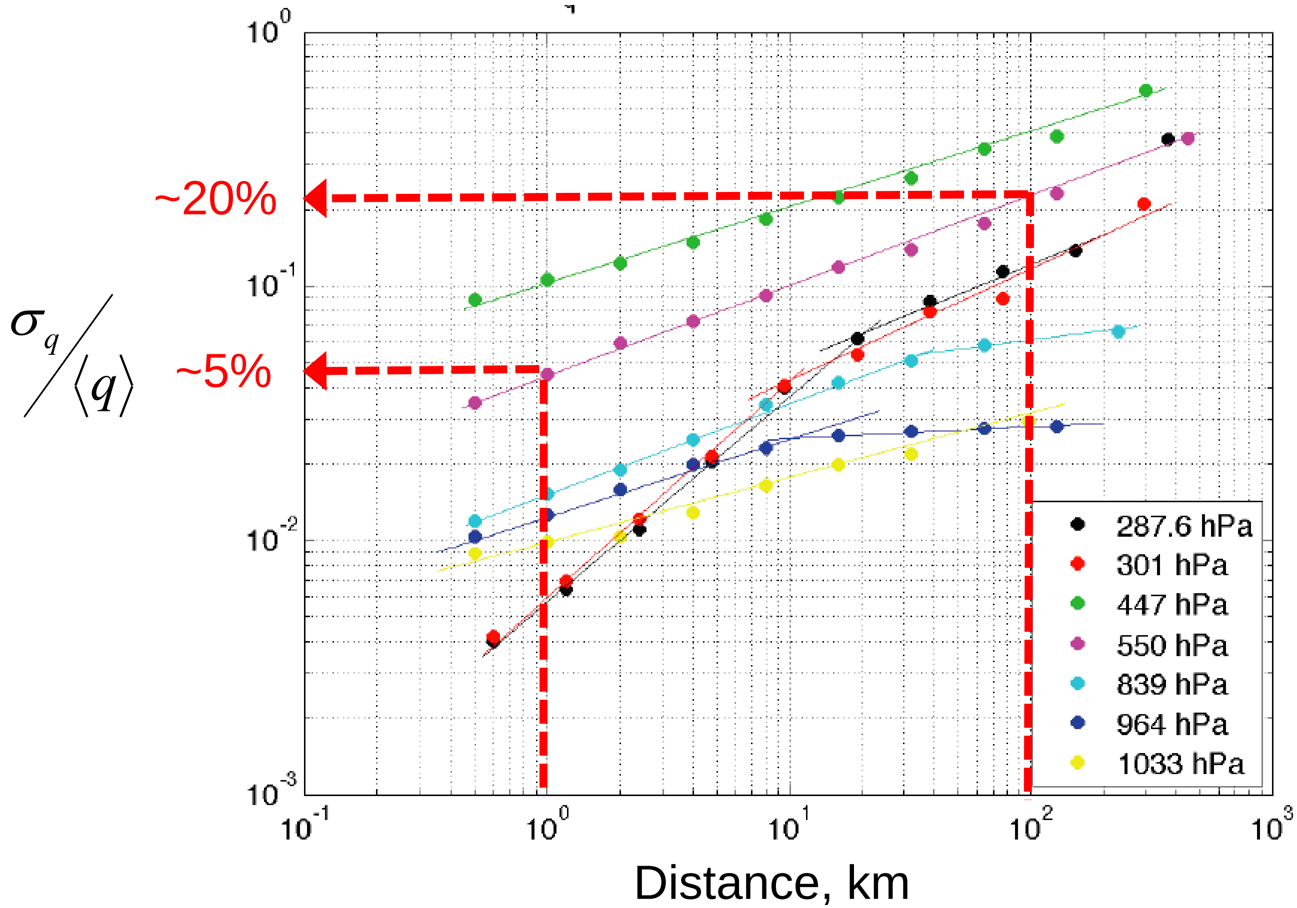




Blue: Original sounding data

Red : After correcting dry-bias (Vomel et al (2007), J. Atmos. & Ocean. Tech., 24, 953-963)

Variability of atmospheric absolute humidity with distance



Use of aircraft data to study the variability atmospheric absolute humidity as a function of spatial scales

Otárola et al.

(ongoing research Using NSF/NCAR HIAPER aircraft And Lockeed ELECTRA Aircraft data)

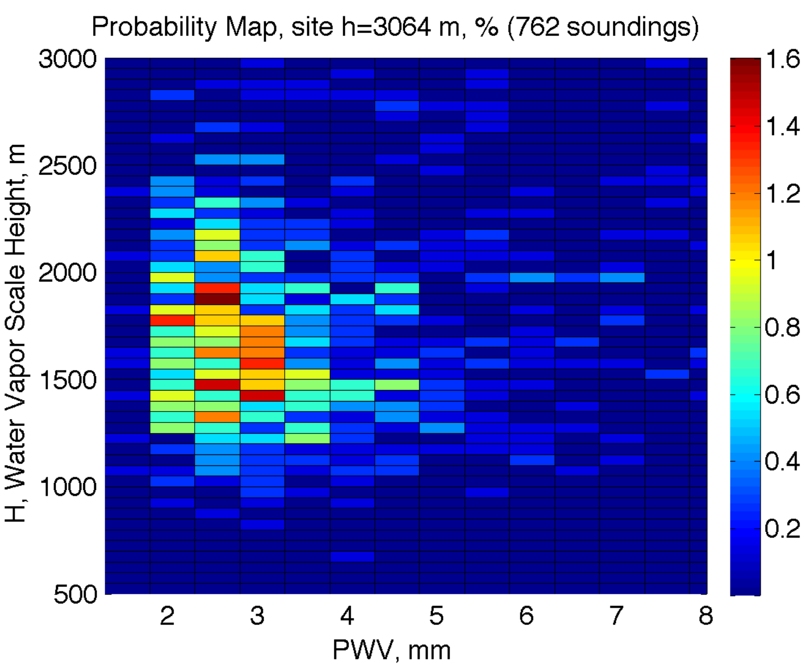
20% of 2.3mm is 0.46 mm

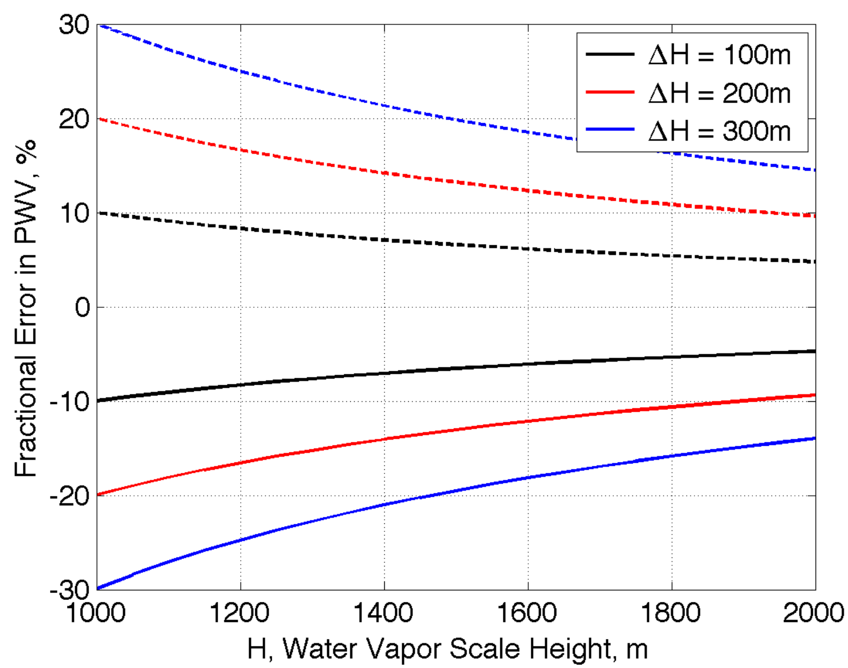
The importance of the water vapor scale height (H)

An error/uncertainty in H translates 1:1 into a Fractional error in PWV

$$PWV(z_0) = \rho_{v0} \cdot H \cdot \left(1 - e^{\frac{(z_0 - z_{MAX})}{H}} \right)$$

$$\frac{dPWV}{PWV} \sim \frac{dH}{H}$$





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Conclusions

- Under the particular conditions of humidity profiles in the Atacama desert. TMT was able to use surface measurements of temperature and relative humidity to infer the PWV in the atmospheric column.
- The PWV derived from surface data in the period 2004-2007, were used to compute the global PWV statistics
- The results compare within 20% with the preliminary studies of Erasmus & van Staden.
- In the process we have learned that radiosonde data has to use with care. Daytime humidity profiles from radiosonde soundings are affected by a dry bias. The relative humidity profiles need to be corrected before attempting to derived PWV from them.
- Spatial variability of the specific humidity field needs to evaluated when comparing in-situ results of PWV with PWV derived from soundings launched far from the location of interest.
- In computing PWV from surface data (or from mm/IR-wavelength radiometers is very important to take into account the uncertainty in the water vapor scale height

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Suggestions for monitoring the local water vapor scale height

- Install weather stations, at different geographic height, to monitor temperature and relative humidity. The PWV scale height can be estimated from the water vapor densities at the two stations and their known altitude difference.

- Use of a tethersonde equipped with temperature and relative humidity sensors. There are models with 500m range and more. Height difference between sensors gets affected by the pressure exerted in the tethersonde balloon.

- Launch a radiosonde from site. This has the advantage to provide also information about the height of the boundary layer. This can be take into account to improve the model that uses surface water vapor density to estimate the integrated water vapor in the atmospheric column.

Acknowledgements

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British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.