METEOROLOGY

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CHALLENGES OF CHARACTERISING WATER VAPOUR IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE

Michaela I. Hegglin, *University of Reading, UK*

CHALLENGES

Characterising UTLS water vapour distributions is challenging due to strong variability on spatio-temporal scales and large dynamic range:

- Small scale structures (vertical and horizontal) need high-resolution measurements (in-situ), However, they are inherently limited in terms of global coverage.
- Knowledge of global distributions can only be derived from remote instruments. However, they have limited spatial resolution.
- Long-term trends in UTLS water vapour are difficult to obtain due to this scale problem, but also due to the high accuracy and stability needed to derive changes in small numbers.

THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE (UTLS)

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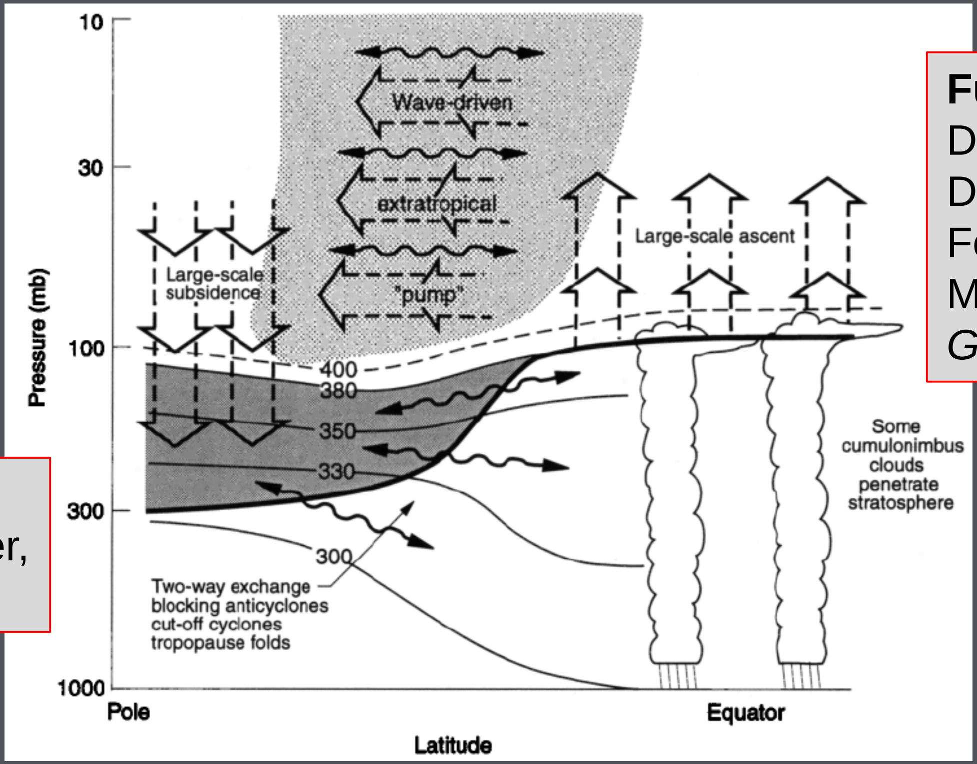
The wave-driven stratospheric ‘Brewer-Dobson’ circulation shapes the UTLS region.

- Air enters the stratosphere through the tropical tropopause, where it is dehydrated.



Fueglistaler, Dessler, Dunkerton, Folkins, Fu & Mote, *Rev. Geophys.*, 2009.

Gettelman, Hoor, Pan, Randel, Hegglin & Birner, *Rev. Geophys.*, 2011.

***Holton** et al., JGR 1995*

FREEZE-DRYING AT THE TROPICAL TROPOPAUSE

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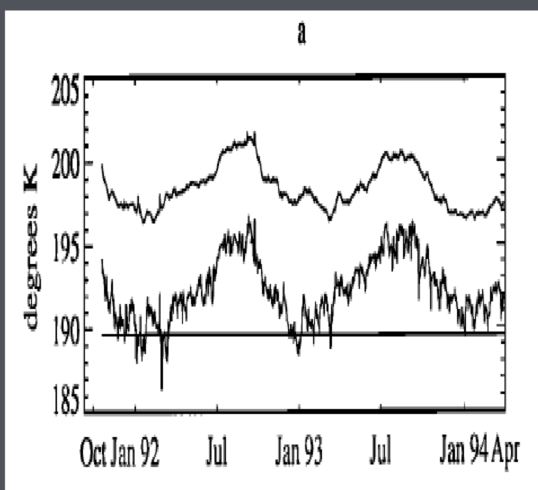
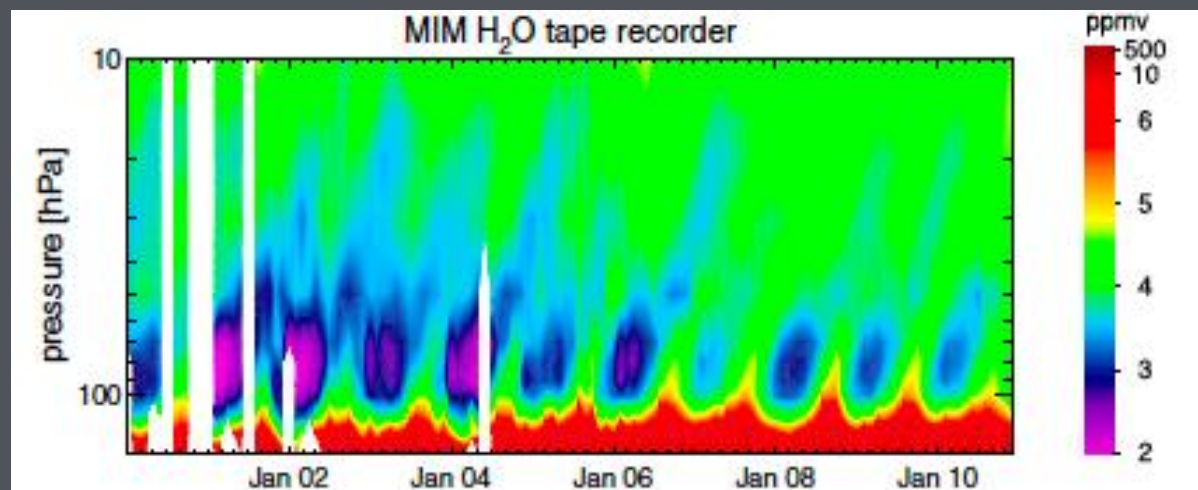
The seasonal cycle in the strength of the Brewer-Dobson circulation causes a distinct seasonality in tropical tropopause temperatures.

- The seasonality is reflected in the tropical tape recorder in water vapour.
- Note the very small water vapour concentrations of a few ppmv in the LS!



Mote *et al., JGR 1996*



Hegglin *et al., JGR 2013*

MODES OF NATURAL VARIABILITY

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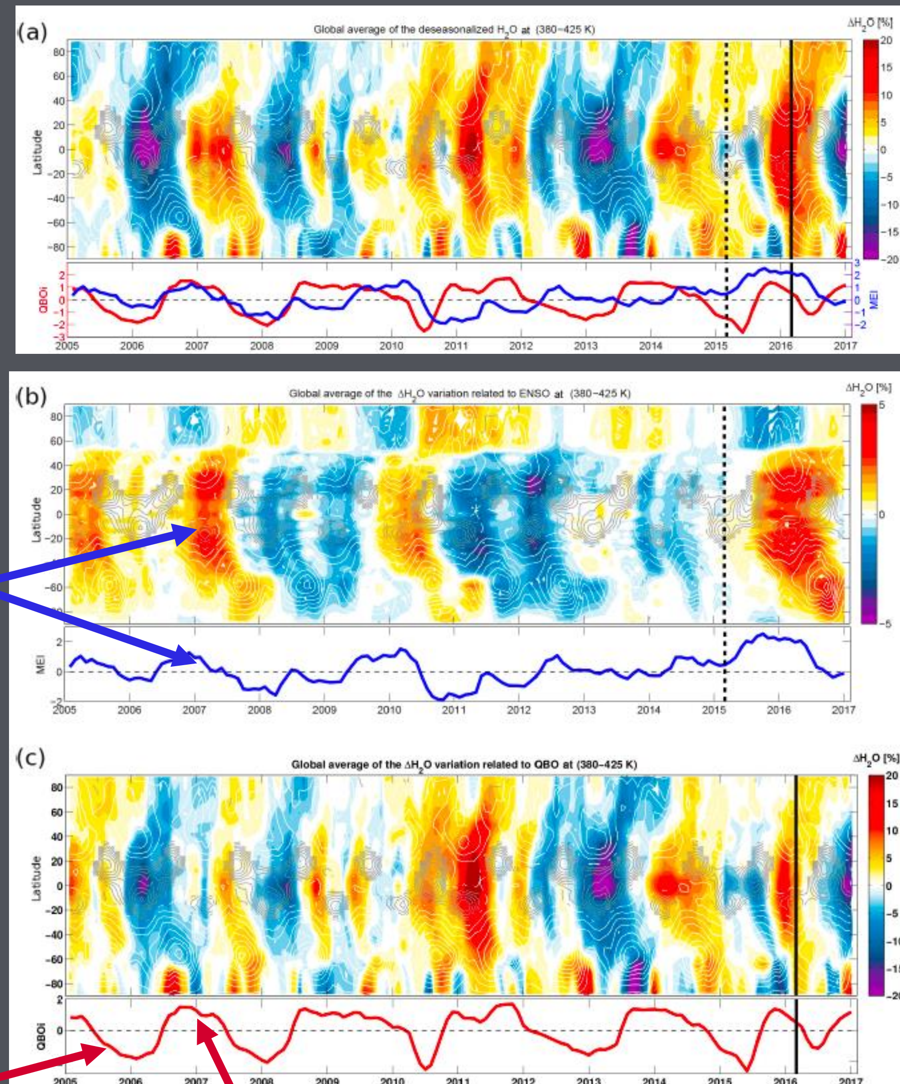
Modes of (internal) natural variability (QBO and ENSO) also modulate the stratospheric water vapour entry value.

- The effects of the QBO and ENSO phases reach into the extratropics!



El Niño

MEI: multi-variate ENSO index

QBO: Quasi-Biennial Oscillation index

Easterly QBO phase

Westerly QBO phase

***Diallo** et al., ACP 2018*

MICROPHYSICS VERSUS CHEMISTRY

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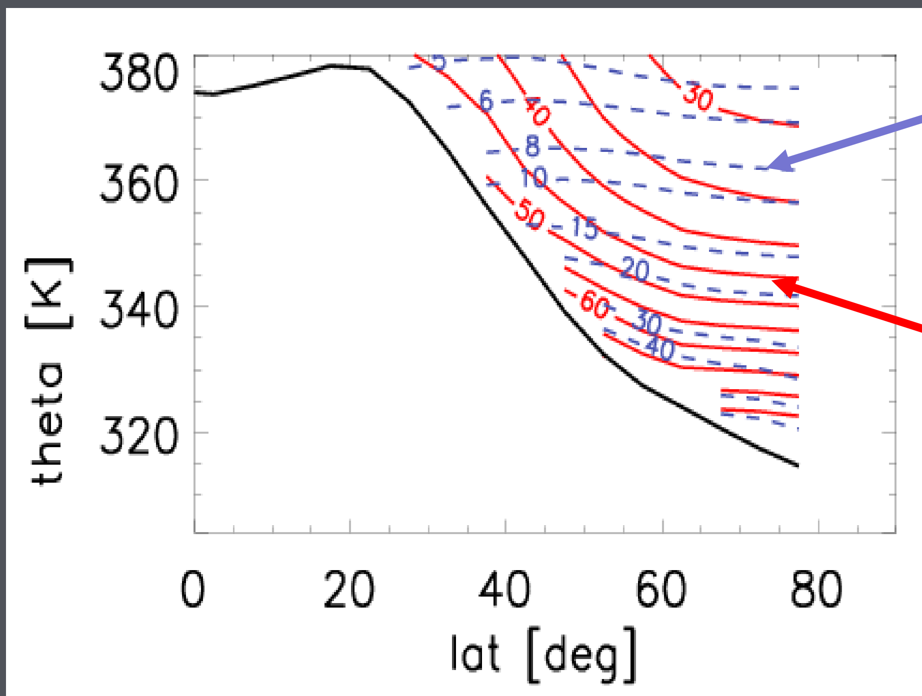
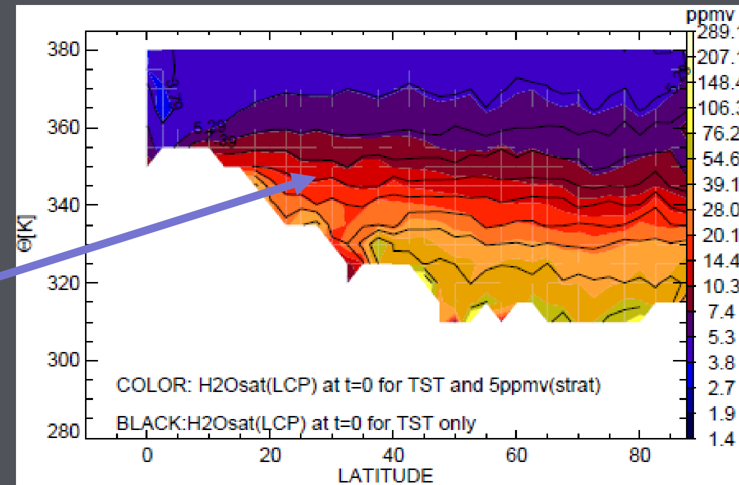
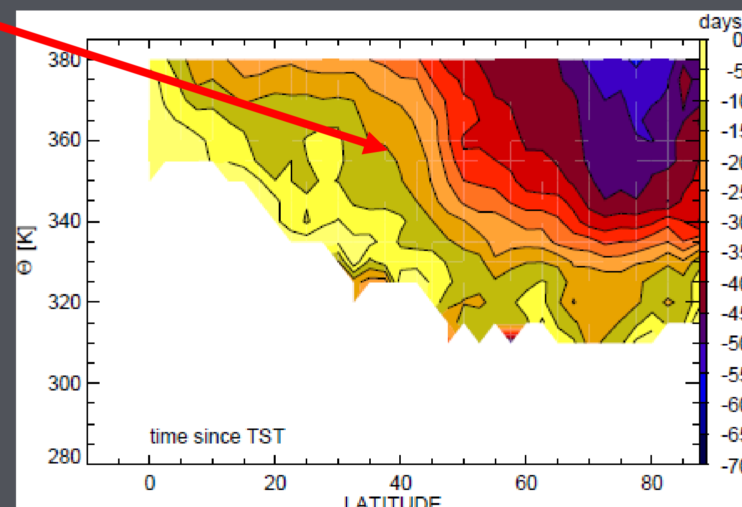
The H_2O distribution is determined by the Lagrangian cold point temperature (i.e., the lowest saturation mixing ratio)



The CO distribution is determined by the residence time in the lower stratosphere.



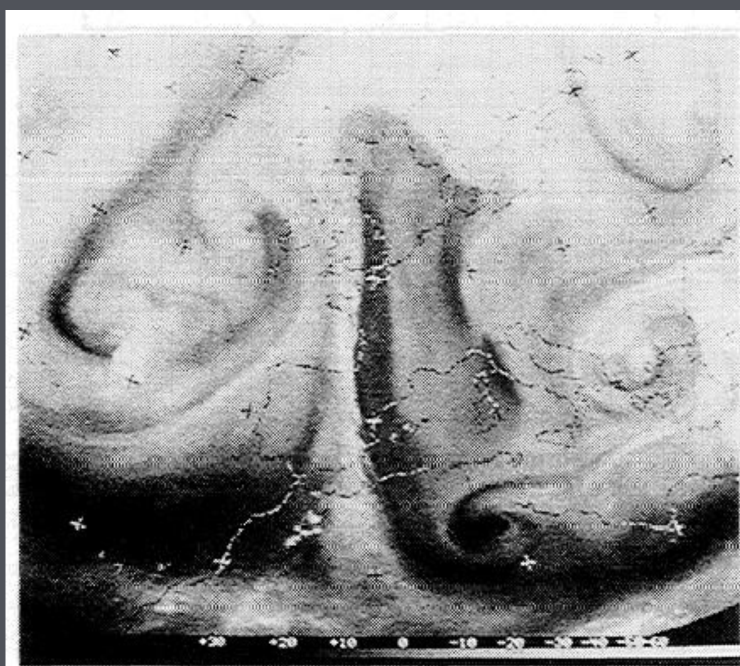


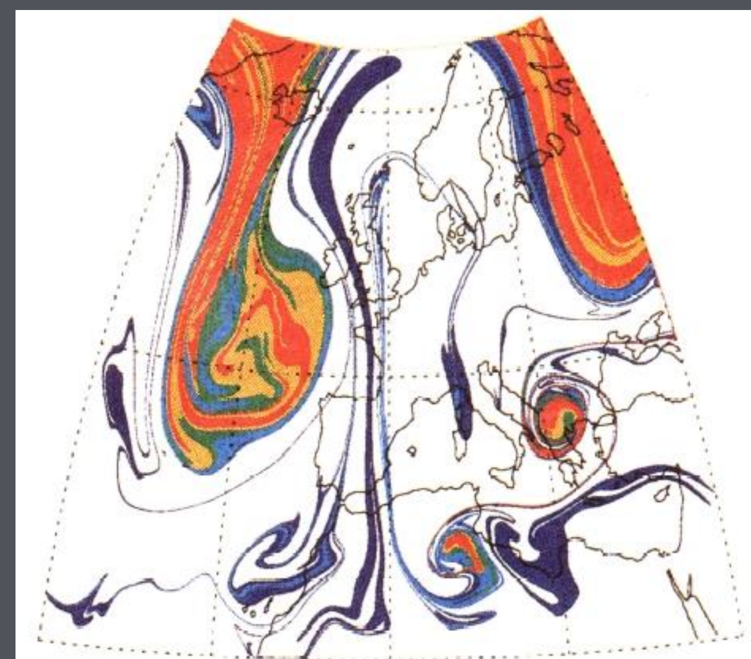
***Hoor**, Wernli, Hegglin & Bönisch, ACP 2010*

EXTRATROPICS: LARGE-SCALE STRUCTURES

First imagery from space was obtained from meteorological satellites, here e.g., a Meteosat water vapour field.

- The structures revealed the importance of horizontal advection and stirring, which can be inferred from large-scale wind fields.





Appenzeller *et al., JGR 1996*

MIXING DERIVED FROM AIRCRAFT OBSERVATIONS

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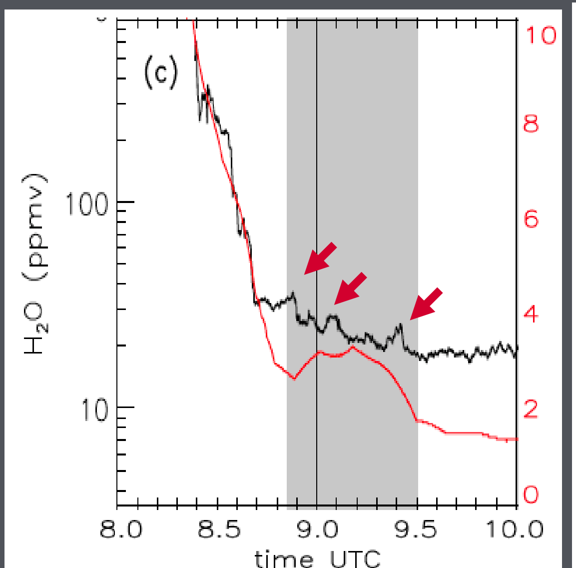
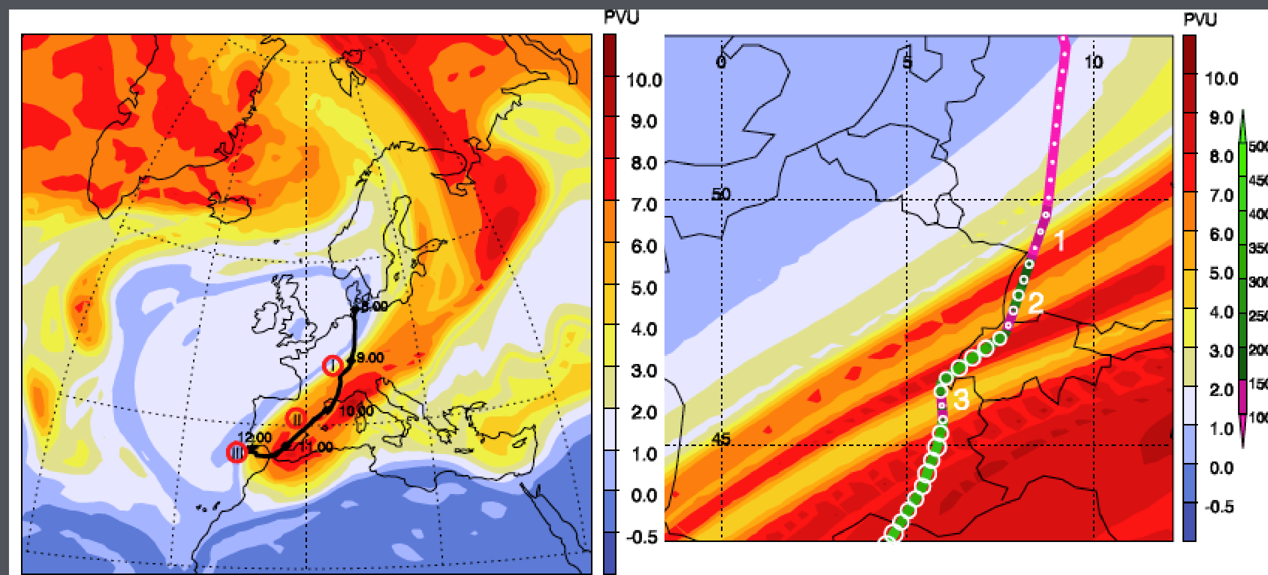
Troposphere-to-stratosphere transport by breaking Rossby waves brings moist tropospheric air (and pollutants) into the stratosphere.

Hegglin *et al., ACP 2004*





A reverse domain filling (RDF) analysis of potential vorticity shows that troposphere-to-stratosphere transport has taken place 24h prior to the measurements.

INVESTIGATING THE GLOBAL UTLS STRUCTURE

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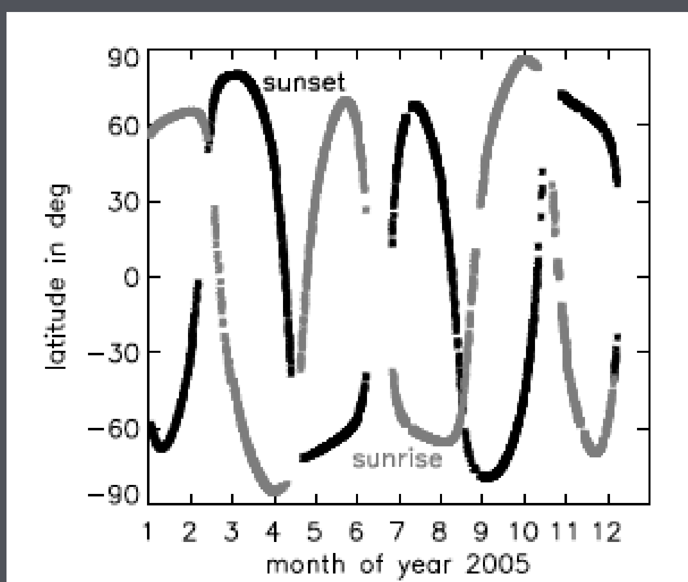
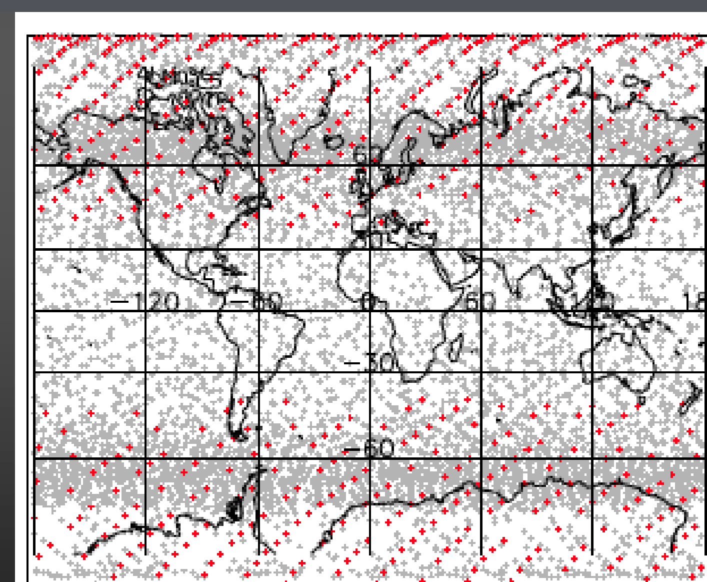
Atmospheric Chemistry Experiment Fourier Transform Spectrometer **(ACE-FTS)**

***Hegglin et al.**, JGR 2008, 2009*

- A solar occultation instrument with high signal-to-noise ratio and relatively high effective vertical resolution (approx. 1 km).
- Provides accurate measurements of a number of species throughout the stratosphere and mesosphere since February 2004.
- Provides a seasonally varying coverage of the globe, with an emphasis on NH midlatitudes and the polar region.





MIXING LAYER ACROSS THE TROPOPAUSE

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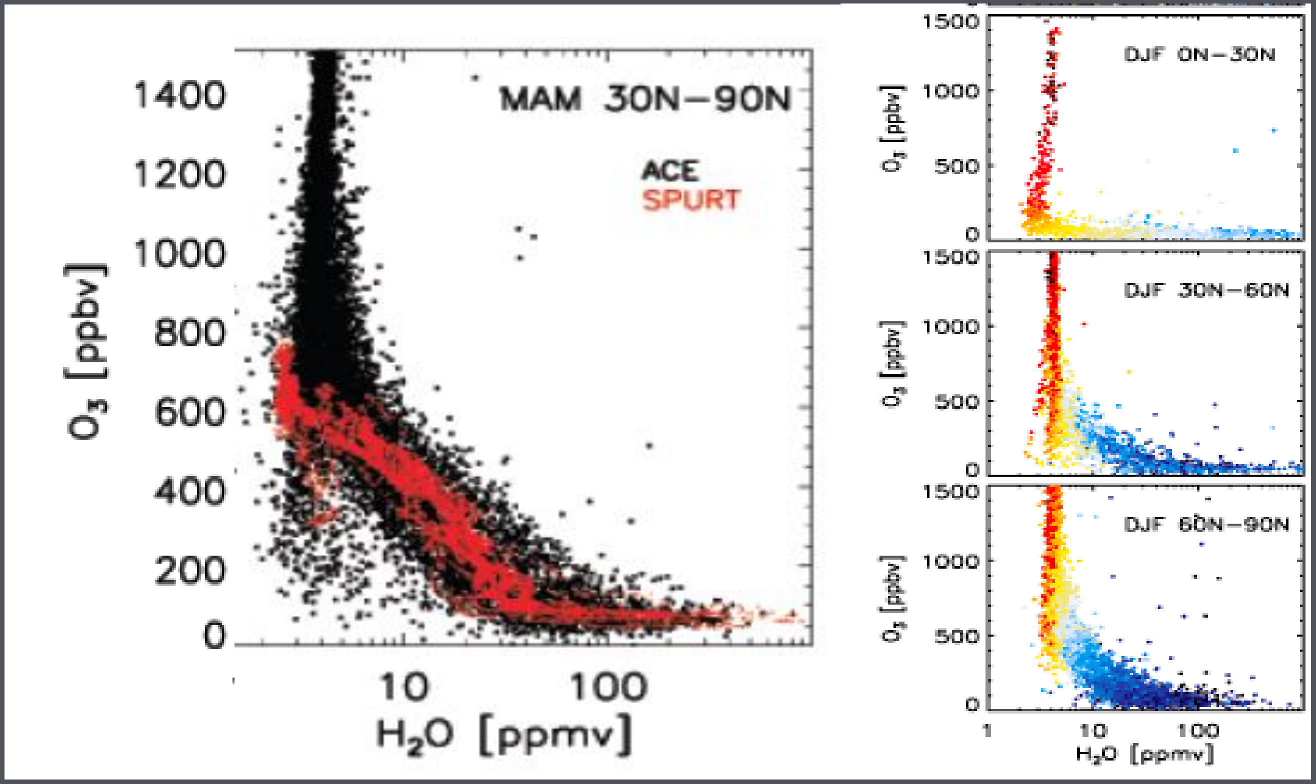
Dehydration of air at the tropical tropopause and the large scale stirring and mixing in the extratropics lead to **the extratropical tropopause transition layer.**

Tracer-tracer correlations



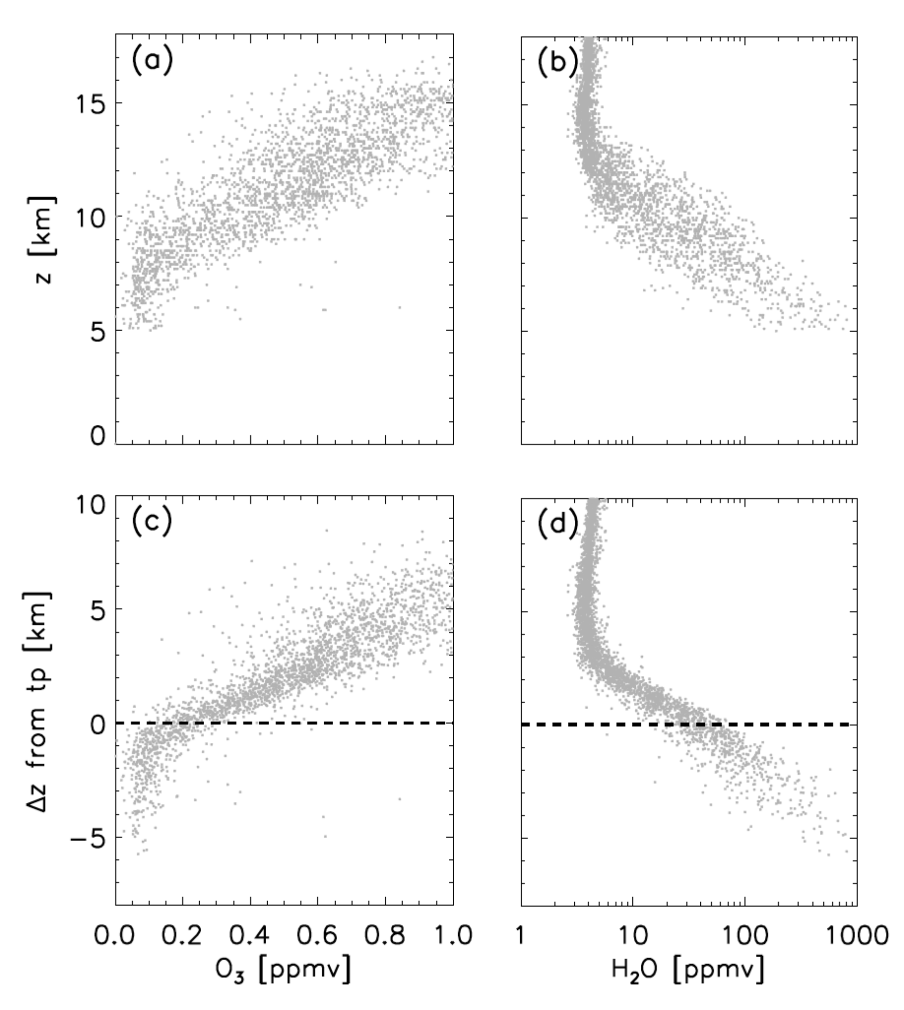
***Hegglin et al.**, ACP 2008; JGR 2009*

GLOBAL UTLS STRUCTURE

Looking at the vertical structure, strong gradients are found across the tropopause.

- Tropopause-based altitude coordinates reveal these strong gradients.
- Typical stratospheric values range from 4-6 ppmv, while tropospheric values are many orders of magnitude larger.

***Hegglin** et al., JGR 2009*



GLOBAL TROPOPAUSE-BASED STRUCTURE

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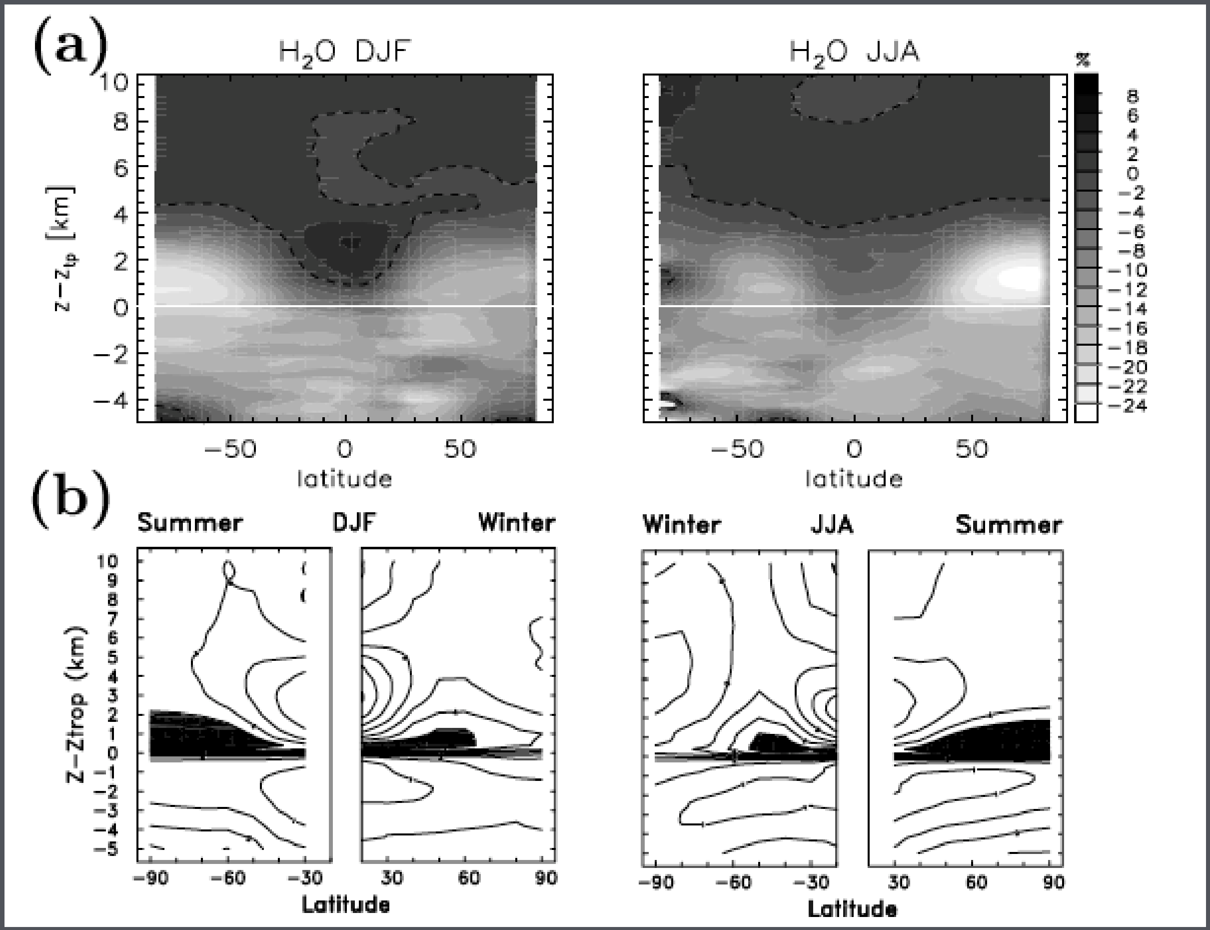
The gradients in water vapour have strong radiative effects and may affect the temperature structure. ***Hegglin*** *et al., JGR 2009*



(b) from Randel et al., 2007

TRENDS IN WATER VAPOUR - BALLOONS

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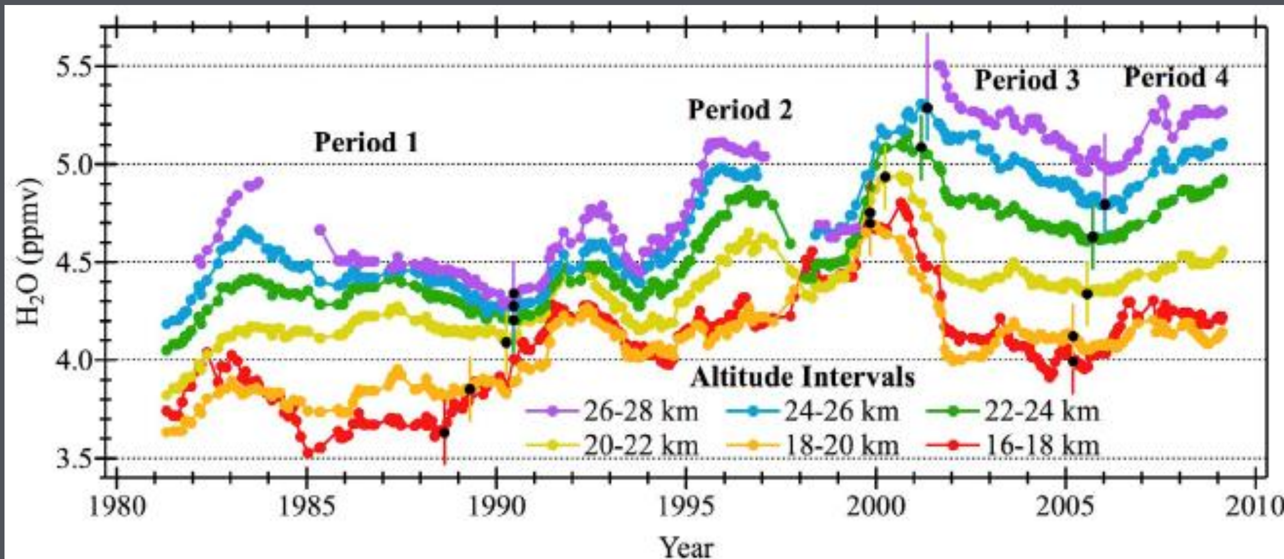
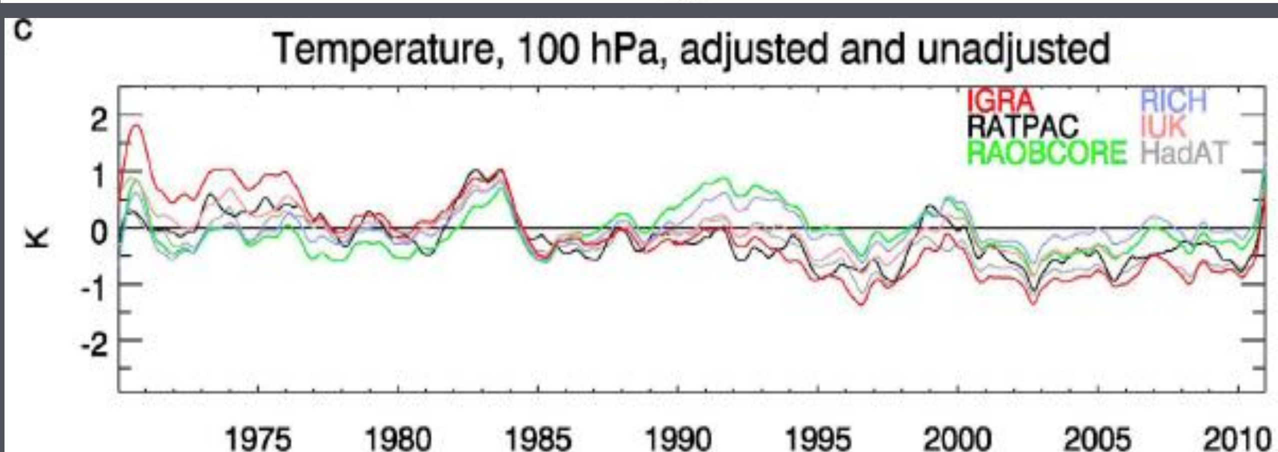
***Hurst** et al., JGR* 2011



- Long-term balloon measurements (FPH) over Boulder indicate an increase of 1.0 ± 0.2 ppmv from 1980 to 2010. At most one-third of this trend can be explained by CH_4 oxidation.



***Wang**, Seidel & Free, JGR* 2012

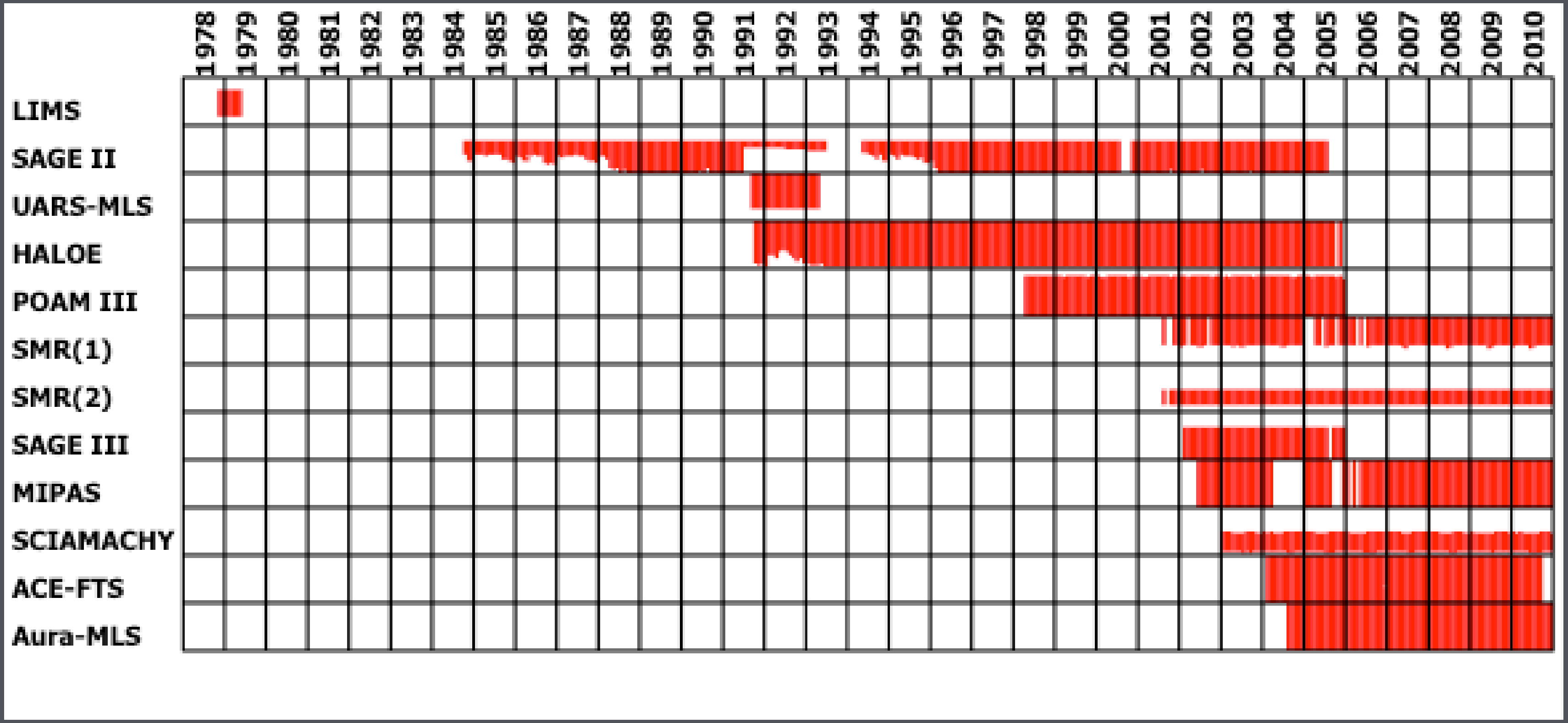
- Tropical tropopause temperatures, understood to be the main other driver of stratospheric water vapour changes, show however a negative or zero trend.

SATELLITE OBSERVATIONS OF H_2O

- SPARC Data Initiative satellite limb sounder data sets.
- Comprehensive assessment for mean biases and structural problems.

Temporal & altitude coverage

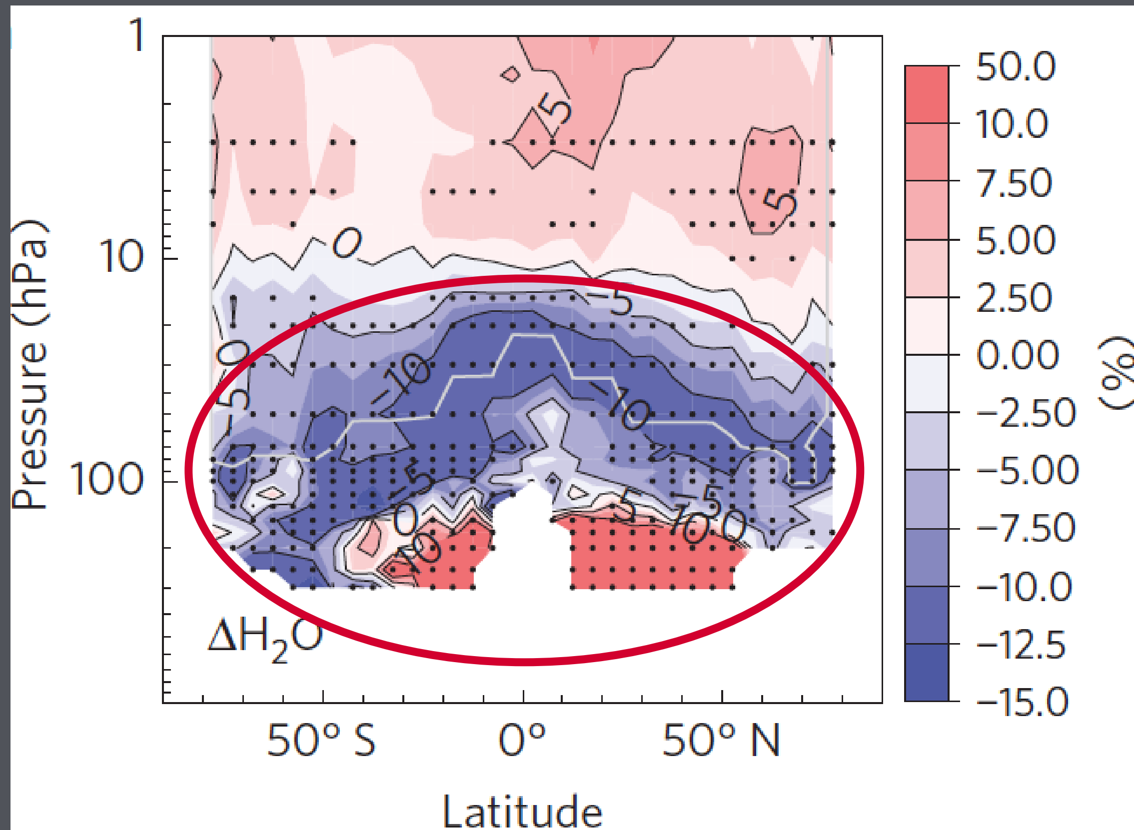
***Hegglin** et al, JGR 2013; **SPARC Data Initiative** Report no 8, 2017*



TRENDS IN UTLS WATER VAPOUR DISTRIBUTIONS

- A new merging technique using a nudged model as transfer function can be used to construct long-term timeseries.
- Study of long-term H_2O changes using climatologies derived from satellite limb sounders reveal negative trends in the lower to mid stratosphere.
- In contrast, the tropical UT shows clear positive trends in H_2O, as expected in a warming climate.

H_2O trends late 1980s–2010



***Hegglin** et al., Nature Geoscience 2014*

CONTRIBUTIONS OF DRIVERS

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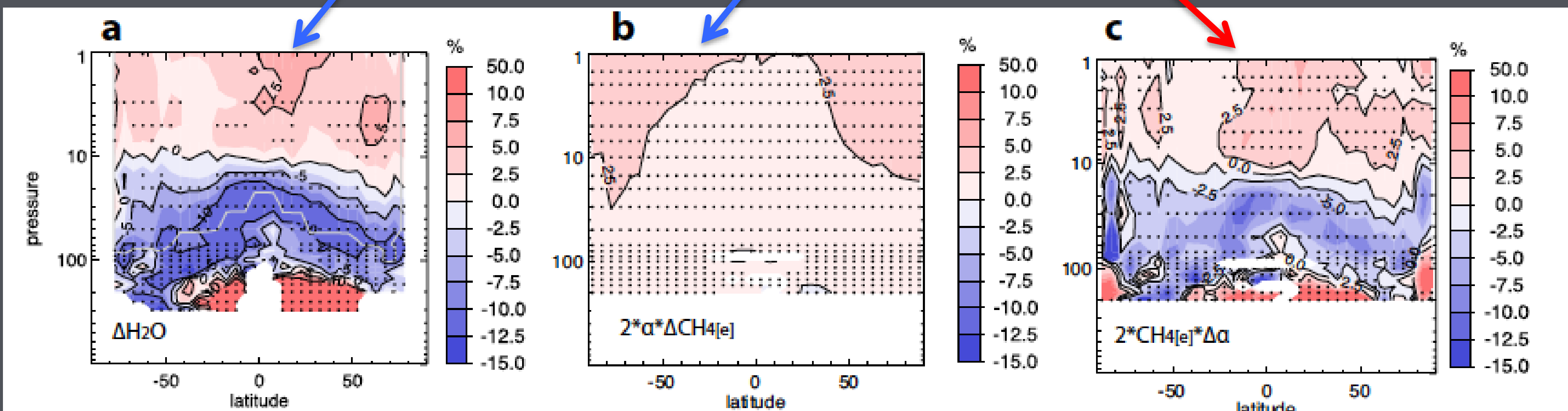
- The difference in sign of the water vapour trends between the upper and lower stratosphere can only be explained by changes in the stratospheric circulation:

$$H_2O = H_2O_{[e]} + 2\alpha CH_{4[e]}$$

$$\Delta H_2O = \Delta H_2O_{[e]} + 2\alpha\Delta CH_{4[e]} + 2CH_{4[e]}\Delta\alpha$$

***Hegglin** et al., Nature Geoscience 2014*



Total change in H_2O

Change in H_2O due to methane increases

Inferred change in H_2O from circulation changes

SUMMARY

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- The UTLS is a highly complex region, governed by multi-scale dynamical, chemical, and physical processes.
  - Lower stratospheric values of H_2O are on the order of a few ppmv only.
  - Strong gradients are observed across the tropopause.
  - Stirring and mixing processes create a mixing layer around the tropopause.
- Aircraft observation provide detailed knowledge on small-scale structures, but remote measurements are needed to capture 3D-distributions and their evolution in time to derive climate information.
  - Most current knowledge stems from limb satellite measurements, with highest accuracy obtained in solar occultation measurements.
- Our knowledge of UTLS H_2O trends and variability is, however, still limited due to large disagreements between instruments on different measurement platforms.
  - Assess consistency of variability an trends among different datasets.

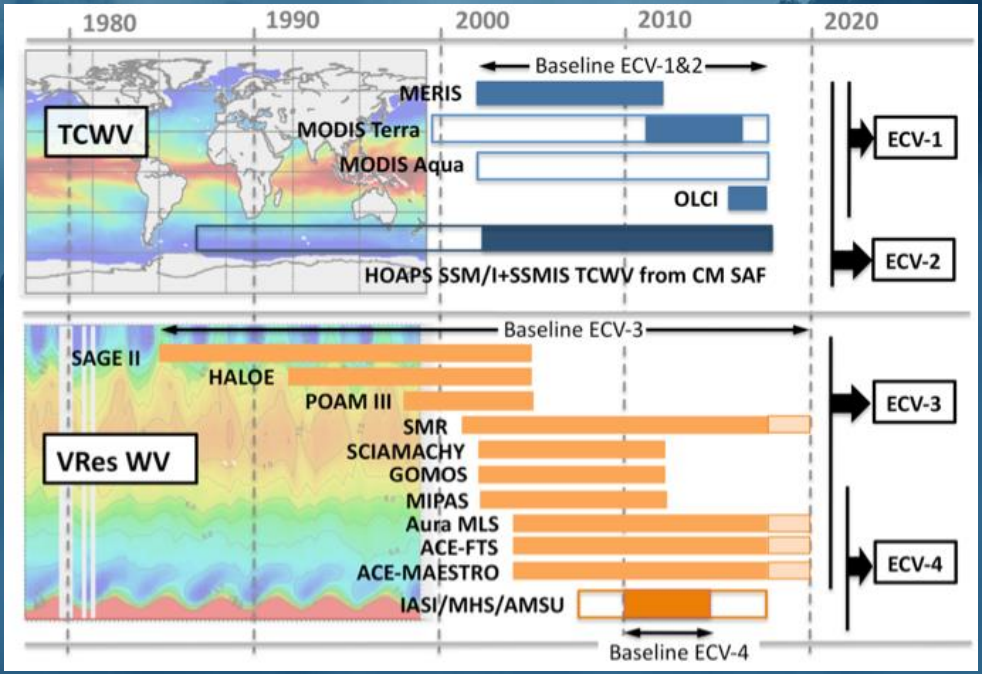
water vapour cci

Project partners

University of Reading (UK)
Michaela I. Hegglin (*science lead*)

DWD (GE)
Marc Schröder (*science co-lead*)

Telespazio VEGA (UK)
BIRA-IASB (BE)
Brockmann Consult (GE)
KIT (GE)
Spectral Earth (GE)
STFC – RAL (UK)
University of Leicester (UK)
University of Toronto / ECCC (CA)
University of Versailles (FR)



- **Producing CDRs** homogeneous in space and time
- **Quantifying uncertainties.**
- **Analysing variability and trends.**
- **Connecting to end users.**
- **Seeking cooperation** with ongoing activities within SPARC, GEWEX/G-VAP, GCOS, and others.

COMPARISON TECHNIQUES

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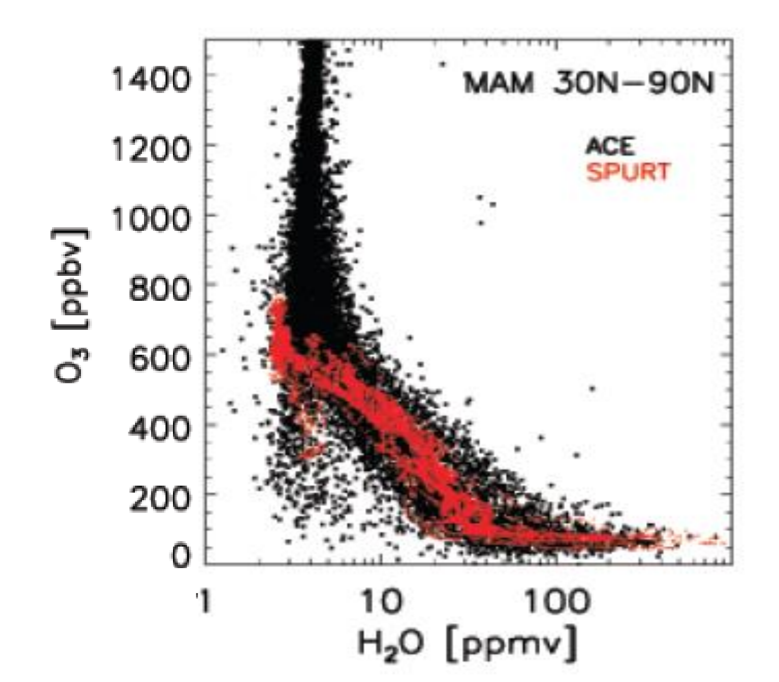
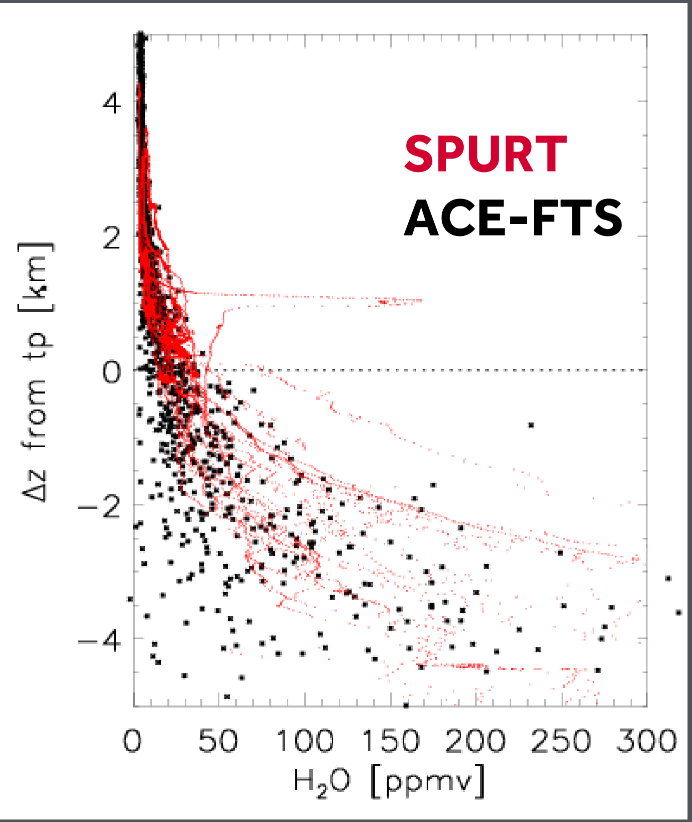
Geophysical noise has to be strongly reduced before comparing trace gas observations, with different techniques introduced in the literature.

Tracer-tracer correlations



Hegglin et al., ACP 2008

Tropopause-based profiles



A POTENTIAL EXPLANATION FOR A LOW BIAS IN H_2O SATELLITE MEASUREMENTS...

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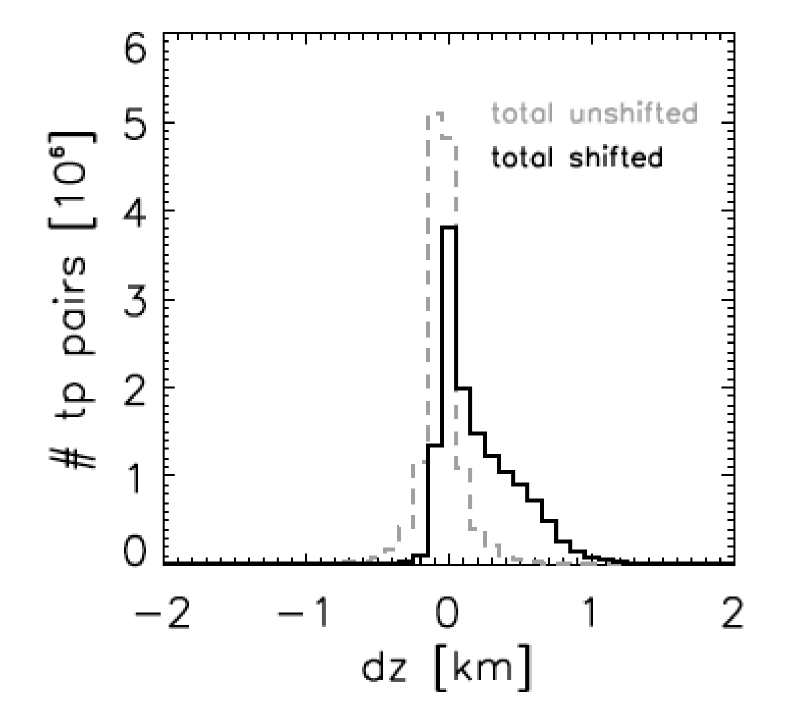
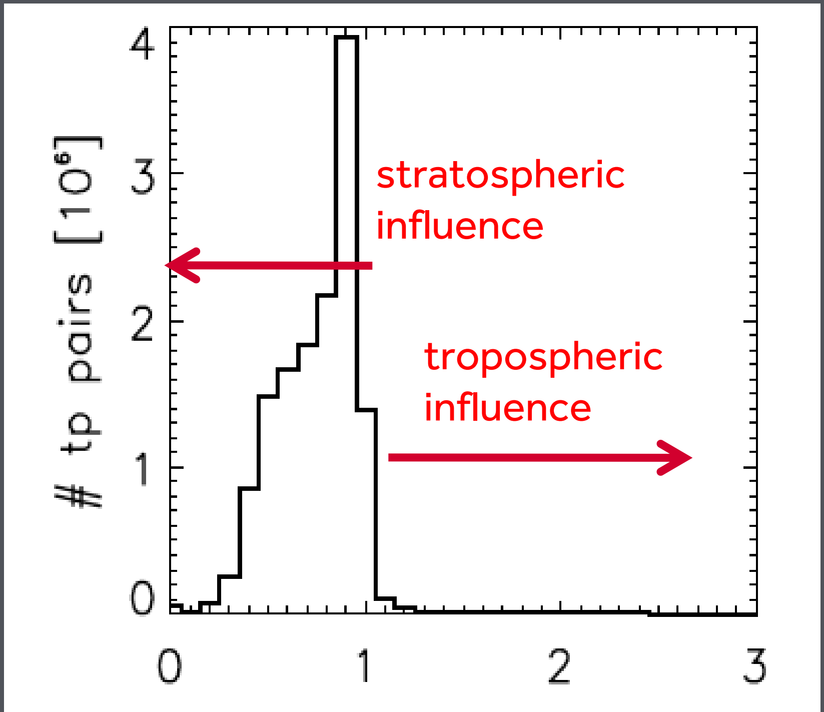
Along the line-of-sight (LOS) of a satellite measurement it is more likely to get a stratospheric contamination than a tropospheric contamination, potentially leading to a low-bias in the measurement. *Hegglin et al., JGR 2009*



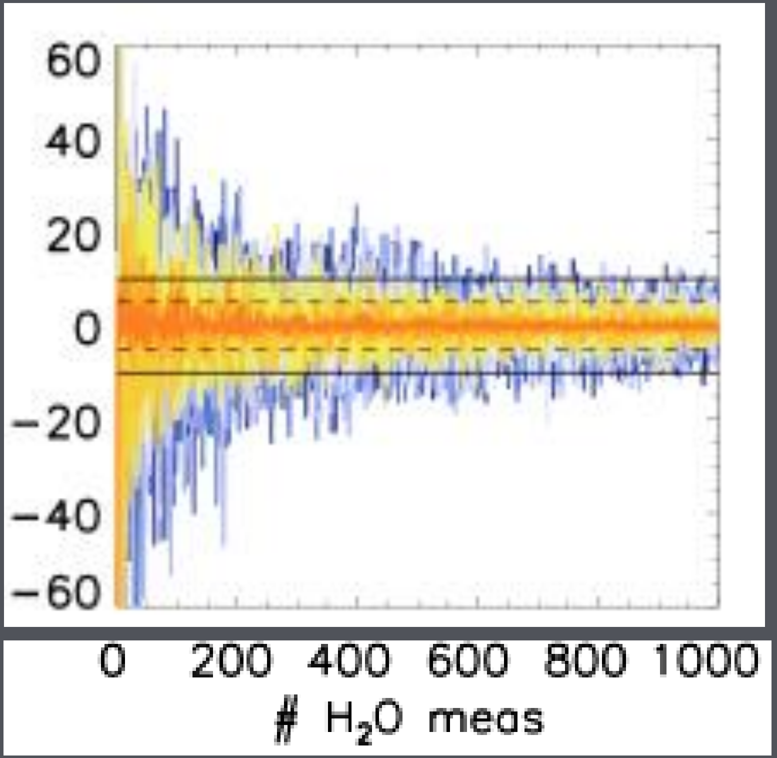
Tropopause displacements along LOS (tangent height-tp)

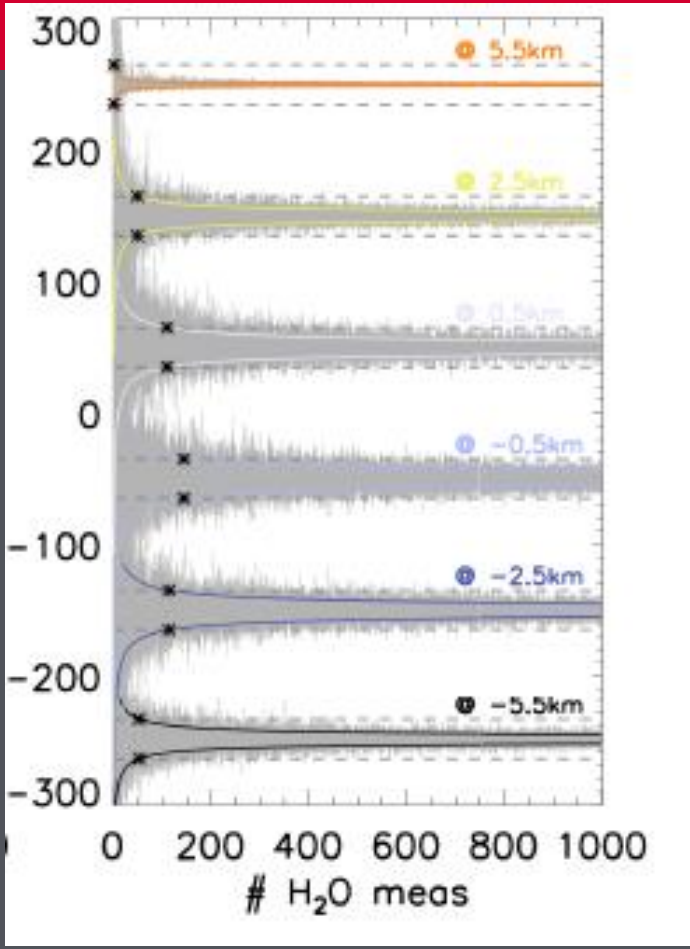


Weighting with exponential function.

ENOUGH COINCIDENCES MAY MITIGATE THE PROBLEM …

Sampling study with model-based H_2O shows that around the tropopause height around 200 measurements are needed to beat down the sampling error per season!



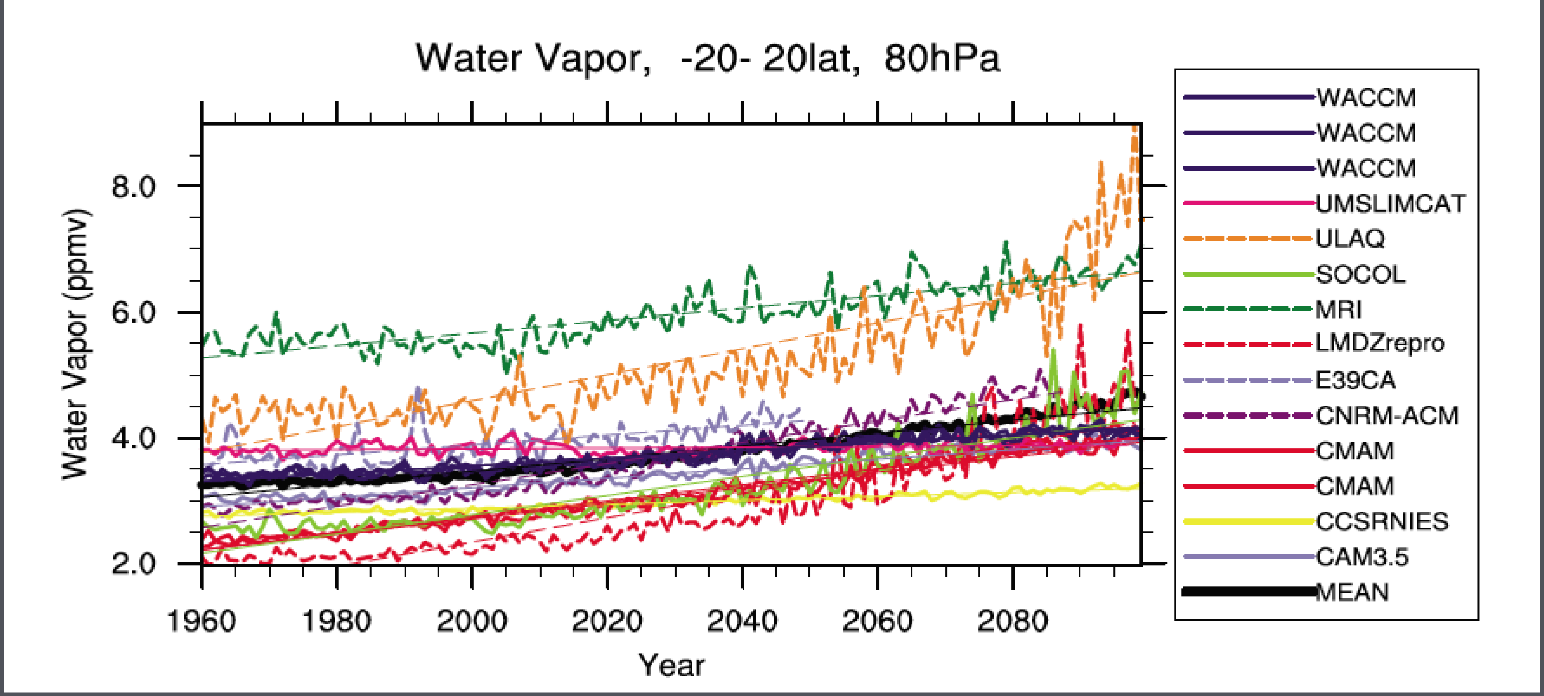


Hegglin et al., ACP 2008

UTLS H_2O TRENDS IN CCMs

- CCMs (from CCMVal-2) do not agree on past nor future changes in stratospheric H_2O, but do not support trends of +0.4 ppmv/dec.

Gettelman, Hegglin, et al. *JGR* 2010



UTLS H_2O IN CCMI models

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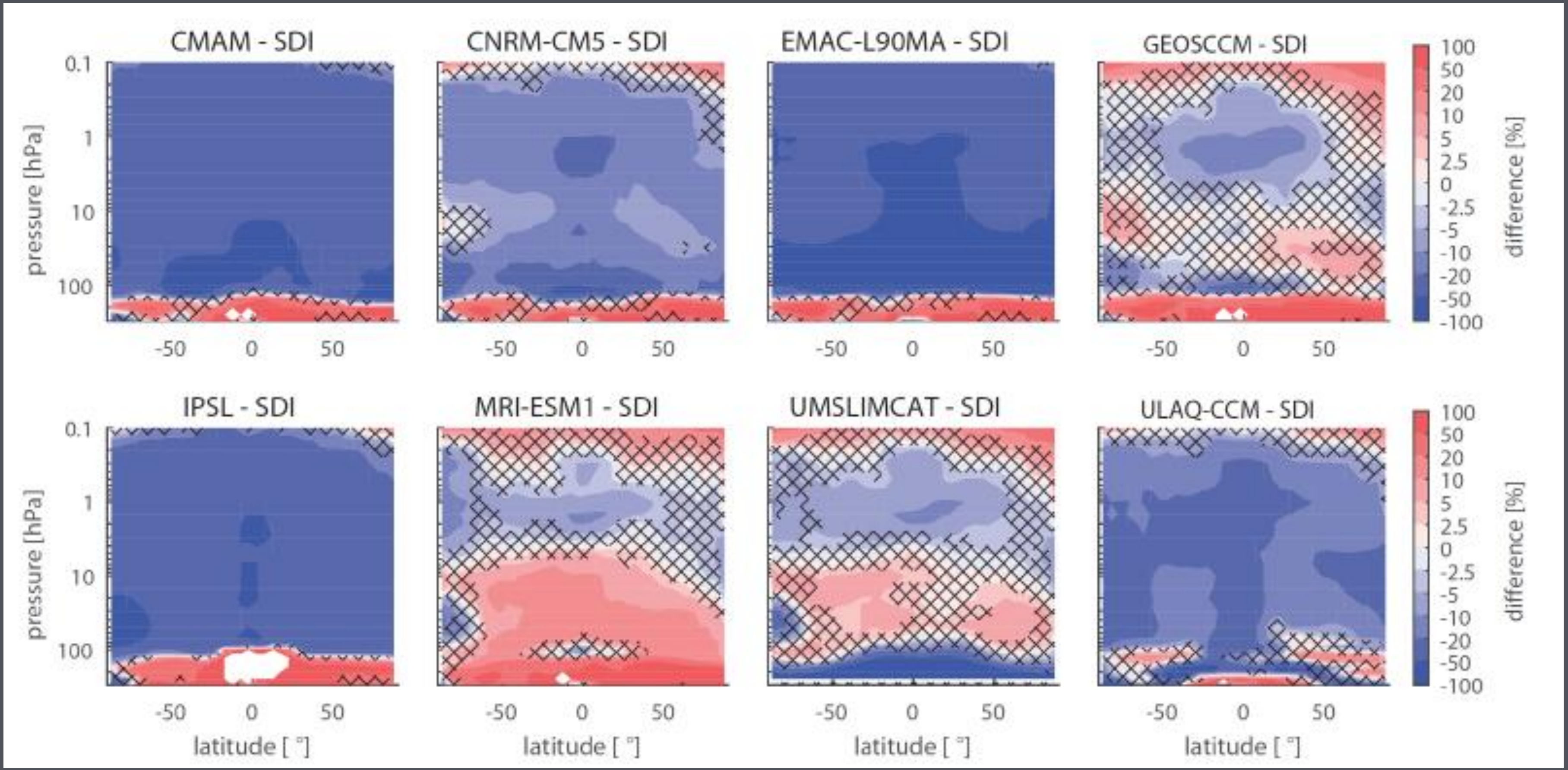
- CCMs participating in CCMI-1 do show large differences to the SPARC Data Initiative satellite observations in the UTLS.

(CCM – SDI MIM)/SDI MIM

Tegtmeier, Hegglin, et al. *in preparation*



UTLS H_2O IN REANALYSES

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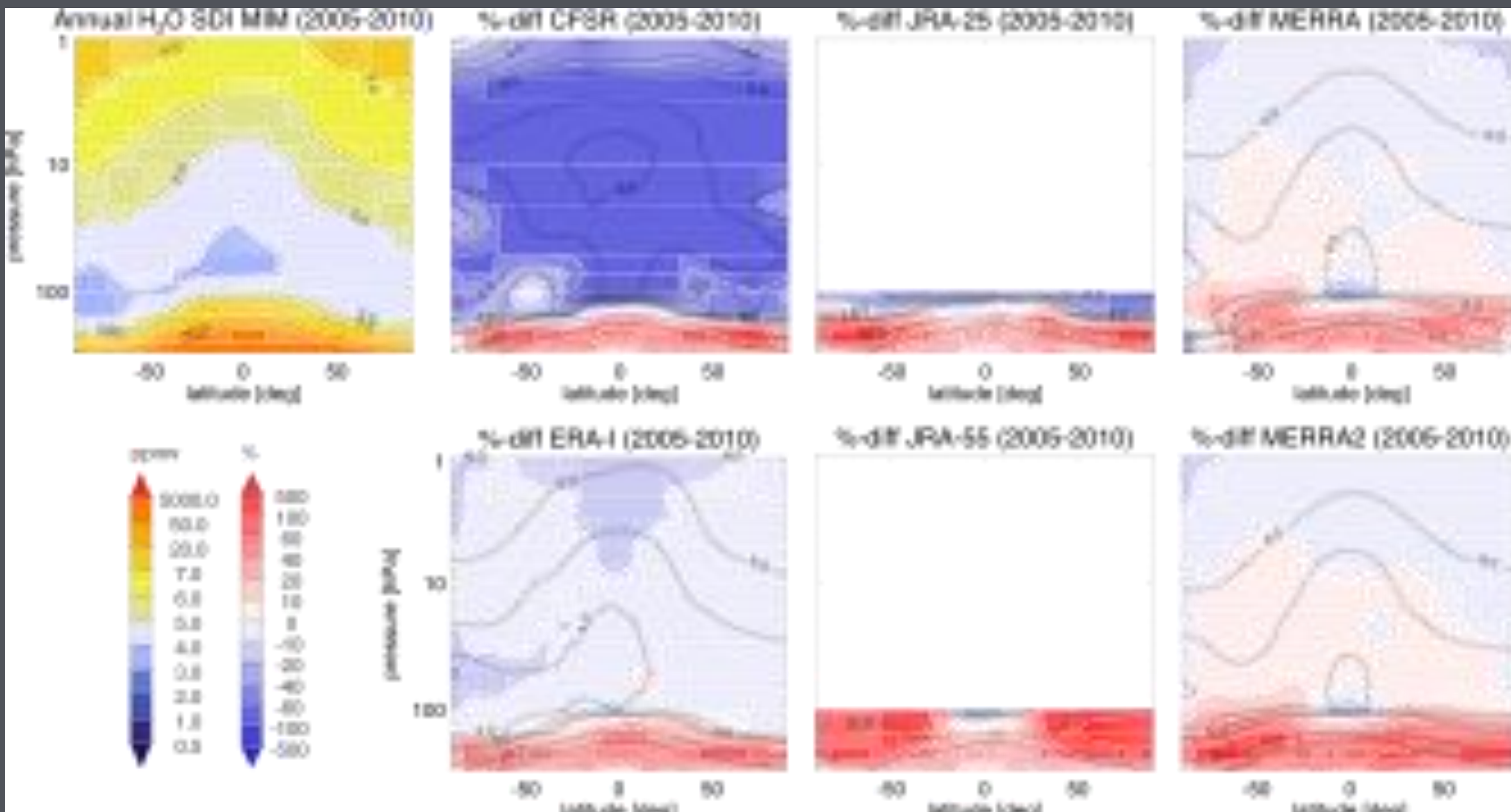
- Reanalyses participating in SRIP do also show large positive differences to the SPARC Data Initiative satellite observations in the UTLS.

Davies, Hegglin, et al. *ACP 2018*

(Ri – SDI MIM)/SDI MIM



H_2O SEASONAL CYCLES IN REANALYSES

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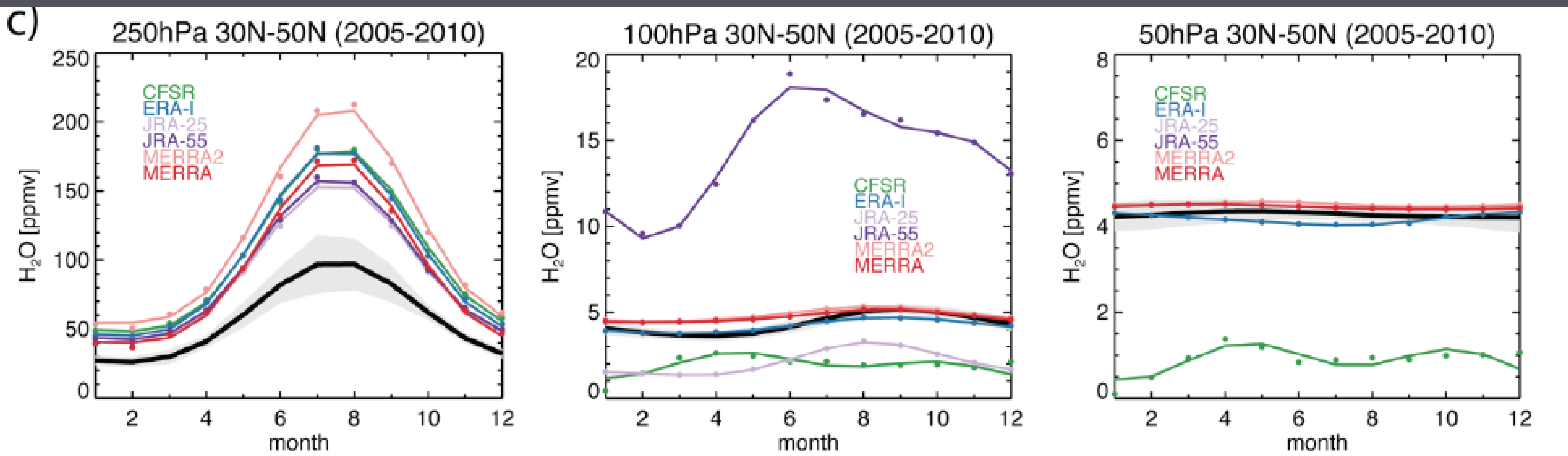
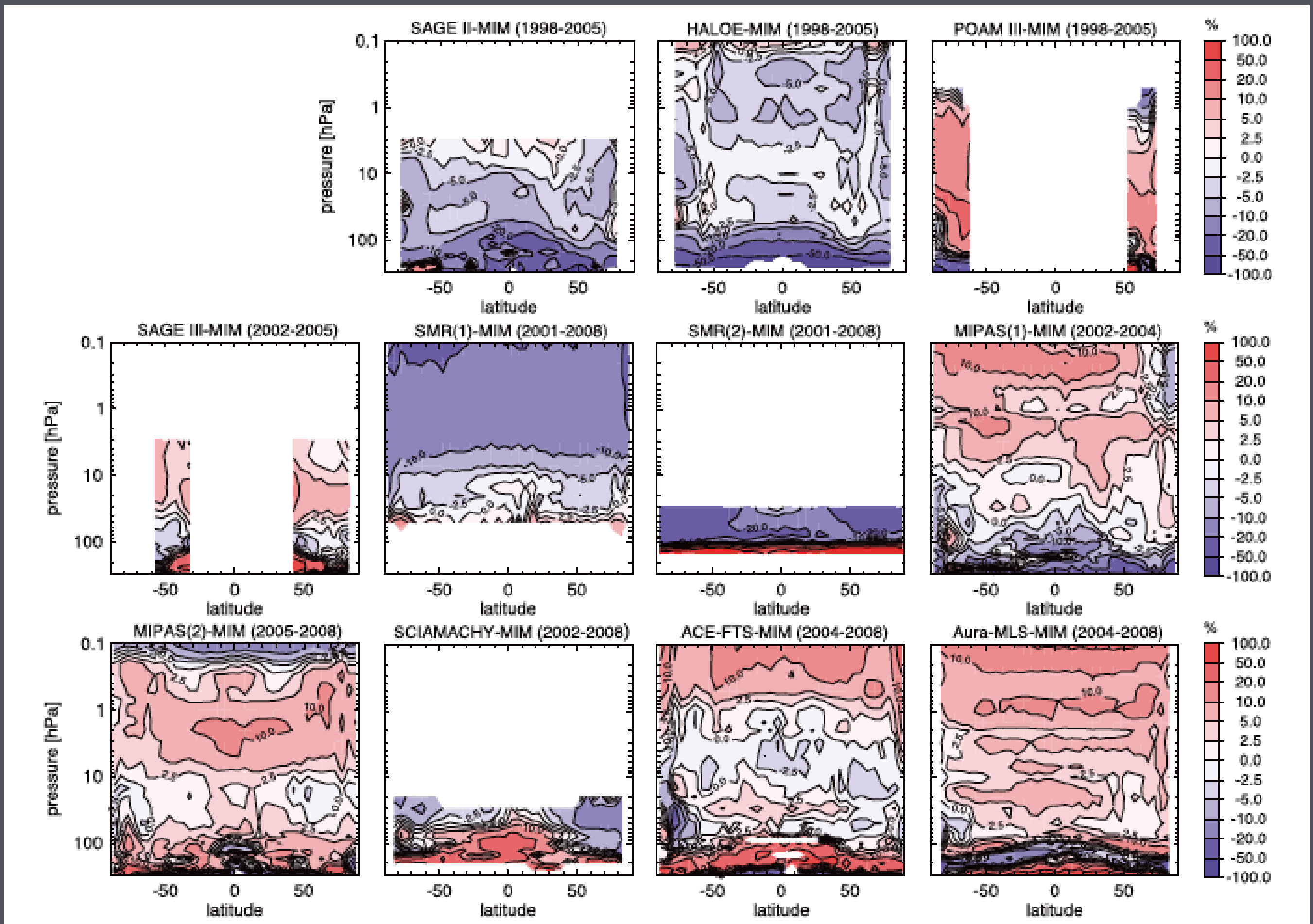
- High bias in reanalyses below 100 hPa are seen throughout the year.

Davies, Hegglin, et al. *ACP 2018*



ZONAL MEAN CROSS-SECTIONS

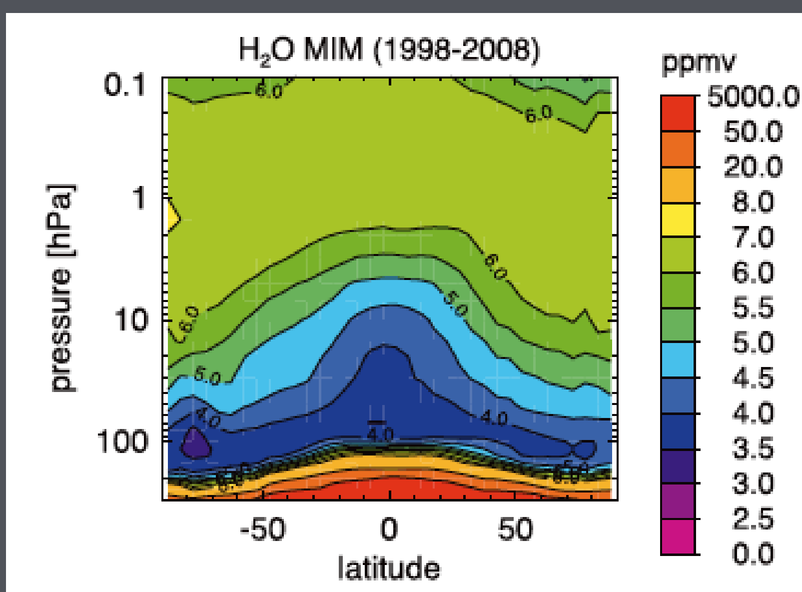


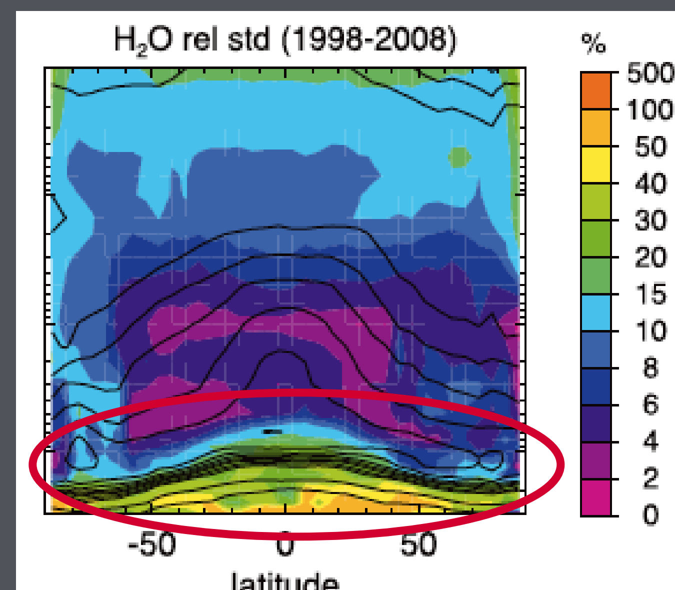
Hegglin et al, *JGR* 2013

- Earlier observations show low biases, later high biases when compared to the mean.
- Large differences in the UTLS.
    - Zonal mean evaluation may not be sufficient to assess data quality in the UTLS!

H_2O ASSESSMENT SUMMARY

- Main results from the SPARC Data Initiative:
  - Atmospheric mean state is well defined in the global MS and extra-tropical LS with a relative uncertainty of 2-6%.
  - This uncertainty in H_2O increases toward the polar latitudes (10% and 15% for NH and SH, respectively), the LM (15%) and the UT (30–50%).
  - Uncertainty in tropical tropopause H_2O minimum (3.5-0.5 ppmv) is about 14%.



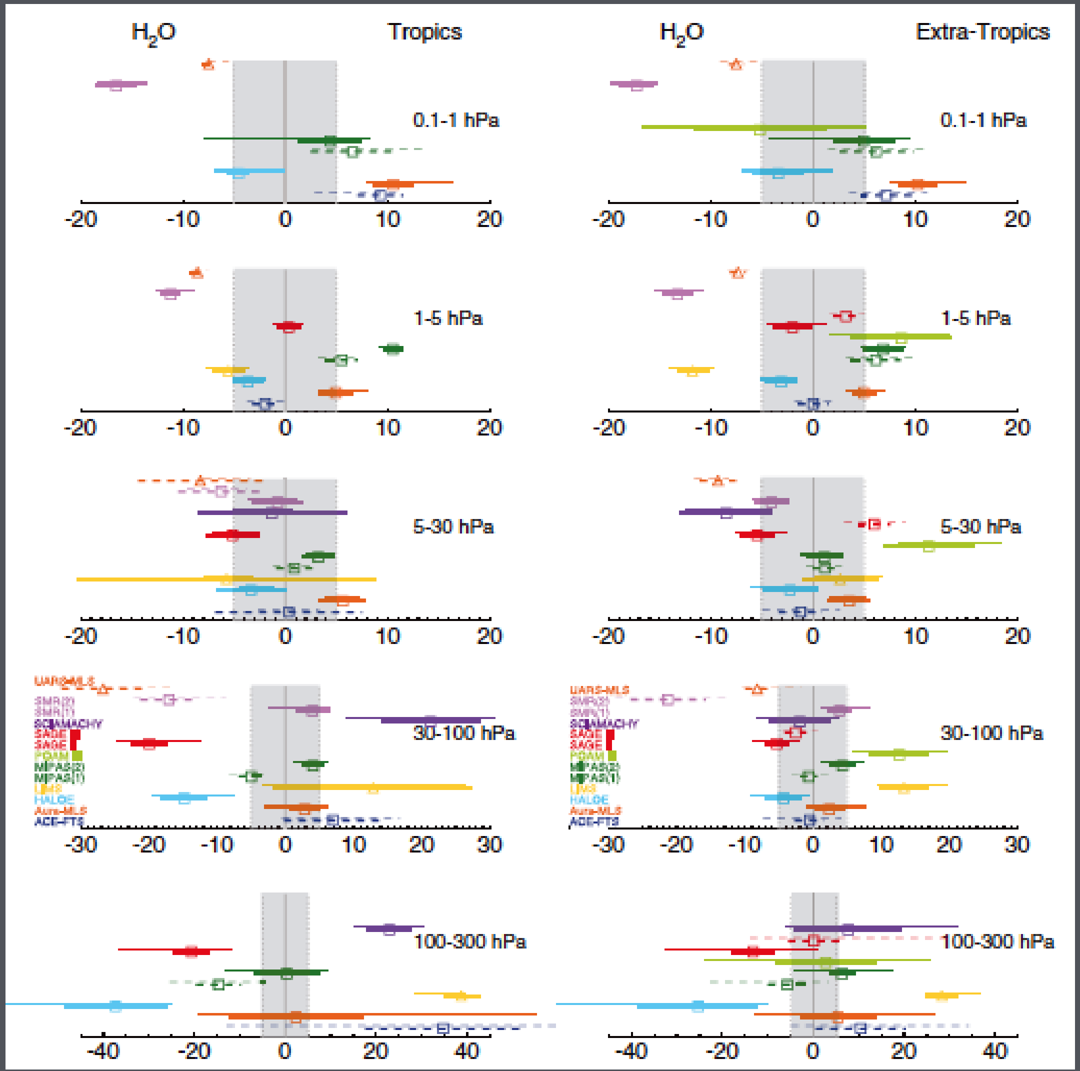


Heglin et al, *JGR 2013; SPARC Data Initiative Report, 2017*

SUMMARY BY REGION

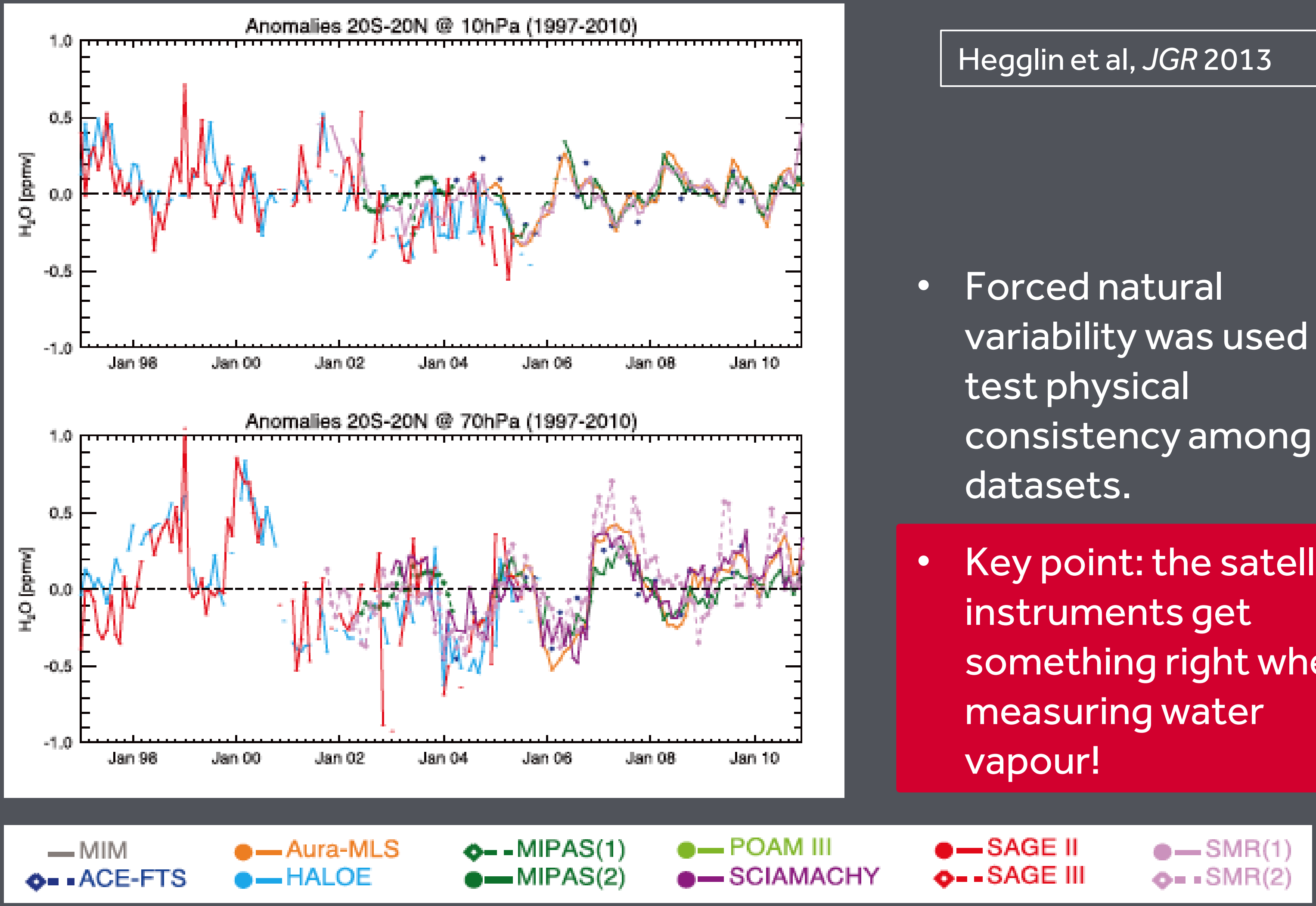
- Figure shows climatological spread in different atmospheric regions.
  - Very good agreement for water vapour climatologies is found in the global MS and extratropical LS (±5%).
  - Agreement between water vapour measurements generally worse in UT and tropical LS.

Water vapour



Hegglin et al, *JGR 2013; SPARC Data Initiative Report, 2017*

INTERANNUAL VARIABILITY



Hegglin et al, *JGR* 2013

- Forced natural variability was used to test physical consistency among datasets.
- Key point: the satellite instruments get something right when measuring water vapour!

DIFFICULTIES WITH INSTRUMENT COMPARISONS IN THE UTLS

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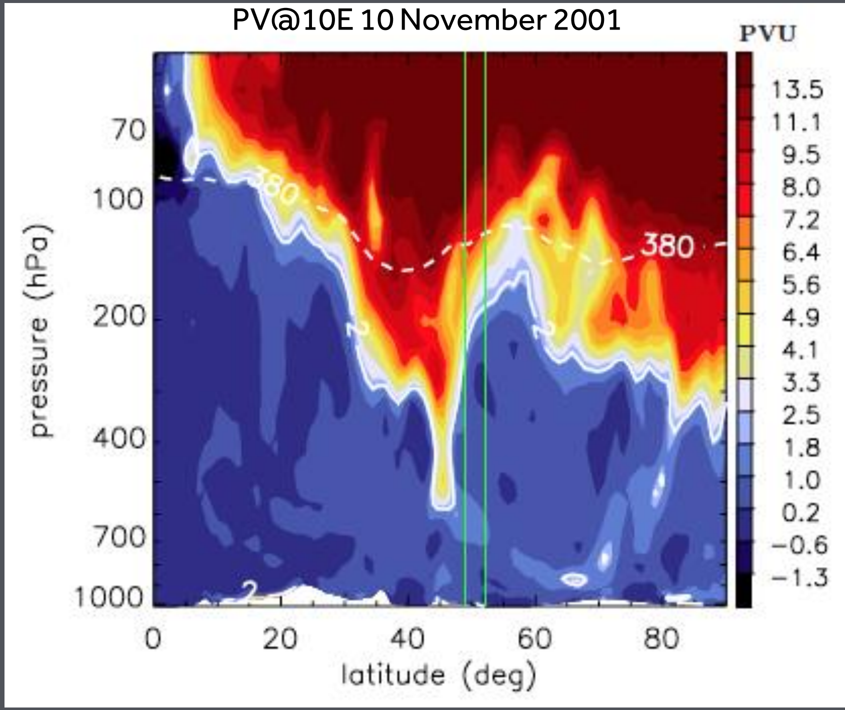
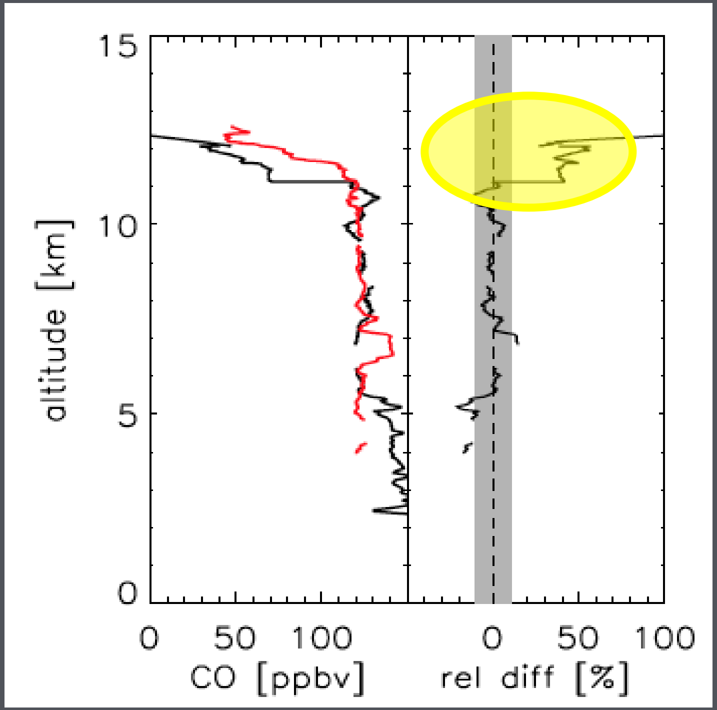
Validation of satellites in the UTLS with coincident measurements suffers from geophysical noise.





Different tropopause heights may lead to large differences in trace gas profiles!

The large errors of 50% in the tropopause region are due to small scale features in meteorology, not low instrument precision!

Hegglin et al., ACP 2008