MARS ATMSOPHERIC WATER RESEVOIRS

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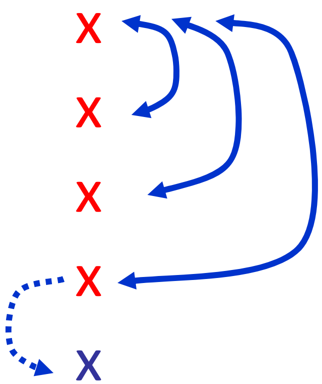
Introduction

Where is the water ?

- Atmospheric vapor
- Atmospheric clouds
- Surface frosts
- Surface ices
- Subsurface ice



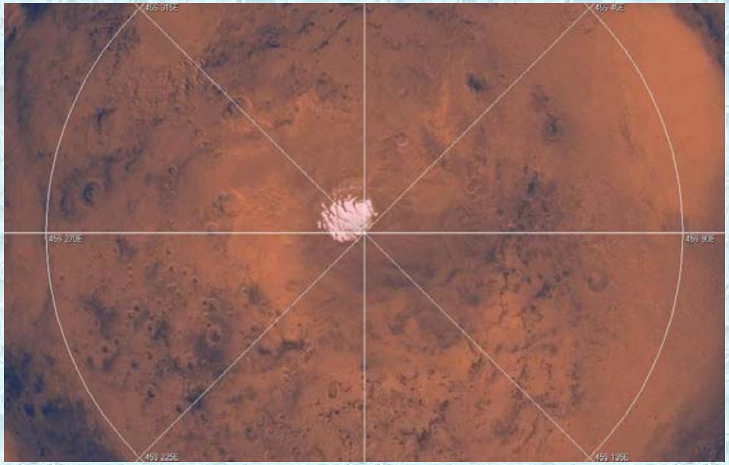
Spring sublimation is accompanied by percolation, which, on timescales of millions years can build icy-rich subsurface layers.

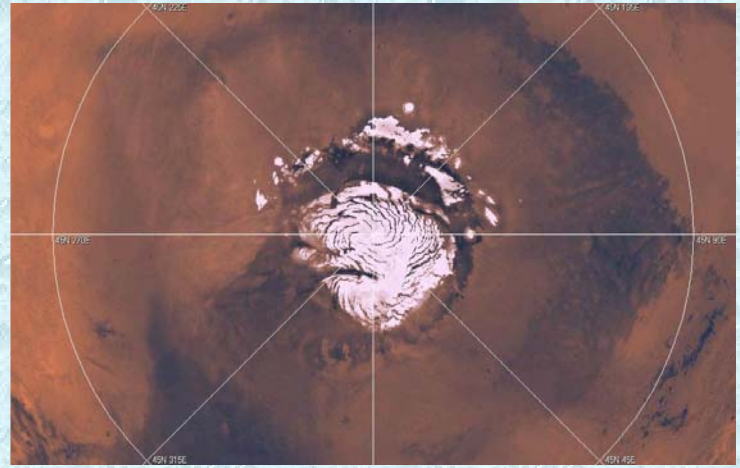
Global atmospheric water vapour amount is small: 10-20 pr µm → 1-2 km^3
But it is directly connected to most other water reservoirs,
and it can be dependably measured and continuously monitored

Introduction: Global asymmetry of Mars climate

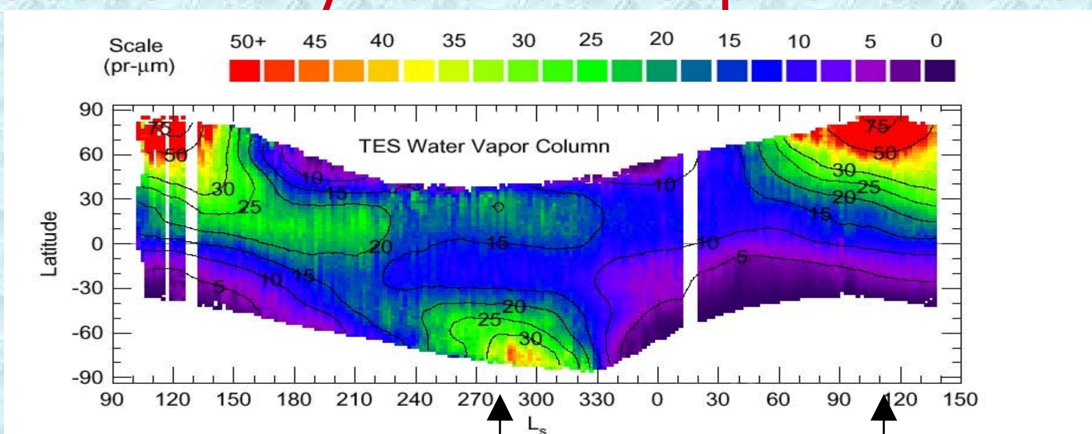
Perennial polar caps

South (CO_2) — North (H_2O)





Seasonal cycle of atmospheric water



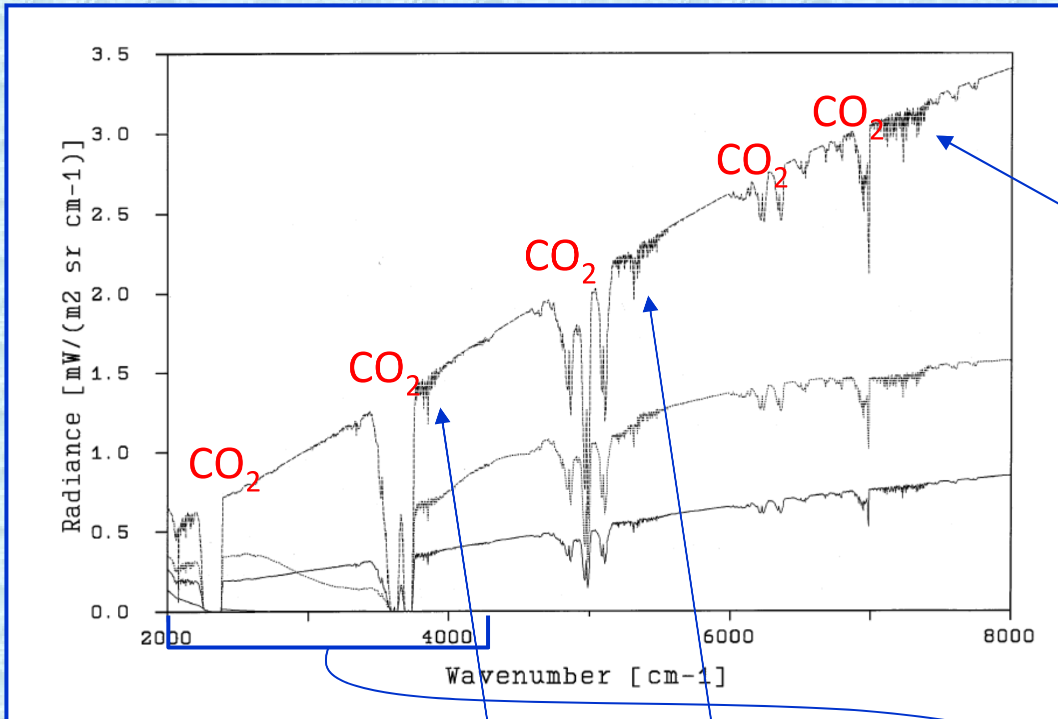
Southern summer (perihelion)

Northern summer (aphelion)

Spectroscopy is the only mean to detect H_2O remotely

Band	Comment	When, how measured	References
820-870 nm	abs; weak	Detection, Ground based	Spinrad et al 1963 Barker 1970, 76; Rizk et al 1991; Sprague et al 1996-2005
936 nm	abs; weak	Mars Pathfinder camera	Titov et al 1999
1.1 µm	abs		
1.38 µm	abs	IV/Mars 5; MAWD/Viking; SPICAM/MEX	Moroz, Nadjip 1975 Jakosky, Farmer 1982, Fedorova et al., 2004, 2006, 2010
1.9 µm	abs	Auguste/Phobos 88	Krasnopolsky et al 1991 Rodin et al 1997
2.56 µm	abs	OMEGA/MEX; CRISM/MRO PFS/MEX	Melchiorri et al 2007 Maltagliaty et al 2008 Smith et al 2008, 2009 Tschimmel et al 2008, Sindoni, Formisano 2010
6.3 µm	abs/emis 3.7; 8µm HDO	IRIS/Mariner 9 IRTF, TEXES ground based	Ignatiev et al 2002 Novak et al 2002 Encrenaz et al 2005, 2008
30-50 µm	emission	IRIS/Mariner 9; TES/MGS; PFS/MEX	Hanel et al 1972; Smith, 2002, 2004, 2008 Fouchet et al 2007
557 GHz	HDO, etc. iso	MIRO/Rosetta fly-by	
183 GHz	203 $H_2{}^{18}O$ 226 HDO	IRAM ground based	Encrenaz et al 1995, 2001
22 GHz	weak	VLA ground based	Clancy et al. 1992

Spectral bands and spectra: near infrared



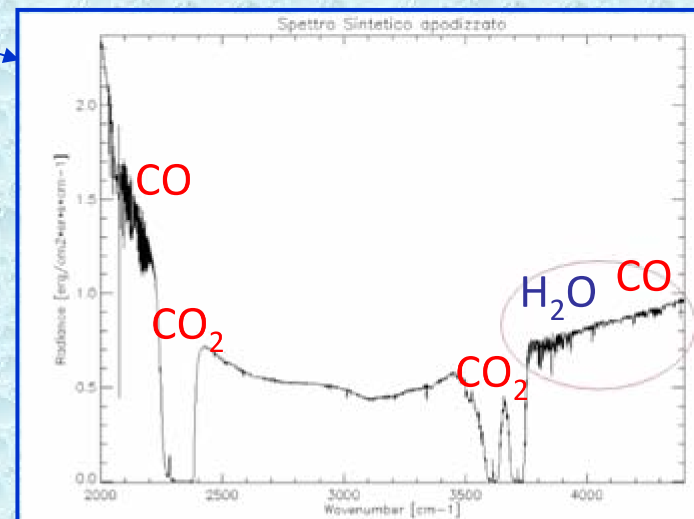
Haus&Titov 1999, spectra computed to simulate PFS signal

1.38-µm band
MAWD, SPICAM

2.56-µm band
PFS, OMEGA, CRISM

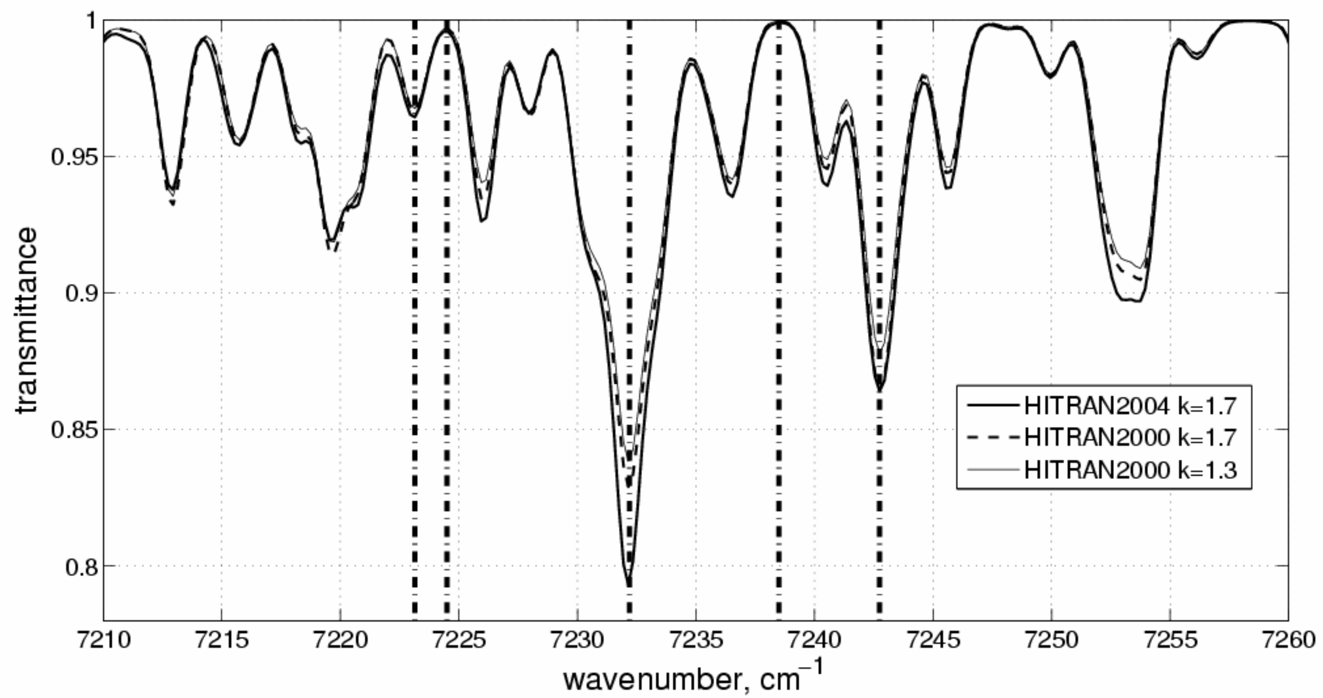
1.87-µm band
Auguste/Phobos 88

Measured PFS spectrum



Near-infrared example: MAWD/Viking

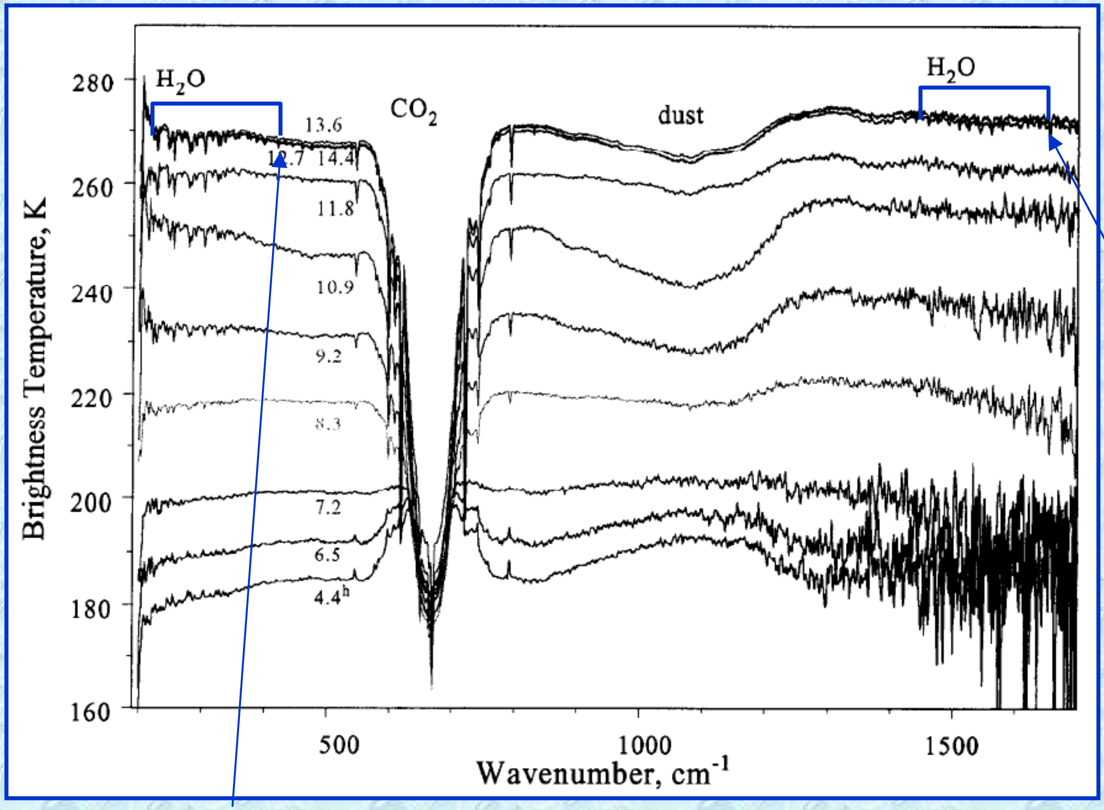
MAWD: grating spectrometer on Viking Orbiter 1, 2 dedicated to H_2O
5 channels; spectral resolution= 1.2 cm^{-1}
Farmer, LaPorte 1977; Farmer et al 1977; Jakosky, Farmer 1982
Account for aerosol: Fedorova et al 2004
Reprocessing: Fedorova et al 2010



Fedorova et al 2010

Synthetic spectra of water vapour in the 1.38-µm band, and the positions of MAWD channels

Spectral bands and spectra: thermal infrared



Ignatiev et al 2002, IRIS/Mariner 9 spectra

"6.3-μm" band
IRIS

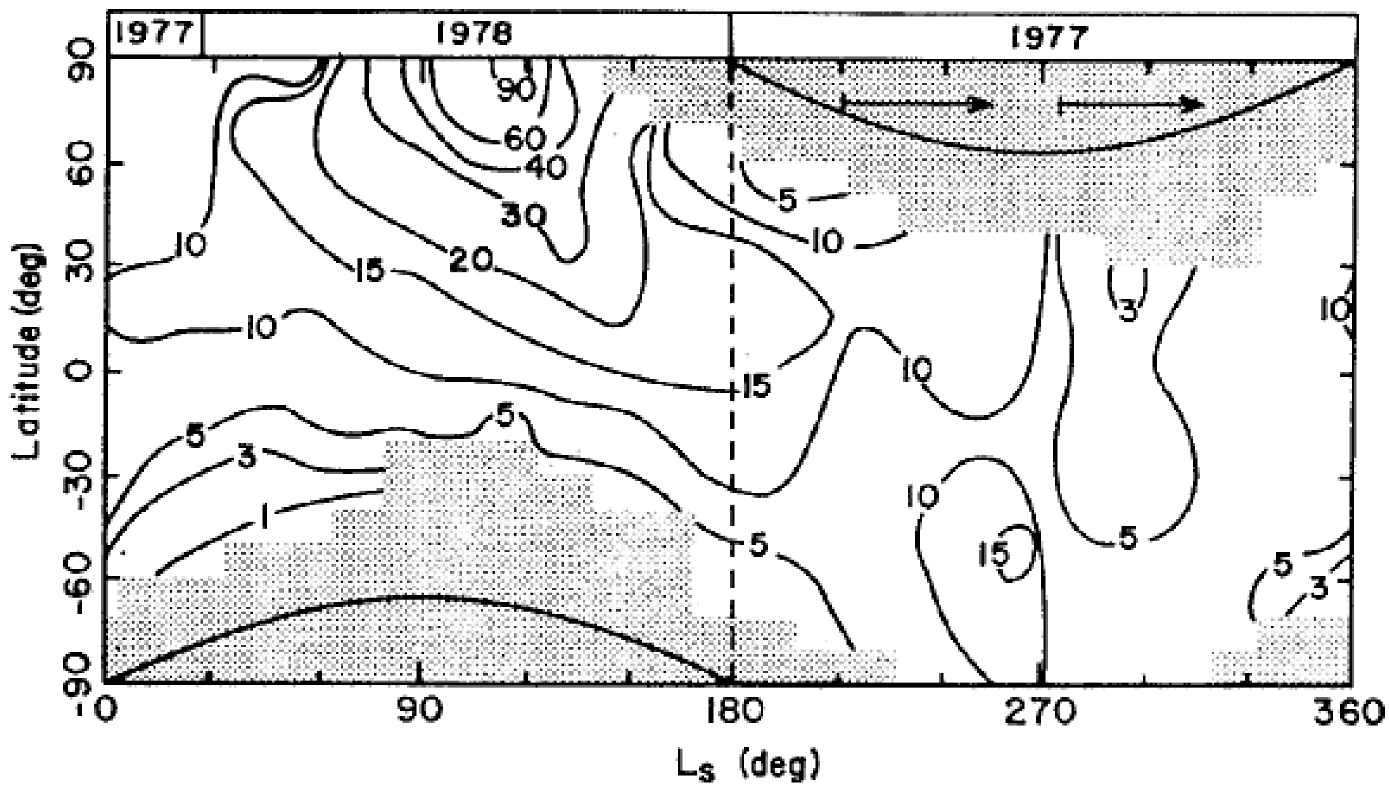
"50-μm" band
IRIS, TES, PFS LW

IRIS: Fourier-spectrometer on Mariner 9 (1971-72)
Many spectra, but only a limited part of seasonal cycle (Ls=290-340°)
Spectral resolution= 2.4 cm^{-1}
Water vapour retrieved by Hanel et al., 1972; Ignatiev et al., 2002

Discovery and early observations of H_2O on Mars

- Discovery:
  - Spinrad, Münch, Kaplan ApJ 1963: echelle spectrograph with photographic registration in 818–820-nm absorption band, using Doppler shift from telluric lines : 10 pr µm. Long follow-up with similar measurements, with photoelectric, then linear array registration.
- First spacecraft measurements:
  - Hanel et al. 1972: IRIS/Mariner 9, 50-µm (200-300 cm^{-1}) emission band
  - Moroz, Nadjip 1975: IV/Mars 3, Mars 5, 1.38-µm absorption band
- First systematic measurement:
  - Jakosky, Farmer 1982: MAWD/Viking orbiters, 1.38-µm absorption band

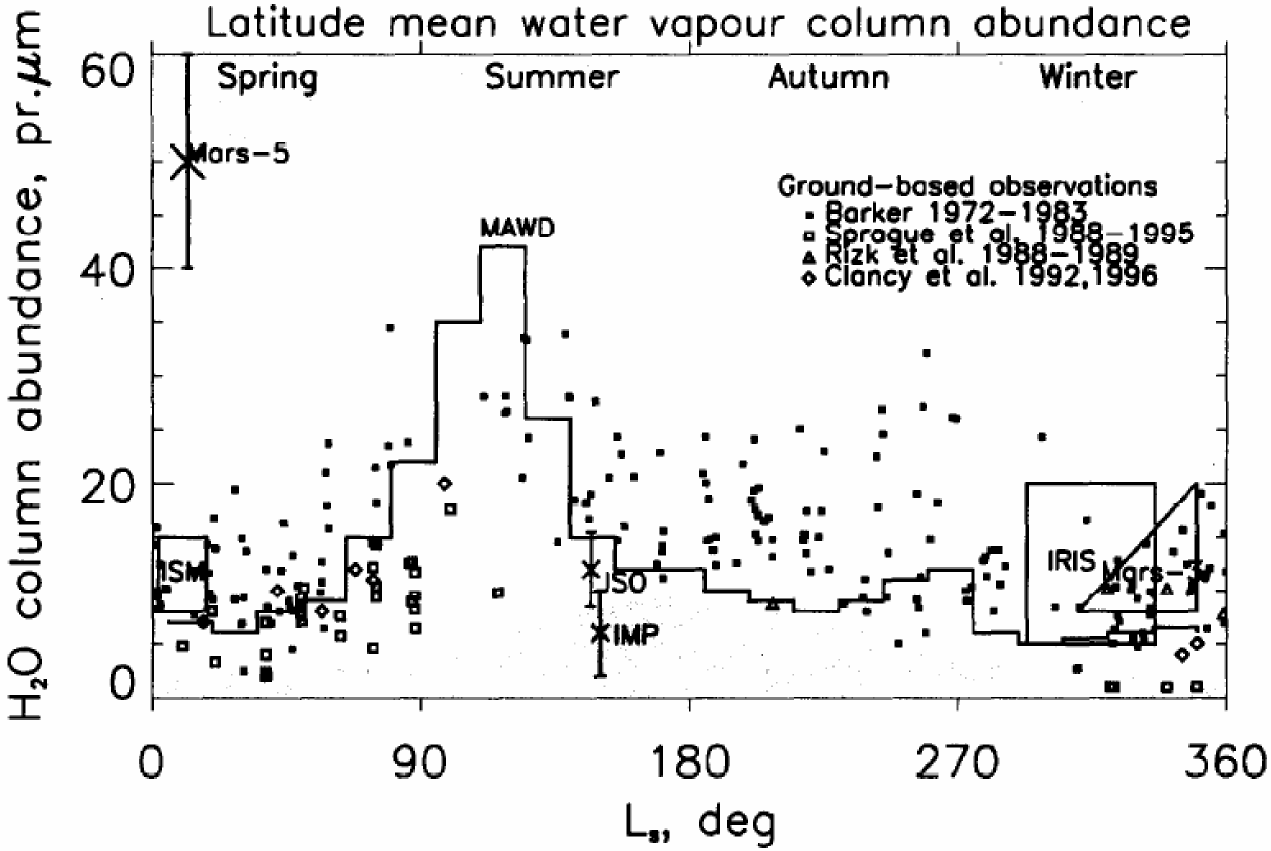
MAWD Viking measurements of seasonal cycle



- Northern summer polar maximum (NPM)
- Asymmetry of the water cycle
- Basis for atmospheric models (e.g. Haberle, Jakosky 1991)
- Supposed exchange with regolith (e.g. Houben et al 1997; Jakosky et al 1997)
- Discarded exchange with regolith (Richardson, Wilson 2002)

Comparison of early water vapour datasets

- Jakosky, Barker 1984
- Titov, 2002

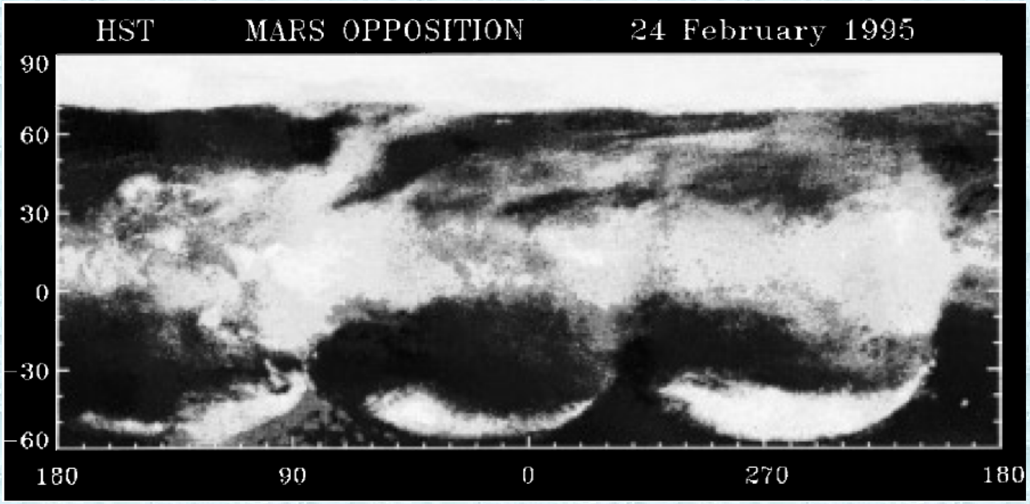


Clancy et al., Icarus 1996:

- Clancy et al. monitored atmospheric temperature from microwave measurements of CO lines, 1980, 1982, 1989, 1991, 1993, 1995; H_2O and clouds on some of these oppositions.
- They retrieved temperature 15-20K colder than Viking in aphelion seasons, low water amounts, and low saturation of water
- This associated with persistent low-latitudes clouds (aphelion cloud belt, ACB)

➔ "Clancy hypothesis": Asymmetry of water cycle explained by orbit eccentricity

Aphelion cloud belt observed by Hubble Space Telescope (Clancy et al. 1996)



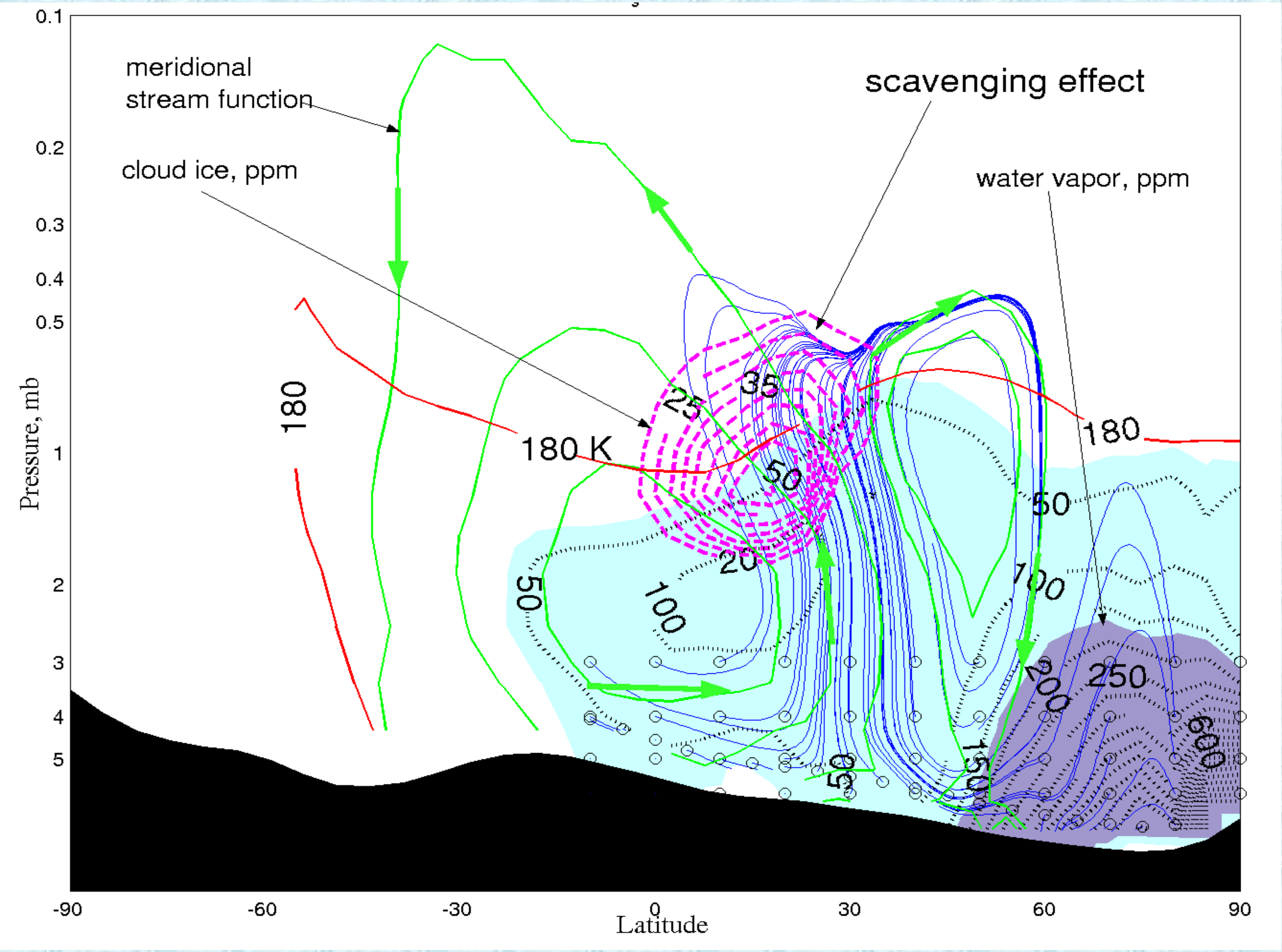
Clancy hypothesis

- Unlike on Earth, Hadley circulation cell on Mars transports air from summer to winter hemisphere, and extends up to polar latitudes
- In cold aphelion (Northern summer), global equatorial cloud belt blocks water in the northern hemisphere.
- In warm perihelion (Southern summer) no clouds form, and water is distributed evenly

Supporting facts:

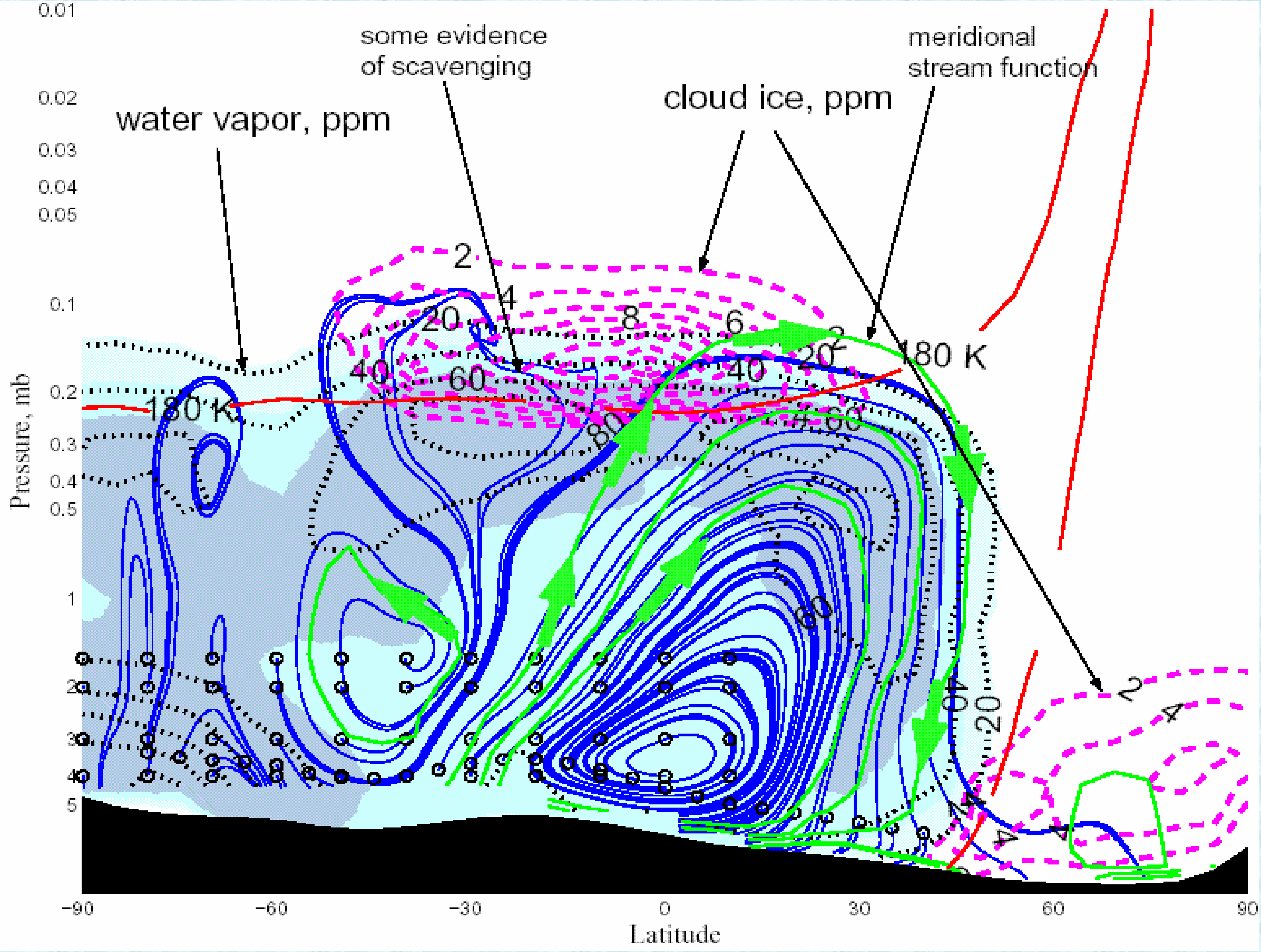
- Colder Viking climate (correction of IRTM results, Wilson, Richardson, 2000)
- Discovery of water ice on perennial South polar cap (Bibring et al., 2004; inversion of perihelion is estimated at the scale of 50 000y, cf lecture by F. Forget)
- Dryer Viking climate (correction of MAWD results, Fedorova et al., 2010; see below)

Aphelion atmospheric water cycle: MGCM



Moroz et al. Priroda 2005 (courtesy S. Rodin). Similar figure published by Rodin, Wilson, Cosm.Res 2006

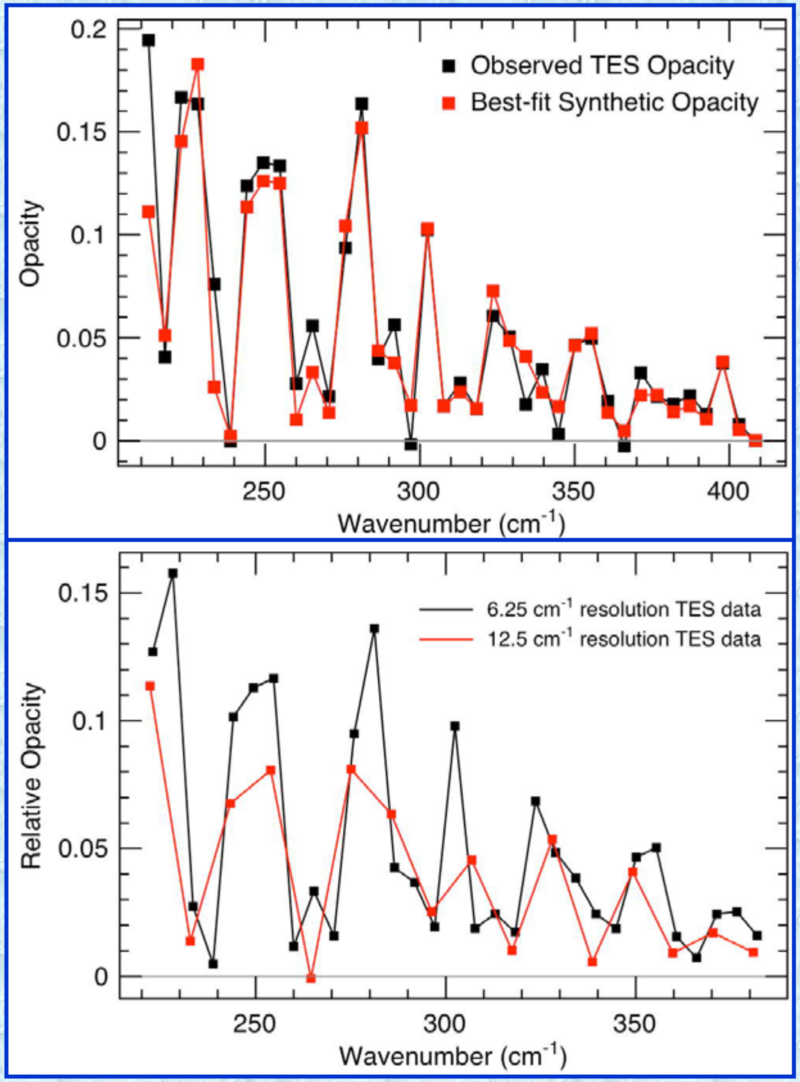
Perihelion atmospheric water cycle: MGCM



Recent measurements: I. TES/MGS

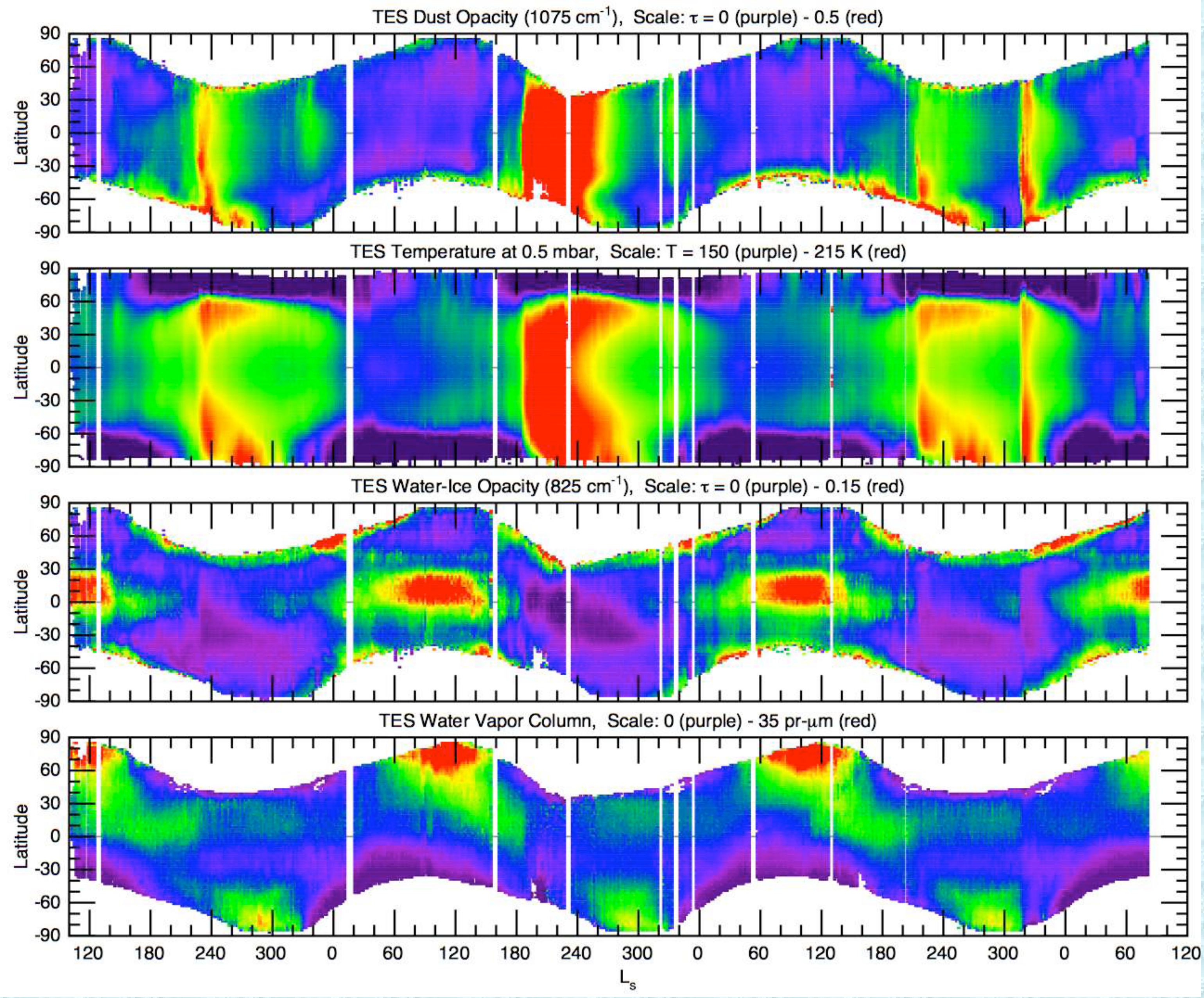
- TES: Fourier-spectrometer on MGS (1999-2004)
- Spectral resolution= 6.25 or 12.5 cm^{-1}
- Nearly polar orbit, 12 orbits/day, ~2:00 AM and 2:00 PM

- Measures temperature, dust opacity, water ice clouds opacity, and water vapor (MD Smith, 2002, 2004, 2008)



M.D. Smith, JGR 2002

MGS TES: dust, temperature, clouds and water vapour



M. Smith, 2008

Recent measurements: II. Mars Express

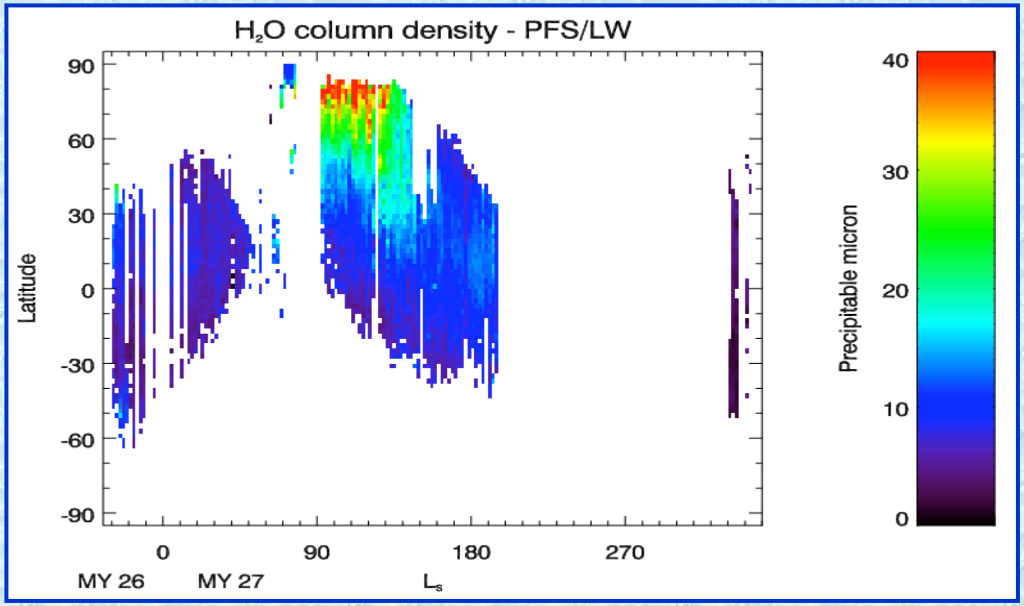
- PFS spectral resolution 1.4 cm^{-1}
  - LW 25-35 µm: processed by 2 groups: Fouchet et al., Icarus 2007
  - SW 2.56 µm: processed by 3 groups: Tschimmel et al., Icarus 2008, Encrenaz et al. A&A 2009; Sindoni, Formisano, 2010.

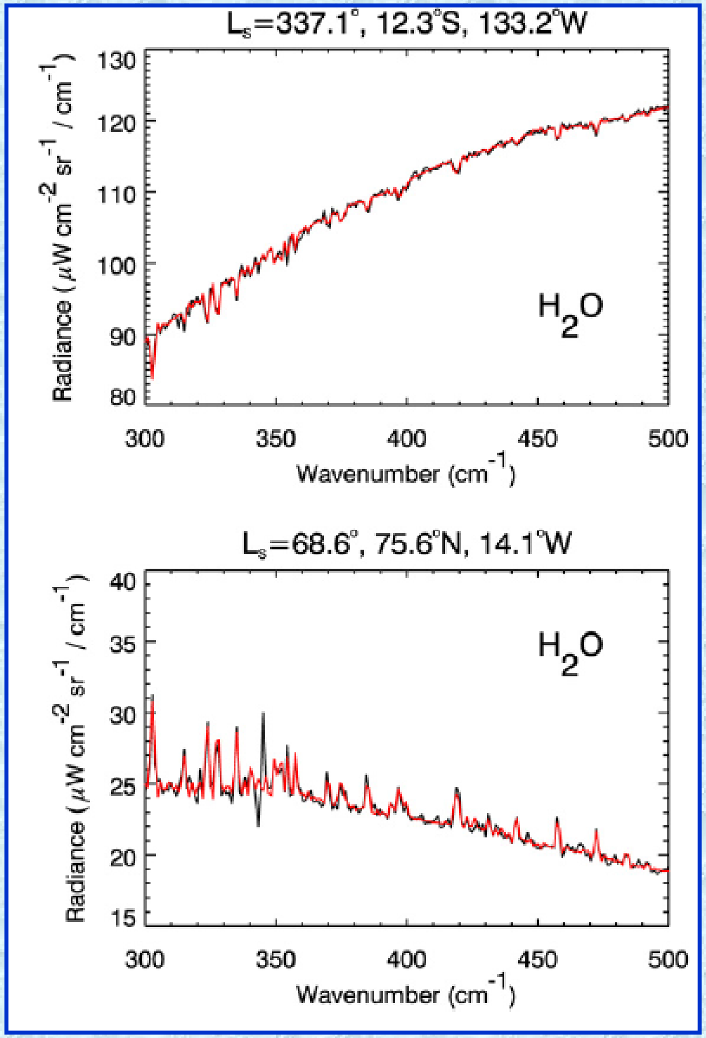
- OMEGA 2.56 µm low spectral resolution, but mapping. Processed by 2 groups
  - Encrenaz et al. A&A 2005, 2008, 2009; Melchiorri et al. PSS 2007, Icarus 2009
  - Maltagliaty et al., 2008

- SPICAM 1.37 µm spectral resolution 3.5 cm^{-1} processed by
  - Fedorova et al., JGR 2006, Icarus 2010

PFS LW/ Mars Express

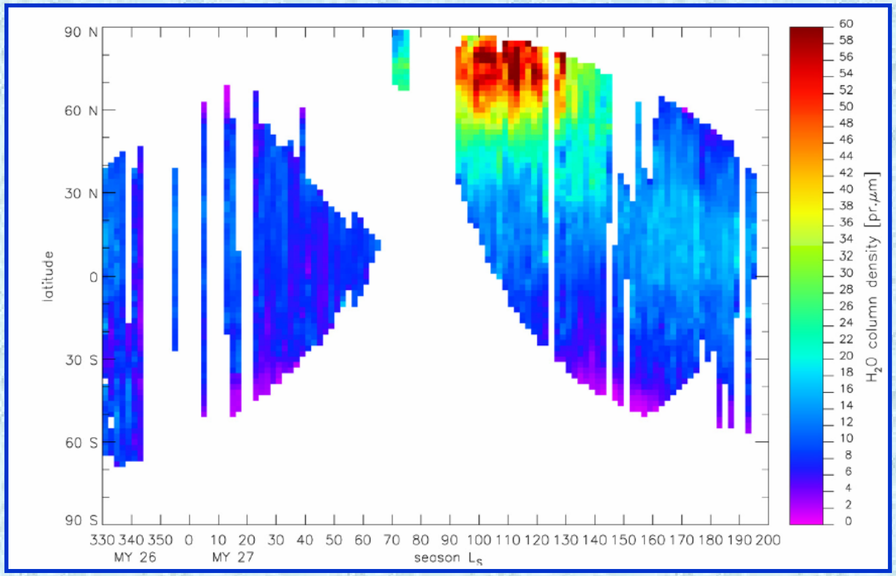
PFS-LW: Fourier-spectrometer
Spectral resolution= 1.4 cm^{-1}
Only a fraction of data available
H_2O retrieved by Fouchet et al 2007





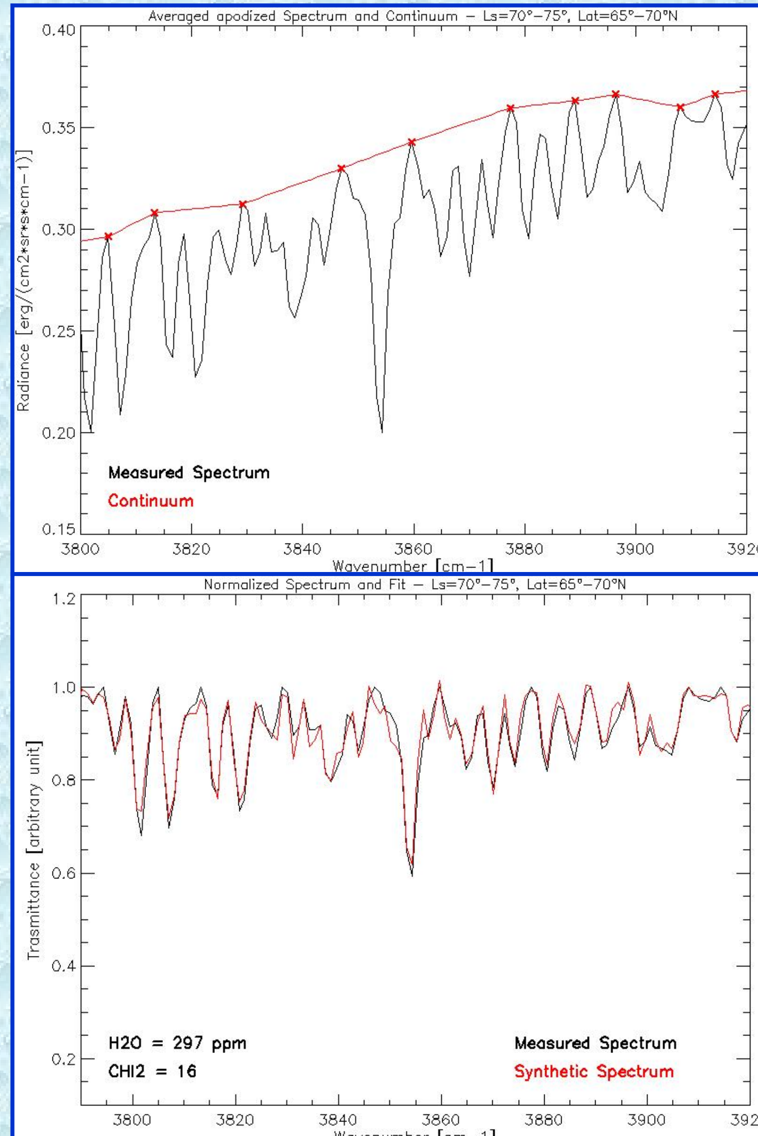
Fouchet et al., Icarus 2007

PFS-SW/Mars Express



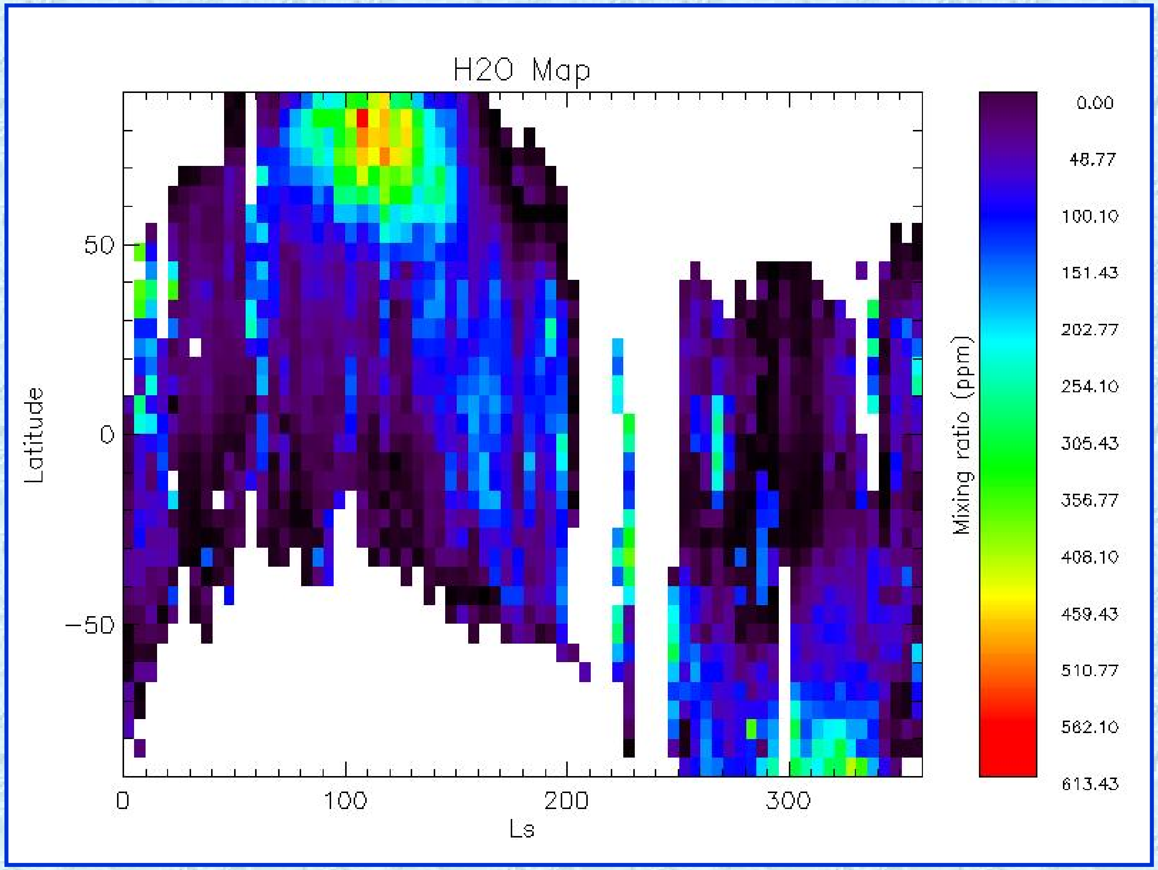
Tschimmel et al Icarus 2008

- PFS-SW: Fourier-spectrometer
- Spectral resolution= 1.4 cm^{-1}
- Problems with spectral continuum; work in progress
- H_2O retrieved by Tschimmel et al 2008; Sindoni, Formisano 2010



Sindoni, Formisano 2010

PFS LW/ Mars Express



- PFS-SW by Sindoni, Formisano 2010 : full set of data on one seasonal graph

OMEGA: spectra

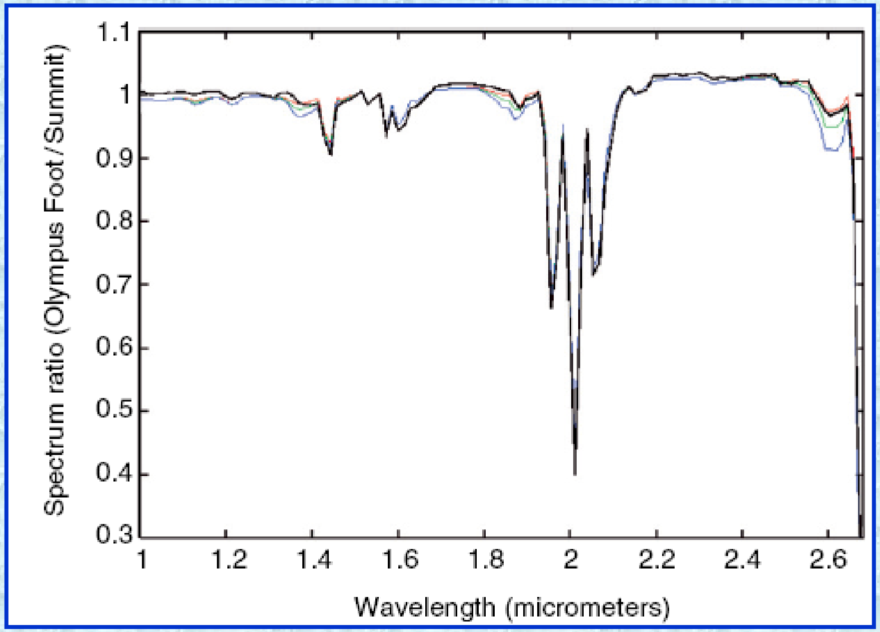
OMEGA: grating spectrometer

Resolving power ~ 300

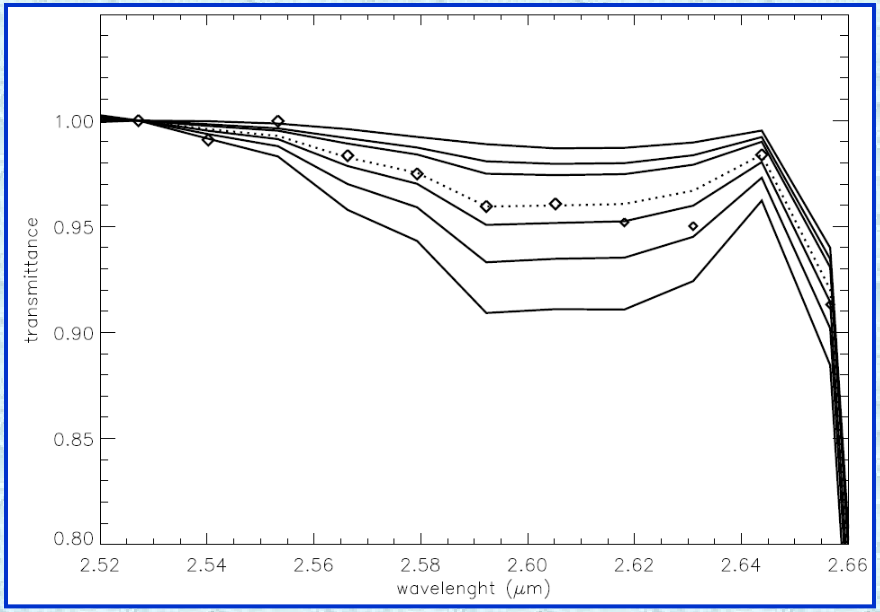
Mapping capability

Correction for aerosol is an issue

Water vapour retrieved by Meudon and MPS teams



Melchiorri et al., PSS 2007



Maltagliati et al., A&A 2007

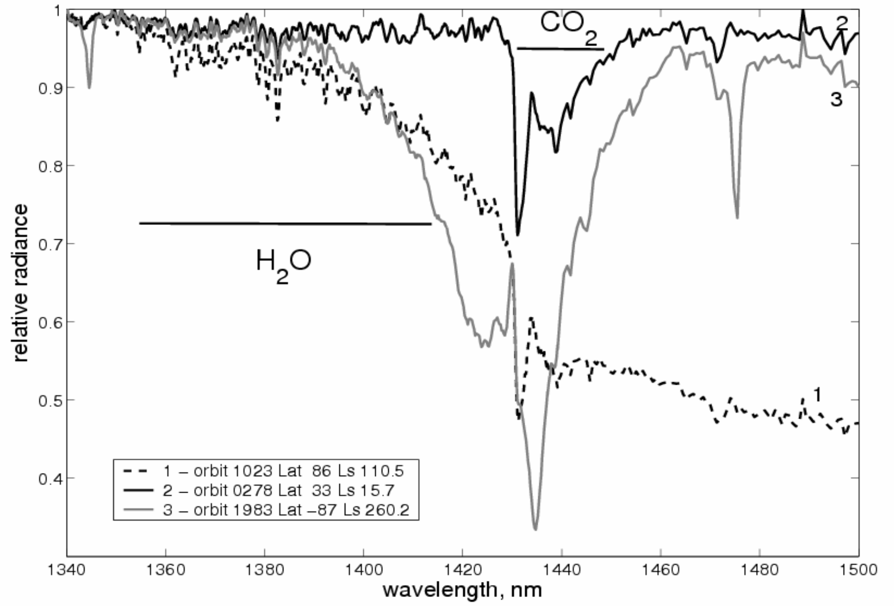
SPICAM/Mars Express

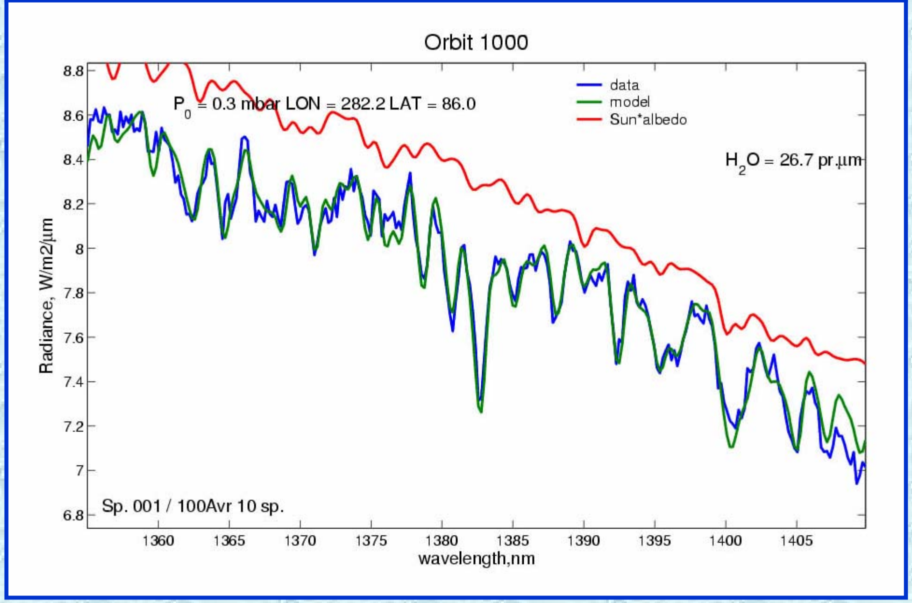
SPICAM: AOTF spectrometer

Spectral resolution= 3.5 cm^{-1}

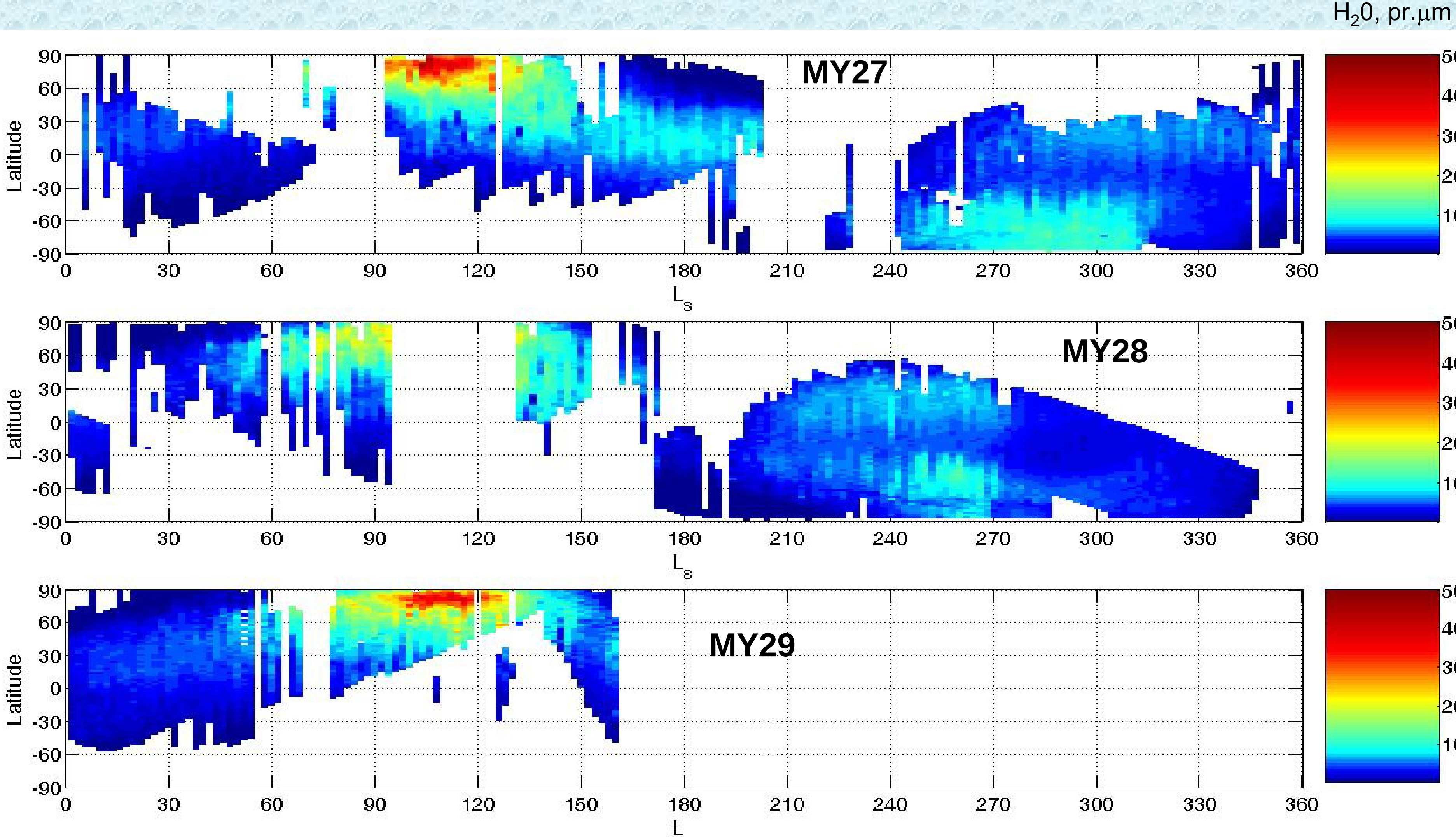
Correction for aerosol is an issue

Water vapour retrieved by Fedorova et al., 2006, 2010



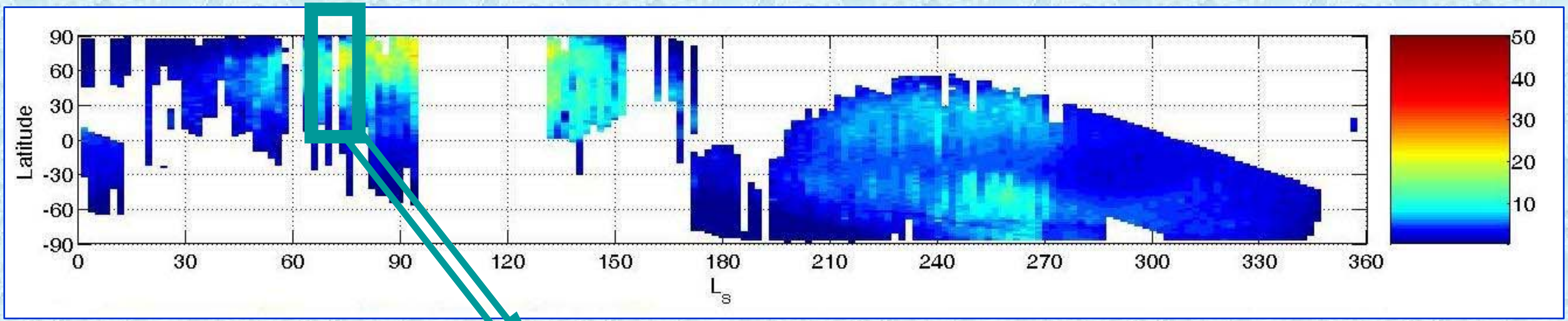


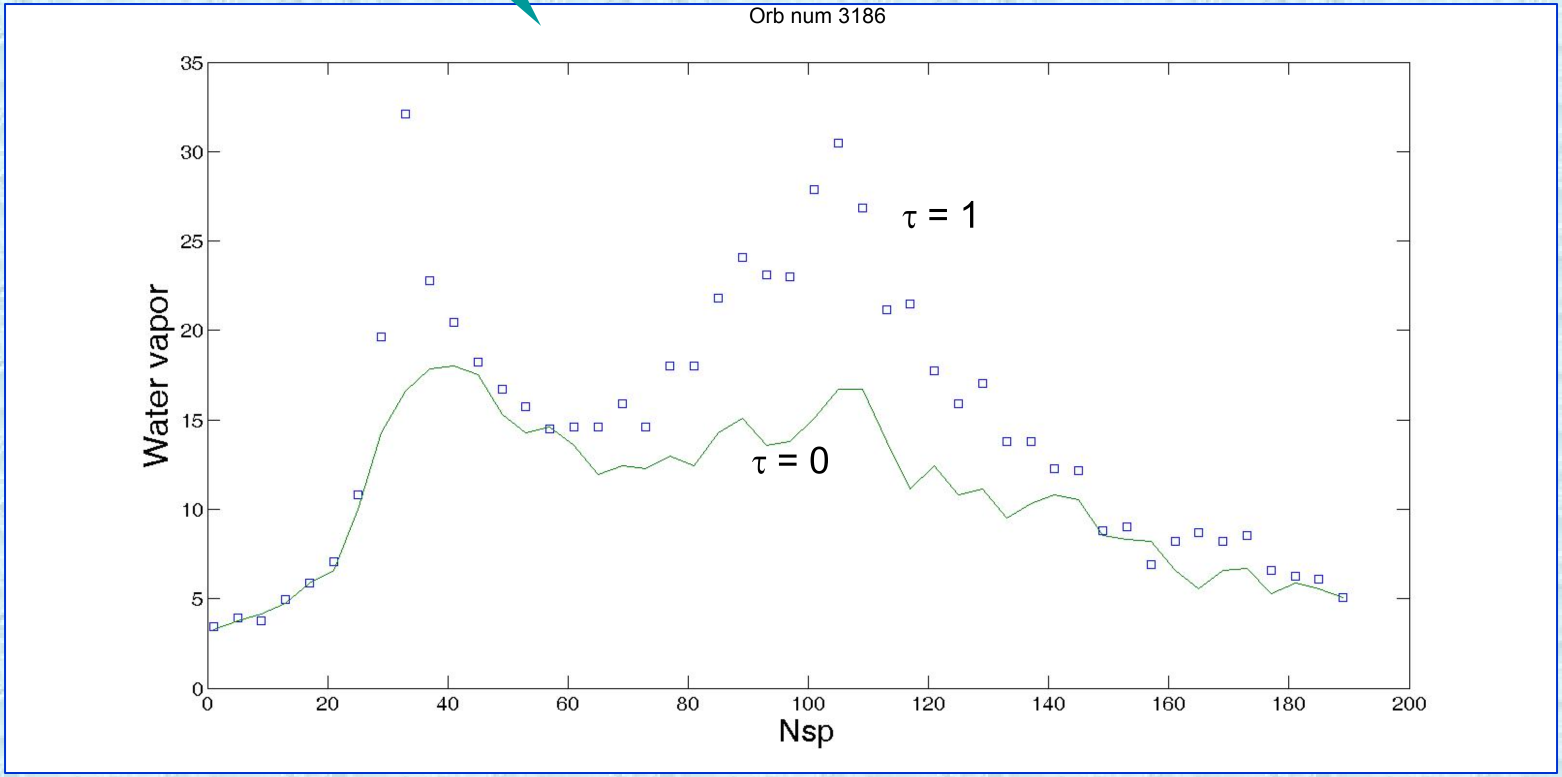
SPICAM: seasonal distribution of H_2O



Water vapor band 1.38 mm, HITRAN2004, Martian Climate Database V4.2   Trokhimovskiy et al 2009 EPSC

Aerosol bias on SPICAM H_2O retrieval: worst case





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WATER IN MARS ATMOSPHERE: COMPARISON OF RECENT DATA SETS (2005-2006)

O. Korablev, JL Bertaux, RT Clancy, T. Encrenaz, A. Fedorova, V. Formisano, T. Fouchet, N. Ignatiev, E. Lellouch, L. Maltagliati, R. Melchiorri, F. Montmessin, A. Rodin, MD Smith, A Sprague, D. Titov, A. Trokhimovskiy, M. Tschimmel, L. Zasova,

Data of 3 Mars Express instruments, TES/MGS, and ground-based compared and validated

Assumptions and methods for H_2O retrieval in MEX experiments.

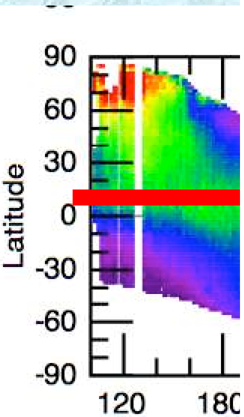
Instrument	Spectral data, broadening	Synth spectrum comp.	Temp. profile	Saturation altitude	Pressure definition, footprint	PFS data processing	Dust-aerosol	Solar spectrum	Comment
PFS LW (NI)	HITRAN 04 Gamache95	LUT from LBL step 0.002 15T x10p	D. Grassi ~60 layers, adaptive like EMCD	From T mixed below	EMCD, MOLA with 0.5° averaged along PFS track (>10sp)	Calibrated by Giuranna apod	no	N/A	
PFS LW (TF)	GEISA 03 Gamache93	LUT from LBL step 0.01 12T x45p	15-µm inv. 45 layers, 12mb	From T mixed below supersaturation allowed	Same 9 sp	Calibrated by Giuranna unapod	no	N/A	
TES	GEISA 97 1.5	Correlated k, LUT for H2O 10Tx10p	15-mm inv (Conrath 2000)	From T mixed below	MOLA+ VL seasonal	n/a	Derived from TES 9-µm	N/A	

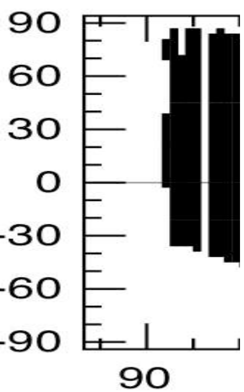
Instrument	Spectral data, broadening	Synth spectrum comp.	Temp. profile	Saturation altitude	Pressure definition, footprint	PFS data processing	Dust-aerosol	Solar spectrum	Referecnce
PFS SW	HITRAN 04 Gamache95	Same as LW	EMCD	From T mixed below	15 sp	Uncalibrated, no phase corr, apod.	no	Fiorenza &F. 2005	Nicolay Ignatiev, personal communication
PFS SW	GEISA 03 Gamache93	Same as LW	EMCD	From T mixed below supersaturation allowed	16 sp	Uncalibrated, no phase corr, unapod.	no	Fiorenza &F. 2005	Fouchet et al., Icarus 2007
PFS SW	HITRAN 04 Gamache	LUT from LBL 20T	EMCD 0-98 km step 2	From T Mixed OR CONFINED below	15 sp with MOLA; press EMCD	Calibrated, no phase corr, apod.	no	Fiorenza &F. 2005	Tschimmel et al., Icarus 2008
SPICAM	HITRAN 04 1.5	LUT from LBL adaptive grid, min 0.001 16T x13p	LMD, grid is kept	From T 0 water above, mixed below	EMCD (3.5x5°), 6 or 10 sp	n/a	no	Fiorenza &F. 2005	Fedorova et al., JGR 2006; corrected in Icarus 2010, in press
OMEGA	GEISA 03 Old Gamache (1993)	Curves of growth, varied p0	single profile	From a chosen T profile	"Pres0" (0.1°, up to 1/32°) Omega data at 0.1x0.1°	n/a	no	Relative to Olympus top	Encrenaz et al. A&A 2005, 2008 Melchiorri et al. PSS 2007, Icarus 2009
OMEGA	HITRAN 04 Gamache	LUT from LBL 20T	EMCD, 5 profiles per cube	From T mixed below	EMCD	n/a	no	Fiorenza &F. 2005	Maltagliaty et al., Icarus 2008

Side effects of MEX water vapour comparisons

- TES/MGS database modification
  - Bug in processing low resolution (12.5 cm^{-1}) portion of data
  - Reduction of H_2O content in these data by **30%**
- MAWD/Viking dataset modification
  - Reprocessing of MAWD with new spectroscopic database (HITRAN 2004)
  - Reduction of the entire dataset by **60%**

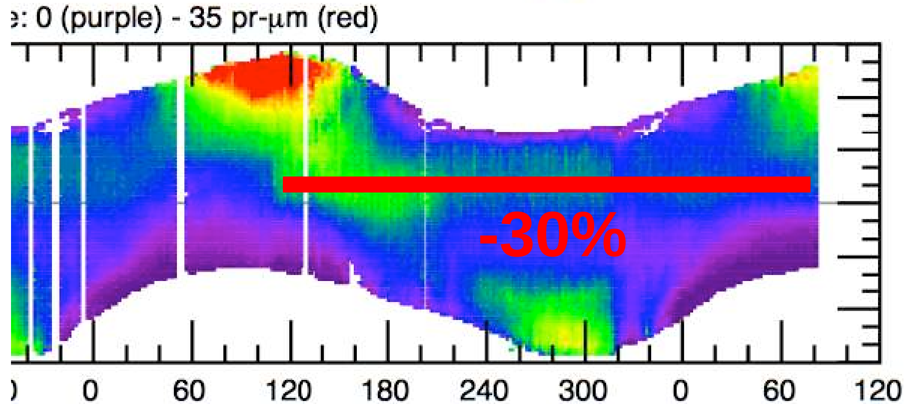
TES database modification

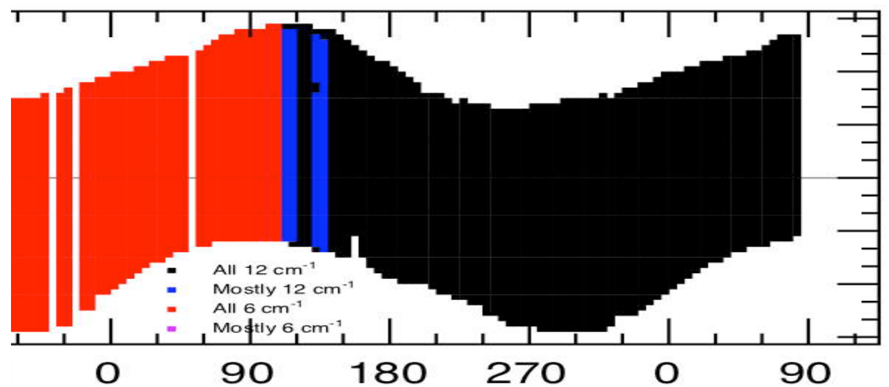




Modification to TES Water Vapor Retrieval: A reanalysis of the TES water vapor retrieval was performed in early 2006 when a comparison against concurrent retrievals from PFS/LW spectra (at the same wavelength as TES) showed that the TES retrievals gave significantly higher water vapor abundances than the corresponding PFS/LW retrievals (*Fouchet et al*. 2007). The analysis showed that for the spectra taken at the TES higher spectral resolution (6.25 cm^{-1}), retrievals using each of the four water vapor bands gave consistent results, but for spectra taken at the lower spectral resolution (12.5 cm^{-1}), retrievals using the two weaker bands (300 and 330 cm^{-1}) were significantly higher and not consistent with other observations. Using only the two stronger bands at 250 and 280 cm^{-1}, retrieved water vapor abundances are consistent between the higher and lower spectral resolution TES observations, and are much closer to the values retrieved using PFS/LW spectra.

This correction to the TES water vapor retrieval results in a reduction in derived water vapor abundance by about 30% in the TES lower resolution data. The TES higher resolution data are not affected by this correction. Lower resolution data were taken at the beginning (MY 24, Ls=103° to MY 25, Ls=90°) and end of the TES dataset (MY 26, Ls=120° to MY 27, Ls=80°), while higher resolution data were taken during the middle of the TES dataset

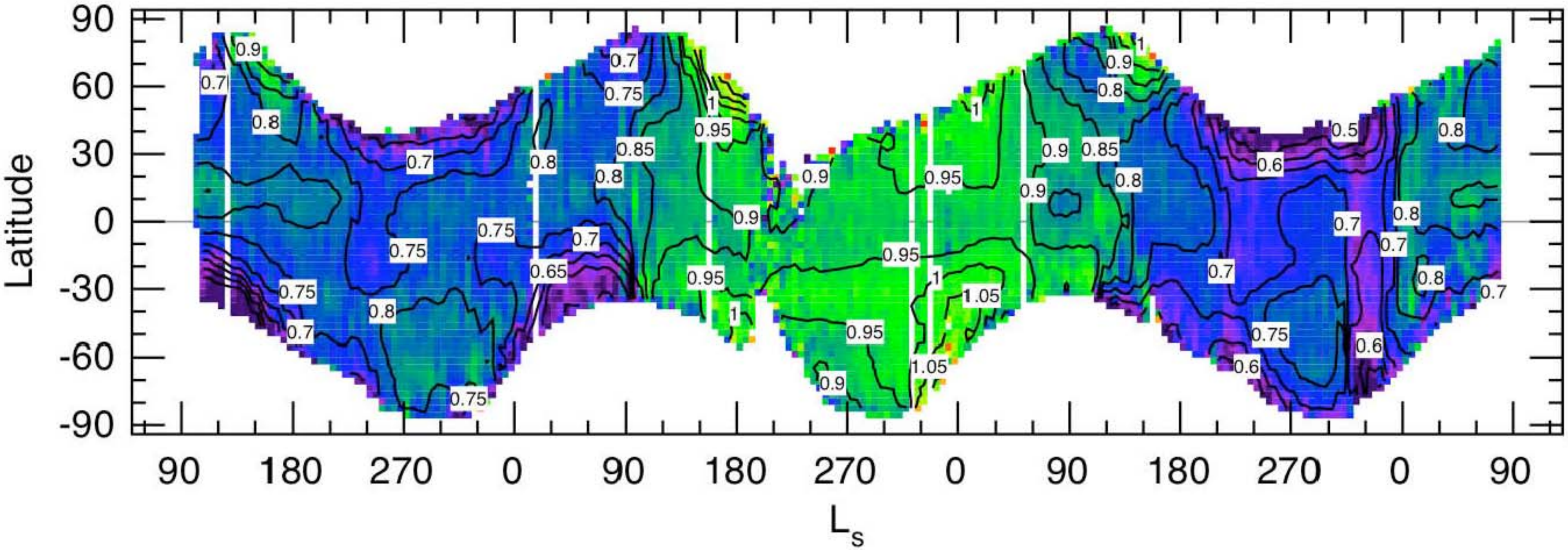




M.D. Smith, MWCW 2008

TES database modification

Ratio of “New” / “Old” abundance

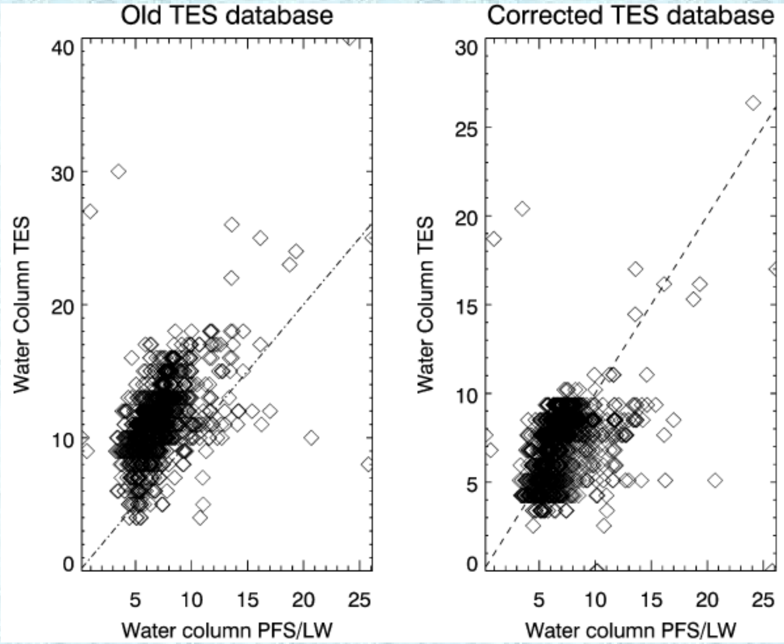


- Higher resolution observations: decrease of ~5%
- Lower resolution observations: decrease of ~20-30%
- More consistency from year to year (from higher to lower resolution data)

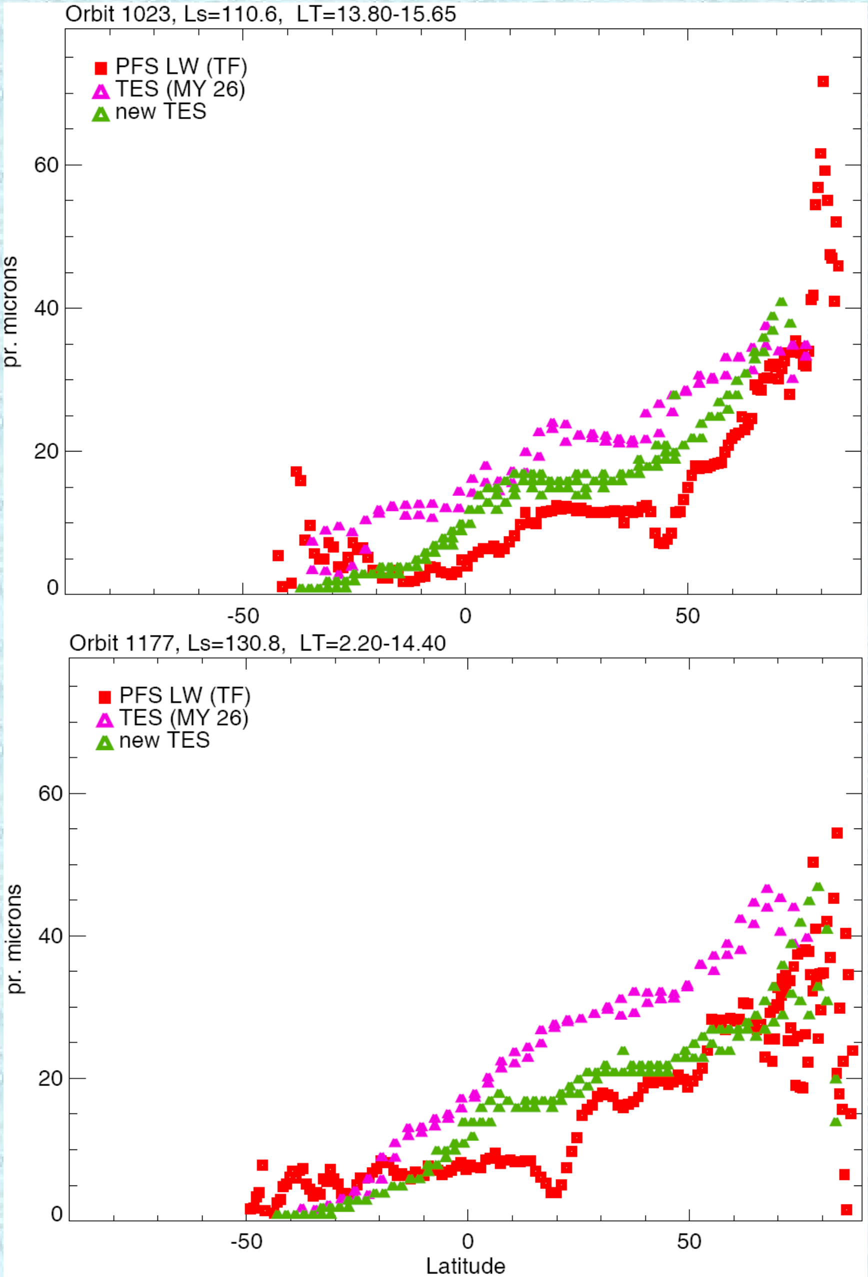
M.D. Smith, MWCW 2008

PFS LW vs TES

Good agreement after correction of TES

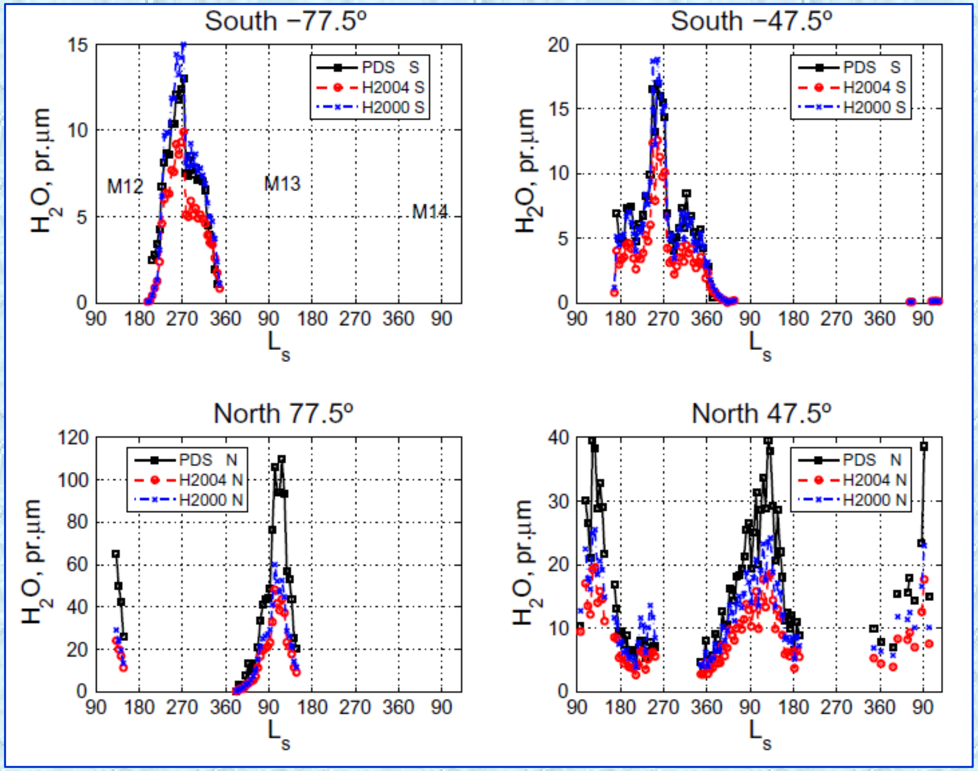


Fouchet et al., Icarus 2007



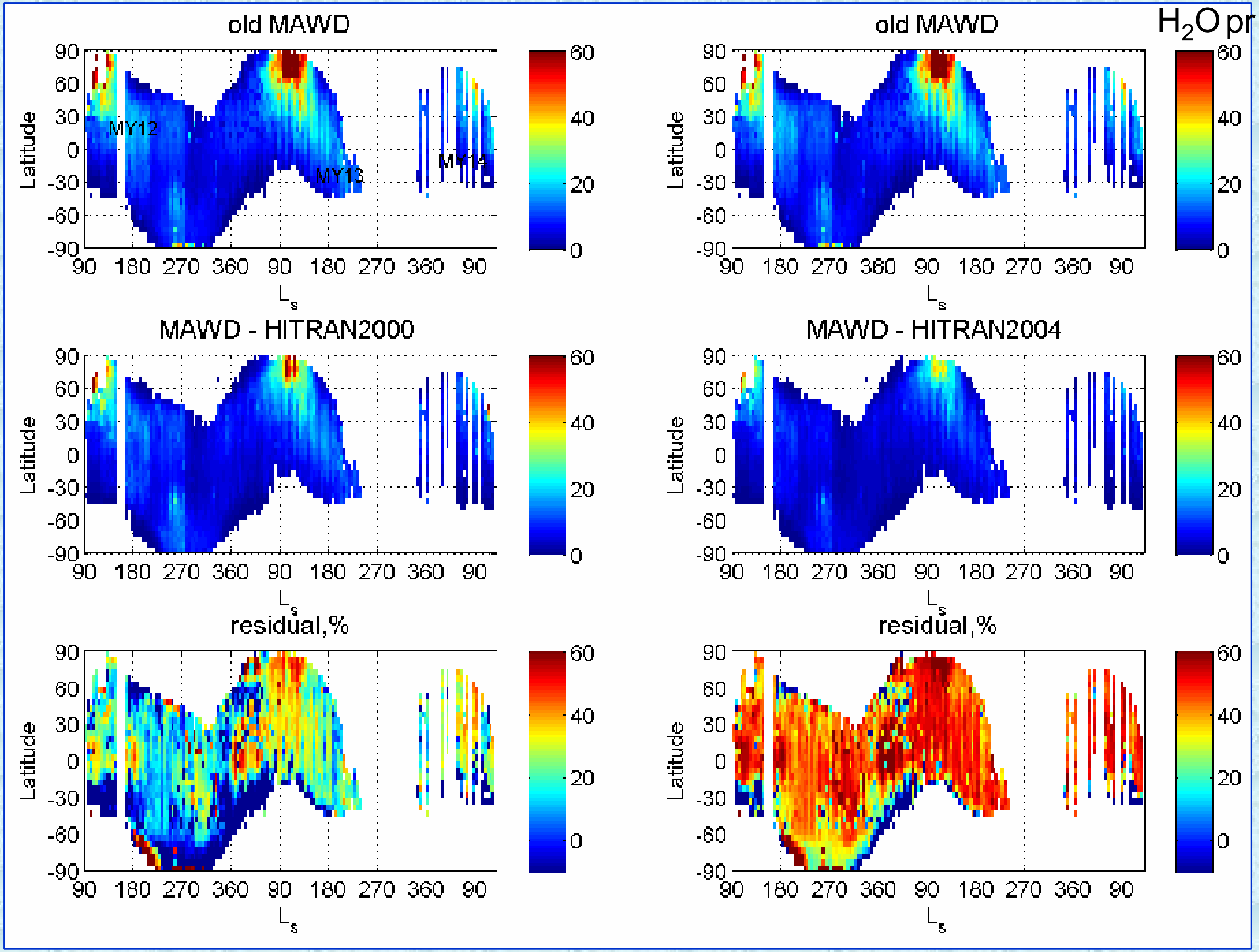
MAWD database modification

- Sensitivity to spectroscopic database
  - HITRAN 2004 (and later): x2 more H_2O lines in the 1.38-µm band
  - Different line parameters
  - More apparent absorption → less retrieved water
- More realistic retrieval assumptions
  - EMCD 4.2 atmospheric profiles
  - Lower saturation altitude → less retrieved water
  - Accurate account for solar spectrum
  - MOLA topography



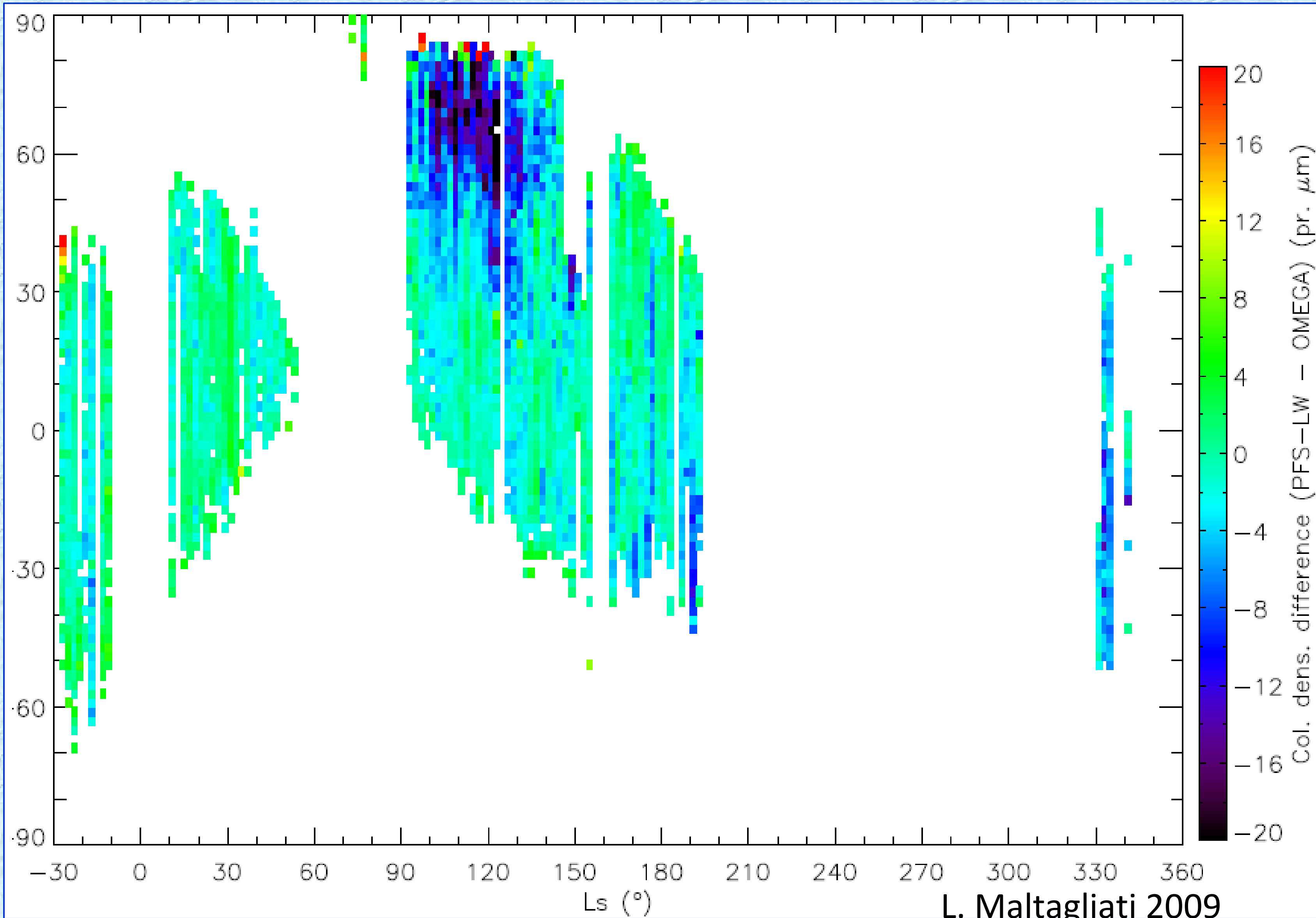
Fedorova et al., 2010

MAWD database modification: results



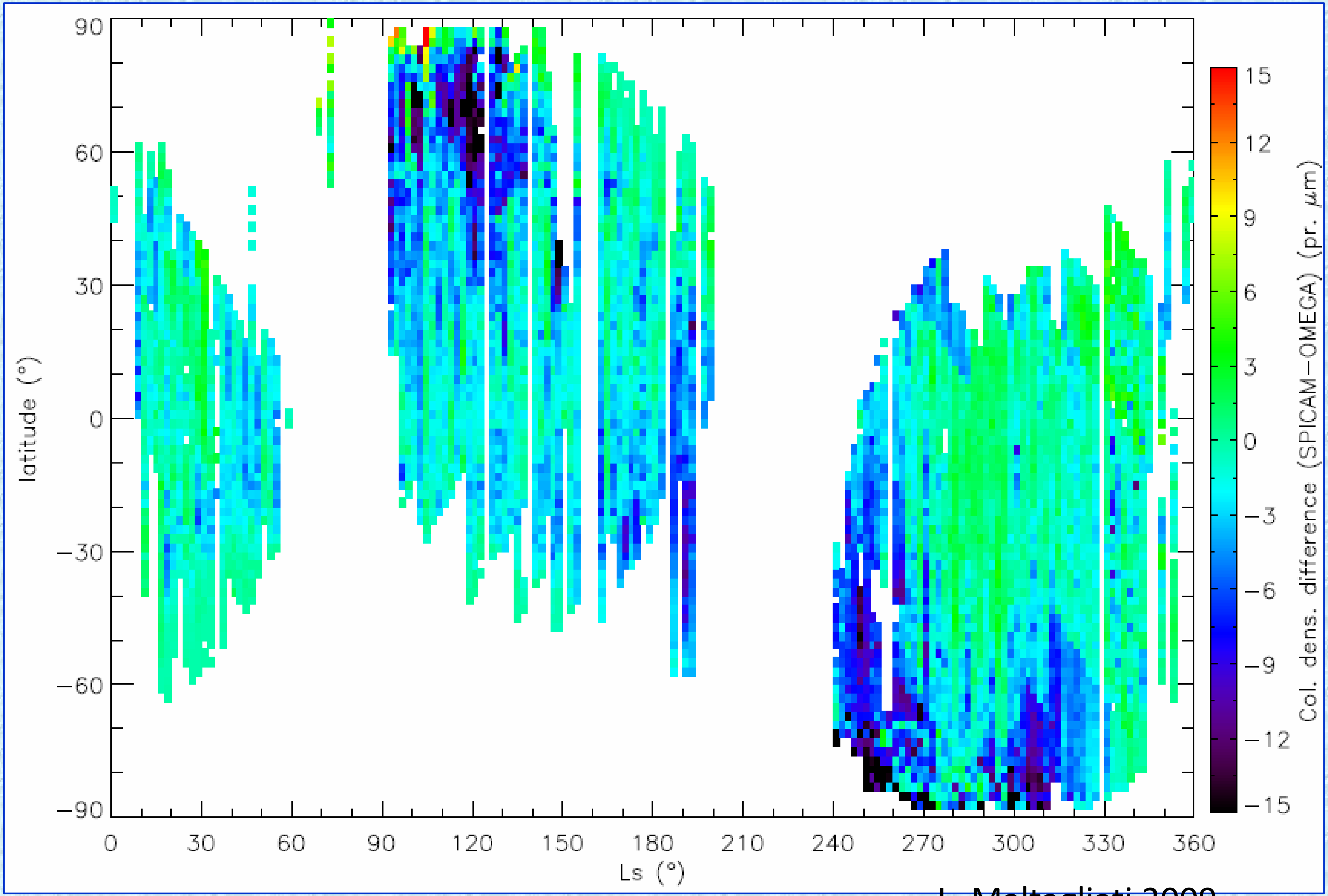
Fedorova et al. 2010 Icarus in press

PFS LW-OMEGA



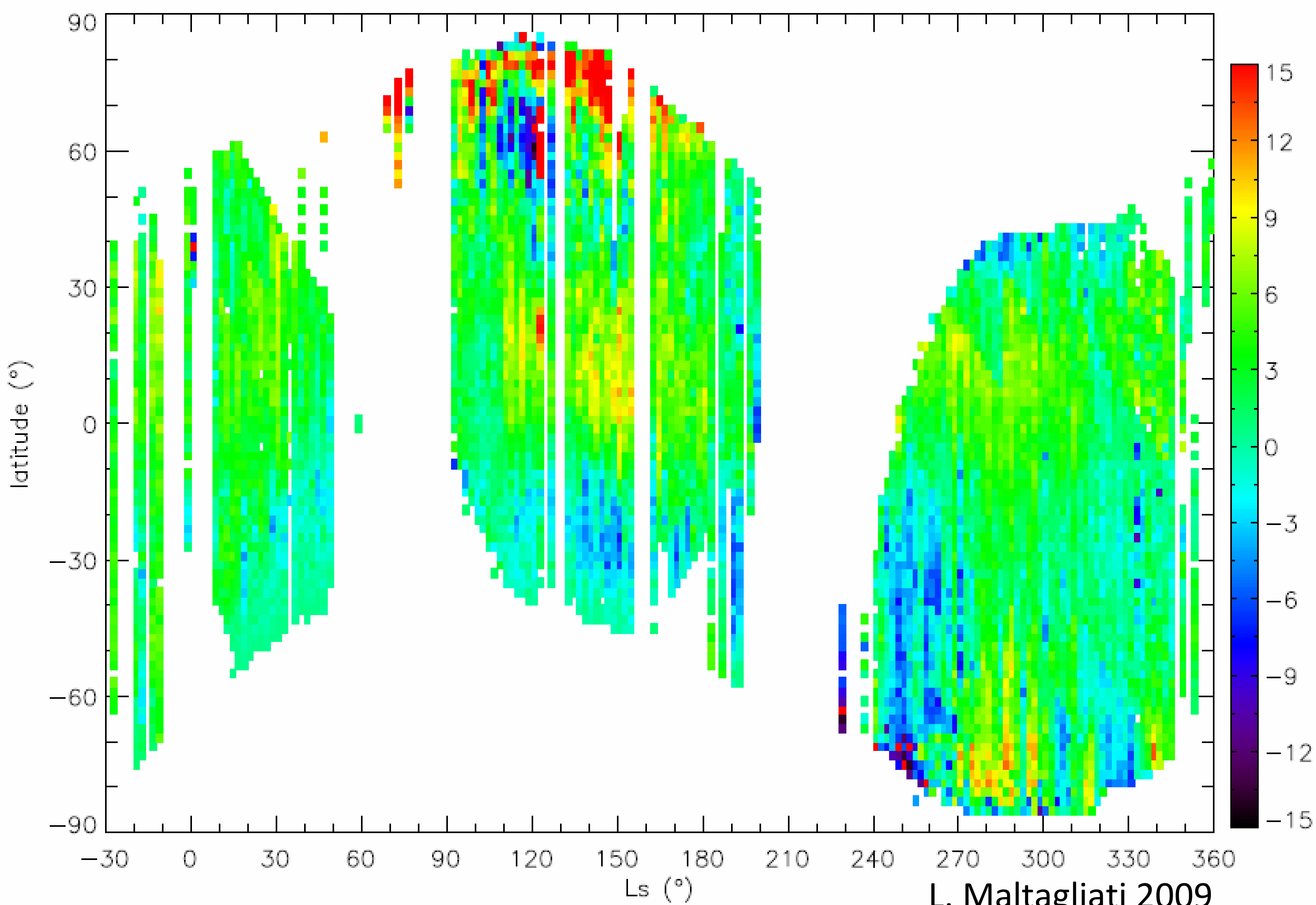
L. Maltagliati 2009

SPICAM-OMEGA



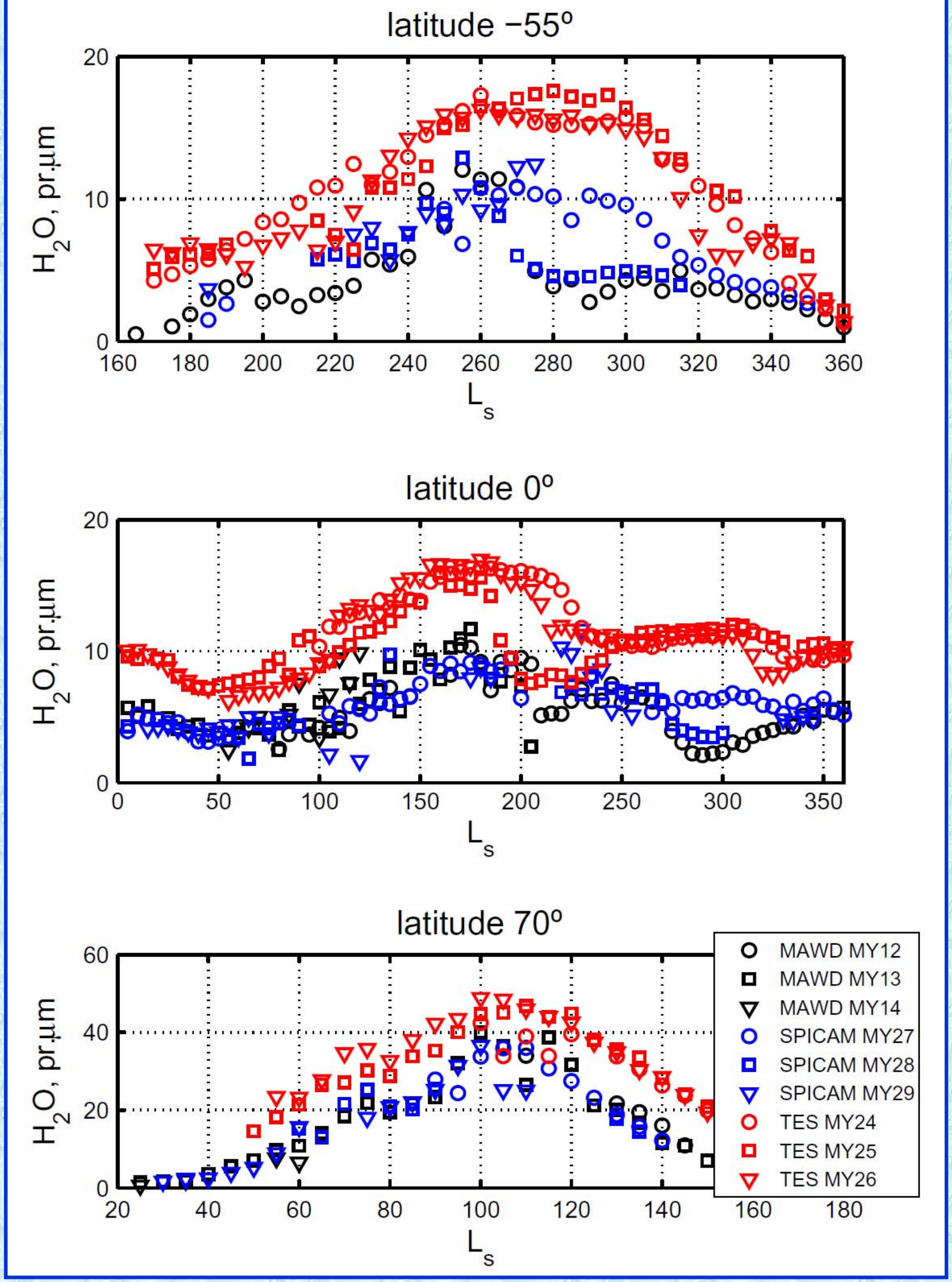
L. Maltagliati 2009

TES-OMEGA

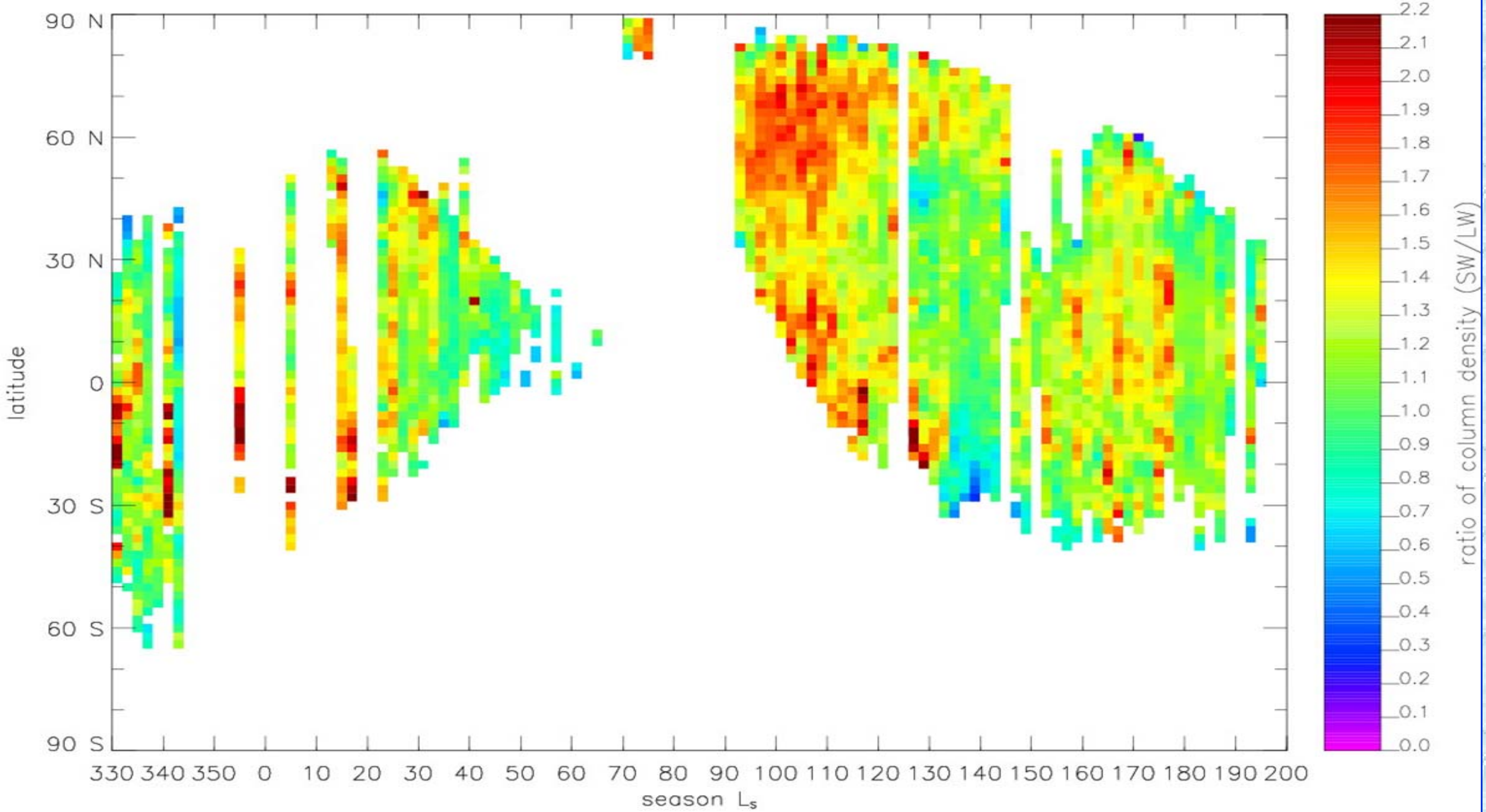


L. Maltagliati 2009

MAWD-TES-SPICAM



PFS SW/PFS LW



PFS SW data can be reconciled only if H_2O profile confined to lowest 2 km

Tschimmel et al., Icarus 2008

Conclusions

- Reasonable agreement of Mars Express data sets, TES, and recently MAWD has been achieved

MAWD* ≈ SPICAM ≤ PFS LW ≤ OMEGA ≤ TES* ≤ PFS SW

* Correction of TES (–30% for 60% of data) → new TES database (2006) available from M. Smith

* Correction of MAWD PDS dataset (–50-60% global; no aerosol accounted for; Fedorova et al, 2010)

- Generally dryer water cycle
- Much less seasonal variations

Conclusions: MEX

- Thermal IR (PFS LW)
  - Most trustworthy (low contribution of aerosol)
  - Vulnerable to line broadening approximation in CO_2
  - Short dataset of PFS
- OMEGA (2.56 µm)
  - Spectra of low resolution, vulnerable to contamination by H_2O ice and other surface features
- PFS SW (2.56 µm)
  - Unexplained overestimation of H_2O
- SPICAM (1.38 µm)
  - Most vulnerable to aerosol scattering

Terrestrial remote sensing parallels

- Montoux et al., ACP 2009:
- The reference is balloon TDLAS (5-10% accuracy)
- HALOE displays the best precision (2.5%), followed by SAGE II (7%), MIPAS (10%), SAOZ (20–25%) and SCIAMACHY (35%), all of which show approximately constant H_2O mixing ratios between 20–25 km. Compared to HALOE of ±10% accuracy between 0.1–100 hPa, SAGE II and SAOZ show insignificant biases

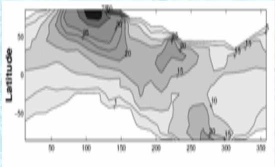
  MIPAS is wetter by 10% and SCIAMACHY dryer by 20%.

- MIPAS (6.1, 10.5, 12.4 µm) may be considered as an analogue to TES and PFS LW
- SCIAMACHY (1.38 µm) is similar to SPICAM and MAWD

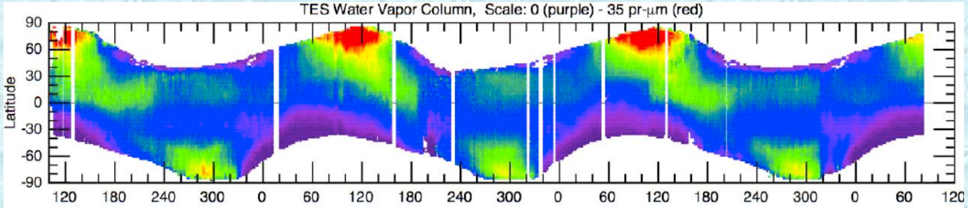
➔ We must use "proxies" like on Earth

What do we have for water vapor

MAWD MY 12-13



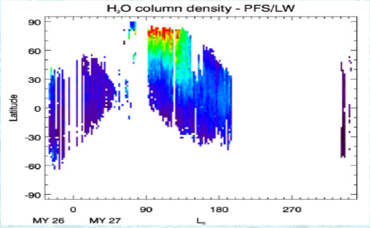
Jakosky and Farmer 1982,
Reprocessed by
Fedorova et al, 2004, 2010



TES MY 24-26

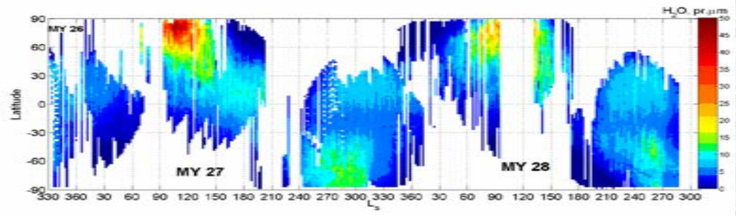
M.D. Smith 2004, 2006, 2008

Fouchet et al., 2007
Tschimmel et al., 2008
Sindoni, Formisano 2010



PFS MY 27

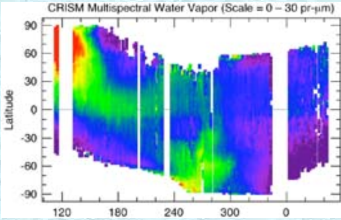
Fedorova et al., 2006
Trokhimovskiy et al 2008
Maltagliati et al 2008



SPICAM, OMEGA MY 27-28

- ➔ Reasonable convergence of Mars Express data sets and TES is achieved
- ➔ Lessons for MAWD/ Viking: decrease of Viking results [Fedorova et al., Icarus 2010]

M.D. Smith et al., 2008, 2009



CRISM MY 28

Vertical structure of atmospheric water

- Constraints from temperature and column measurements
- Constraints from microwave measurements (line profile allows to determine saturation altitude)
- Solar occultation measurements: both water and aerosols (difficult to disentangle ice and dust)
  - Auguste/Phobos 88 (Krasnopolsly et al., 1991; Rodin et al., 1997)
  - SPICAM/MEX (Fedorova et al., Icarus 2009)
- Limb radiation profiles (MCS/MRO expected)

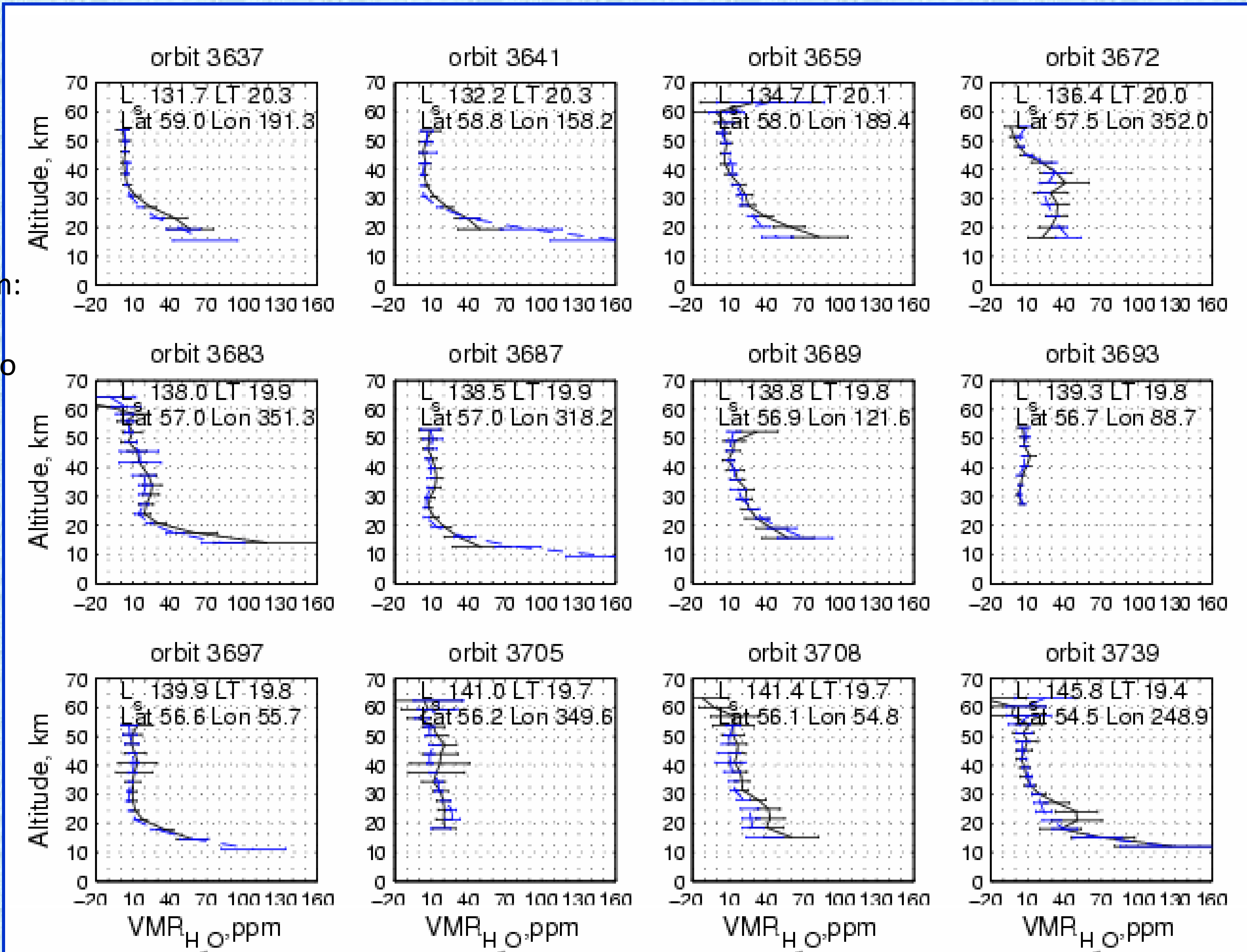
H_2O profiles by SPICAM/MEX

25 to 45 km:

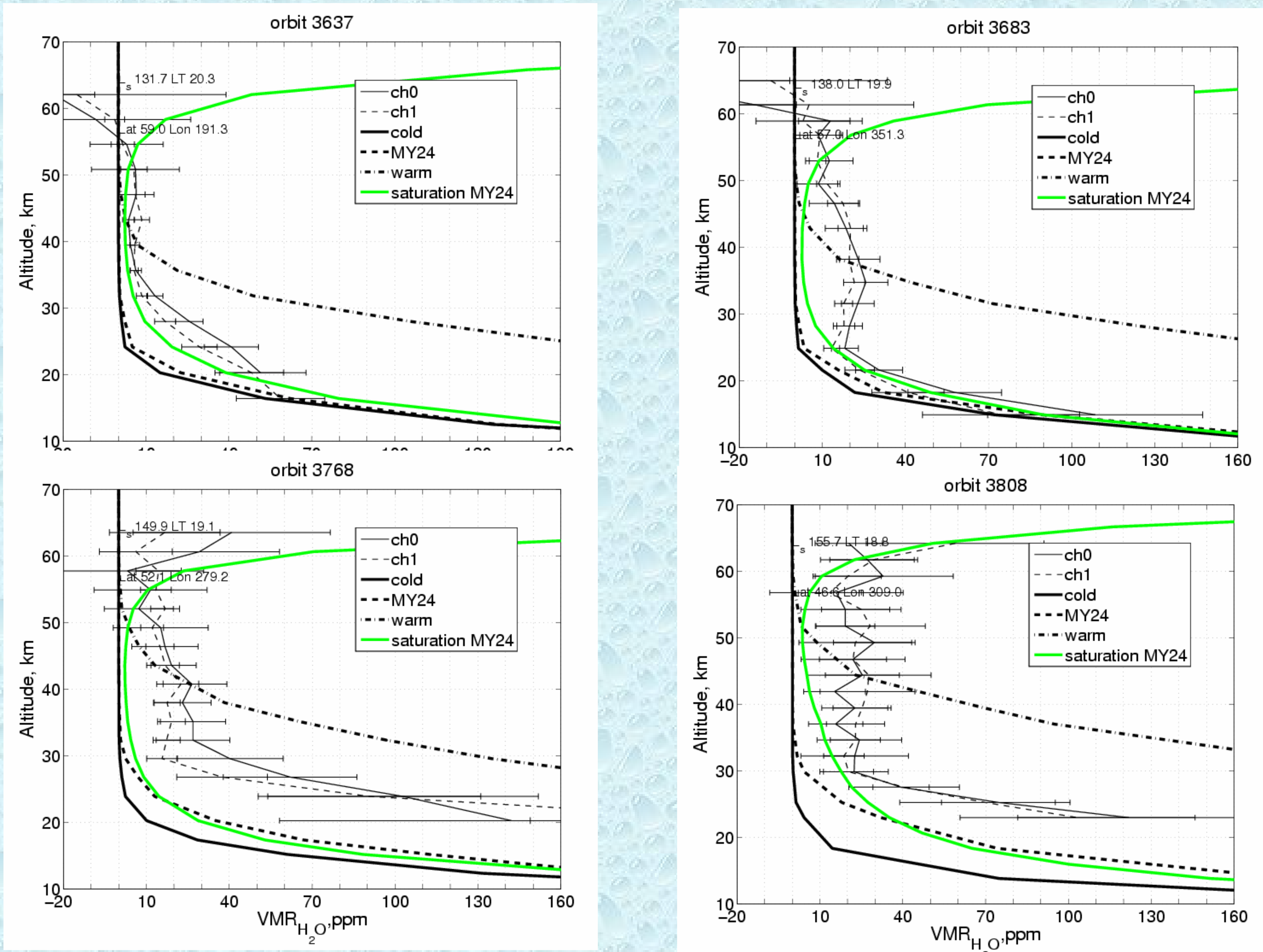
5-15 pmm

Below 20-25 km: fast increase of H_2O mixing ratio to

50-100 ppm

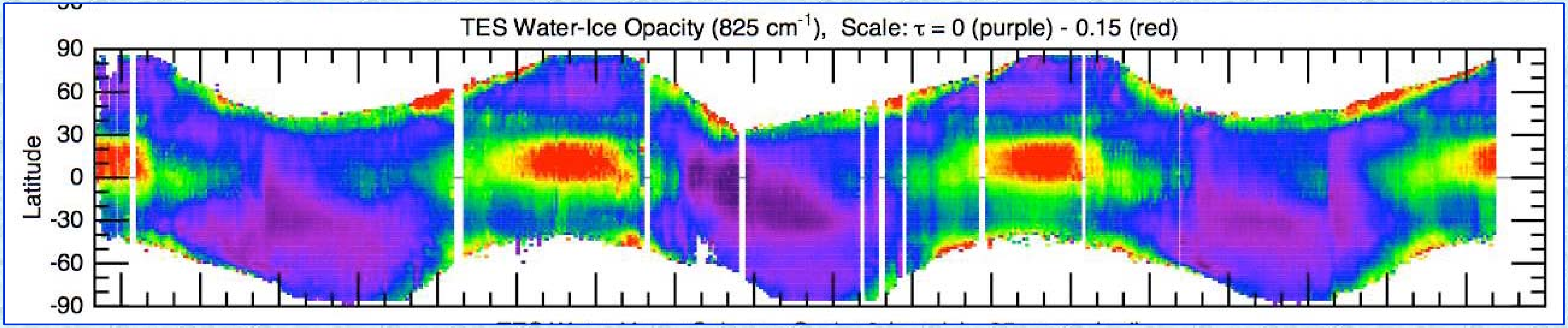


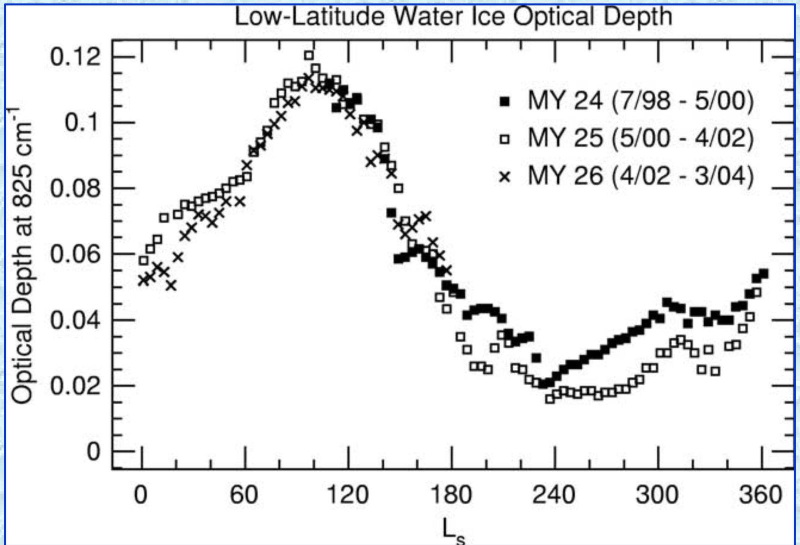
Comparing SPICAM profiles with MGCM



Water ice clouds

- Telescopic observations (e.g. HST)
- TES (and PFS) 12-μm measurements
- IR mapping by OMEGA and CRISM (good for local mapping)
- UV measurements by SPICAM





Future work

- Need to account for aerosol !
  - No regular aerosol database for Mars Express
  - Very difficult from NIR CO_2 bands
  - Scale coefficient =? when using SPICAM UV opt. depth
  - Could be only checked with EPFs
  - **Expected PFS aerosol database**
- Future measurements (ExoMars Orbiter 2016; surface network; future supporting orbiters):
  - Need continuity in monitoring of water vapour
  - Explore all types of orbits to characterize different cycles
  - IRIS-type instrument may be optimal (versatile "weather" instrument)
  - Possibly 6.3-µm band useable (simplifies FTS)
  - Supporting NIR instrument (spectral resolution about MAWD)
  - Accurate measurements near the surface to characterize surface-atmosphere exchange: high sensitivity needed (night, southern winter): TDLAS
  - Profiling of the low scale height : bistatic lidar?