Major advances foreseen in humidity profiling from space

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on behalf of the WALES Managment Advisory Group

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[EG3], 2nd ENVISAT summer school
Frascati, Italy, 16-26 Aug 2004

WALES
Water Vapour Lidar Experiment in Space

- Selected as an Earth Explorer Core Mission for Phase-A study in Nov 2001, Granada, Spain
- Phase-A studies presented at the Earth Explorer User Consultation Meeting, 19-20 Apr 2004, Frascati, Italy
- Not selected for Phase B study

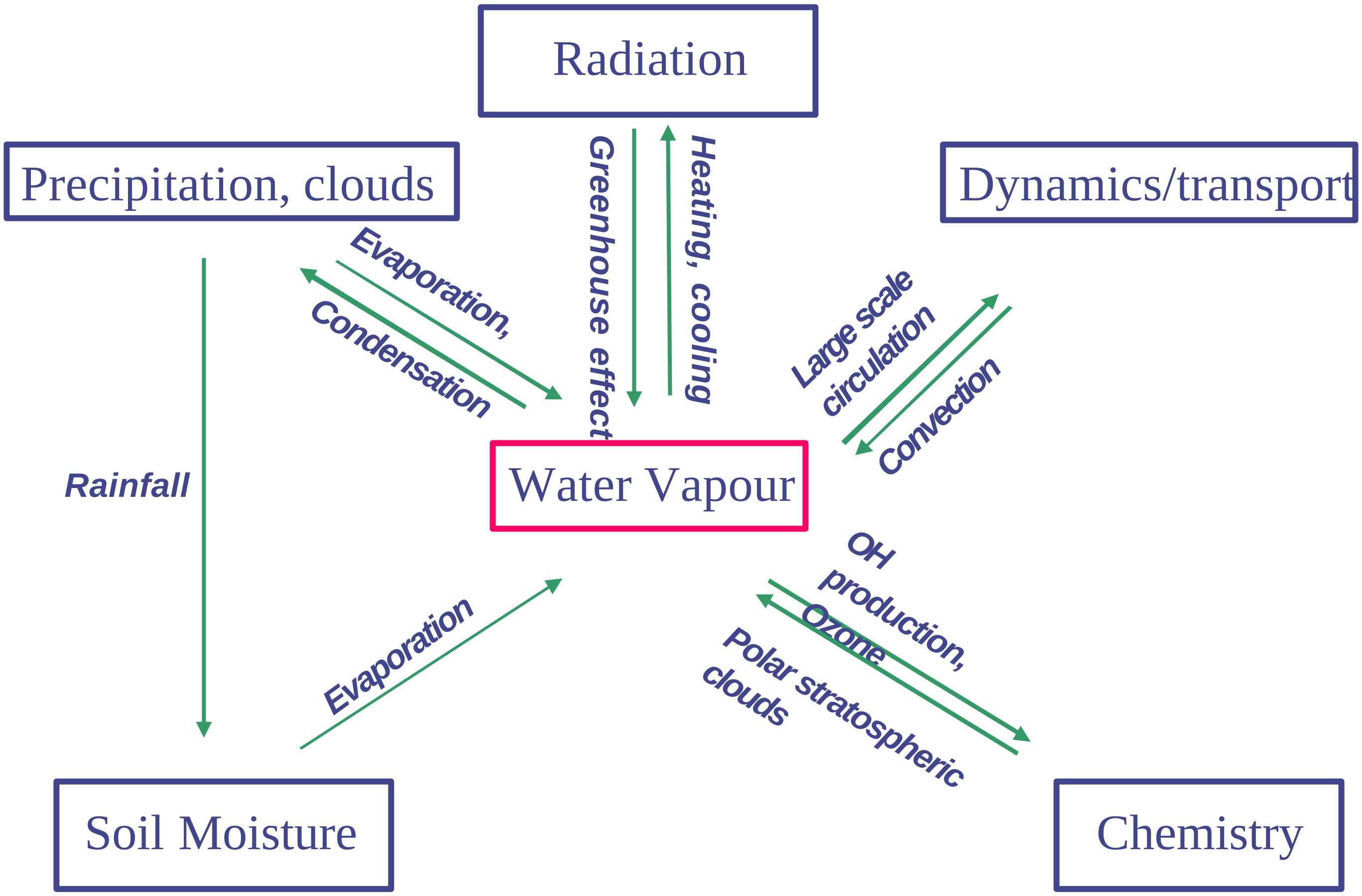
WALES mission objective

To provide independent global water vapour profiles covering the entire troposphere in clear and partially cloudy regions with unprecedented accuracy and vertical resolution in support of climate research and numerical weather prediction applications and as a reference for all other satellite sensors.

Overview

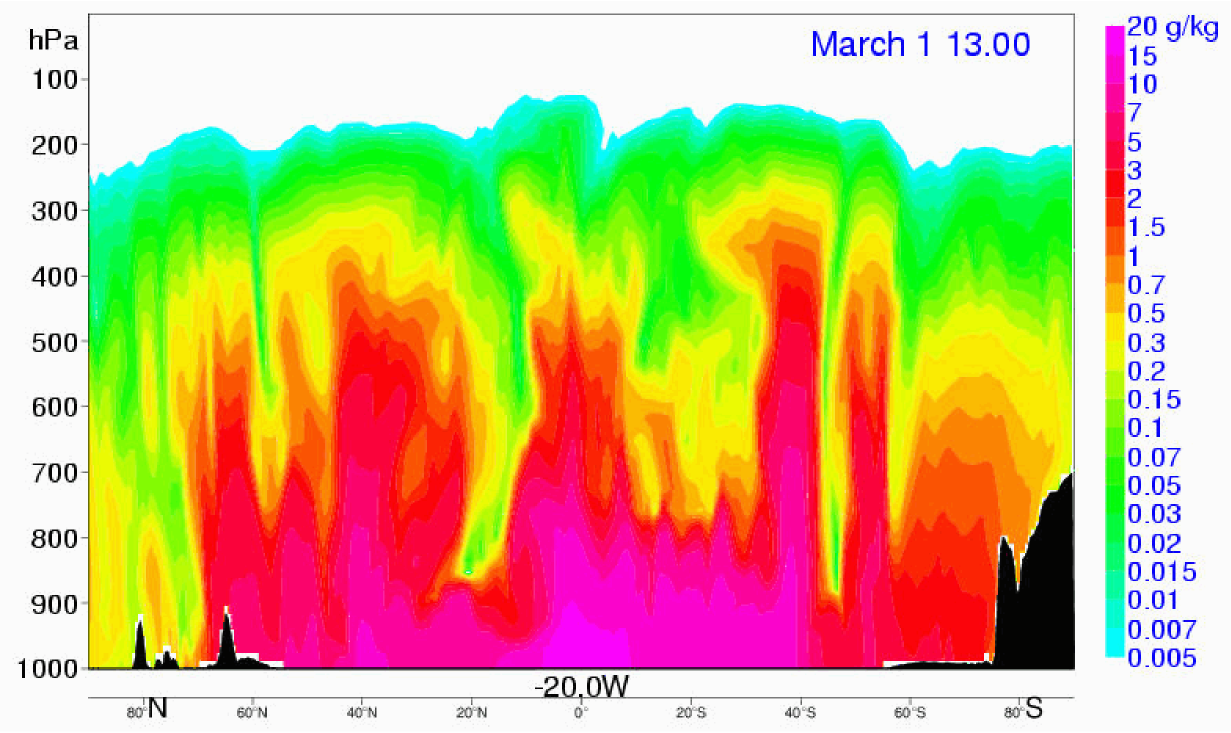
- Motivation
- Observation requirements
- Observation principle
- Mission performance
- Application potential
- Outlook

The central role of water vapour



Water vapour

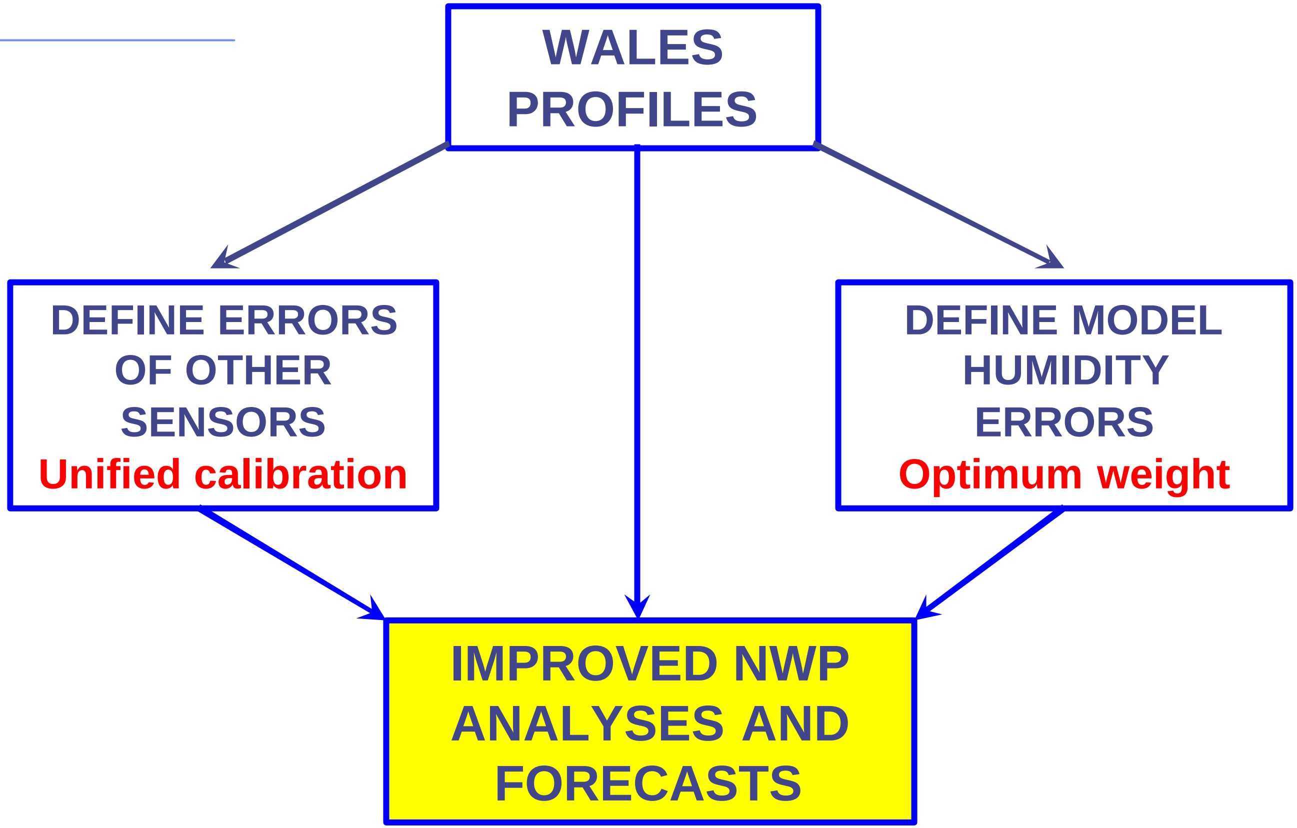
Water vapour is highly variable in space and time with a very large dynamic range



Weather forecasting objectives

- Assimilating higher vertical resolution water vapour data
- Better estimating model humidity errors and thus the relative weight between observations and model background in data assimilation
- Unifying the calibration of all other humidity sensors, notably that of satellite radiometers
- Identifying model deficiencies and improve the modelling of physical processes

WALES 3-way impact on NWP



Climate objectives

- Improve the understanding and modeling of water vapour physical and chemical processes from simulation studies based on WALES observations, notably near the tropopause
- Develop methodologies to deduce climate trends, through inter-calibration of passive remote sensing techniques
- Use the high temporal/spatial coverage at high latitudes to infer the first reliable climatology in these areas

Water vapour measurements

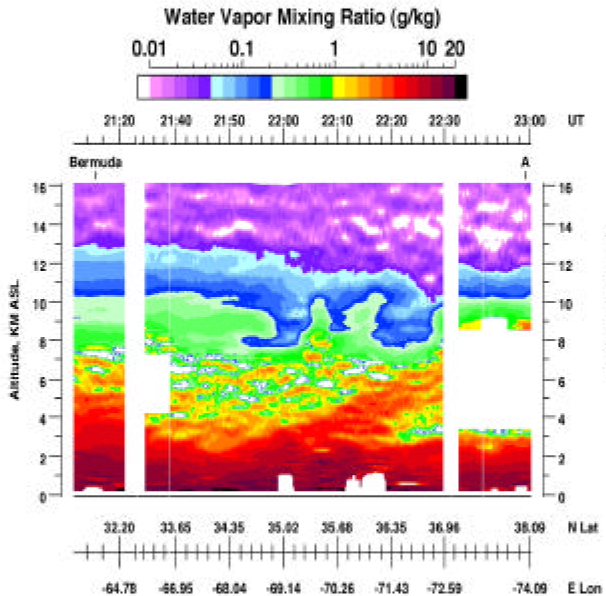
- Accurate measurements are needed to improve weather/climate forecasting and trend analysis
- Current and planned measurements include:
  - **Radiosondes:** non global, limited to ~8 km, highly variable error characteristics
  - **GPS occultation:** limited to 3-10 km; indirect measurement
  - **Passive microwave and infrared measurements:** lack an absolute humidity reference, limited to ~10 km, modest vertical resolution

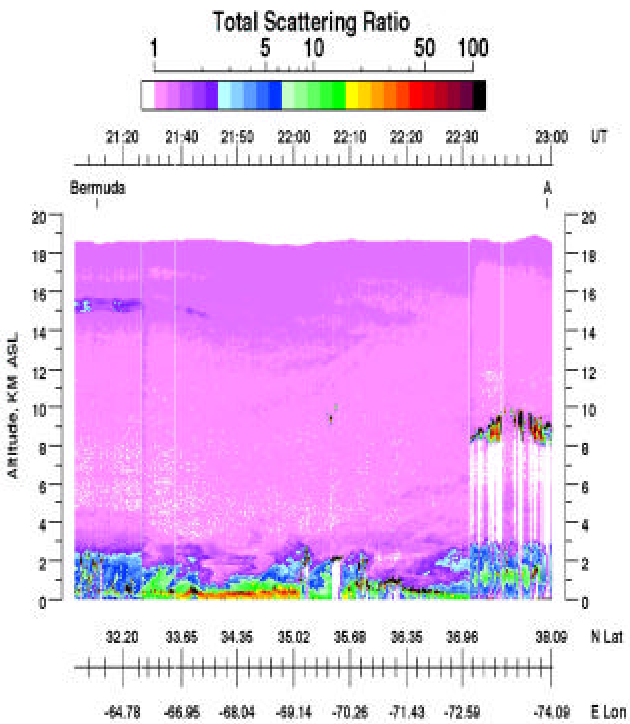
WALES addresses the weakest observational aspects: lack of accuracy, vertical resolution and vertical extent

Unique WALES characteristics

- Direct, self-calibrated, range-resolved water vapour measurement
- High precision and low bias
- Very low sensitivity to temperature in the measurement of water vapour
- High vertical resolution
- Vertical extent from near the surface to the lower stratosphere
- Capability to measure humidity above clouds and through broken and thin clouds
- Simultaneous information on water vapour, cloud and aerosol profiles, and boundary layer height

WALES heritage to airborne DIAL systems

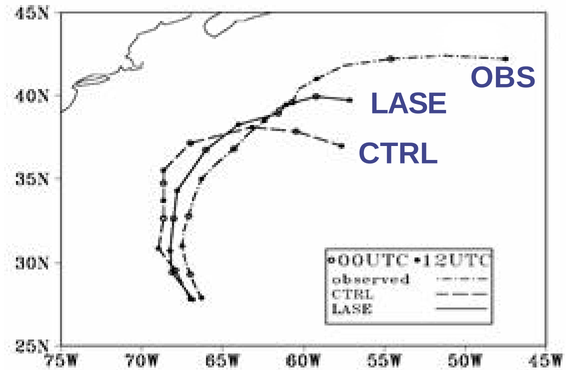


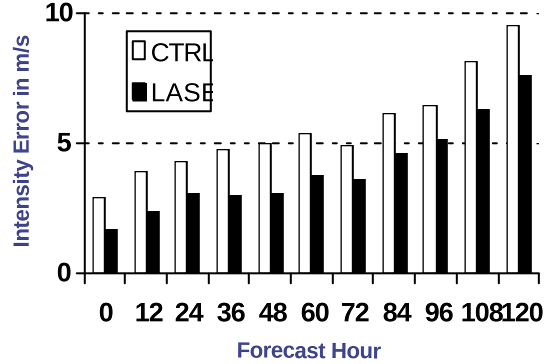


Simultaneous information on water vapour, aerosol, clouds, boundary layer

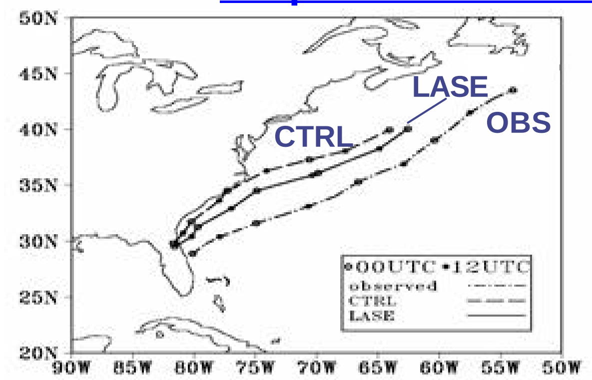
Impact of LASE data on hurricane and tropical storm forecasting

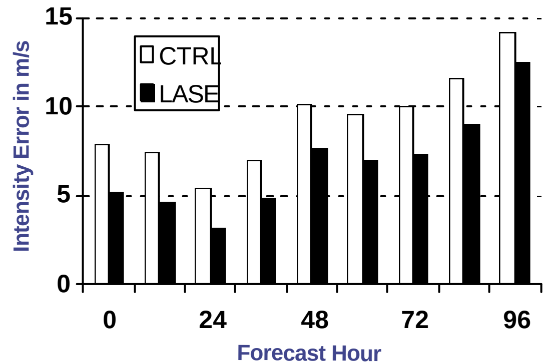
Hurricane Humberto, 22 Sept. 2001





Tropical Storm Gabrielle, 15 Sept. 2001





Nominal observation requirements

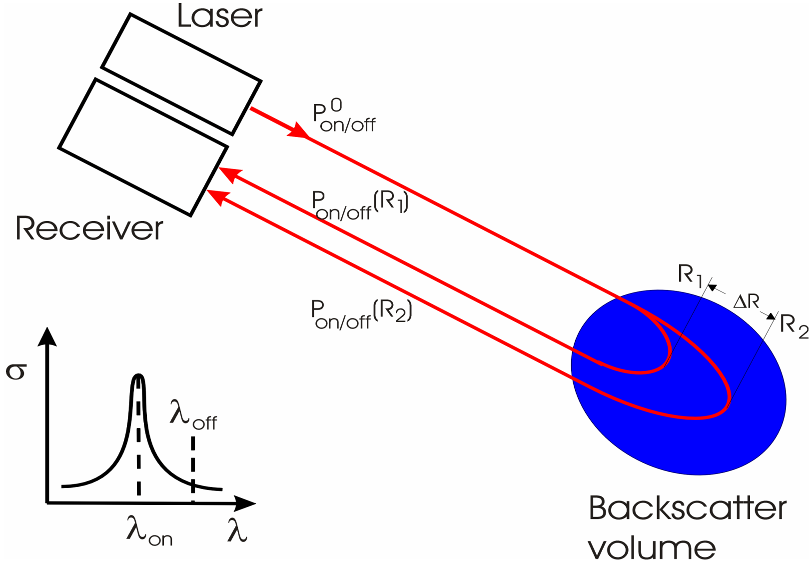
adapted from World Meteorological Organization / Commission on Basic Systems

		Requirement			
Altitude Range	**[km]**	**0-2**	**2-5**	**5-10***	**10*-16***
Vertical Resolution	**[km]**	**1.0**	**1.0**	**1.0**	**1.5**
Horizontal Domain		**Global**			
Horizontal Integration	**[km]**	**25**	**100**	**150**	**200**
Dynamic Range	**[g kg^{-1}]**	**0.01 - 15**			
Precision (1 s)	**[%]**	**20**			
Accuracy (bias)	**[%]**	**< 5**			
Lifetime	**[year]**	**2-3**			
Data reliability	**[%]**	**95**			
Timeliness	**[hour]**	**< 3**			

* *altitude subject to dynamic range limits*

Additional profiling above optically thick clouds and across and below optically thin clouds.

Observation principle

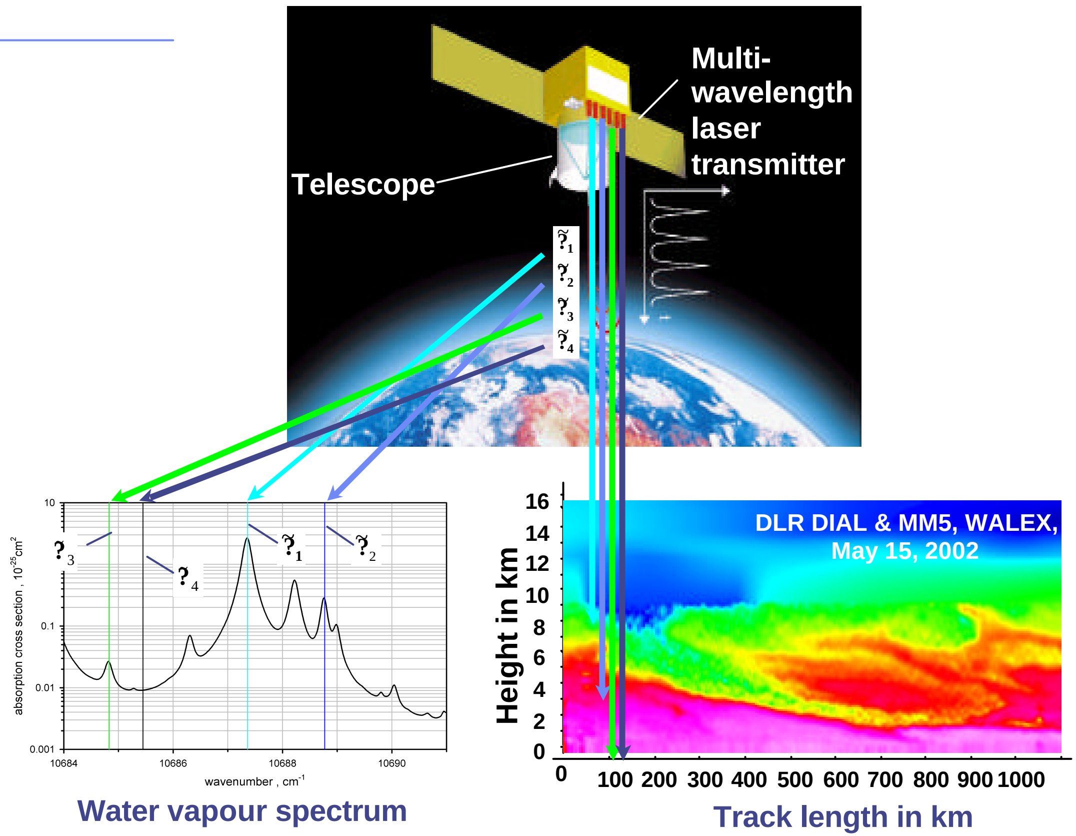


- The Water Vapour Differential Absorption Lidar equation:

$$n_{H_2O}(R) = \frac{1}{2(s_{on} - s_{off})\Delta R} \ln \frac{P_{off}(R_2) P_{on}(R_1)}{P_{on}(R_2) P_{off}(R_1)}$$

- 4 wavelengths required to cover the large dynamic range

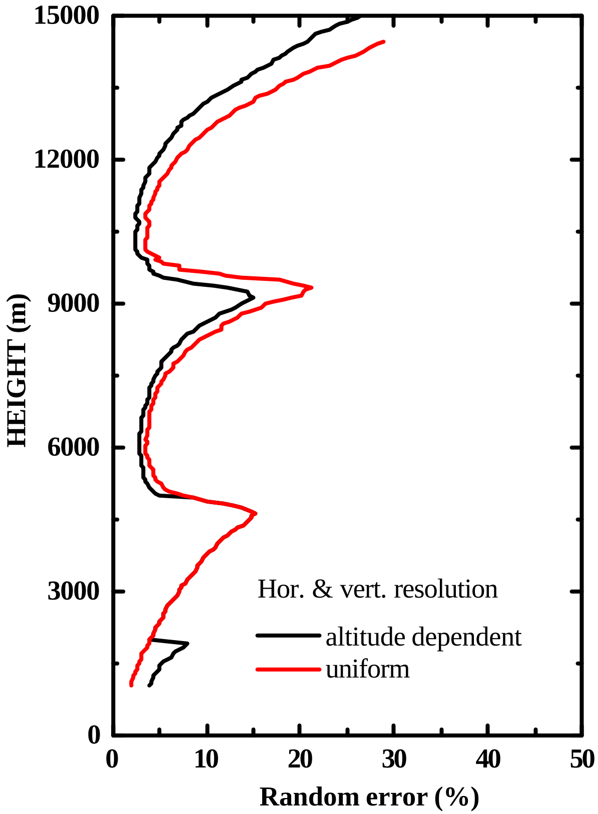
WALES configuration



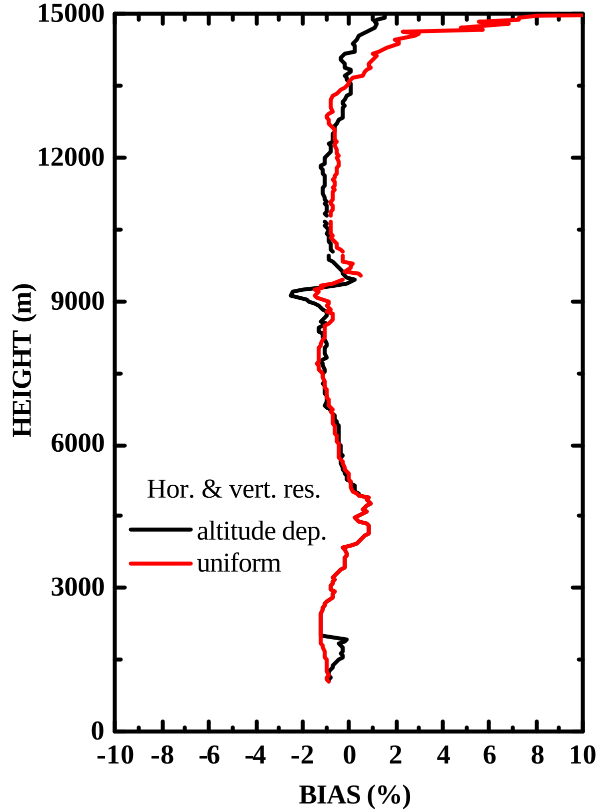
Mission performance

Clear sky performances

Random Error (%)



BIAS (%)



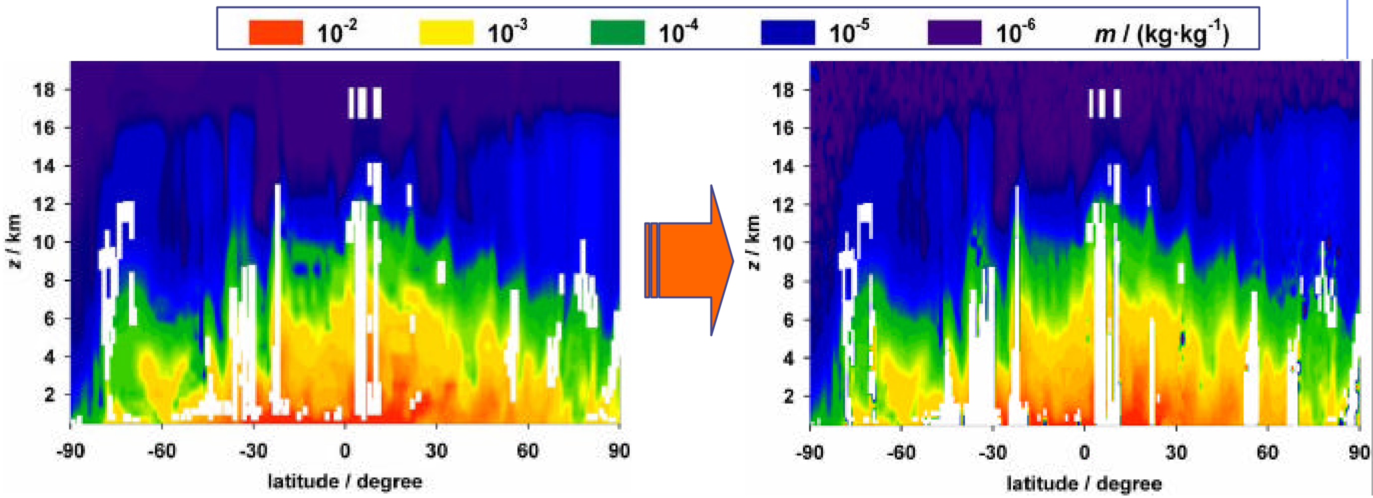
US Standard Atmosphere

WALES expected performance

	Nominal Requirement	WALES expected performance
Dynamic Range [g kg^{-1}]	0.01 – 15	0.005-16
Precision (1s) [%]	20	5-18
Accuracy (bias) [%]	5	< 4

Mission performance

WALES simulation from global model data

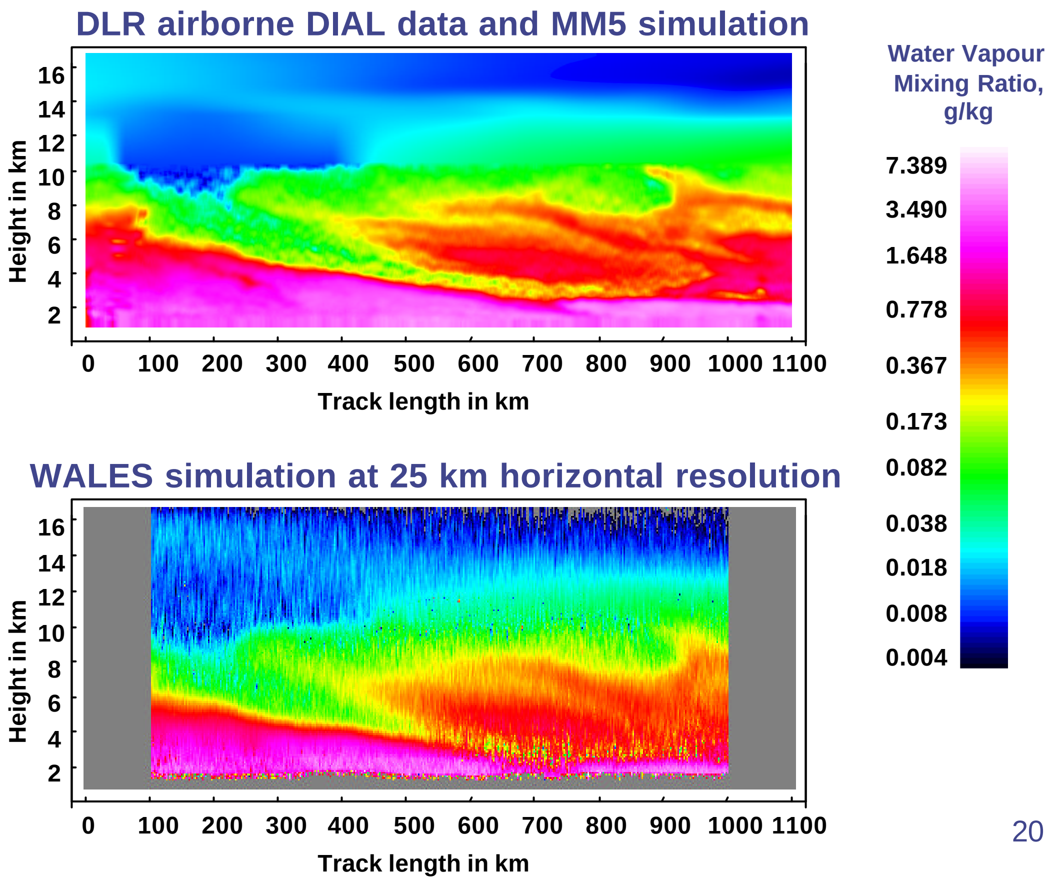


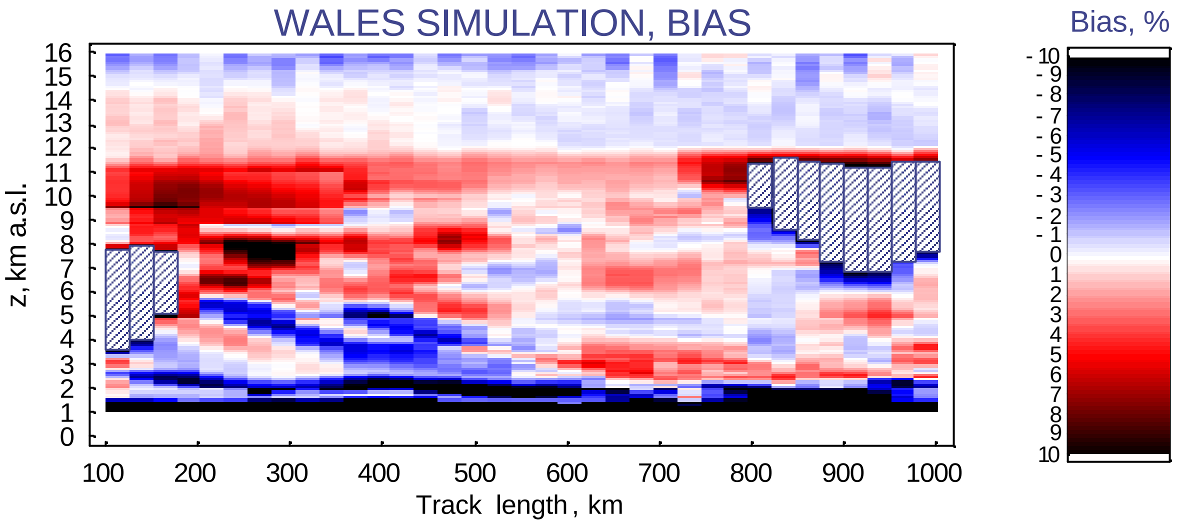
Cross-section based on 6-h forecast **WALES simulation**

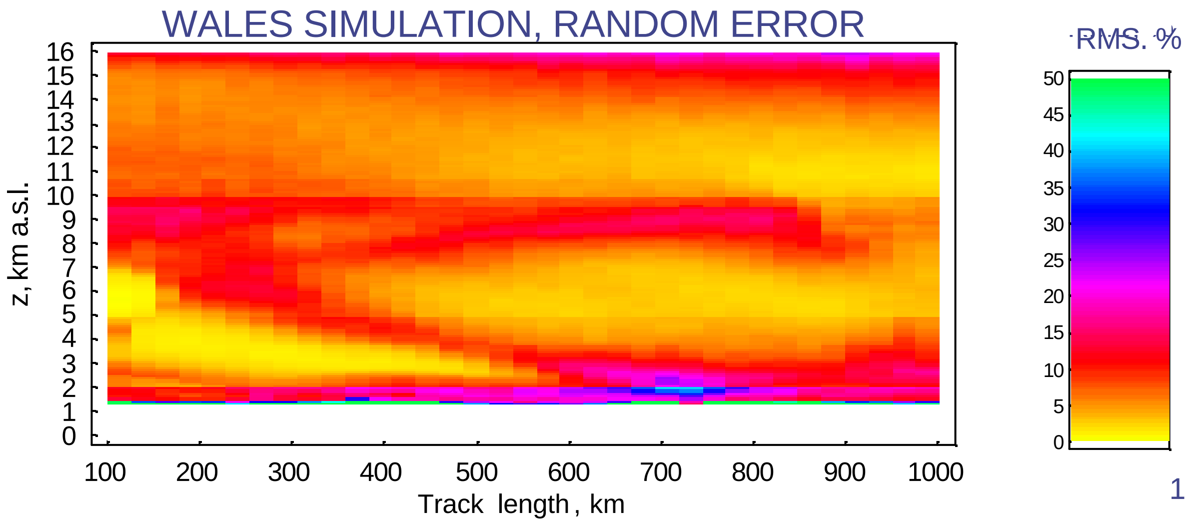
Global water vapour profiles. Information under thin clouds

Mission performance

WALES simulation from observed DIAL data




WALES SIMULATION, BIAS
Bias, %
z, km a.s.l.
Track length, km


WALES SIMULATION, RANDOM ERROR
RMS, %
z, km a.s.l.
Track length, km

Mission performance Gérard et al., 2004 [BAMS]

Information content for WALES and IASI

Linear optimal estimation theory

$$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{H}^{T}\,\mathbf{R}^{-1}\,\mathbf{H}$$

with background **B**, observation **R** and analysis **A** error covariance matrices and linearised observation operator **H**

Degrees of Freedom for Signal DFS=trace($\mathbf{I}$-$\mathbf{AB}^{-1}$)

Measure of the reduction of uncertainty in information

Analysis Vertical Resolution $\mathbf{AVR}_i = dz_i / \mathbf{MRM}_{ii}$

where $\mathbf{MRM} = \mathbf{A}\ \mathbf{H}^{T}\ \mathbf{R}^{-1}\ \mathbf{H}$ and dz_i layer thickness

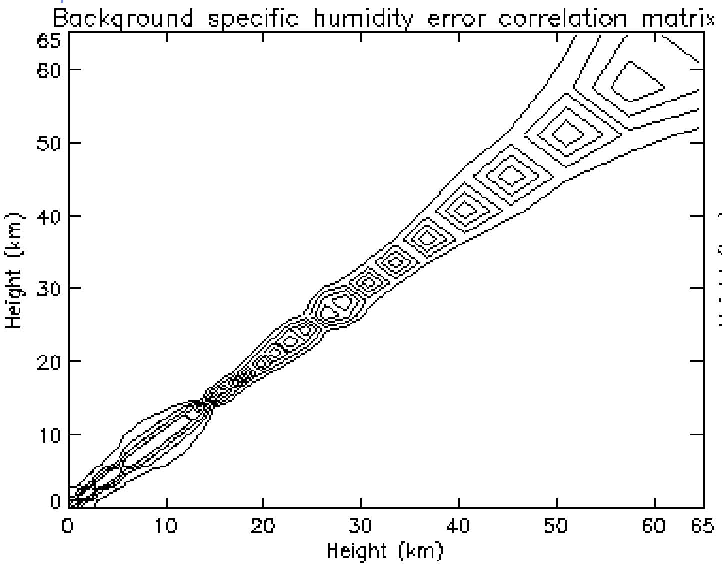
MRM (Model Resolution Matrix) indicates to what extent the analysis represents reality

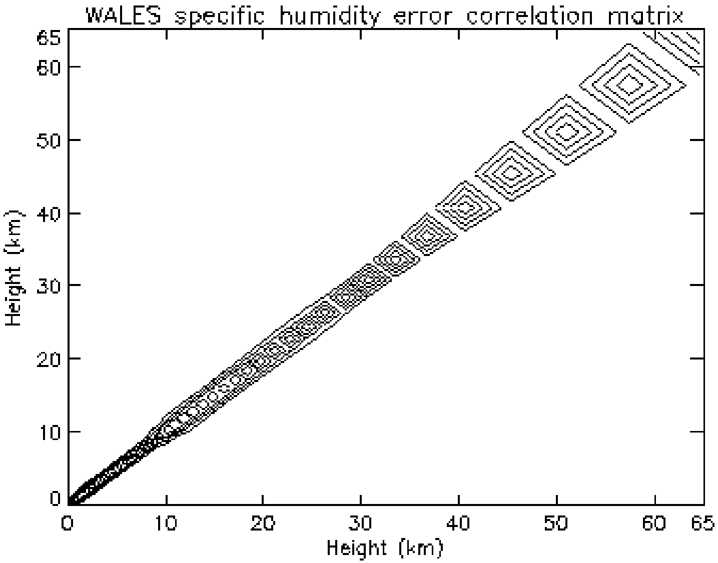
$MRM_{ii} \leq 1$ ($MRM_{ii} = 1$ ↪ maximum resolution ↪ $\mathbf{AVR}_i = dz_i$)

WALES and IASI simulations

- IASI simulations from 8461 channels
  - *H resolution from 12 km to 100 km*
- 43 fixed pressure vertical levels
  - *Radiative Transfer (RTTOV) model*
- B matrix:
  - *Correlation from ECMWF and variances » CMC*
- R matrix for WALES
- R matrix for IASI
  - *RT model error: 0.2 K*
  - *Measurement error: 0.1-0.22 K at wavenumbers 645 to 2250 cm-1 and increase up to 1.9 K at 2760 cm-1*
  - *Correlation between adjacent channels ignored*
  - *Radiances assumed to be free from systematic biases*

Error correlation matrices





Backround error correlation matrix

WALES observation error correlation matrix

WALES and IASI DFS for humidity

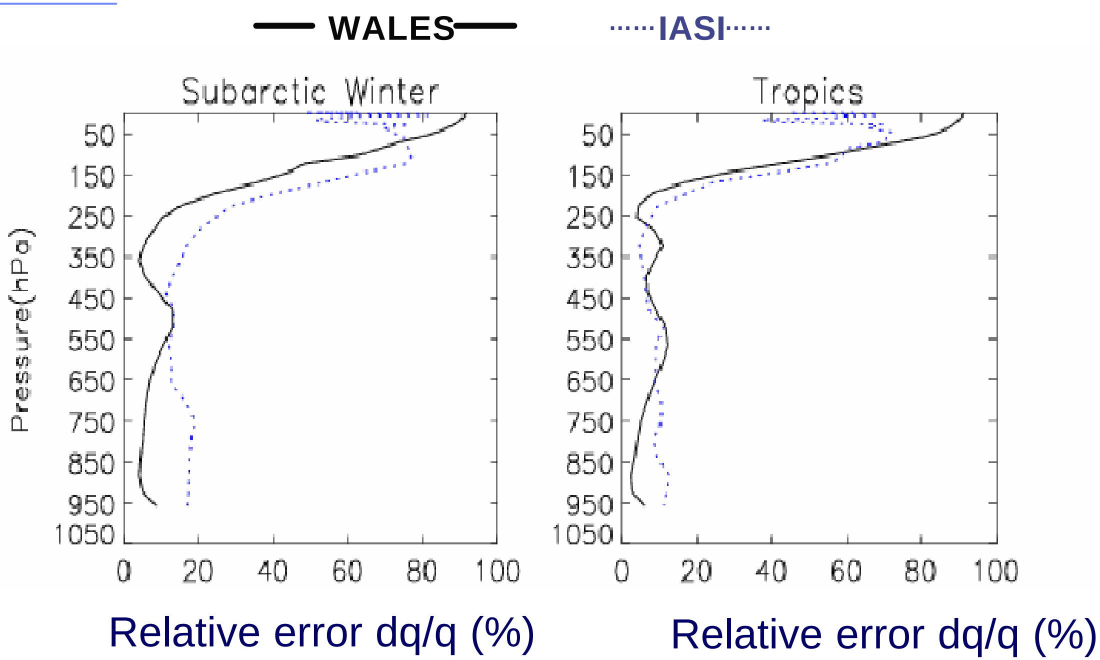
Selected atmospheres	WALES	IASI
Subarctic winter	23.5	12.5
Subarctic summer	23.8	17.0
Midlatitude winter	23.9	14.1
Midlatitude summer	23.2	18.9
US standard	23.8	17.2
Tropics	23.1	19.4
Average	23.5	16.5

+7 units
+ 42 %

Max DFS = 43
Max DFS (surf. - 100hPa) = 28
DFS for WALES independent of type of profile
Higher vertical extent of IASI in warm atmospheres than in cold atmospheres

Mission performance

Analysis errors for WALES and IASI



Wales: superior to IASI - lower dq/q and higher vertical extent

Mean WALES and IASI relative errors (%) below 250 hPa (where 20 % threshold is met)

Selected atmospheres		WALES	IASI
Subarctic winter	+	7.3	15.9
Subarctic summer		6.5	10.5
Midlatitude winter		6.8	14.0
Midlatitude summer		7.4	9.0
US standard		8.0	10.5
Tropics	-	7.0	8.6
Average		7.2	11.4

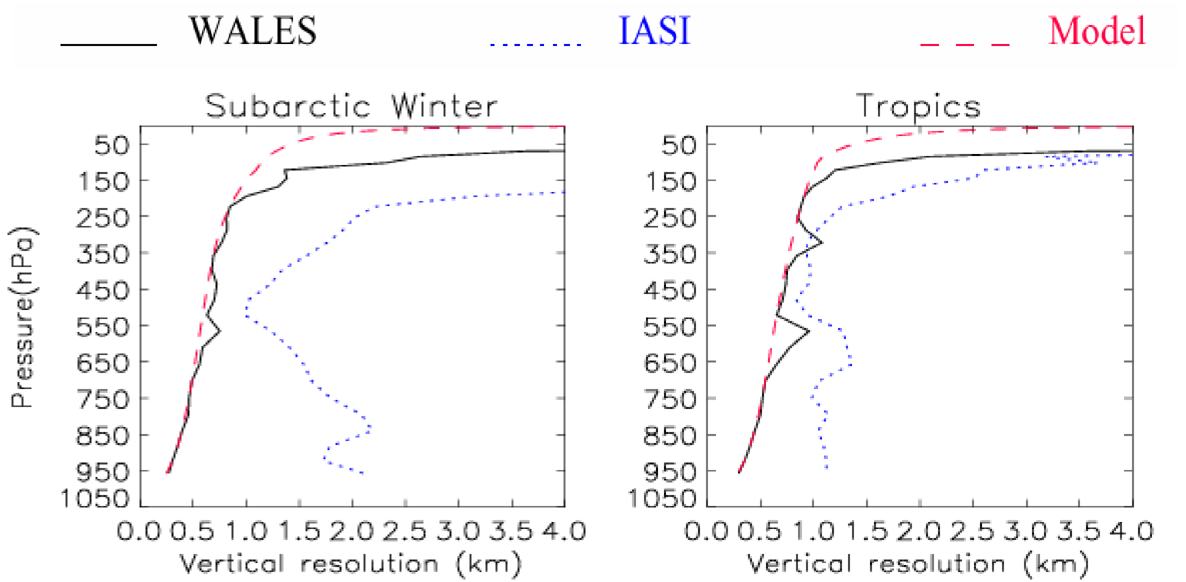
-37 %

Relative improvement of WALES over IASI is

- largest for the subarctic winter profile
- lowest for the tropical profile

Mission performance

Analysis vertical resolution using WALES and IASI



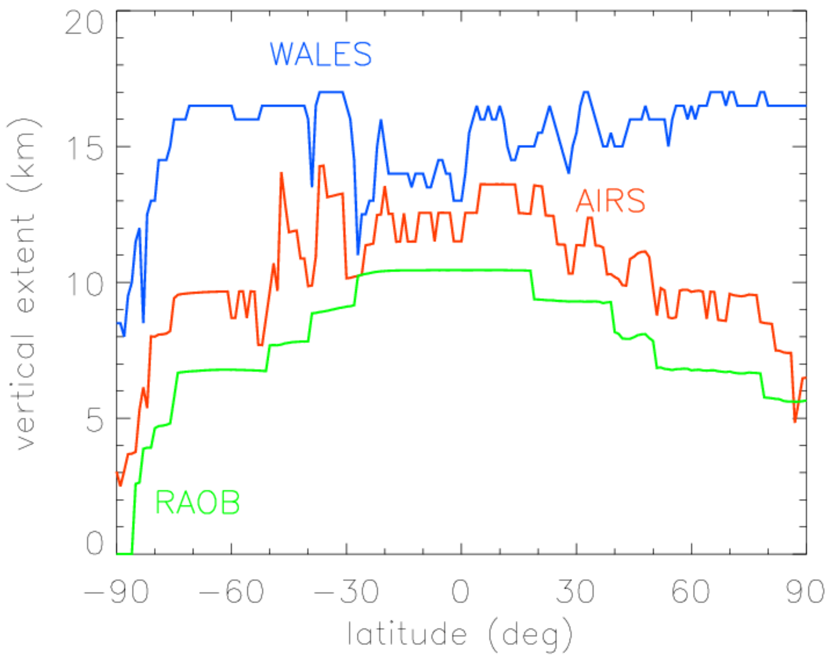
Analysis using WALES superior to IASI.
Better vertical resolution and higher vertical extent

WALES information content

Conclusion

- WALES will provide about 42 % more independent pieces of information than IASI
- WALES superior to IASI
  - Lower analysis relative error
    - about 37 % less error
  - Higher vertical extent
    - 12 - 14 km for WALES
    - 10 - 12 km for IASI
- Vertical resolution
  - WALES: 0.5 - 1 km
  - ... systematically “higher” than ...
  - IASI: 1 - 2 km

Vertical extent alternative comparison WALES / AIRS / Radiosondes



6h forecast cross-section (valid 24 May 2001 06 UTC)

WALES
dq/q < 30%

AIRS:
J(q) > 0.05 K per 10% change in q for high peaking channel 6.61 μm)

Radiosondes
T > 233 K

Clear sky vertical extent

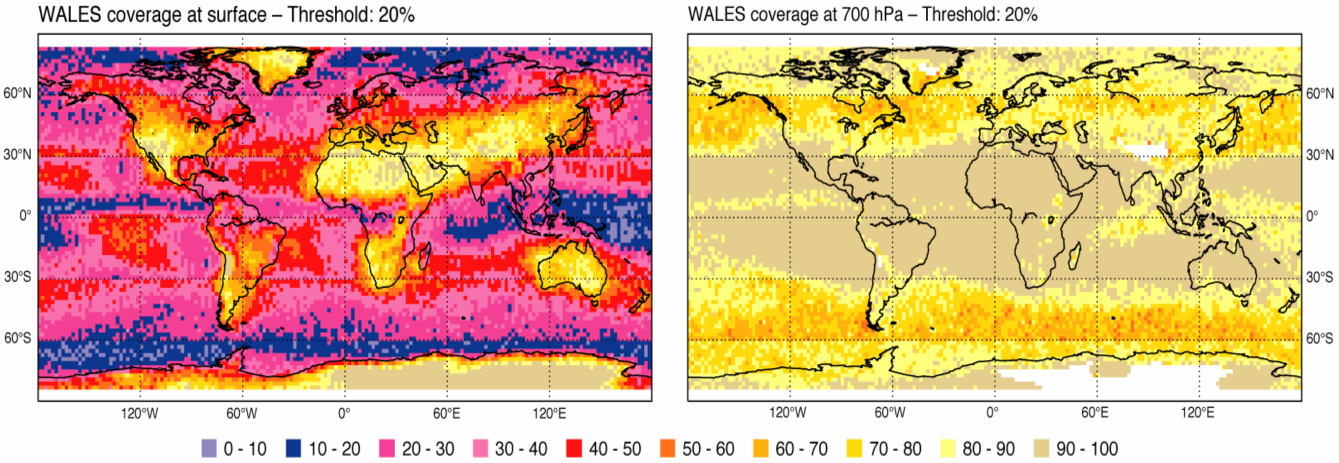
Results

- Advantage of WALES obvious and very significant, notably in high-latitude regions
- Only WALES can provide humidity information between 100 and 250 hPa
- Mean vertical extent for the cross section
  - 15.4 km (114 hPa) for WALES
    - 20% error threshold would lower that height by ~ 0.5 km
  - 10.3 km (252 hPa) for AIRS
  - 7.9 km (363 hPa) for radiosondes

Mission performance

Impact of clouds on coverage

WALES coverage satisfying the 20 % precision requirement:



Obtained from one-year simulation of WALES orbiting using ECMWF archived cloud fields

- 85 % coverage above 700 hPa
- 40-50 % coverage above the surface

WALES links to other missions (1/2)

For 2010 there are expected to be ~30 humidity measuring satellite instruments:

- Microwave (MW) and infrared (IR) nadir and limb sounders descending from today's instruments, e.g.:
  - Nadir IR: CrIS, GIFTS, GOES, HIRS, IASI, SEVIRI, TES
  - Nadir MW: AMSU, ATMS, MHS, SAPHIR, SSMIS
  - Limb IR/MW: HIRDLS, MLS, TES
- GPS radio occultation instruments, e.g.:
  - COSMIC, GRAS

WALES links to other missions (2/2)

WALES would interact with these missions by:

- Providing a high quality reference of humidity for all instruments. No other planned mission provides this reference
- Assisting retrieval of temperature and cloud related parameters through better humidity fields and cloud information
- Providing aerosol measurements, complementing information from other instruments (active predecessors are ADM and CALIPSO)

WALES application potential

- Use water vapour profiles in global and regional models to improve weather forecasting
- A humidity benchmark for other humidity sensors
- In climate monitoring for accurate humidity trends
- Use as reference to test retrieval algorithms for other instruments
- Use aerosol backscatter profiles in global and regional models to advanced aerosol forecasting

Summary and outlook

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- Provides accurate water vapour distributions with high vertical resolution needed for weather forecasting and climate research
- Provides *the* reference data source for validating and calibrating other remote sensing techniques
- Provides data for improving model parameterizations in clear and partially cloudy conditions
- Takes advantage of an extensive heritage of ground-based and airborne lidar applications and recent advancements in laser and receiver technologies
- Would enable a new generation of active remote sensors for Earth and Planetary atmospheric science applications

→ ***WALES would make major contribution to weather forecasting and climate research and would enable a new era of water vapour remote sensing from space***