Intercomparison of High Arctic satellite water vapour measurements at Ellesmere Island, Nunavut

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1. Why study water vapour?

Water vapour profoundly shapes our planet and society.

Atmospheric H_2O plays crucial roles in atmospheric chemistry, dynamics, and the hydrological cycle. It is also the most important greenhouse gas on Earth (Dessler et al. 2008). Polar region climates are particularly sensitive to H_2O changes, motivating research into Arctic H_2O abundances and trends (e.g. Serreze et al. 2012).

The World Meteorological Organization (WMO) considers measurements of H_2O profiles to an accuracy of 5% essential for understanding the climate system (GCOS, 2016). However, producing global, high vertical resolution H_2O profiles is challenging. Comparisons between the latest satellite retrievals and ground-based reference measurements offers an opportunity to assess progress towards these goals.

The Goals:

(1) Assess high Arctic UTLS H_2O measurements produced by satellite instruments on board the Atmospheric Chemistry Experiment (ACE) using comparisons to ground-based measurements at Eureka, Nunavut.

(2) Examine other available satellite datasets to place ACE results in context.

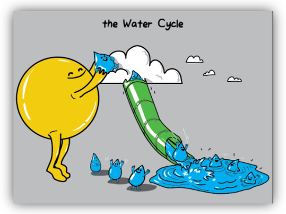


Image: the Awkward Yeti

Where?

Eureka, Nunavut in the Canadian high Arctic (Ellesmere Island)

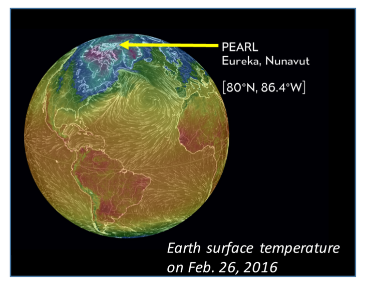
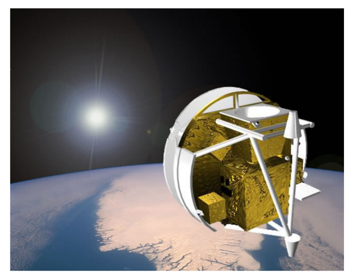
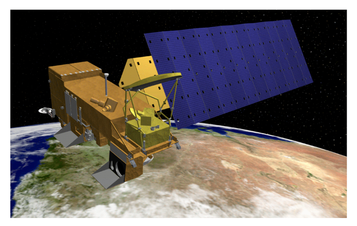


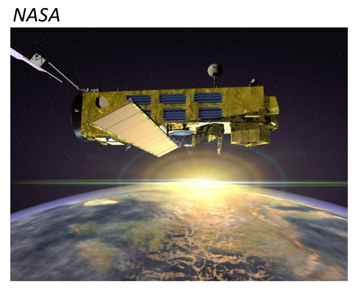
Image: earth.nullschool.net

Image: Google Maps

2. Water vapour measurements


SCISAT
Canadian Space Agency


Aqua
NASA


ENVISAT
European Space Agency

Satellite-based instruments:

Satellite measurements offer wide geographic coverage. However, orbits and measurement techniques introduce many constraints on capturing the full global state of the atmosphere, e.g. limb-sounder measurements involve information collected across a wide horizontal area, nadir-viewing measurements often struggle to capture high vertical resolution.

Satellite instruments with high Arctic H_2O measurements examined include ACE-FTS and ACE-MAESTRO on SCISAT, MIPAS and SCIAMACHY onboard ENVISAT, MLS and TES onboard Aura, and AIRS onboard the Aqua satellite.

A summary of datasets used in this study:

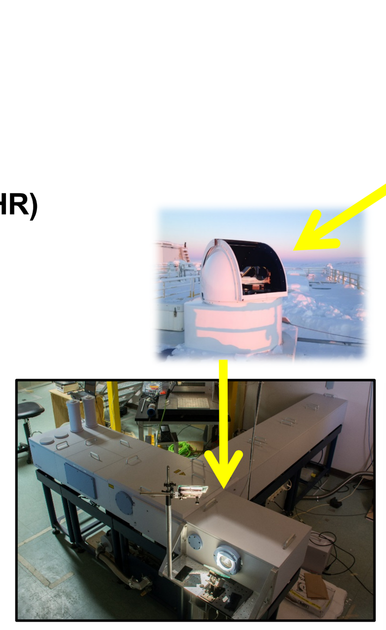
Type	Location	Instrument	Instrument type	Measurement geometry	Retrieval version	Time range	Measurements 500 km of Eureka (Aug. 2006 onwards)	Valid altitude range
Satellite	SCISAT	**ACE-FTS**	FTS	limb	v3.6	2004 - Mar. 2017	551	stratosphere to mid-troposphere
		ACE-MAESTRO	grating spectro photometer	limb	v30	2004 - 2016	382	stratosphere to mid-troposphere
	AURA	**TES**	FTS	nadir	v6	Sept. 2004 - June 2015	5,630	P > 100 hPa
		MLS	radiometer	limb	v4.20-v4.22	Aug. 2004 - Dec. 2015	108,072	P <= 316 hPa
	ENVISAT	**MIPAS**	FTS	limb	IMK v5 & v7	2002-2012	v5: 10692; v7: 10974	12 - 50 km
		SCIAMACHY	imaging spectrometer	limb	v3.01 & v4.2	Aug. 2002 - March 2012	v3.01: 1638; v4.2: 14530	25 - 10 km recommended; available as low as 4.5 km
	AQUA	**AIRS**	grating spectrometer	nadir	v6	Sept. 2002 - 2016	1,892,348	P >= 100 hPa
Ground-based	PEARL	**125HR**	FTIR	sun-viewing	MUSICA v2015	Aug. 2006 - Sept. 2014	1889 (std); 3364 (ext)	below ~12 km (varies)
	Eureka Weather Station	**Radiosondes**	capacitance sensor	balloon	GRUAN processed	Sept. 2008 - Sept. 2017	5515	below 8 - 15 km (varies)

Ground-based instruments:

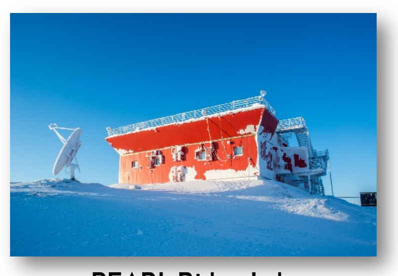
Bruker IFS 125HR
Fourier Transform Infrared (FTIR) spectrometer (125HR)

The PEARL 125HR records high resolution solar absorption spectra in clear-sky conditions. Measurements began in August 2006 at the PEARL Ridge Lab, approximately 15 km from Eureka, atop a ridge at 610 m altitude. These measurements regularly contribute to the validation of ACE measurements.

The 125HR water vapour product is derived from a recently-developed technique under the framework of the MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water (MUSICA) project (Schneider et al. 2016).



PEARL 125HR FTIR spectrometer



PEARL Ridge Lab (610 m a.s.l.)

Radiosonde launch at the Eureka Weather Station (10 m a.s.l.)

Radiosondes (RS)

Radiosondes are balloon-based instruments that measure temperature, pressure, and humidity profiles. They are often used as a reference for other measurements and as inputs to models. Radiosondes are typically launched twice per day from the Eureka Weather Station.

Although Eureka is not an officially participating site, the Global Climate Observing System Reference Upper Air Network (GRUAN) processed a subset of Eureka radiosonde data for this study. This processing aims to enhance the accuracy of the measurements (Dirksen et al. 2014) by correcting for known biases and calculating uncertainties, used for quality control filtering. Profiles are limited in this study to altitudes where uncertainties are smaller than 20%. Typically, Eureka radiosonde profiles processed by GRUAN have uncertainties of 3-4%.

Raw files for the Eureka radiosondes were required for GRUAN processing. These files were only available starting in mid-2008. This limits the time frame for which radiosondes are available in this study.

3. Profile comparisons

Satellite profiles coincident within 500 km and 3 hour of the reference measurements have been compared using differences calculated using:

$$\Delta\,[ppmv] = X - Y,$$

$$\Delta\,[\%] = \frac{(X-Y)}{Y} * 100\%\,,$$

where X is the satellite measurement and Y is the reference measurement.

To illustrate the overall agreement observed between the measurements, the mean of the profile-to-profile differences is calculated. Altitude ranges for which there are measurements available varies for each contributing matched pair of profiles. The number of contributing profiles at a given altitude (N) is noted on the comparison figures.

Reference: PEARL 125HR

To compare satellite and PEARL 125HR measurements, satellite instrument profiles were smoothed by the 125HR measurement's averaging kernels to account for altitude sensitivity differences.

Since the MUSICA water vapour retrievals are performed on a logarithmic scale, the smoothed profile is calculated using:

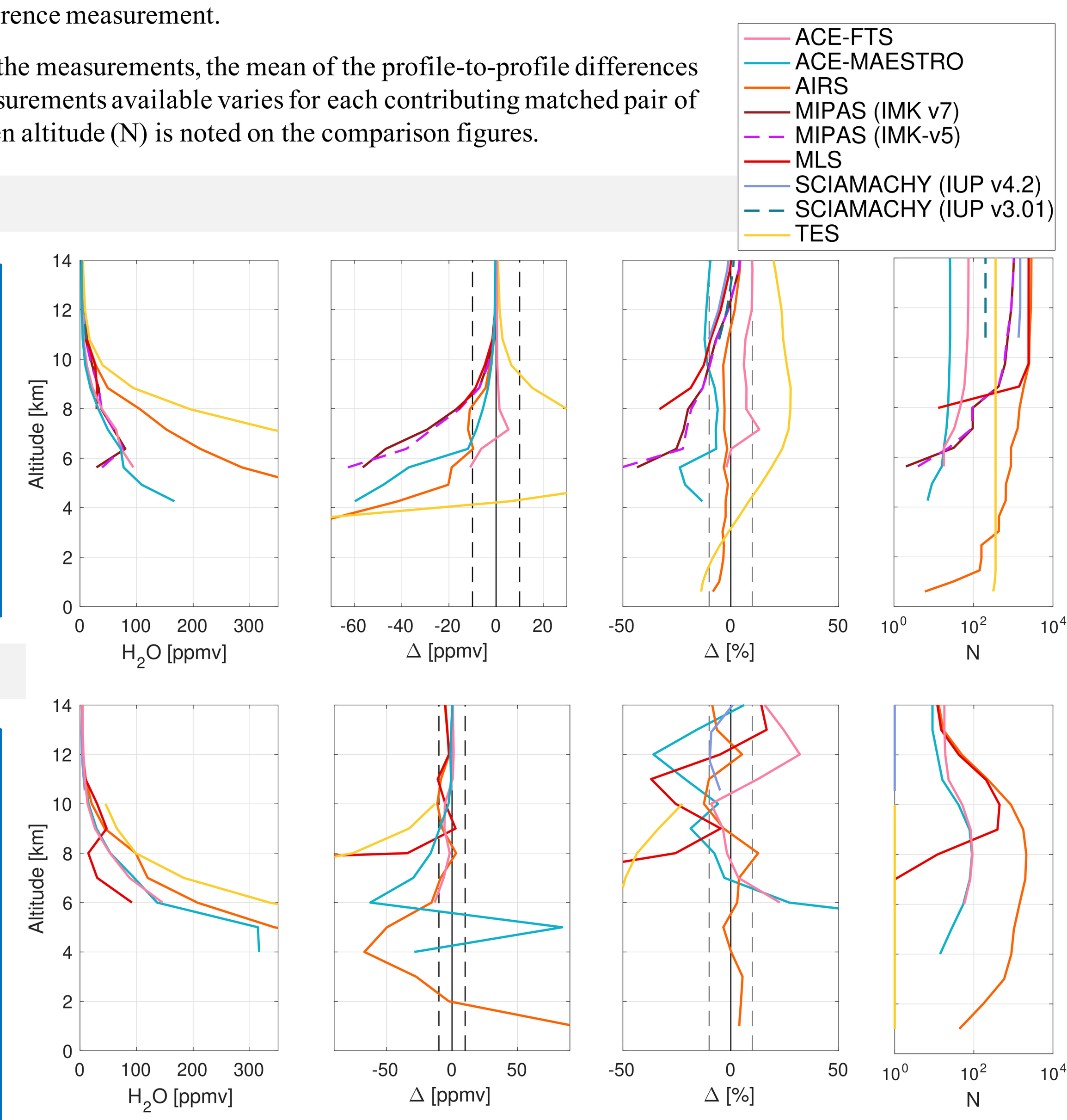
$$x_{smoothed} = e^{A(x - x_a) + x_a},$$

where x, x_a, and A are in $\log_e$-space.

Reference: Eureka radiosondes

To compare satellite and radiosonde profiles, radiosonde profiles have been smoothed using the satellite's averaging kernels where possible, i.e. MIPAS, SCIAMACHY, TES.

In the cases of ACE-FTS, ACE-MAESTRO, AIRS, and MLS, the vertical resolution of the radiosonde profiles has been smoothed using Gaussian weighting functions with a full width half max (FWHM) that approximates the vertical resolution of the satellite measurement. This aligns with the technique used by Sheese et al. (2017) to compare ACE with MLS and MIPAS.

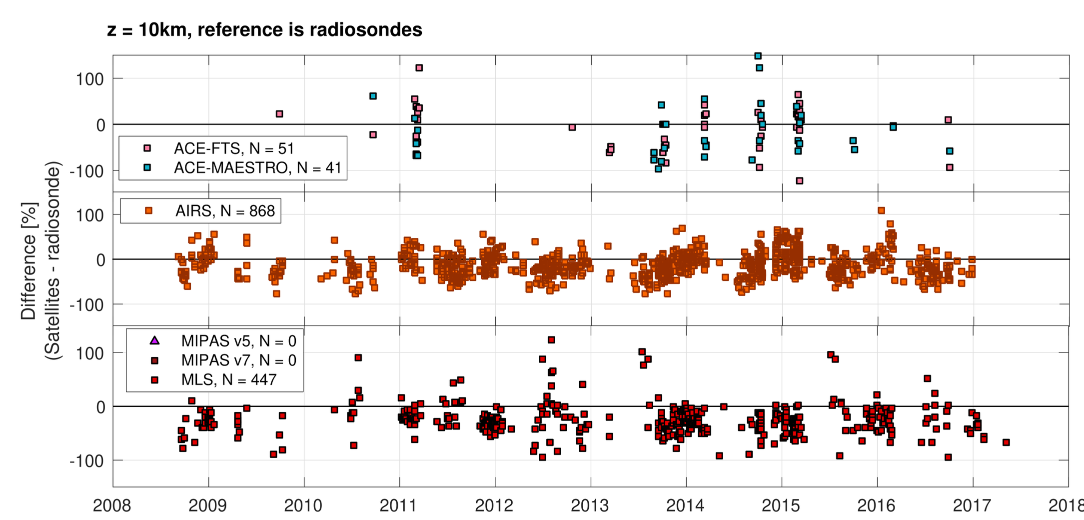


Coincidence criteria: 500 km and 3 hours. Vertical grey dotted lines indicate ±10%.

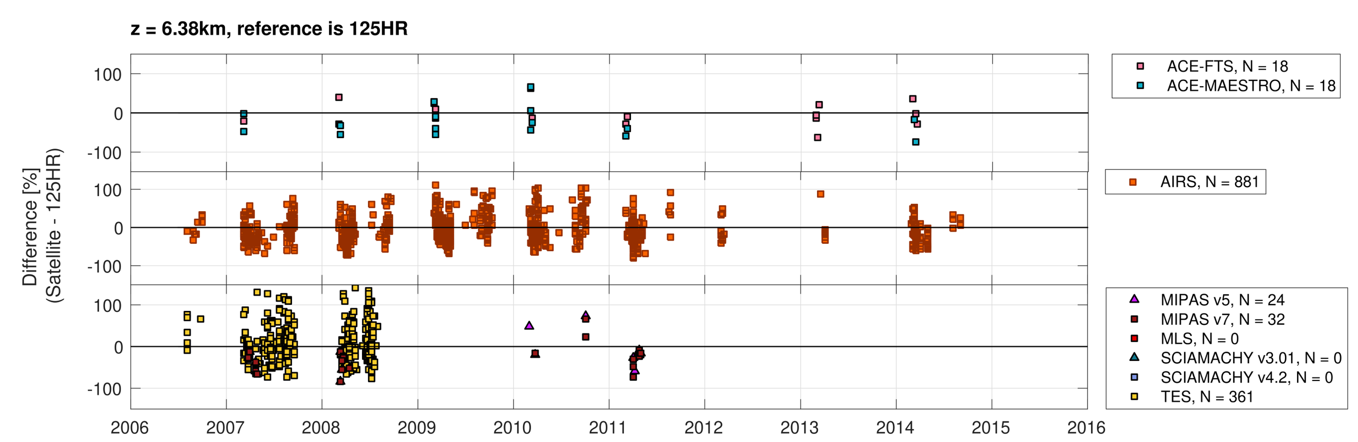
4. Comparisons at specific altitudes

Difference timeseries are shown to illustrate the agreement observed at altitudes representative of UTLS comparisons.

Comparisons between satellite measurements and Eureka radiosondes are shown at 10 km (right), where there is significant overlap between datasets and vertical sensitivities.



Comparisons between satellite measurements and the PEARL 125HR are shown (right) at 6.4 km to illustrate upper tropospheric agreement at an altitude where the 125HR retrieval has excellent sensitivity.



Coincidence criteria: 500 km and 3 hours.

5. Summary of results

- **ACE-FTS:** agreement with the 125HR was better than 11 ppmv (13%) between 6 and 14 km. Between 8 and 11 km a wet bias of approximately 7% relative to the 125HR is observed. Relative to the Eureka radiosondes, ACE-FTS had mean agreement closer than 13 ppmv at 6 km and above. Between 7 and 10 km, agreement was better than 10%.
- **ACE-MAESTRO:** above 6 km, mean differences with the PEARL 125HR show a dry bias of approximately 7 to 10%, with greater differences observed below 6 km. ACE-MAESTRO also shows a dry bias of approximately 10% relative to the Eureka radiosondes above 7 km.
- **AIRS**: shows close agreement with both the PEARL 125HR, i.e. within 5% between 1 and 14 km, and the Eureka radiosondes, i.e. within 5% between 1 and 7 km.
- **MLS**: showed a wet bias relative to radiosondes between 8 and 12 km, e.g. 25% at 10 km.
- **SCIAMACHY**: agreement with 125HR and radiosondes within 10 ppmv and 10% above 10 km.
- **TES**: A wet bias of approximately 25% was observed relative to the 125HR above 5 km; a dry bias of approximately 10% was observed relative to the 125HR near 2 km. Only one coincident measurement was found with the Eureka radiosondes.

6. Conclusions

ACE measurements contribute accurate information about UTLS H_2O in the high Arctic. However, agreement with the Eureka reference measurements did not reach the 5% accuracy goal set by the WMO. ACE H_2O measurement accuracy worsens at the lowest altitudes, e.g. for the ACE-MAESTRO below 7 km. Overall, ACE-FTS and ACE-MAESTRO H_2O measurements had closer agreement with the 125HR and radiosondes in the UTLS than other instruments used in this study - except AIRS.

Close agreement (e.g. within 5%) between AIRS and both the 125HR and the radiosondes shows AIRS provides highly accurate measurements of H_2O in the troposphere above Eureka. This suggests the potential for using AIRS as a reference for climatologies and for further comparisons. Use of AIRS as a reference may be especially useful in cases where radiosondes and 125HR do not offer sufficient numbers of coincident measurements.

Comparisons show MLS with a dry bias relative to Eureka radiosondes altitudes between 8 and 12 km.

MIPAS showed increasingly large differences with 125HR profiles at UTLS altitudes. This is consistent with the general recommendation to limit MIPAS profiles to altitudes above 12 km. v5 and v7 MIPAS retrievals showed similar results.

Limited conclusions can be drawn from comparisons conducted with SCIAMACHY and TES due to the limited overlap in profile altitudes and measurement times.

7. Future Work

Close agreement between the AIRS measurements and radiosondes motivates further use of the AIRS dataset for analysis of the H_2O abundances in the high Arctic. Given the high density and frequency of coincident measurements, it would be useful to calculate and examine climatologies of H_2O near Eureka. In addition, global UTLS comparisons between AIRS and ACE H_2O measurements could also be examined to better understand the accuracy of the ACE-FTS and ACE-MAESTRO H_2O datasets.

The validation of ACE-FTS and ACE-MAESTRO H_2O products (as well as PEARL 125HR H_2O measurements) could be enhanced by launching frostpoint hygrometers (FPH) from Eureka. FPH measurements would provide very high accuracy and vertical resolution H_2O in the UTLS. FPH measurements have been used to validate other satellite H_2O datasets (e.g., Hurst et al. 2016, to monitor MLS H_2O accuracy).

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