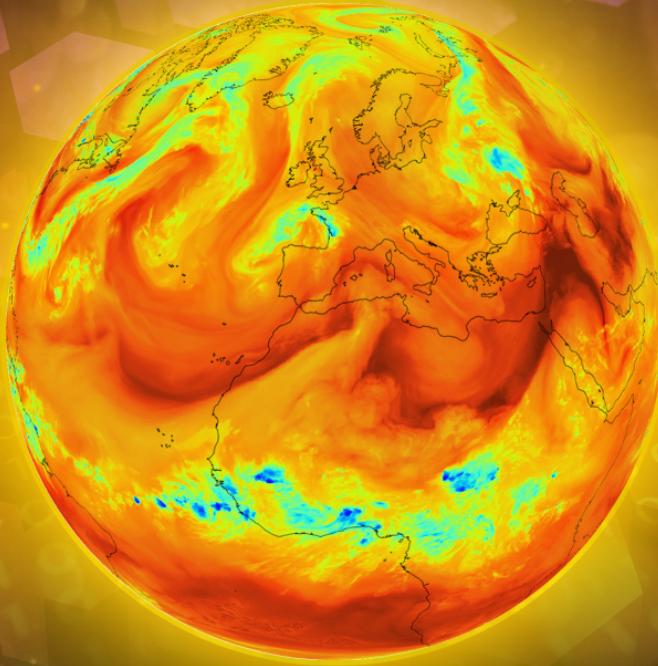


Far-infrared Outgoing Radiation Understanding and Monitoring (An ESA Earth Explorer 9 Candidate Mission)



forum

→ UNDERSTANDING HOW
EARTH IS LOSING ITS COOL

Richard Bantges
Imperial College London

CEOS & WMO-GSICS Workshop
NPL, UK, 9-11 September 2019

www.esa.int

European Space Agency



Imperial College
London

Overview

- Brief history
- Science Drivers & FORUM's objectives
- Proposed Mission Concept
 - Instrument Payload Concept & Specifications
 - Proposed L1 and L2 Products
- Schedule

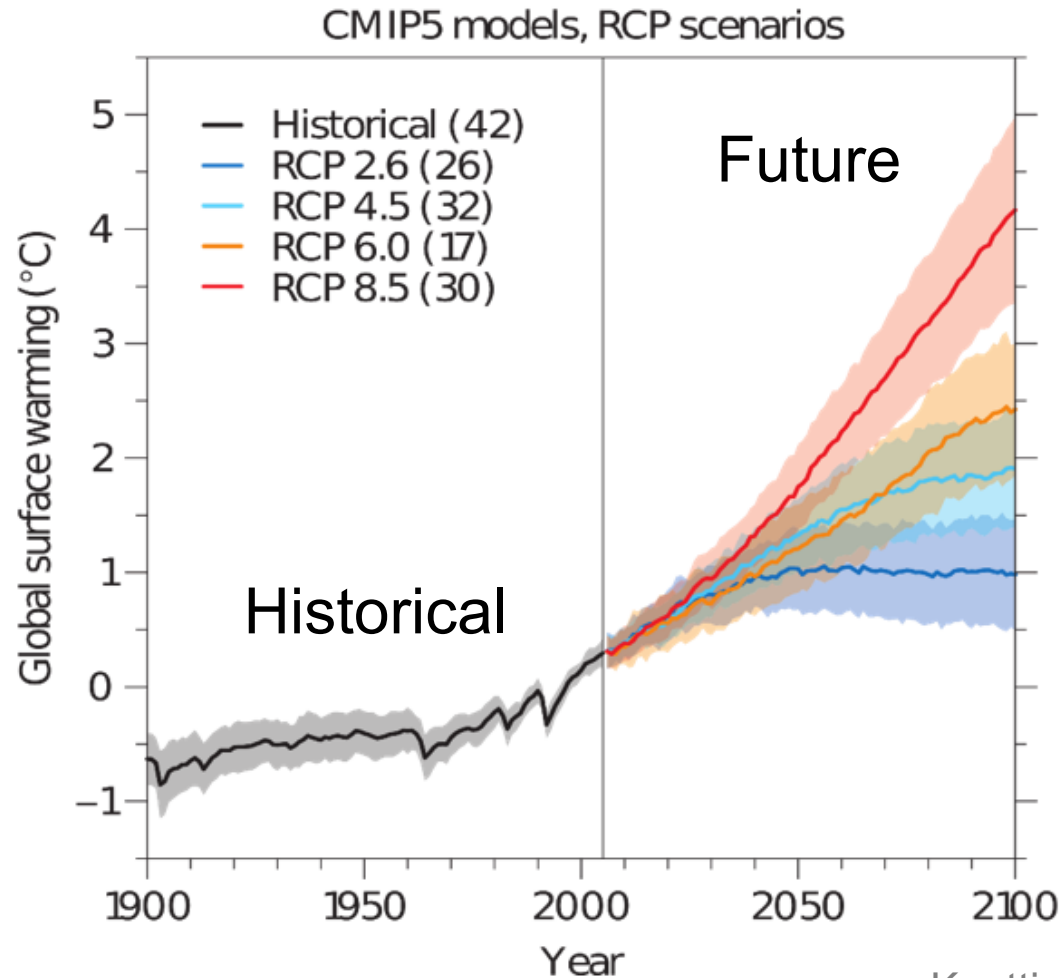
BRIEF HISTORY

History of FORUM

- Submitted to ESA Earth Explorer 8 (2010) – ESA's top 4 (rec. further study)
- EE-9 Call (Nov. 2015) – FORUM proposal submitted (June 2016)
- EE-9 Revised Call (Dec. 2016) – FORUM proposal submitted (June 2017)
- Selected as 1 of 2 missions to enter competitive feasibility studies (Phase A, Nov. 2017)
- Submitted Report for Mission Selection (June 2019)
- ESA EE-9 User Consultation Meeting (July 2019)
 - ACEO (previously ESAC) provide their recommendation to PB-EO
 - PRESENTATIONS & MSR:
<https://atpi.eventsair.com/QuickEventWebsitePortal/19m11---earth-explorer-9-user-consultation-meeting/website>
- Decision to be announced soon (more later)

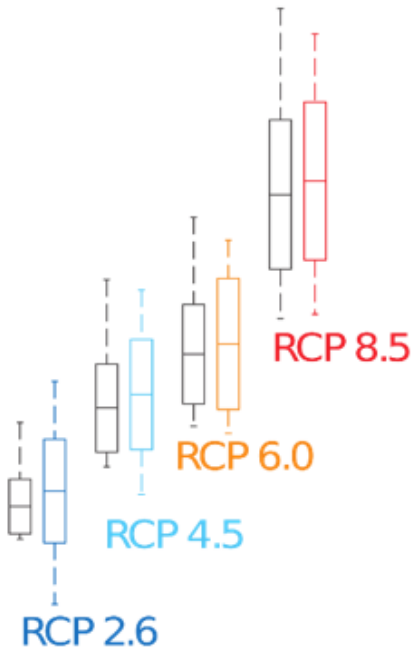
SCIENCE DRIVERS & OBJECTIVES

Science Drivers: Future Climate & Research objective



Knutti and Sedlacek, 2012

Comparison with
emulated CMIP3 RCP

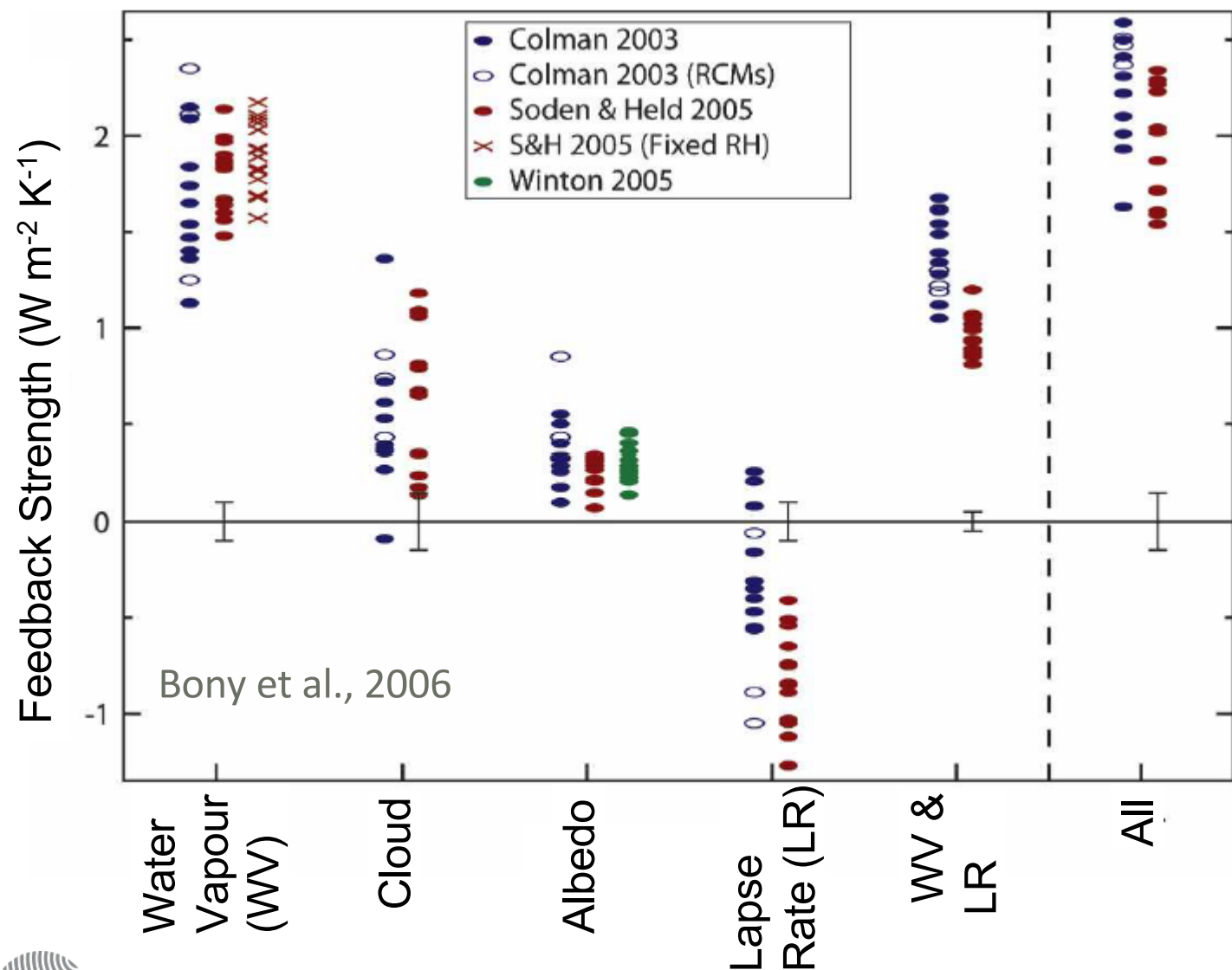


FORUM's Research Objective

"Evaluate the role of the far-infrared in shaping the current climate thereby reducing the uncertainty in predictions of future climate change."

FORUM will provide unique measurements of the **Earth's outgoing energy spectrum** to help reduce this uncertainty

Science Drivers: The climate response - radiative feedback

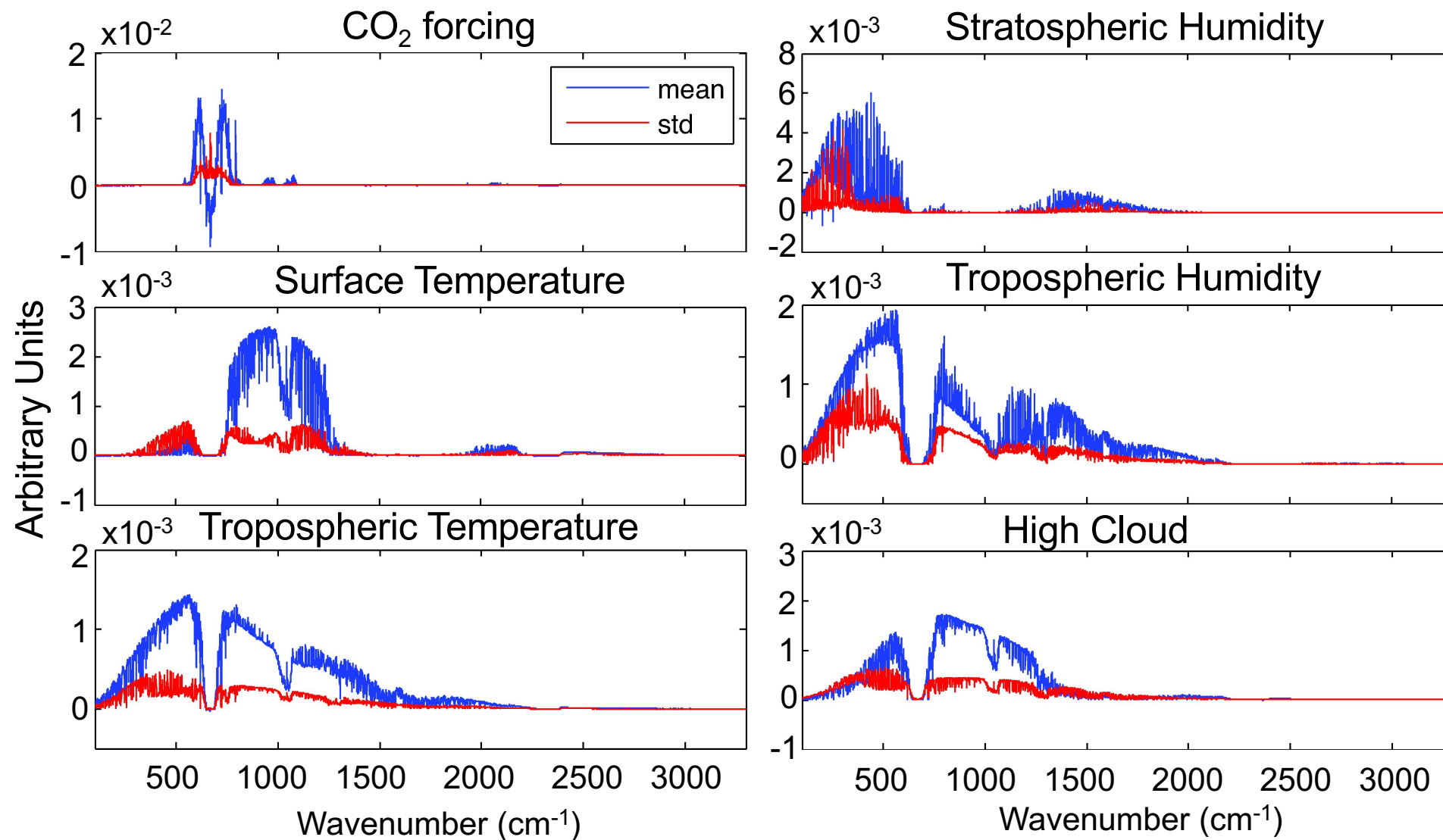


Magnitude and spread of radiative feedbacks is **very uncertain**

This uncertainty **fundamentally drives the spread** in future predictions of climate

Better constraining these radiative feedbacks is arguably the **most important “Grand Challenge”** in current climate research

Science Drivers: The climate response - radiative feedback 2

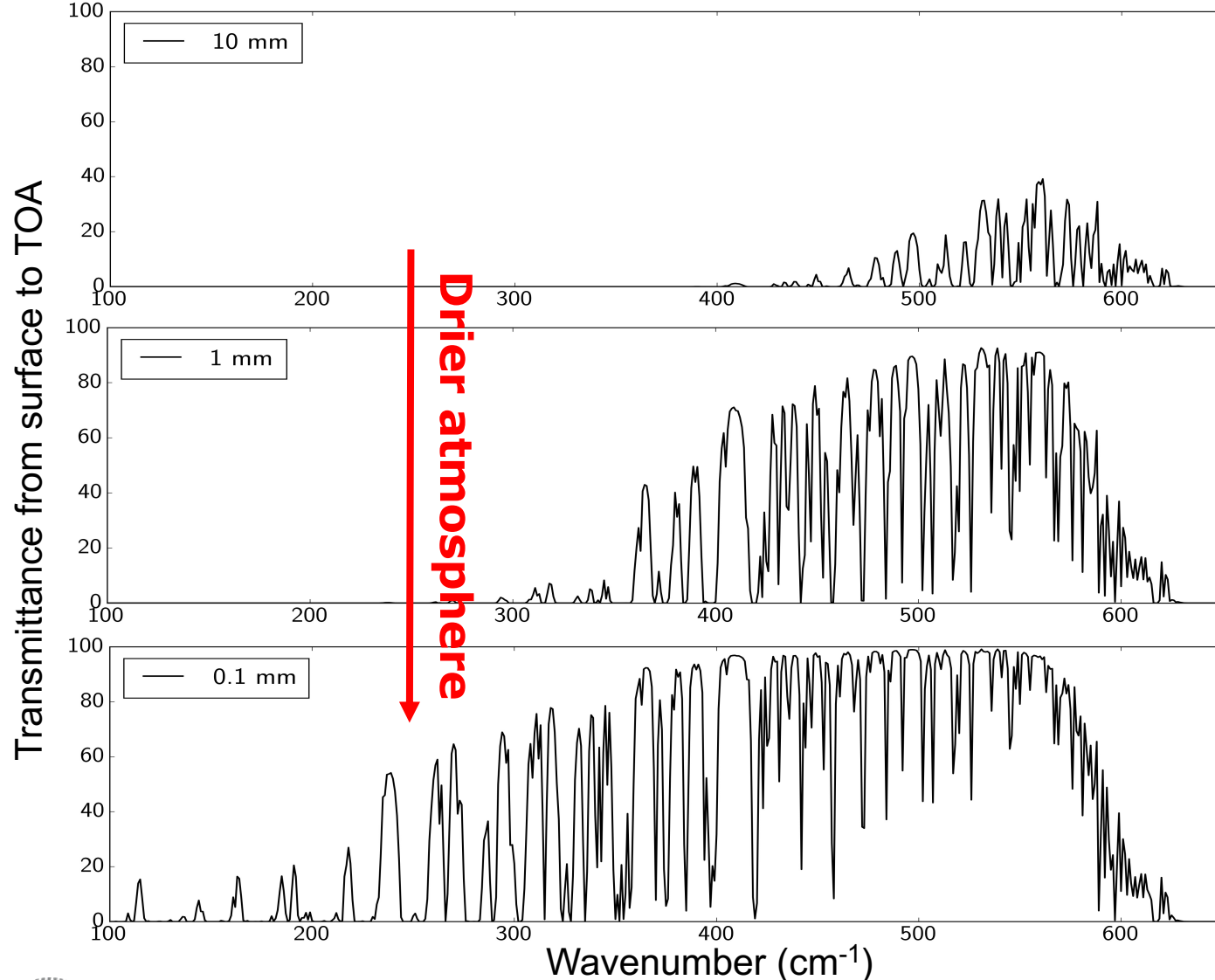


Simulated 2 x CO₂ forcing & associated feedbacks (Huang et al., 2010)

Each feedback has its own **spectral fingerprint**

Spectrum gives **powerful constraint** on climate model performance

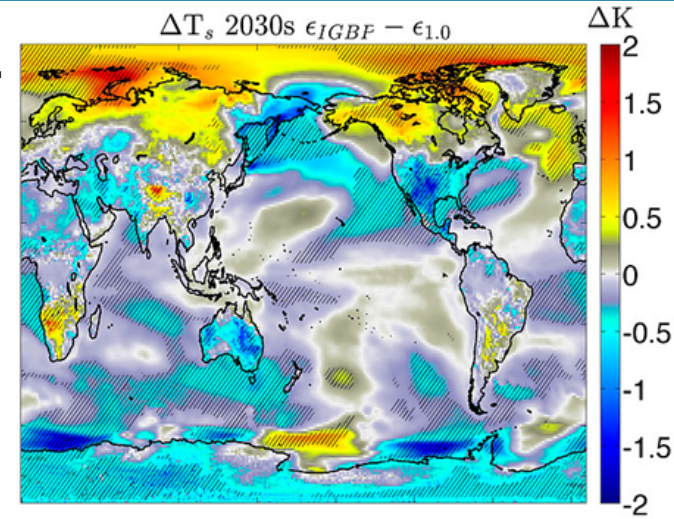
Science Drivers: FIR surface spectral emissivity



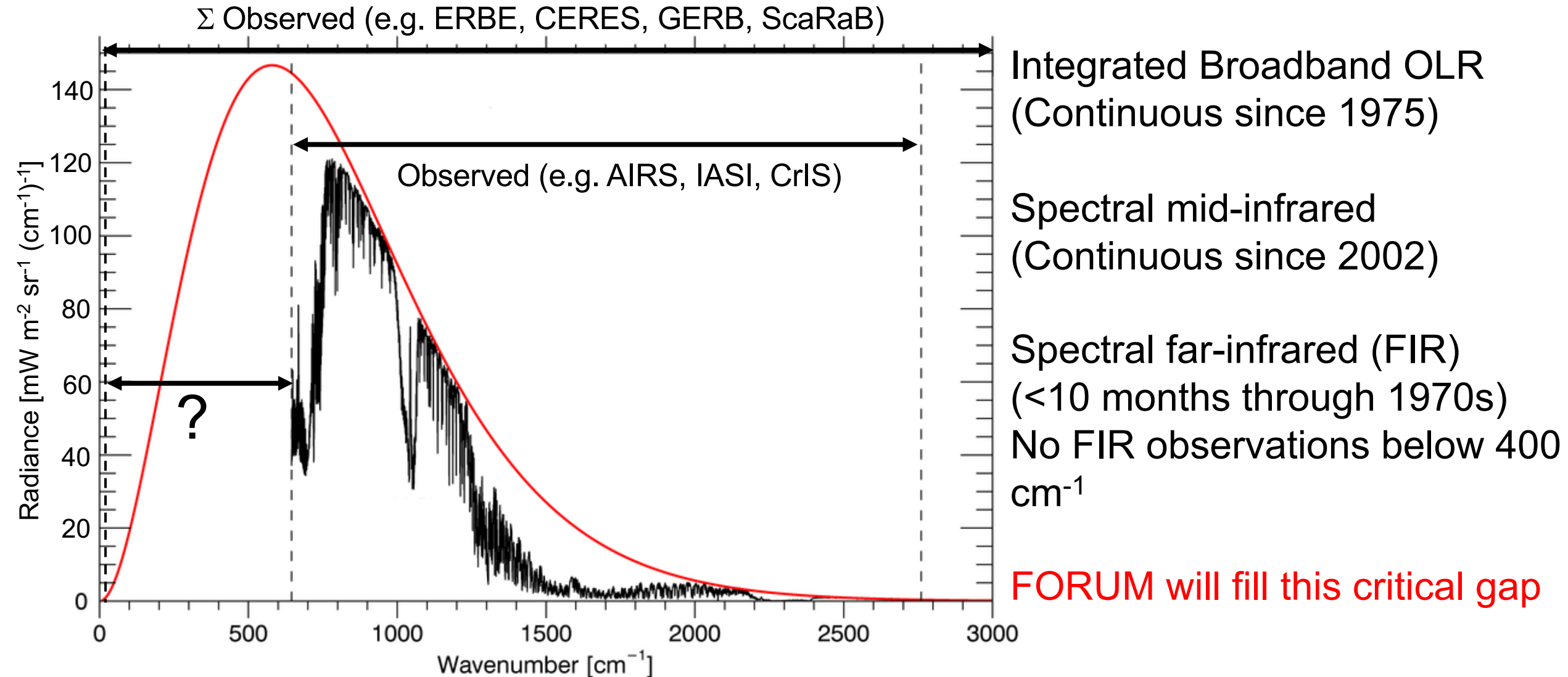
Sensitivity to the **surface**:

- As the amount of water vapour in the atmosphere decreases 'micro-windows' in the far-infrared open allowing surface emission from the FIR to escape to space
- Potentially key for **high latitude and high elevation warming**

Feldman et al. 2014:
Replaced BB emissivity –
FIR estimated spectral ->
Arctic T_s response



Science Drivers: The missing piece - FIR spectral radiation



FORUM'S OBJECTIVES

Mission Objectives

Primary

- Measure the **spectral distribution** of the Earth's OLR encompassing, **for the first time, the FIR**
- Evaluate the **underlying spectroscopy** and **cloud models** currently employed in the FIR
- Tie the **observed radiative signatures directly to** variability in, in particular, **water vapour, greenhouse gases, cloud and surface properties**
- Provide a **stringent evaluation** of **key radiative processes/feedback mechanisms** as currently represented in **climate models**

Additional

- Retrieval of **FIR surface emissivity** in appropriate conditions (clear-sky, dry conditions)
- Assessment of **additional benefit** of FIR spectral observations compared to state-of-the-art hyperspectral mid-infrared radiances for **water vapour retrieval**
- Detection of **optically thin ice-cloud**
- Retrieval of **ice-cloud optical depth, cloud top height and particle size**

FORUM MISSION CONCEPT

Mission Concept: FIR Spectral Measurement requirements

Science driven measurement requirements

Spectral Range	100 – 1600 cm⁻¹
Spectral Resolution FWHM: (Goal) [Threshold]	(0.36 cm ⁻¹) [0.5 cm ⁻¹]
Radiometric Accuracy 3σ (Goal) [Threshold]	300-1100 cm⁻¹: (0.1 K) [0.25 K] 200-300 cm⁻¹: (0.2 K) [0.25 K] 1100-1300 cm⁻¹: (0.2 K) [0.25 K] Elsewhere: (1.0 K) [2.0 K]
Radiometric Precision (Goal) [Threshold]	200-800 cm⁻¹: (0.4) [0.6] mW/(m ² sr cm ⁻¹) Elsewhere: (1.0) [2.0] mW/(m ² sr cm ⁻¹)
Footprint	12 – 15 km (closely match IASI-NG)
Scene homogeneity	Sufficient to identify inhomogeneities in the skin temperatures or in the cloud coverage that produce detectable differences in the spectrometer measurement

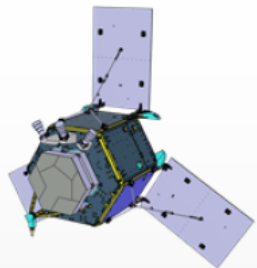
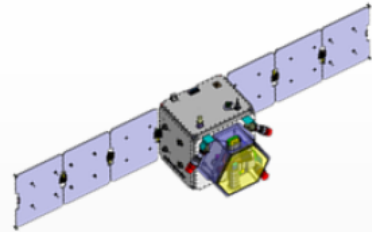
Mission Concepts: 2 concepts during Phase A:

2 industrial consortia:



Baseline Launcher
Vega-C
Dual launch



Concept A	Concept B
	
Mass: ~850 kg Power: ~430W	Mass : ~570 kg Power : ~440 W
Instruments: Fourier Transform Spectrometer (FSI) Imager (FEI)	
Nominal Lifetime: 4 years	
Orbit: SSO at 830 Km; LTND at 9:30 a.m.	
Loose formation with MetOP-SG-A1.	

FORUM: Measurement Requirements & Payload concept

2 instruments – Sounder and Imager

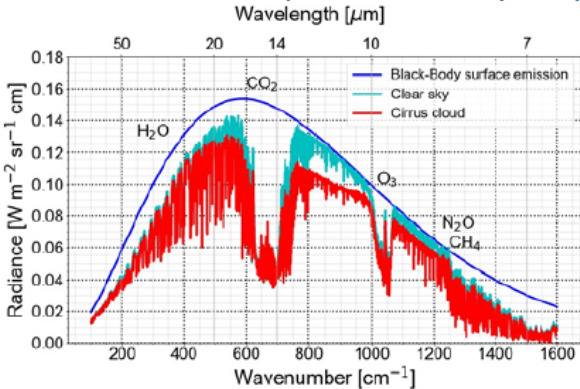
FORUM Sounding Instrument (FSI)

What for?

Spectrally resolved measurement of the Top-of-atmosphere (TOA) spectrum in the **infrared from 100 to 1600 cm⁻¹** (100 μm to 6.25 μm)

How?

SPECTROMETER
Fourier Transform Spectrometer (FTS)



Spectral Resolution FWHM:
(0.36 cm⁻¹) [0.5 cm⁻¹]

Radiometric Accuracy 3σ (Goal) [Threshold]	300-1100 cm⁻¹: (0.1 K) [0.25 K] 200-300 cm⁻¹: (0.2 K) [0.25 K] Elsewhere 1100-1300 cm⁻¹: (0.2 K) [0.25 K] (1, 2 K)
Radiometric Precision (Goal) [Threshold]	200-800 cm⁻¹: (0.4) [0.6] mW/(m ² sr cm ⁻¹) Elsewhere: (1.0) [2.0] mW/(m ² sr cm ⁻¹)

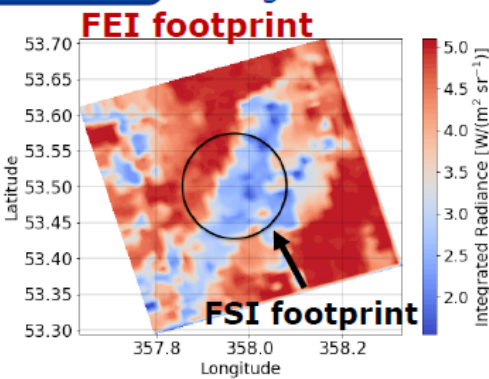
FORUM Embedded Imager (FEI)

What for?

Scene uniformity Assessment

How?

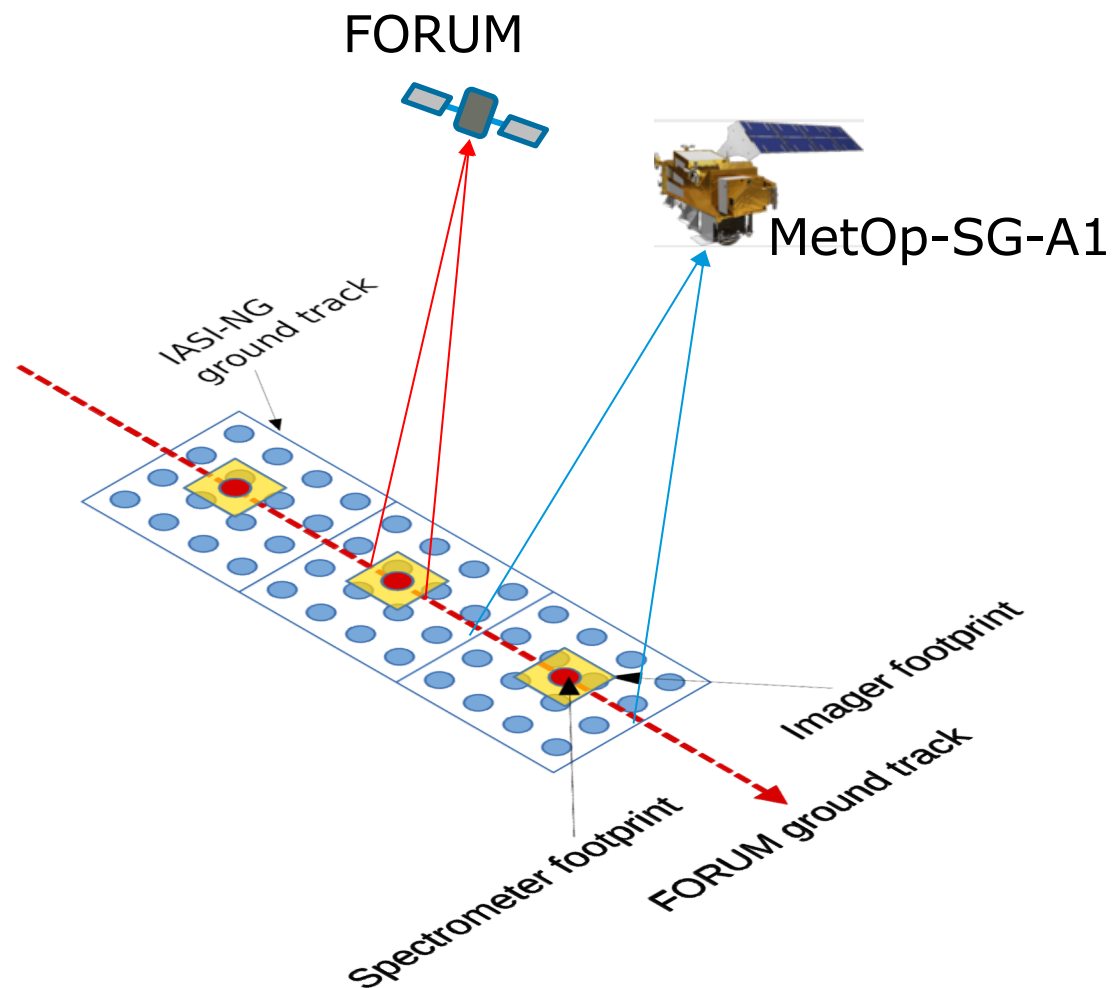
THERMAL IMAGER
Single band



Single channel: 10.5 μm (1.5 μm) (889-1026 cm⁻¹)

Radiometric accuracy	(1 K) [3 K]
NeDT (at 210 K)	(0.3 K) [0.8 K]

Mission Concept: Footprint and Spatial Sampling



Nadir-looking observations

Spectrometer footprint

- single circular **pixel** $\varnothing = 15$ km

Along-track sampling step

Goal = 70 km, Threshold = 100 km

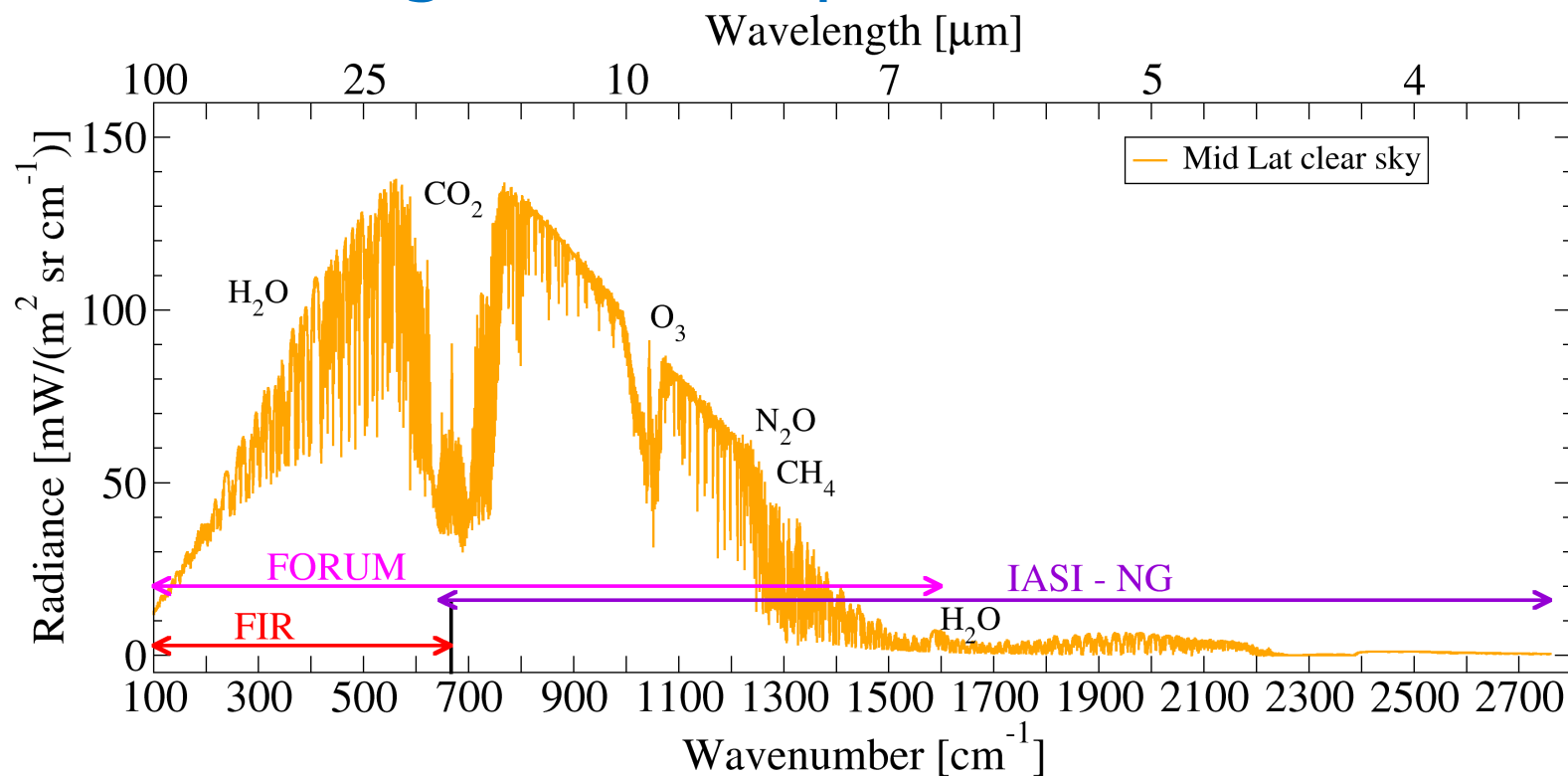
Thermal imager footprint

- 60x60 pixels, 36x36 km²
- **resolution = 0.6 km**

Lifetime = at least 4 years to resolve seasonal & inter-annual variability

Flight in **loose formation with MetOp-SG-A1**
LEO, SSO at 9:30 LT DN – average altitude = 830 km to exploit synergy with IASI-NG

FORUM Spectral Range: Overlap with IASI-NG



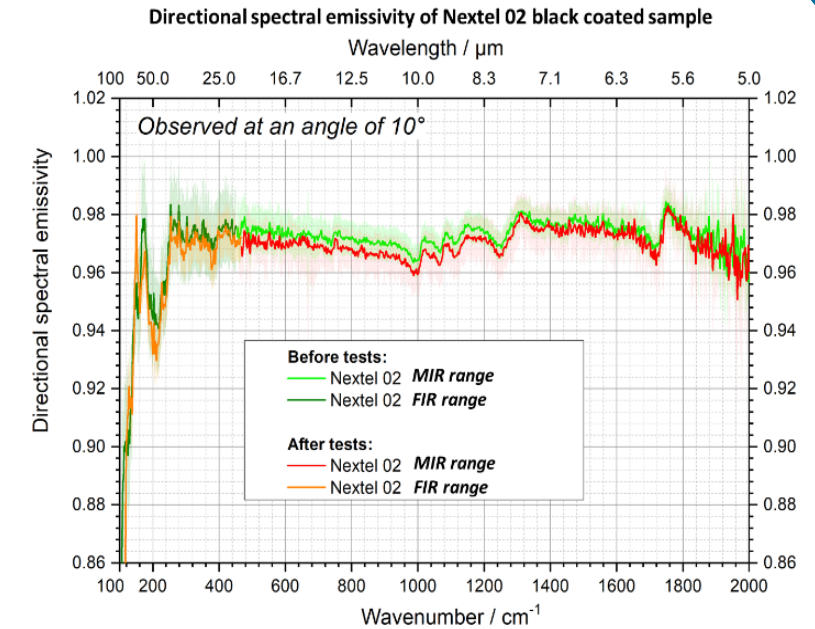
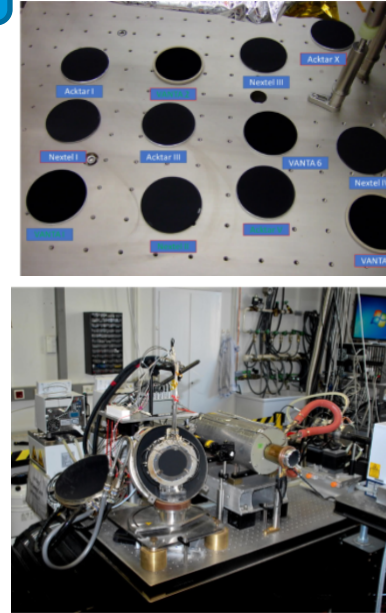
- FORUM spectral coverage from 100 to 1600 cm^{-1} (6.25-100 μm) will cover about 96% of the emitted radiance
- Flight in loose formation with MetOp-SG-A will allow:
 - Cross-calibration with IASI-NG and
 - Delivery of the spectrum from 100 to 2760 cm^{-1} (3.62-100 μm)

Mission Concept: FSI performance / calibration

Phase A technology development

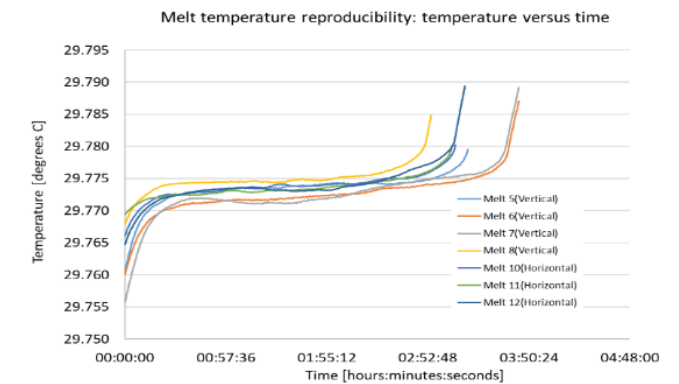
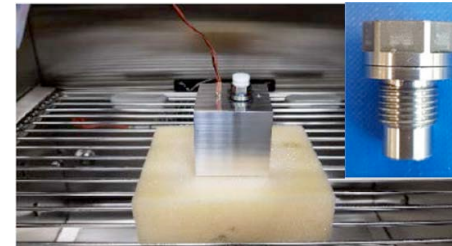
Blackbody emissivity

- Black coating trade off
- **Emissivity characterization** in air on samples
- **Environmental testing** on black coated samples: humidity, adhesion, thermal vacuum cycling
- Blackbody **cavity design and modelling** → Emissivity assessment



Blackbody temperature knowledge

- Phase change cell **design**
- Phase change cell **breadboard**
- Melting temperature reproducibility testing < 10mK



FORUM: Level-1 Products

Level-1 Products	Product Definition
Spectrometer Level-1b	Spectrally and radiometrically calibrated spectral radiance in the 100-1600 cm^{-1} band.
Imager Level-1b	Thermal images radiometrically calibrated and geolocated with preliminary pixel classification.
Spectrometer Level-1c	Spectrally and radiometrically calibrated spectral radiance, resampled at a specific spectral grid. Radiometric, spectral and geometric errors are appended.

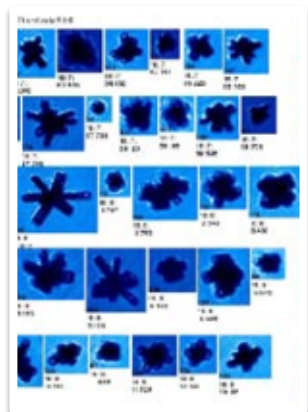
FORUM: Level-2 Products

Level-2 Products	Products Definition and Uncertainty Requirement
All-sky broadband spectral flux	FORUM Level-1c FIR OLR extended to broadband with the Level-1c from IASI-NG
Water vapour profile	Vertical profiles of water vapour concentration with 15 % maximum uncertainty at 2 km vertical resolution
Surface emissivity	Surface emissivity in the 300–600 cm^{-1} spectral range for polar regions. Uncertainty of 0.01 on 50 cm^{-1} spectral grid
Ice water path (IWP)	Integrated ice water content with maximum uncertainty of 20 g/m^2
Cloud Top Height (CTH)	Altitude of the top of the cloud with maximum uncertainty of 1 km
Particle size diameter	Effective diameter of particles with maximum uncertainty of 20%

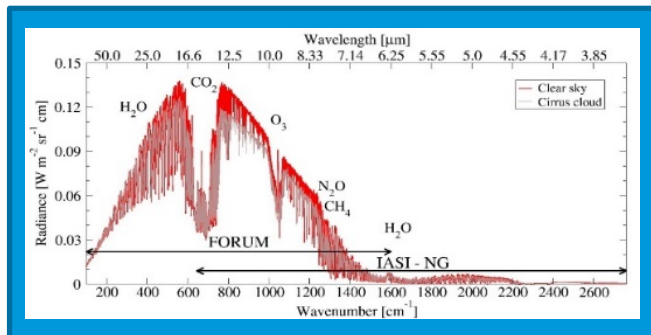
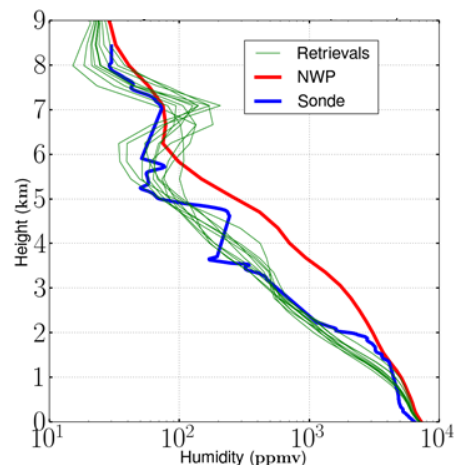
Validation and Quality Monitoring

Products

- Level 1 Radiances
- Cloud detection and classification
- Water vapour profiles
- Surface emissivity
- Cloud properties:
CTH, IWP & De
- Spectral flux



Baran 2009



Validation tools

Dedicated field campaigns: sondes, airborne FIR radiometer observations, detailed surface and cloud measurements including in-situ cloud microphysics

Comparison with other sensors' radiances and products

Radiance and profile comparisons, comparison at high latitude with other sensors, consistency checks on the flux against OLR from broadband sensors.

Ongoing quality monitoring

Using NWP model fields; ongoing cross comparisons and monitoring of quality indicators on the spectrum

FORUM Team (Phase A)

Mission Advisory Group

Helen Brindley (Imperial College London, UK)

Stefan A. Buehler (University of Hamburg, DE)

Dorothee Coppens (EUMETSAT, INT)

Adrien Deschamps (CNES, FR)

Steven Dewitte (Royal Meteorological Institute of Belgium, BE)

Bianca M. Dinelli (ISAC-CNR, IT)

Laurent Labonnote (University of Lille, FR)

Quentin Libois (Météo-France, FR)

Martin Mlynchak (NASA Langley Research Center, US)

Luca Palchetti (INO-CNR, IT)

Marco Ridolfi (University of Bologna, IT)

Martin Riese (Forschungszentrum Jülich, DE)

Roger Saunders (Met Office, UK)

ESA Technical Team

Bernardo Carnicero Domínguez (Technical Coordinator) and Charlotte Pachot (Payload Technical Coordinator)
with contributions from Itziar Barat, Paolo Bensi, Christophe Caspar, Miguel Copano, Mauro Federici, Dulce Lajas, Flavio Mariani, Vasco Pereira, Stefanie Riel, Gonçalo Rodrigues, Bernd Sierk, Kate Symonds and Andrea Tromba

ESA Science Team

Hilke Oetjen, Dirk Schuetttemeyer

SCHEDULE

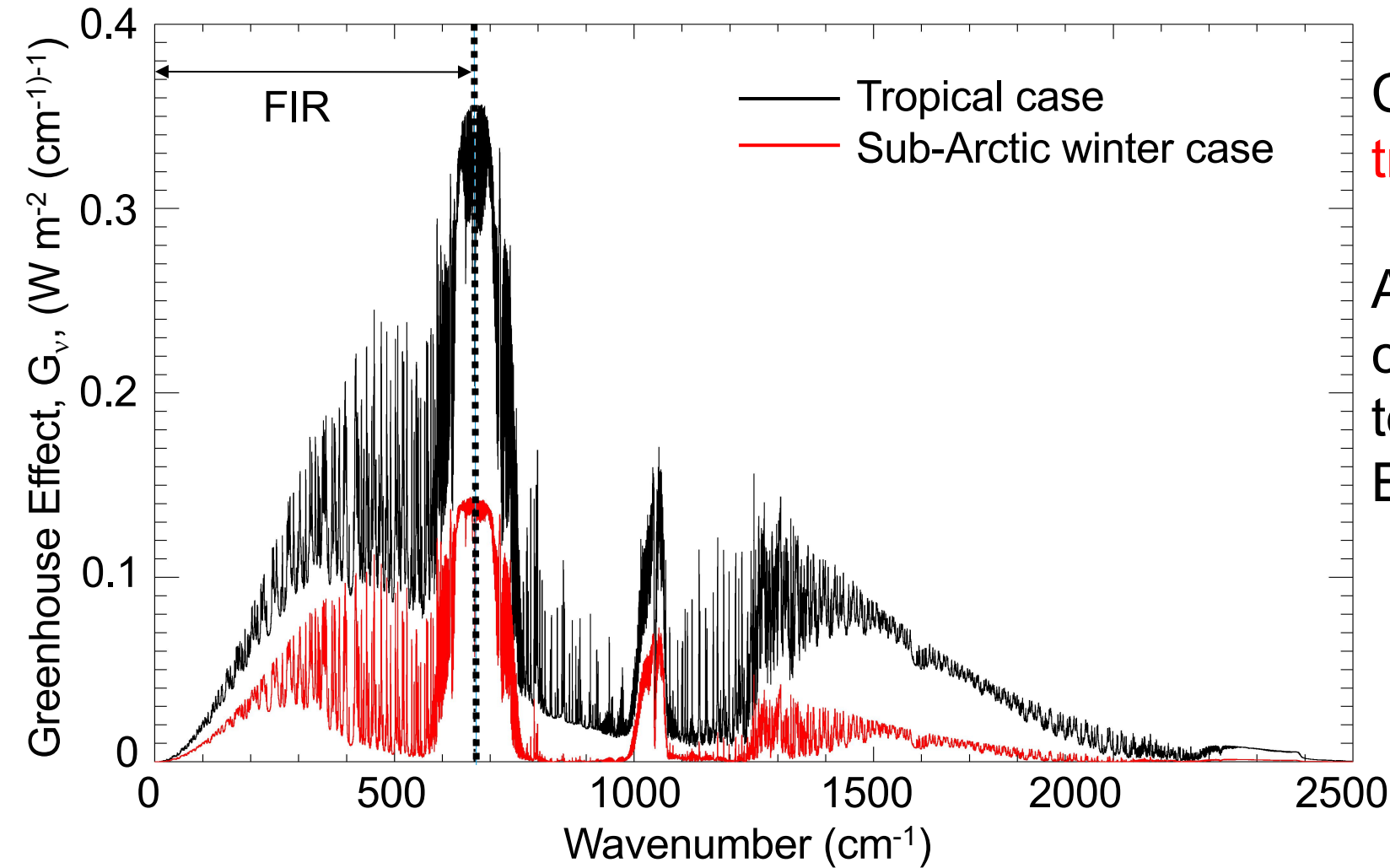
Forward-looking Schedule

- ESA to announce decision on EE9 23/24th September 2019
- Selected mission -> Phase B1 Oct 2019 - Oct 2020
- Phase B1: 2 industry contracts proceed in competitive mode
- Phase B2 – Single contract (multiple sub-contracts)
- Estimated launch 2026



EXTRA SLIDES

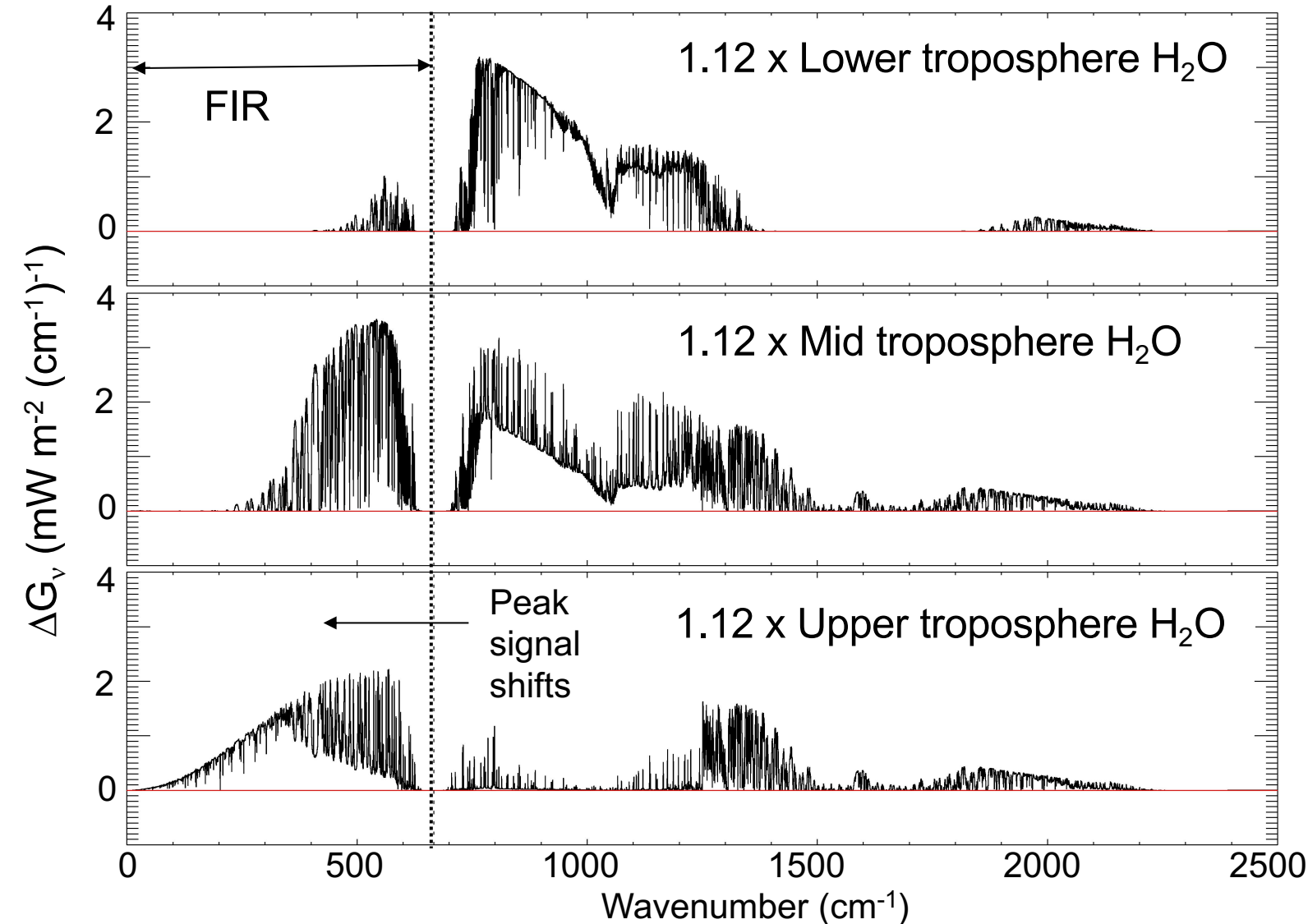
Science Drivers: Why is the FIR so special?



Contribution to **atmospheric trapping**:

Absorption in the far-infrared contributes $\sim 50\%$ to the total clear-sky Greenhouse Effect, G_v

Why is the Far-infrared so special?



Signatures of changes in
atmospheric water vapour:

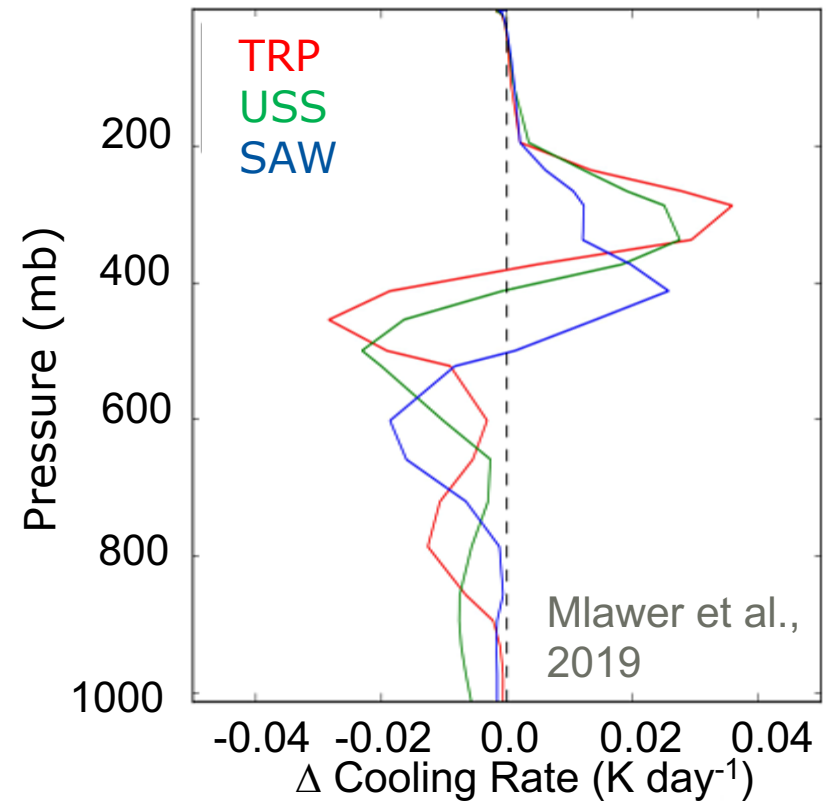
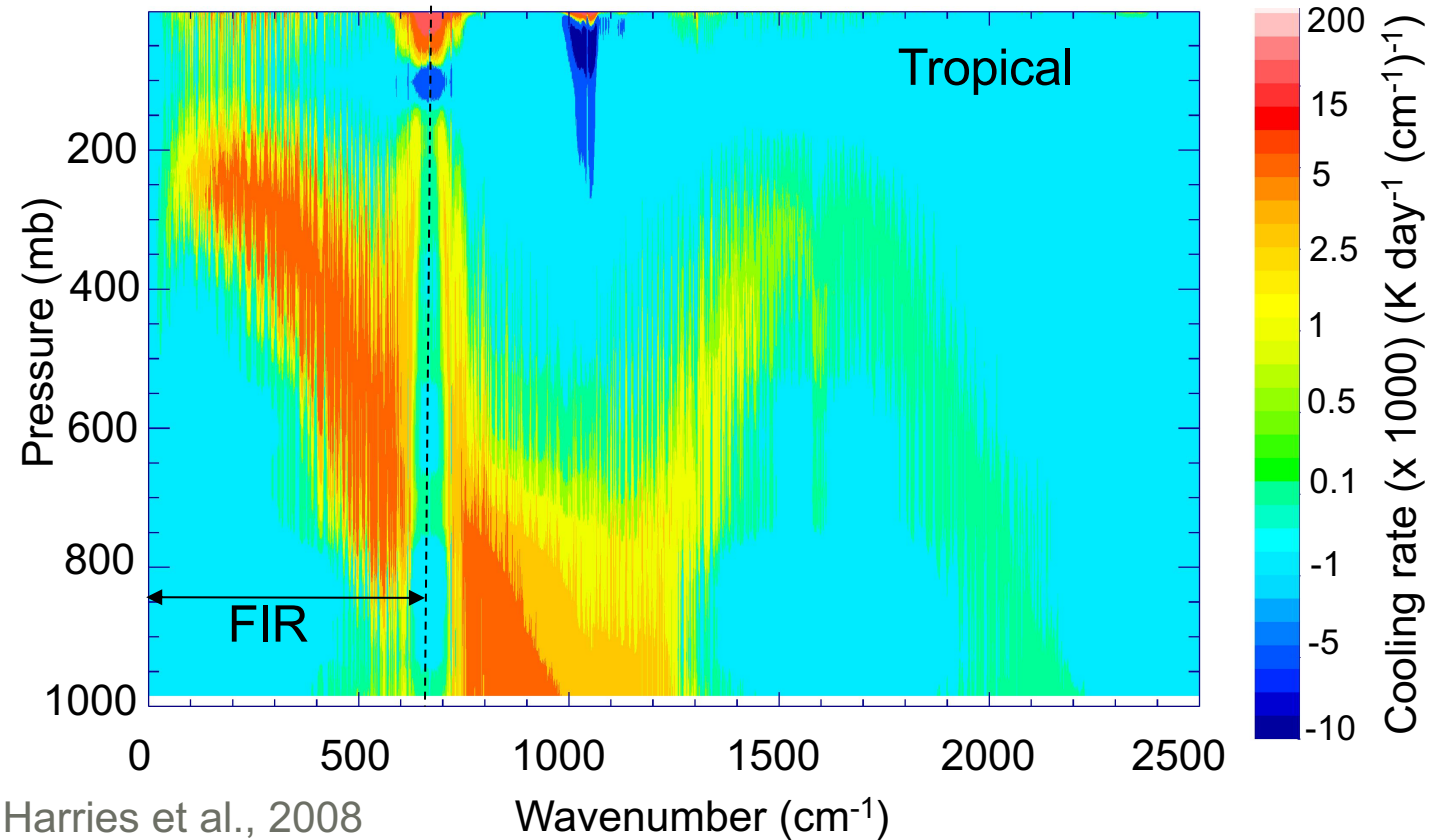
A small increase in water vapour can induce a change in trapping equivalent to **doubling CO₂**.

Significant fraction in far infrared, especially if the perturbation occurs in the **colder upper-troposphere**

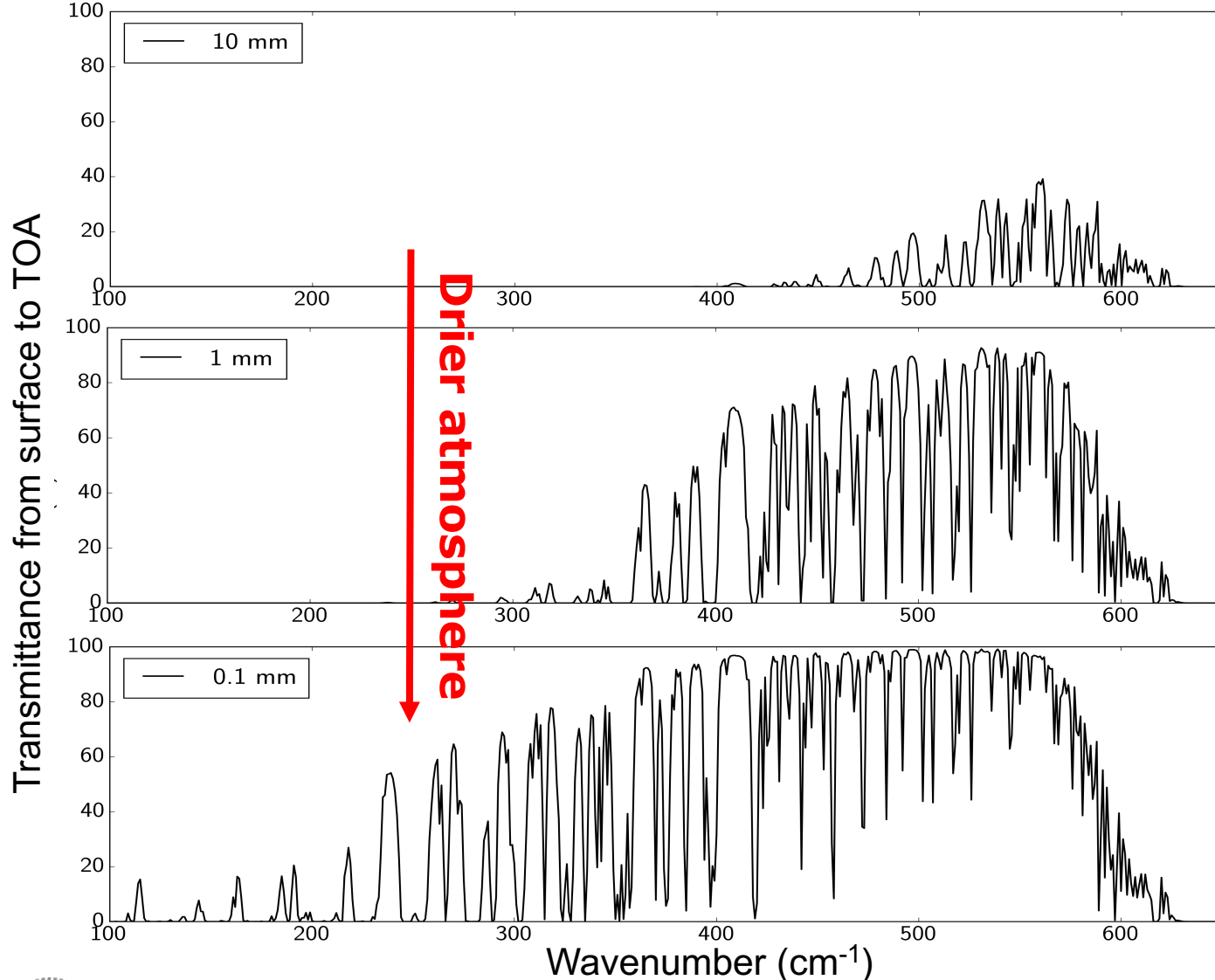
Why is the Far-infrared so special?

Impact **throughout the atmosphere**:

Dominant contribution to **clear-sky atmospheric radiative cooling** also located within the far-infrared: key driver of atmospheric dynamics



Why is the Far-infrared so special?

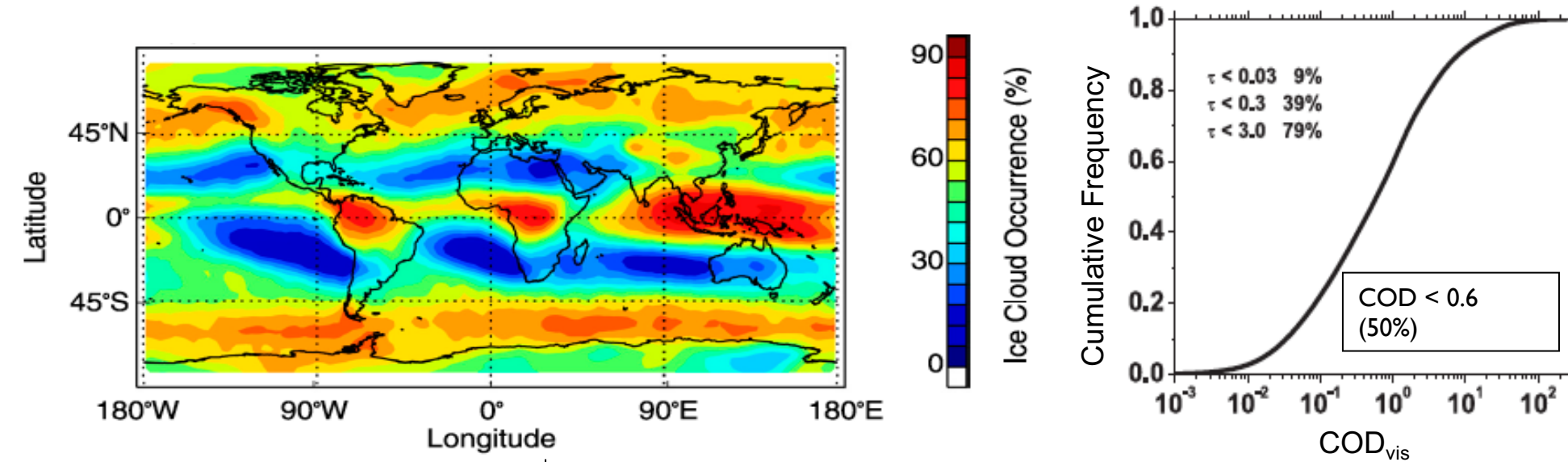


Sensitivity to the **surface**:

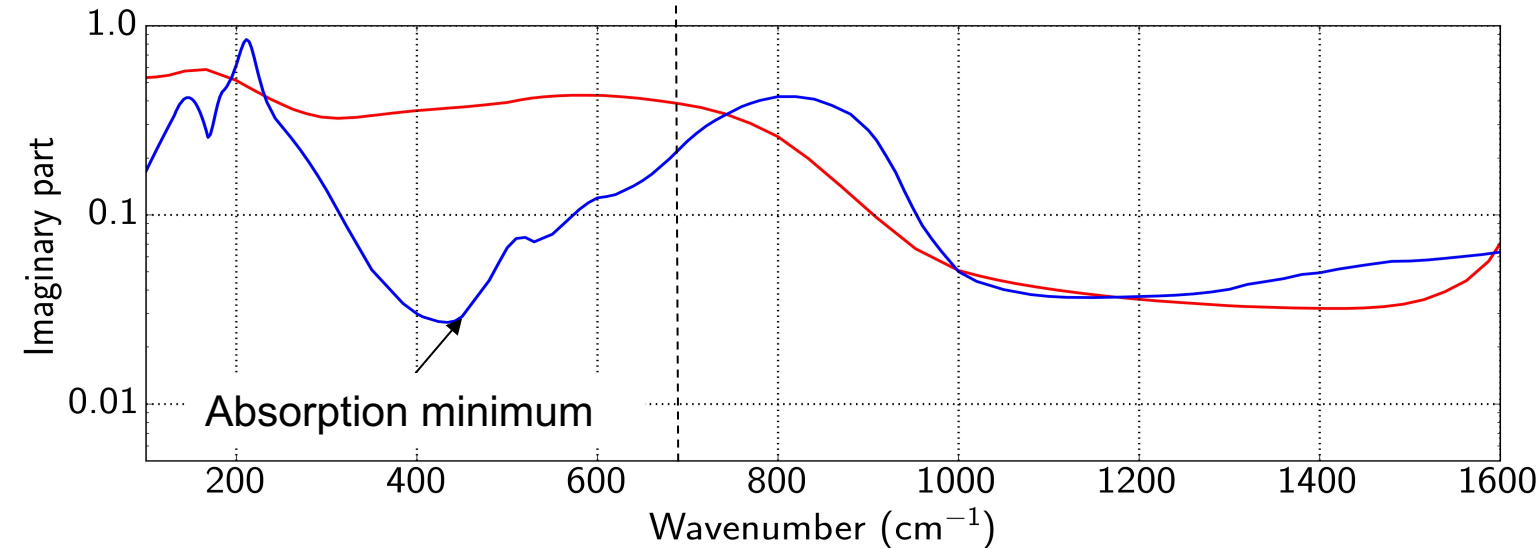
As the amount of water vapour in the atmosphere decreases 'micro-windows' in the far-infrared open allowing surface emission from the FIR to escape to space

Potentially key for **high latitude** and **high elevation** warming

Why is the Far-infrared so special?

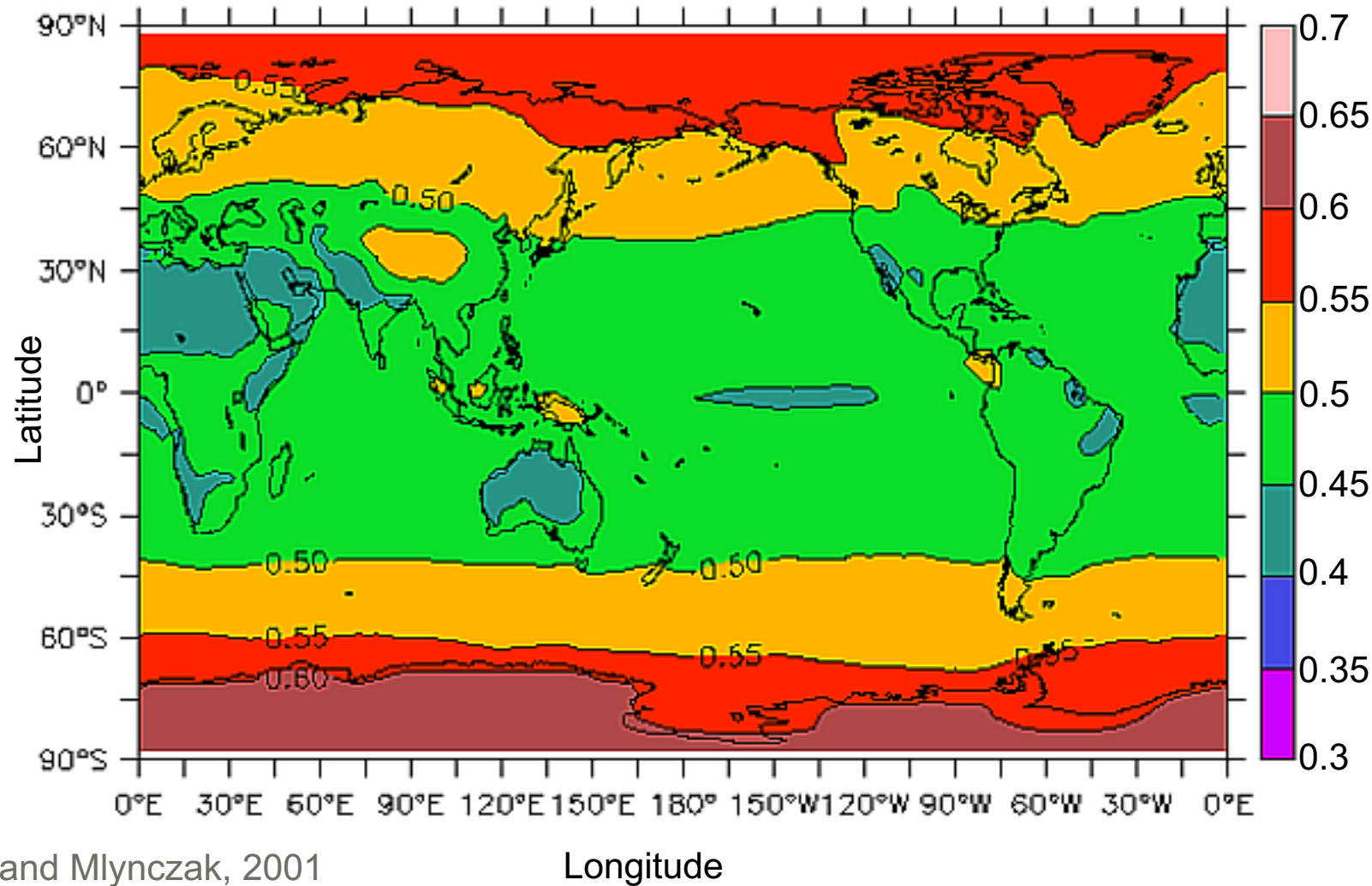


Hong and Liu, 2015



The difference in FIR refractive indices of water and ice mean the region contains **unique information** about **ice cloud habit** and **particle size**, particularly for widespread optically thin cloud

Direct benefits of FORUM



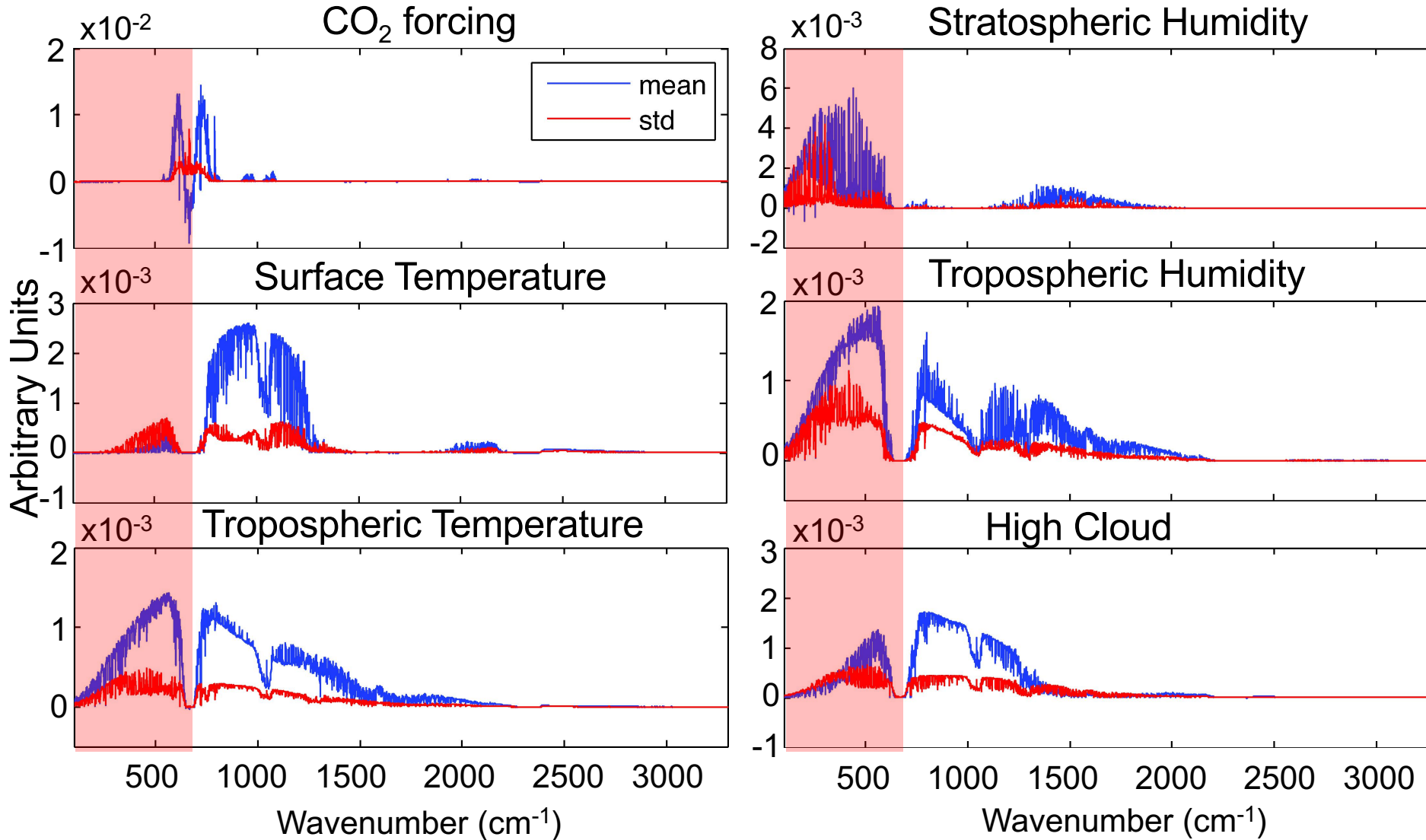
All this means that:

1. >50 % OLR is located in unobserved FIR

FORUM will explore, for the first time, the dominant mechanisms that control FIR OLR avoiding the current dependence on simulation/inference

Collins and Mlynczak, 2001

Direct benefits of FORUM

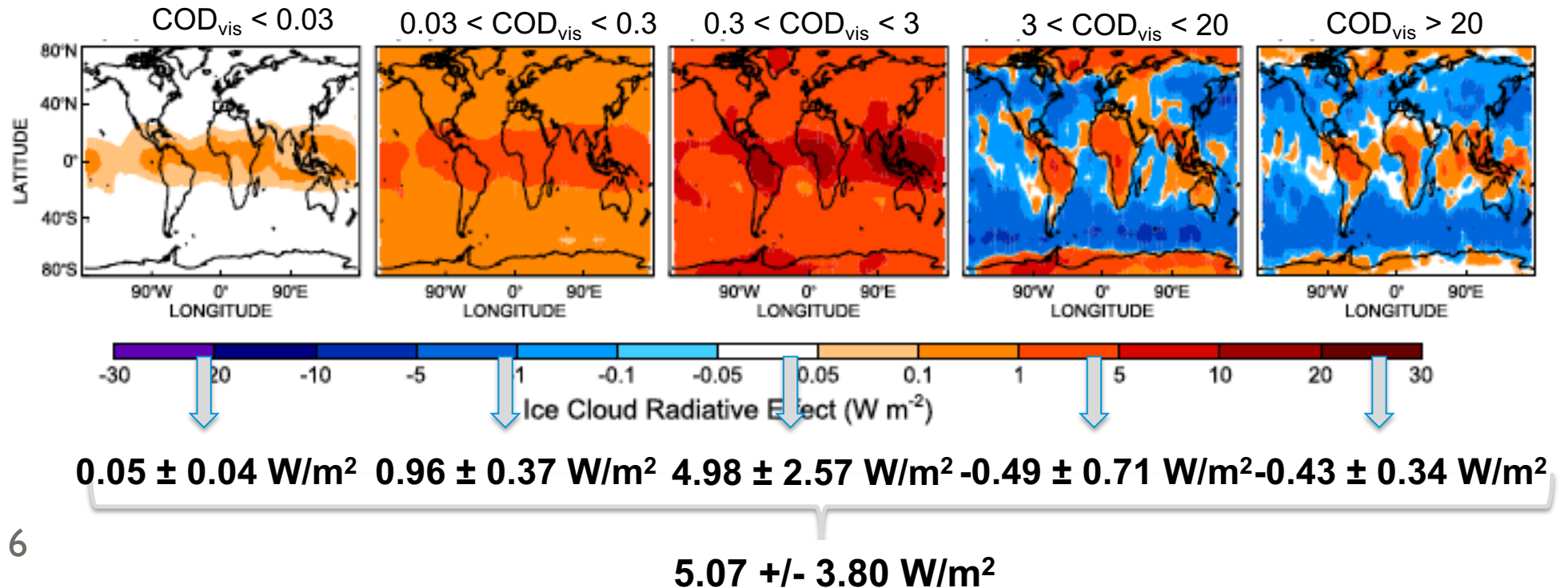


2. A large proportion of the signals associated with key forcings and feedbacks are manifested in unobserved FIR

FORUM observations will inform all of these mechanisms

Direct benefits of FORUM

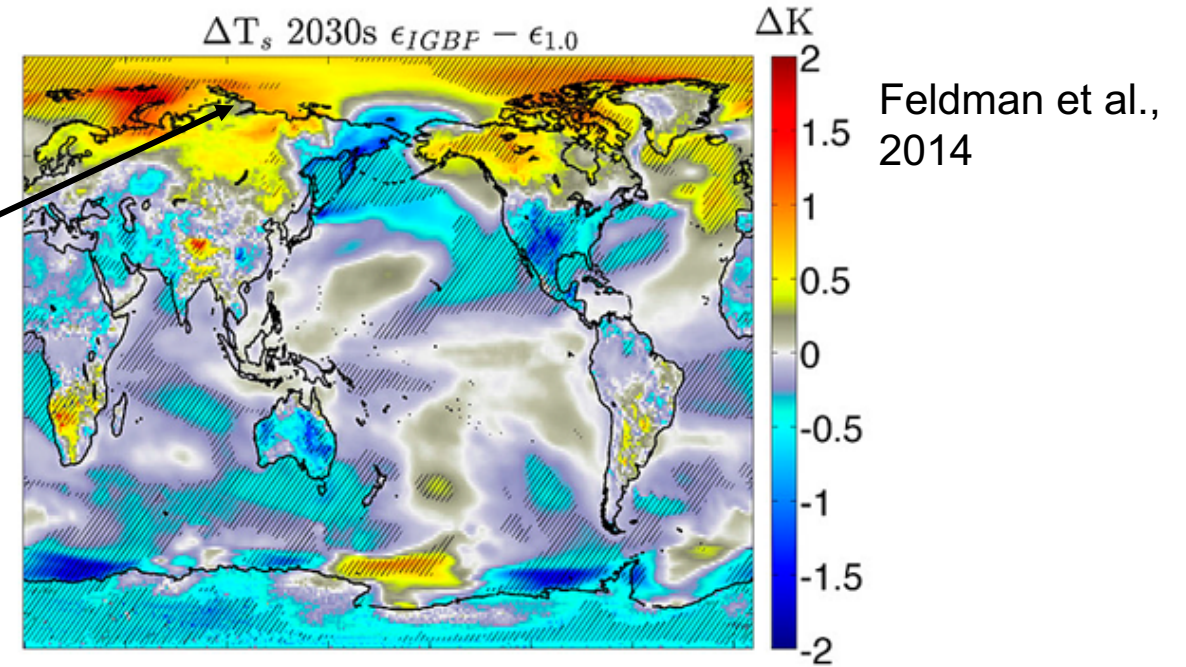
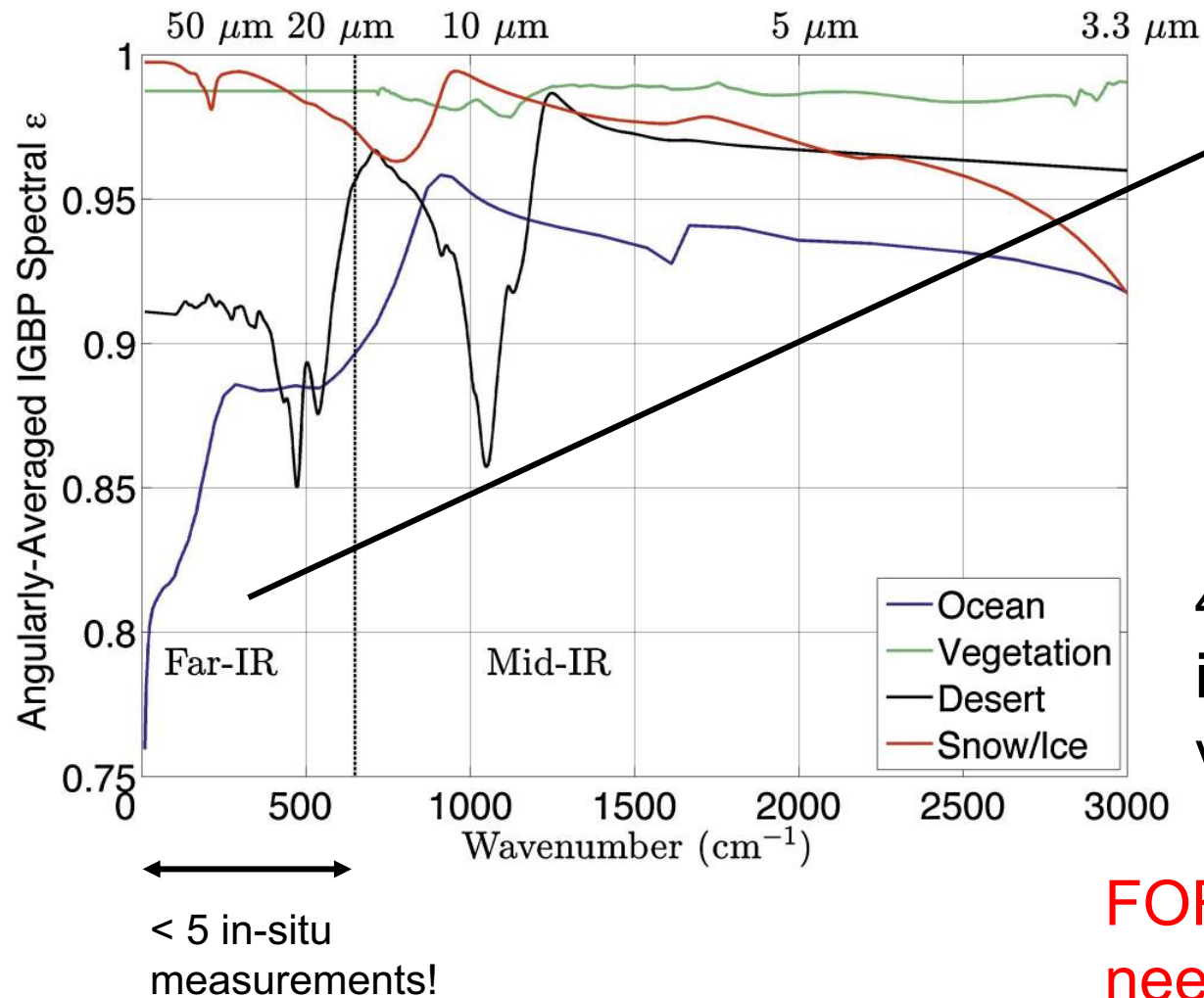
3. Simulations show that optically thin ice cloud have a strong longwave warming effect. These calculations assume specific ice cloud properties which may not be valid in the FIR.



Hong et al., 2016

FORUM will allow this radiative effect to be measured directly for the first time.

Direct benefits of FORUM

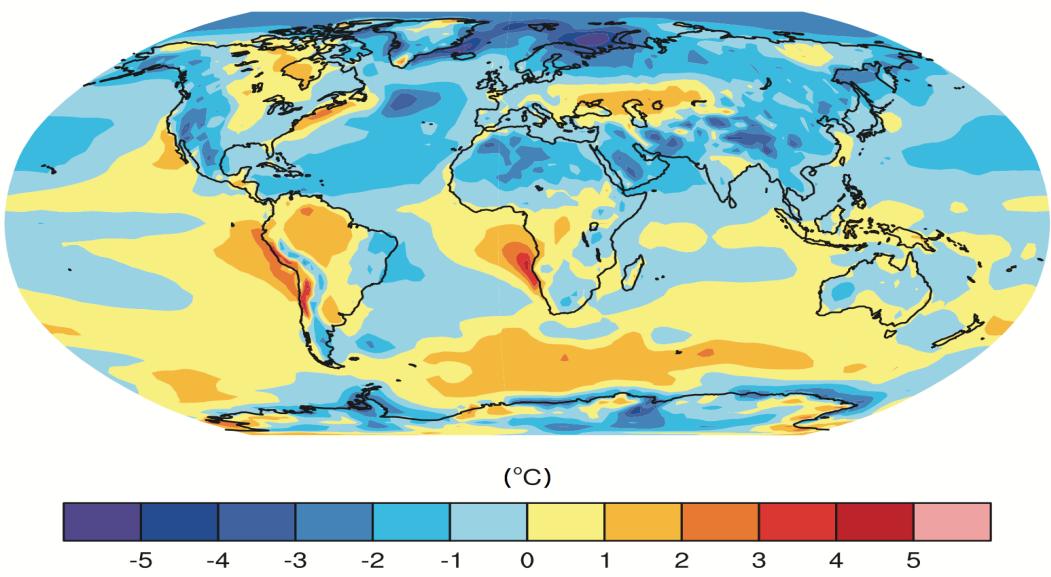


4. Far infrared surface emissivity strongly impacts Arctic surface energy budget – but is very poorly constrained.

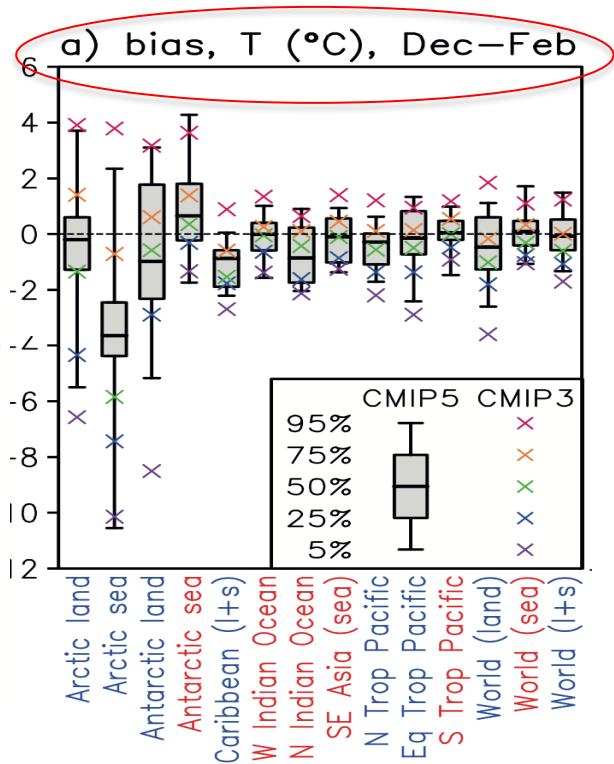
FORUM will provide the spectral observations needed to obtain this information

Direct benefits of FORUM

CMIP5 Multi Model Mean T_s Bias



Flato et al, 2013, IPCC AR5



Feedback	Partial Temperature Contribution (K)
Surface albedo	+1.82 ± 0.77
Cloud radiative effect	+0.69 ± 0.88
Other shortwave clear-sky	-0.43 ± 0.20
Longwave clear-sky	+7.17 ± 1.40
Ocean heat storage	-0.30 ± 1.20
Surface turbulent fluxes	-1.67 ± 0.86

Boeke and Taylor, 2018

5. We can drill down into the mystery behind the **persistent Arctic climate biases that arise in the wintertime.**

Correct representation of longwave radiation is **4 times as important** as any other mechanism for Arctic surface temperature

FORUM's Objectives: Research objective

“Evaluate the role of the far-infrared in shaping the current climate thereby reducing the uncertainty in predictions of future climate change.”

FORUM will achieve this aim by:

- Building a highly accurate global dataset of far-infrared radiances for validation of the present-day state as captured by Earth system models (ESMs).
- Using these measurements to understand and constrain the processes that control far-infrared radiative transfer (and hence the Greenhouse Effect)
- Updating the parameterisations of these processes for implementation in RT codes and ultimately ESMs
- Characterising critical feedback mechanisms

Absolute Radiometric Accuracy

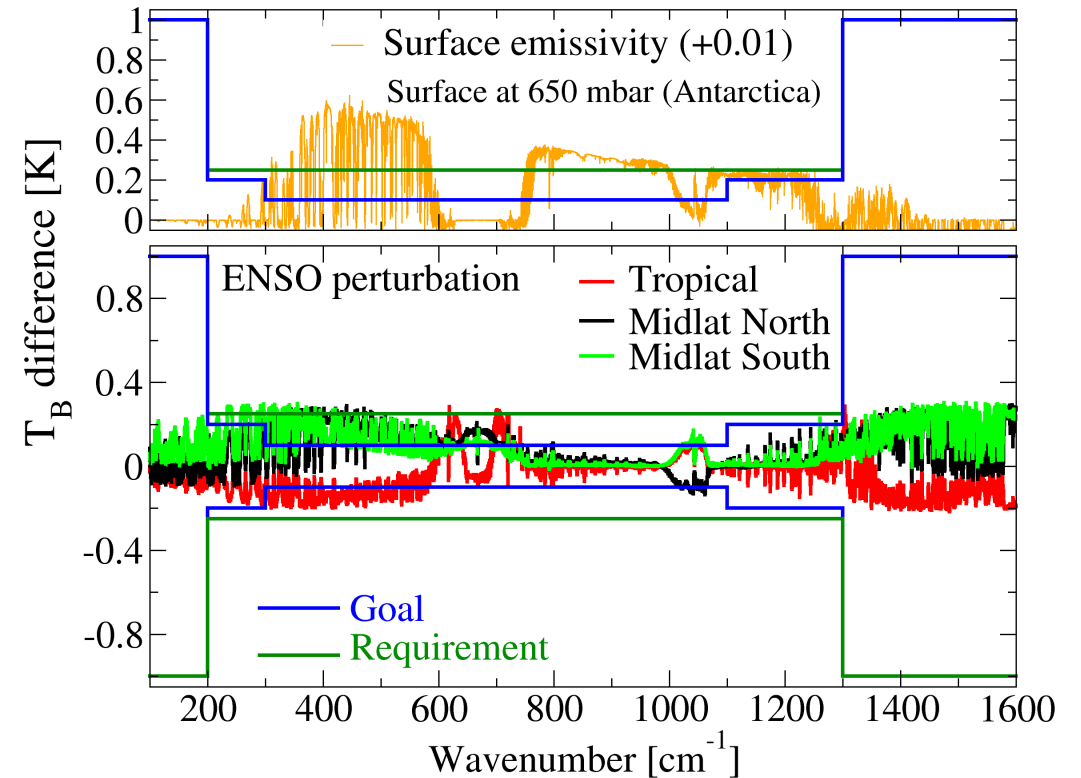
Radiometric accuracy is the difference between the true value and the measurement in absence of random errors

High accuracy is required at 3σ

- to provide **benchmark spectral observations** against which climate models and future observations can be compared, which is the overarching goal of FORUM
- to **derive FIR surface emissivity** with accuracy better than 0.01
- to **observe the effects of small perturbations** in UTLS due to ENSO, QBO, etc. on zonal, monthly means

Goal = 0.1 K in 300-1100 cm^{-1} , 0.2 K in 200-300 cm^{-1} and 1100- 1300 cm^{-1}

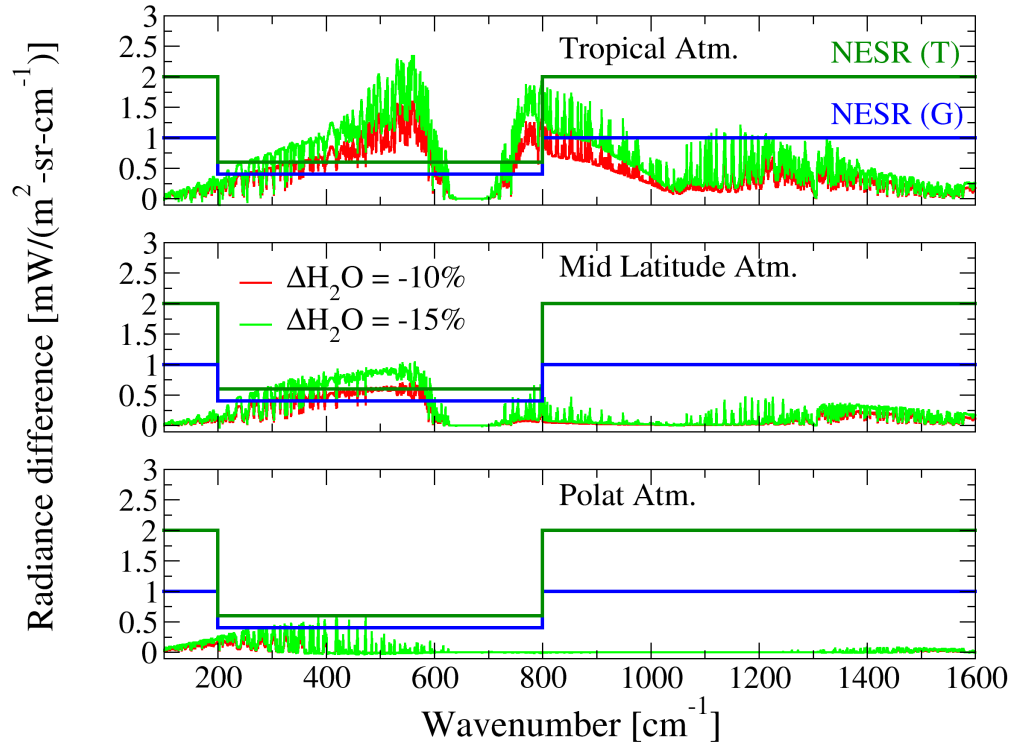
Threshold = 0.25 K in 200-1300 cm^{-1}



Radiometric Precision

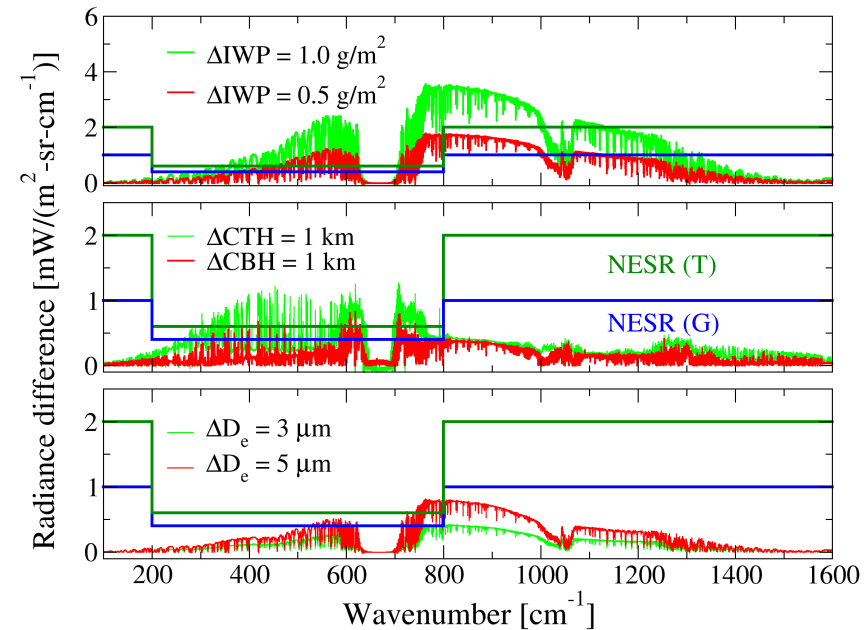
Clear sky

Sensitivity study to water vapour perturbation for different scenarios



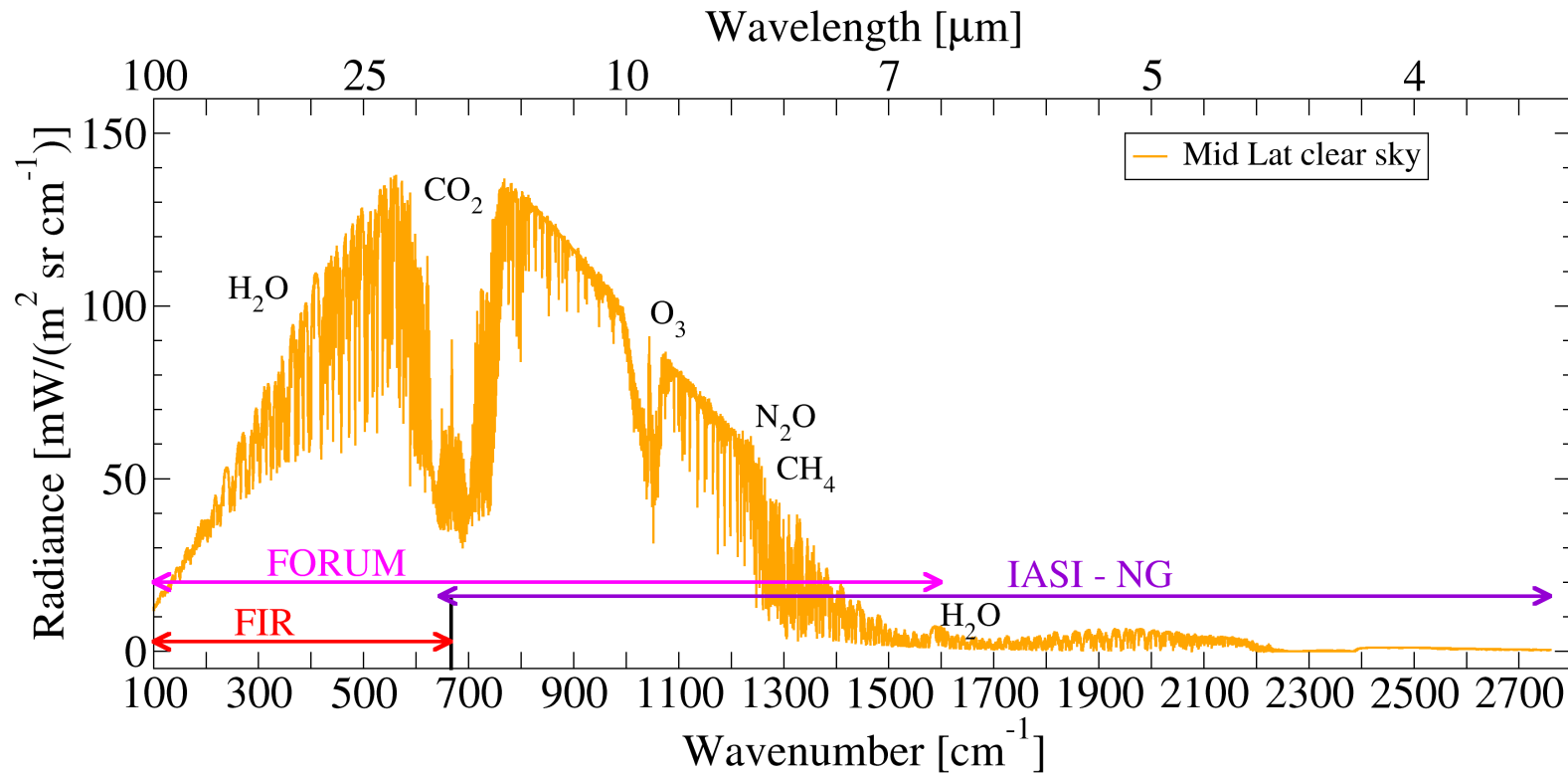
Cloudy case

Sensitivity study to Ice Water Path, CTH / CBH, and Particle size for a mid-latitude thin cirrus cloud (OD=0.3) at 8-10 km, with IWP = 4.58 g/m², D_e = 50 μm



Goal = 0.4 mW/(m² sr cm⁻¹) in 200-800 cm⁻¹, 1 mW/(m² sr cm⁻¹) elsewhere
Threshold = 0.6 mW/(m² sr cm⁻¹) in 200-800 cm⁻¹, 2 mW/(m² sr cm⁻¹) elsewhere

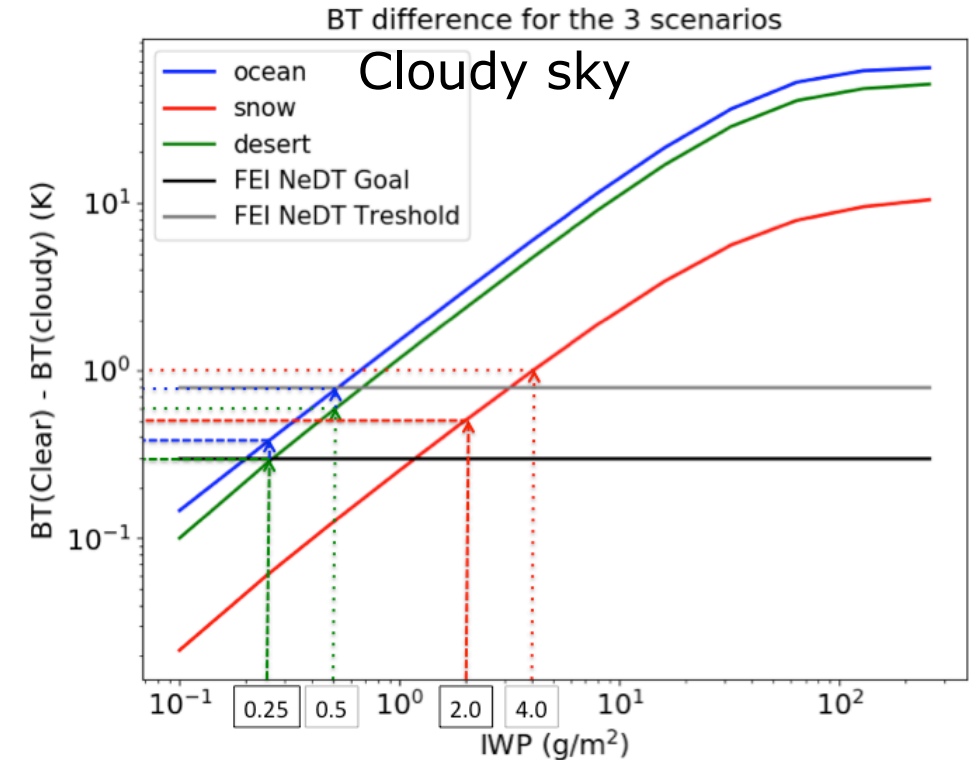
Spectral Range



- FORUM spectral coverage from **100 to 1600 cm^{-1}** (6.25-100 μm) will cover about 96% of the emitted radiance
- Flight in loose formation with MetOp-SG-A will allow:
 - Cross-calibration with IASI-NG and
 - Delivery of the spectrum from 100 to 2760 cm^{-1} (3.62-100 μm)

Requirements for the Thermal Imager

- Single channel centered in the atmospheric window at **10.5 μm with 1.5 μm bandwidth** (889-1026 cm^{-1})
- **Accuracy: Goal = 1 K, Threshold = 3 K**
- Precision (noise) should be sufficient to identify inhomogeneities in the skin temperatures or in the cloud coverage that produce detectable differences in the spectrometer measurement



Noise equivalent delta temperature (NeDT) at 210 K
Goal = 0.3 K, Threshold = 0.8 K

Satellite Configuration

Based on reuse or adaptations of existing platforms.

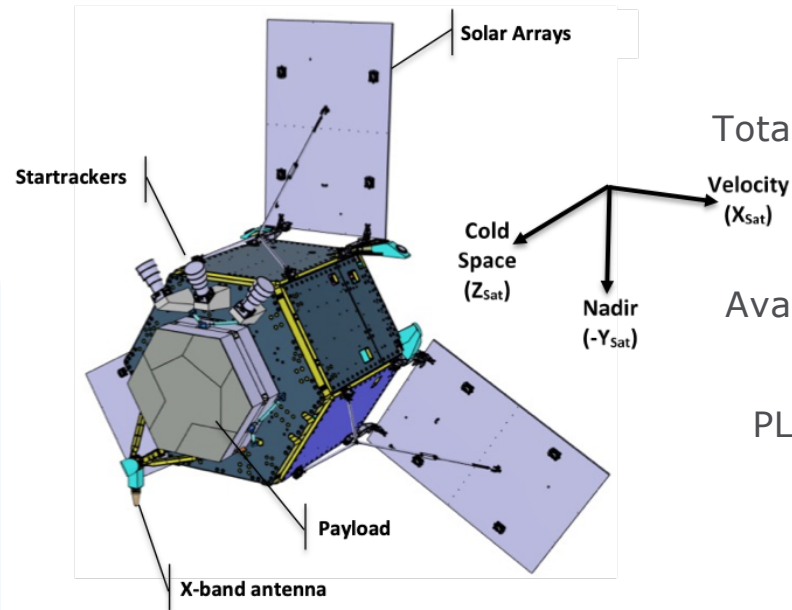
Concept A

Medium Class Size platform. Large margins.
Reuse in full with minor adaptations of Sentinel 5p platform.

Astrobus M standard platform avionics and equipment.

Concept B

Small Class Size platform. Sufficient margins.
Adaptation of Proteus 150/300 standard platform
Sentinel 3 Avionics.
Sentinel 3, Proteus 150/300 and FLEX equipment.



Concept A

Total Mass 850 kg (Payload 107 kg)

Available Propellant 82 kg

Power Consumption ~ 380 W

Available Solar Power ~ 770 W EoL

Gyroless attitude control

PL Data Download Rate 120 Mbps

Concept B

Total Mass 567 kg (Payload 124 kg)

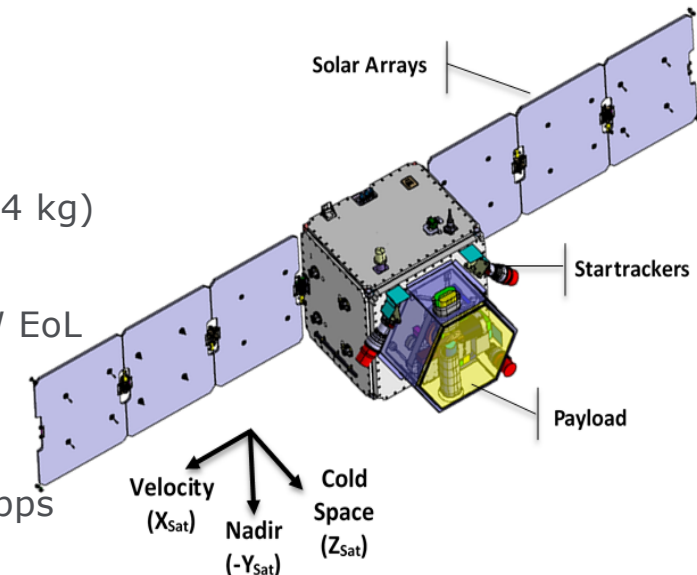
Available Propellant 45 kg

Available Solar Power ~ 760 W EoL

Power Consumption ~ 440 W

Gyroless attitude control

PL Data Download Rate 270 Mbps



Analysis of Campaign Data ?

- The Earth's outgoing longwave radiation can only be measured at the top of the atmosphere.
 - However, the signatures in the far-infrared originating from the atmospheric state and surface parameters can be investigated in ground-based and airborne campaigns.
- ➔ Objective: Test the sensitivity of the far-infrared to water vapour, emissivity and cloud properties.



UK Facility for Airborne Atmospheric Measurements



Zugspitze Observatory, DE

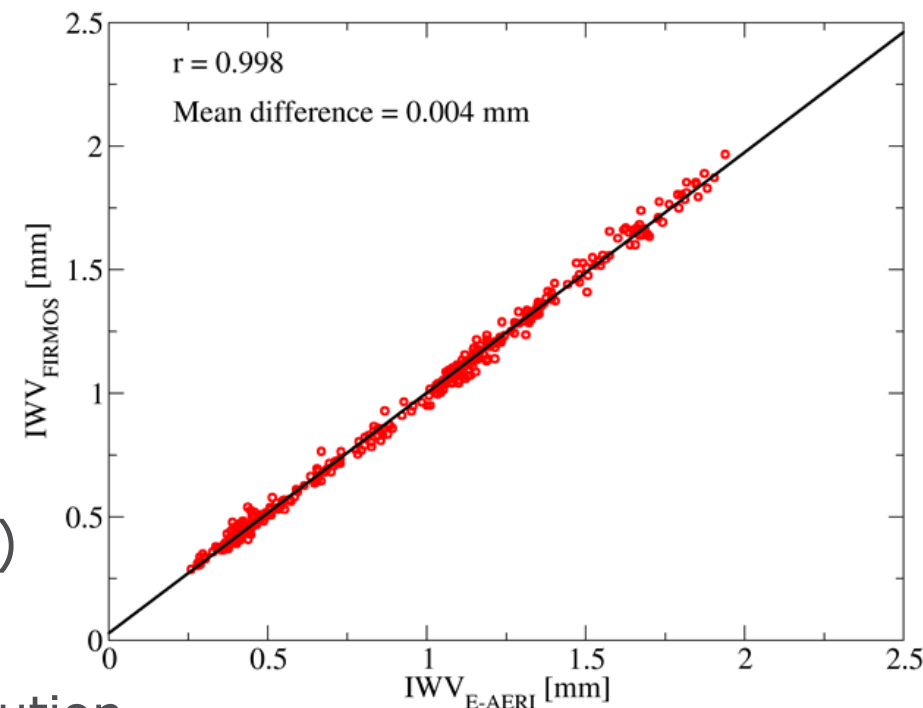
Ground-Based Campaign: Zugspitze, Germany ?

Campaign overview

- November - February 2019
- 47.4°N, 11.0°E, highest mountain in the German Alps: ~2950 m asl

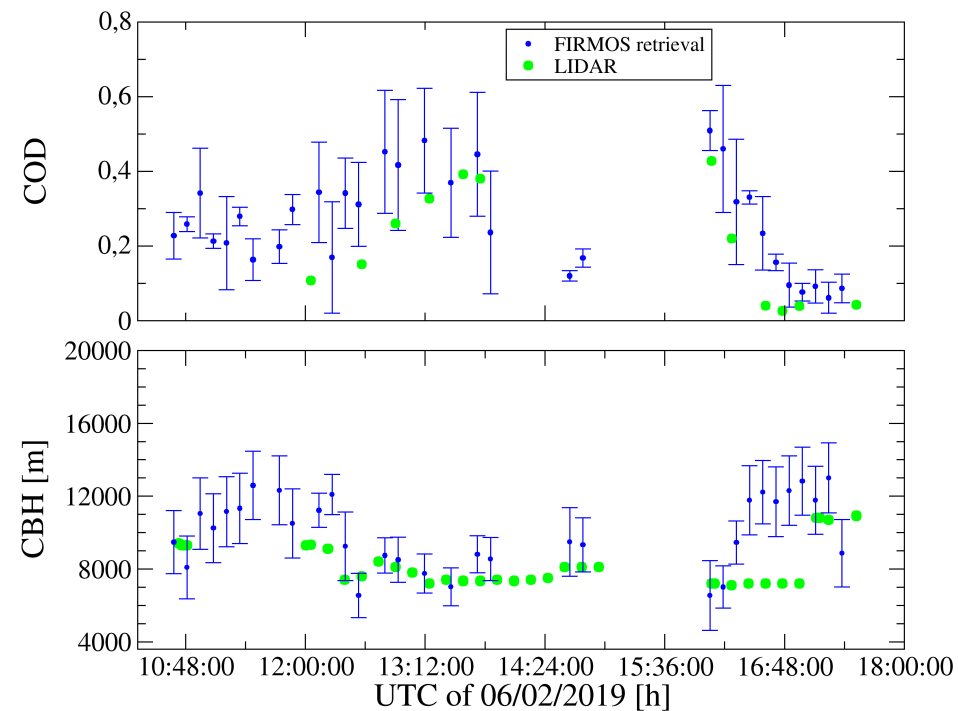
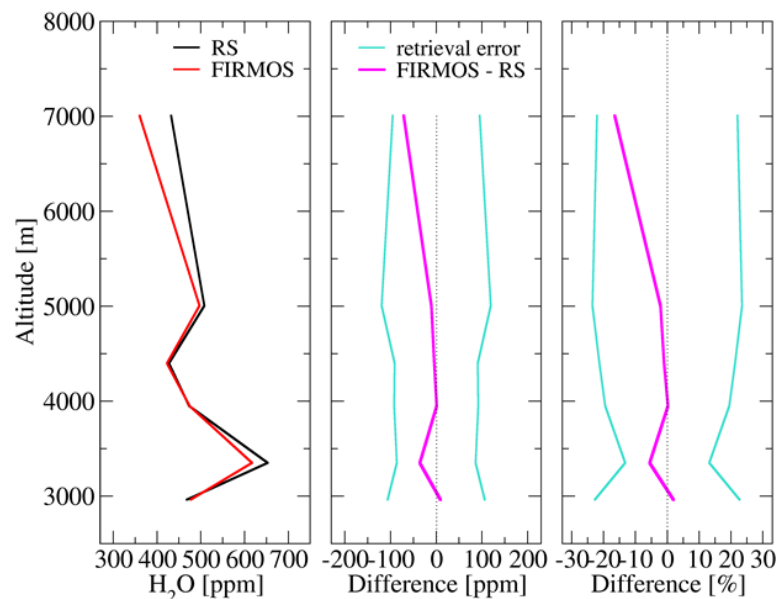
Instrumentation

- FIRMOS (Far-Infrared Mobile Observation System)
 - Custom-built instrument for FORUM Phase A
 - 100–1000 cm^{-1} spectral range, 0.36 cm^{-1} spectral resolution
- Auxiliary instrumentation:
 - E-AERI (ABB, Quebec, CA), 400–3000 cm^{-1} spectral range, 0.6 cm^{-1} spectral resolution
 - High-precision water vapour sondes during special observation period
 - Cloud/aerosol backscatter lidar



Ground-Based Campaign: Zugspitze, Germany ?

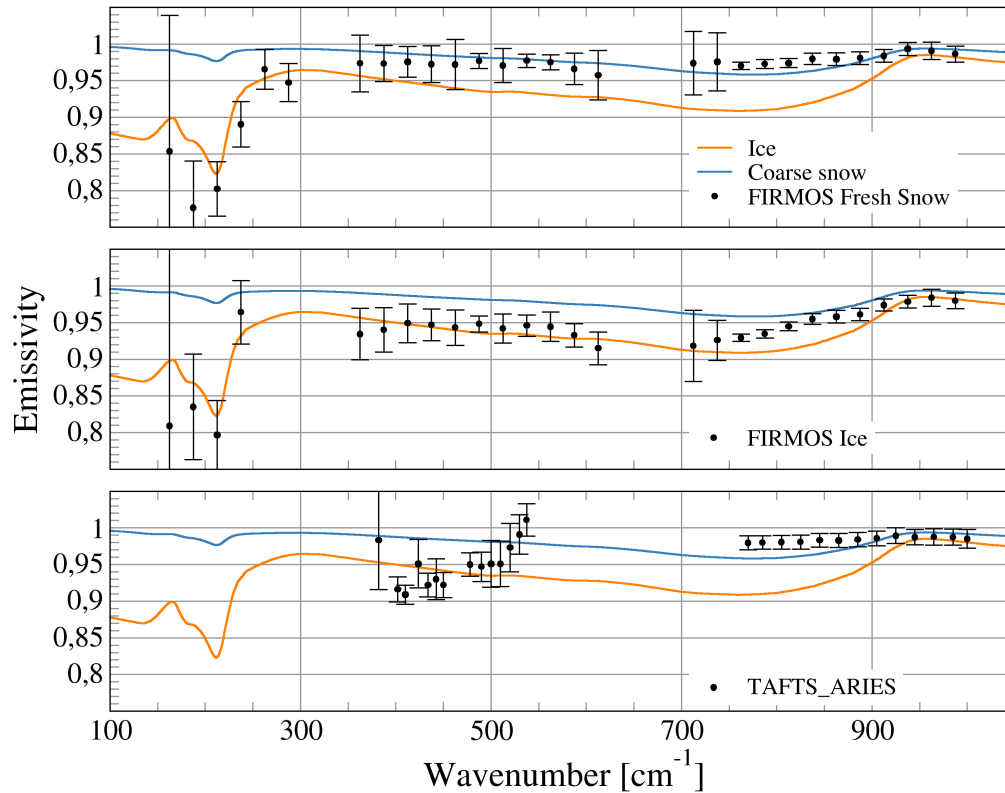
Comparison of FIRMOS-retrieved water vapour and cloud property with independent radiosondes (RS) and lidar



- Good agreement of FIRMOS with independent measurements
- Very good information content of a passive optical sensor to thin cirrus cloud

Ground-Based Campaign: Zugspitze, Germany ?

First experiment under controlled conditions for FIR snow/ice emissivity



FIR emissivity significantly different from unity and shows spectral features dependent on snow/ice type.

