The new features of the σ-FORUM Forward Model, the general purpose Fast Radiative Transfer Model for the present and next hyperspectral instruments

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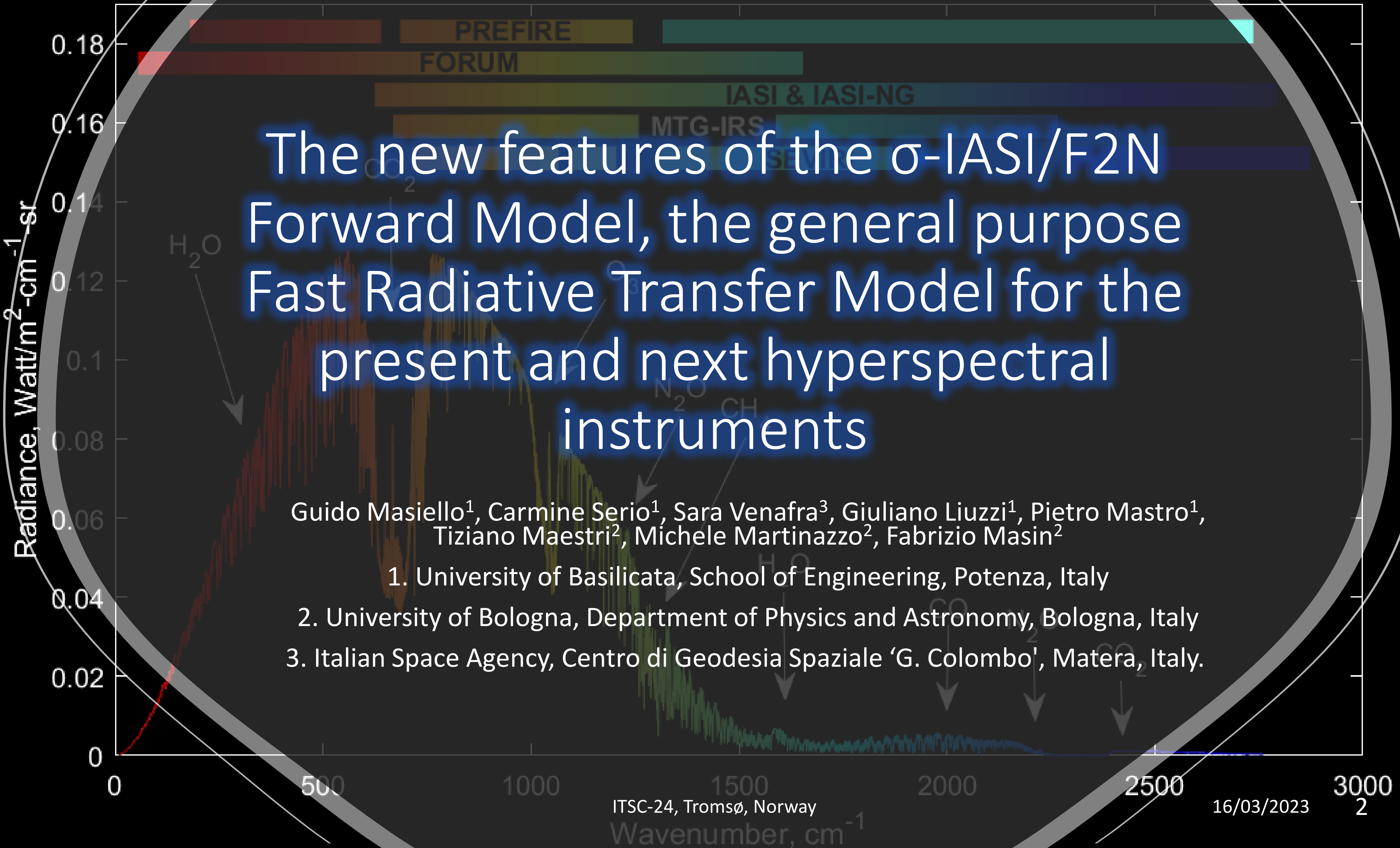

The new features of the σ-IASI/F2N Forward Model, the general purpose Fast Radiative Transfer Model for the present and next hyperspectral instruments

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Acknowledgments

- The forward model we developed in the last 25 years is called σ-IASI
  - We first developed it in the framework of EUMETSAT programs
    - Assessment of IASI data for the Atmosphere (1996-2004) , grants
      - EUM/CO/96/407/DD
      - EUM/CO/99/688/DD
      - EUM/CO/02/1053/PS
  - Italian Space Agency ASI programs (2019-Now)
    - FORUM-Scienza Program of Italian Space Agency
      - ASI Contract No. 2019-20-HH.0
    - FIT-FORUM
      - ASI Call for Ideas “Scientific activities to support development of Earth Observation missions”

Summary

Model Architecture

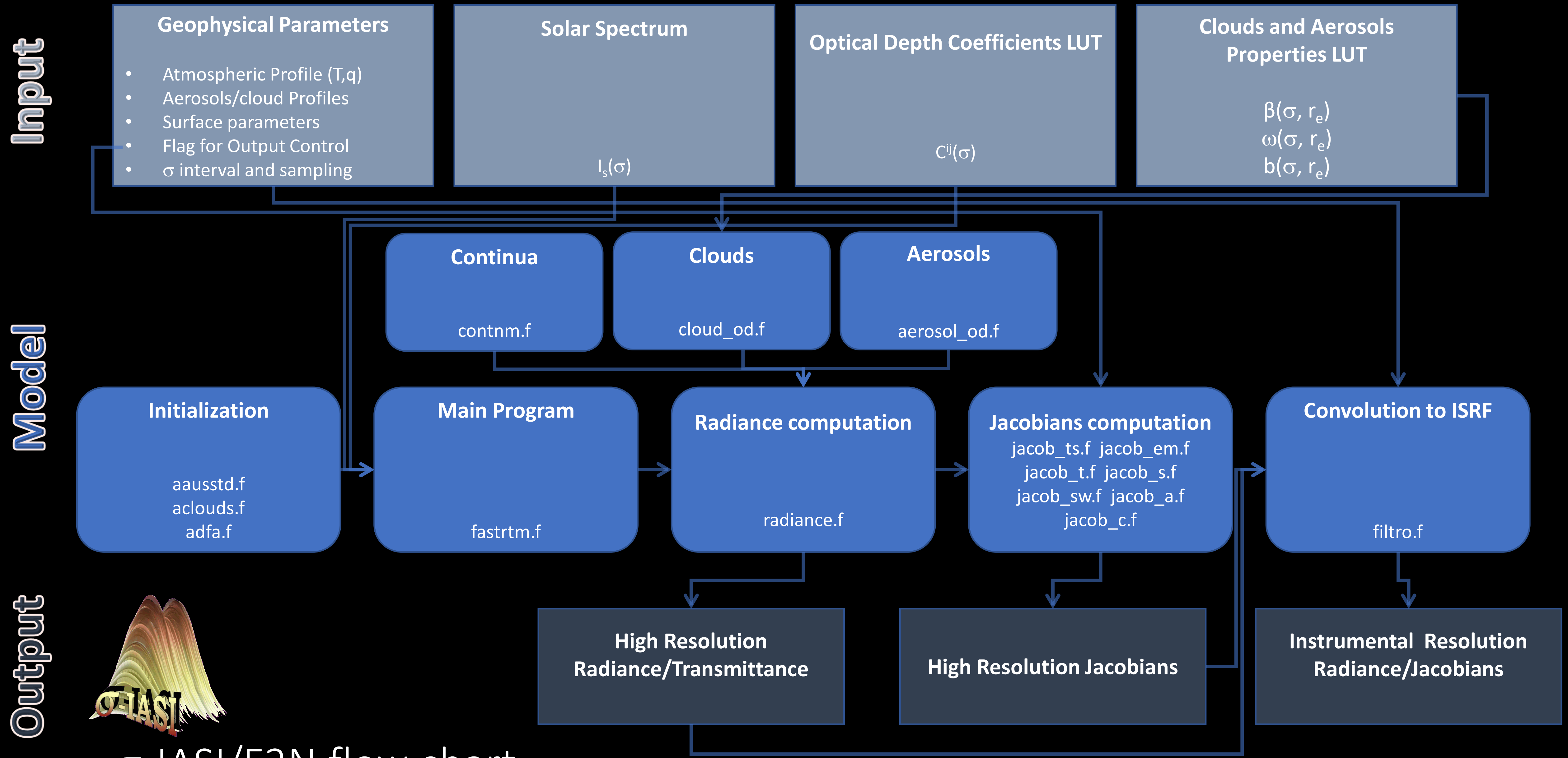
- Look-up-Table
  - Gases
  - Clouds and Aerosol

Validation

- Application to IASI data

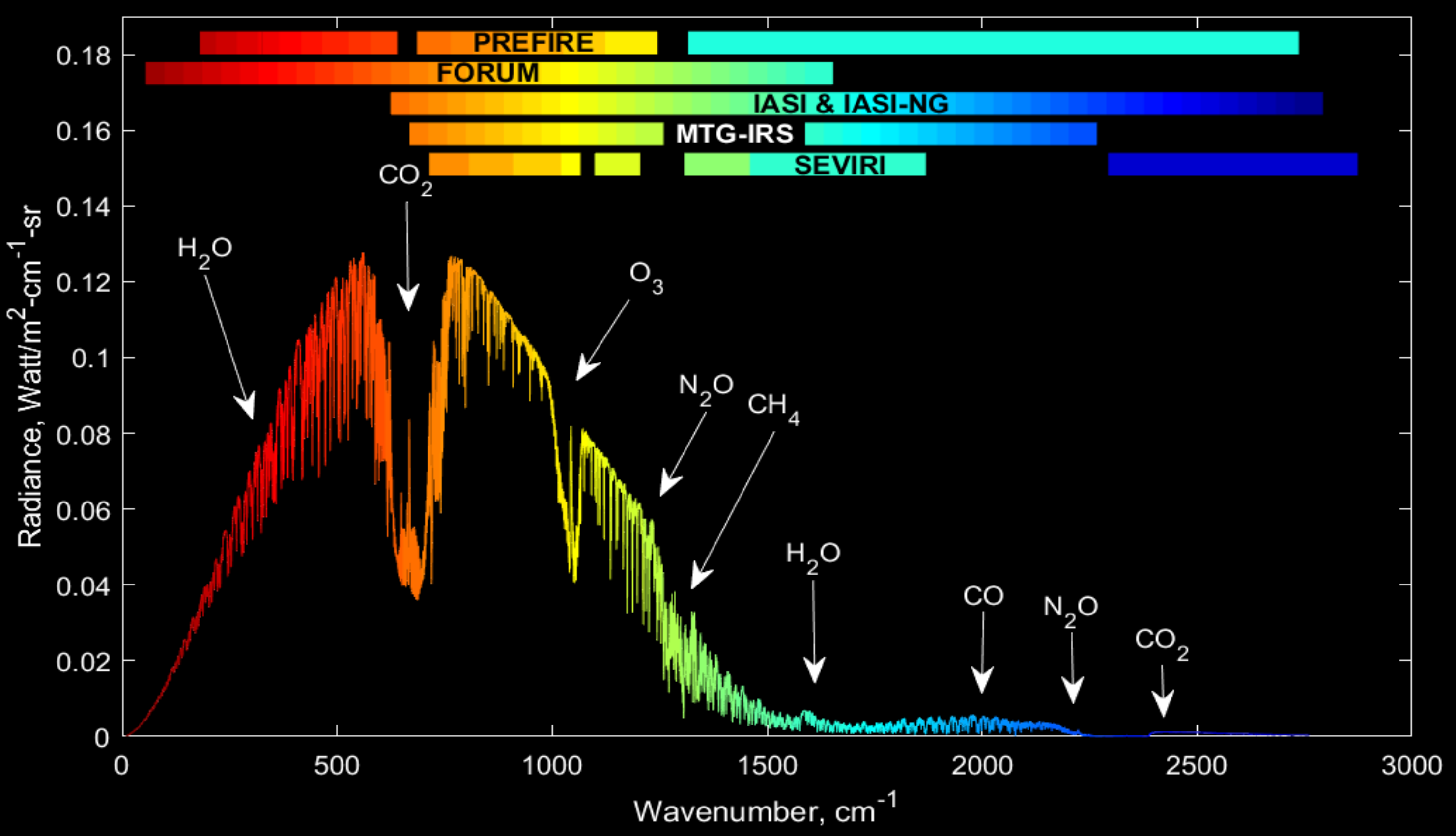
σ-IASI/F2N

- σ-IASI/F2N is a general purpose monochromatic radiative transfer model
- It covers the spectral range [5-3000] cm^{-1}. From Far to Near IR
- It is designed for fast computation of radiance and its derivatives (Jacobian) with respect to a given set of geophysical parameters
- It is based on look-up table of monochromatic optical depth + an interpolation procedure.
- Gases OD look-up-table
  - Was initially built starting from LBLRTM (HITRAN/AER spectral database)
  - We also have look-up-table from KLIMA (HITRAN/AER spectral database in collaboration with IFAC/CNR) and ASIMUT (HITRAN spectral database, in collaboration with BIRA-IABS) line by line models
- Clouds and Aerosols OD look-up-Table
  - particles scattering contribution is accounted for by replacing the optical depth with an apparent optical depth for extinction and parametrized with respect to particles concentrations and radii
- It is a FORTRAN90 Code running on LINUX, iMAC and Windows platform with Intel and gfortran Compiler.



σ-IASI/F2N flow chart

Spectral coverage of FORUM,PREFIRE, IASI-NG and MTG-IRS



Gases OD Look-Up-Table: Parametrization

Low order (2) Polynomial Interpolation

1) For the trace gases (*N*)

$$\chi_{i,N,\sigma} = \rho_{i,N}\left(C_{0,i,N,\sigma} + C_{1,i,N,\sigma}\Delta T_i + C_{2,i,N,\sigma}\,\Delta T_i^2\right)$$

- $\rho_{i,N}$ is the mixing ratio of the species *N* at layer *i*,
- ΔT_i is the difference between the actual and reference temperature
- $C_{0,i,N,\sigma}$, $C_{1,i,N,\sigma}$, $C_{2,i,N2,\sigma}$, parabolic fit coefficients

2) For the Water Vapour (*W*)

$$\chi_{i,W,\sigma} = \rho_{i,W}\left(C_{0,i,W,\sigma} + C_{1,i,W,\sigma}\Delta T_i + C_{2,i,W,\sigma}\,\Delta T_i^2 + C_{3,i,W,\sigma}\,\Delta\rho_{i,W}\right)$$

- $\rho_{i,W}$ is the water vapour mixing ratio ,
- $\Delta\rho_{i,W}$ is the difference between the actual and reference water vapour profiles
- $C_{3,i,N,\sigma}$, Takes into account self broadening of Water Vapour

Analytical Derivatives

With respect to the gas concentration $\rho_{i,N}$

1) For the trace gases (N)

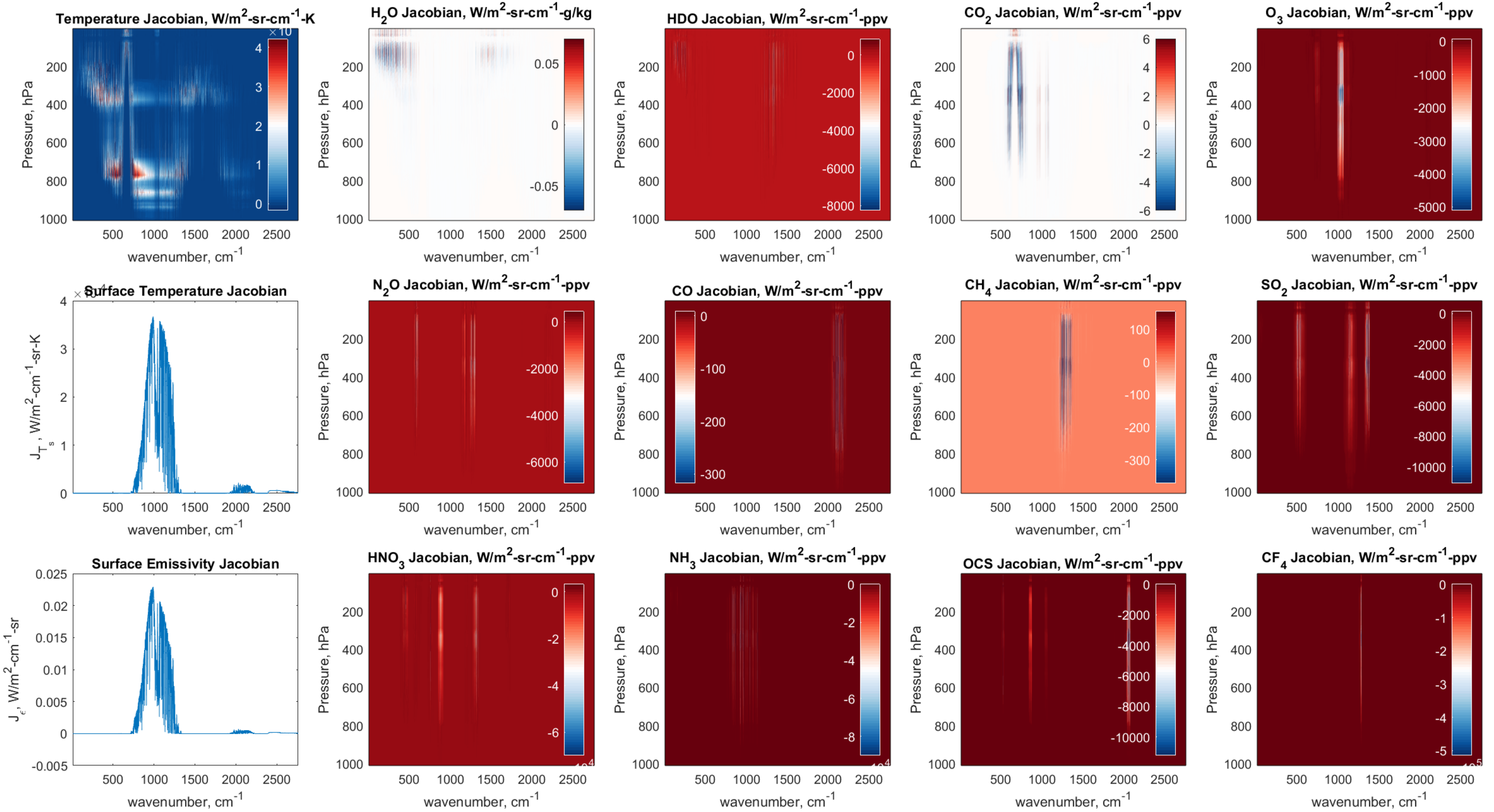
$$\frac{\partial \chi_{i,N,\sigma}}{\partial \rho_{i,N}} = C_{0,i,N,\sigma} + C_{1,i,N,\sigma}\Delta T_i + C_{2,i,N,\sigma}\,\Delta T_i^2$$

2) For the Water Vapour (W)

$$\frac{\partial \chi_{i,W,\sigma}}{\partial \rho_{i,W}} = C_{0,i,W,\sigma} + C_{1,i,W,\sigma}\Delta T_i + C_{2,i,W,\sigma}\,\Delta T_i^2 + C_{3,i,W,\sigma}\left(2\rho_{i,W} - \rho_{0,i,W}\right)$$

With respect to the temperature $\boldsymbol{T_i}$

$$\frac{\partial \chi_{i,N,\sigma}}{\partial T_i} = \rho_{i,W}\left(C_{1,i,W,\sigma} + 2C_{2,i,W,\sigma}\Delta T_i\right)$$



Temperature Jacobian, W/m²-sr-cm⁻¹-K
H₂O Jacobian, W/m²-sr-cm⁻¹-g/kg
HDO Jacobian, W/m²-sr-cm⁻¹-ppv
CO₂ Jacobian, W/m²-sr-cm⁻¹-ppv
O₃ Jacobian, W/m²-sr-cm⁻¹-ppv
Surface Temperature Jacobian
N₂O Jacobian, W/m²-sr-cm⁻¹-ppv
CO Jacobian, W/m²-sr-cm⁻¹-ppv
CH₄ Jacobian, W/m²-sr-cm⁻¹-ppv
SO₂ Jacobian, W/m²-sr-cm⁻¹-ppv
Surface Emissivity Jacobian
HNO₃ Jacobian, W/m²-sr-cm⁻¹-ppv
NH₃ Jacobian, W/m²-sr-cm⁻¹-ppv
OCS Jacobian, W/m²-sr-cm⁻¹-ppv
CF₄ Jacobian, W/m²-sr-cm⁻¹-ppv
Pressure, hPa
wavenumber, cm⁻¹
J_Ts, W/m²-cm⁻¹-sr-K
J_ε, W/m²-cm⁻¹-sr

Clouds and Aerosols OD parametrization

- According the Chou approximation (Chou et al 1999, doi: 10.1175/1520-0442(1999)012<0159:PFCLSF>2.0.CO;2), particles scattering contribution is accounted for by replacing the optical depth with an apparent optical depth for extinction:

$$\chi = \frac{3}{4}\frac{x_{pc}}{r_e \rho_p}\tilde{\beta}\Delta z$$

$$\tilde{\beta} = \beta[(1-\omega) + b\omega]$$

We introduced a new and accurate parametrization of β, b, ω as a function of r_e ,

if Y is one among β,b, ω

$$Y = \sum_{i=1}^{7} P_i x^{i-1}; \quad x = \frac{1}{r_e + t}$$

With P_i, t function of wavenumber

More details in the Maestri et al Poster 1p.08 and in the Radiative Transfer Working Group, Saturday

Analytical Derivatives

- Derivative with respect to the particle concentration

$$\frac{\partial \chi}{\partial x_{pc}} = \frac{3}{4}\frac{1}{r_e \rho_p}\tilde{\beta} = \frac{\chi}{x_{pc}}$$

- Derivative with respect to the effective radius r_e

$$\frac{\partial \chi}{\partial r_e} = -\frac{3}{4}\frac{x_{pc}}{r_e^2 \rho_p}\tilde{\beta} + \frac{3}{4}\frac{x_{pc}}{r_e \rho_p}\frac{\partial \tilde{\beta}}{\partial r_e}$$

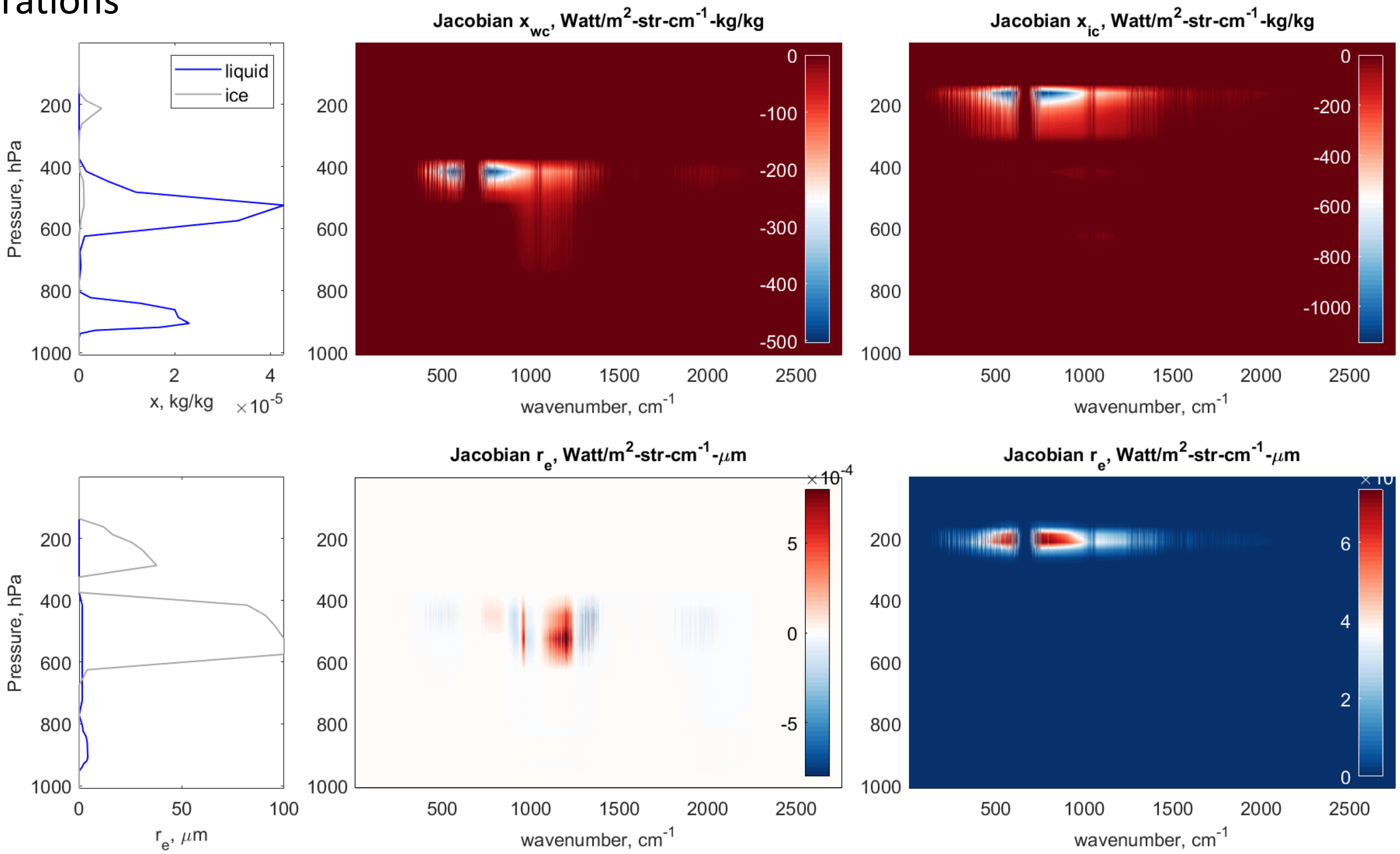
$$\frac{\partial \tilde{\beta}}{\partial r_e} = \frac{\partial \beta}{\partial r_e}[(1-\omega) + b\omega] + \beta\left[\frac{\partial \omega}{\partial r_e}(b-1)\right] + \beta\omega\frac{\partial b}{\partial r_e}$$

- Where $\frac{\partial \beta}{\partial r_e}, \frac{\partial \omega}{\partial r_e}, \frac{\partial b}{\partial r_e}$ come from

$$\frac{\partial Y}{\partial r_e} = \frac{\partial Y}{\partial x}\frac{\partial x}{\partial r_e} = -\frac{1}{x^2}\sum_{i=1}^{7}(i-1)P_i x^{i-2}$$

particles concentrations

Clouds Jacobians



effective radii of particles

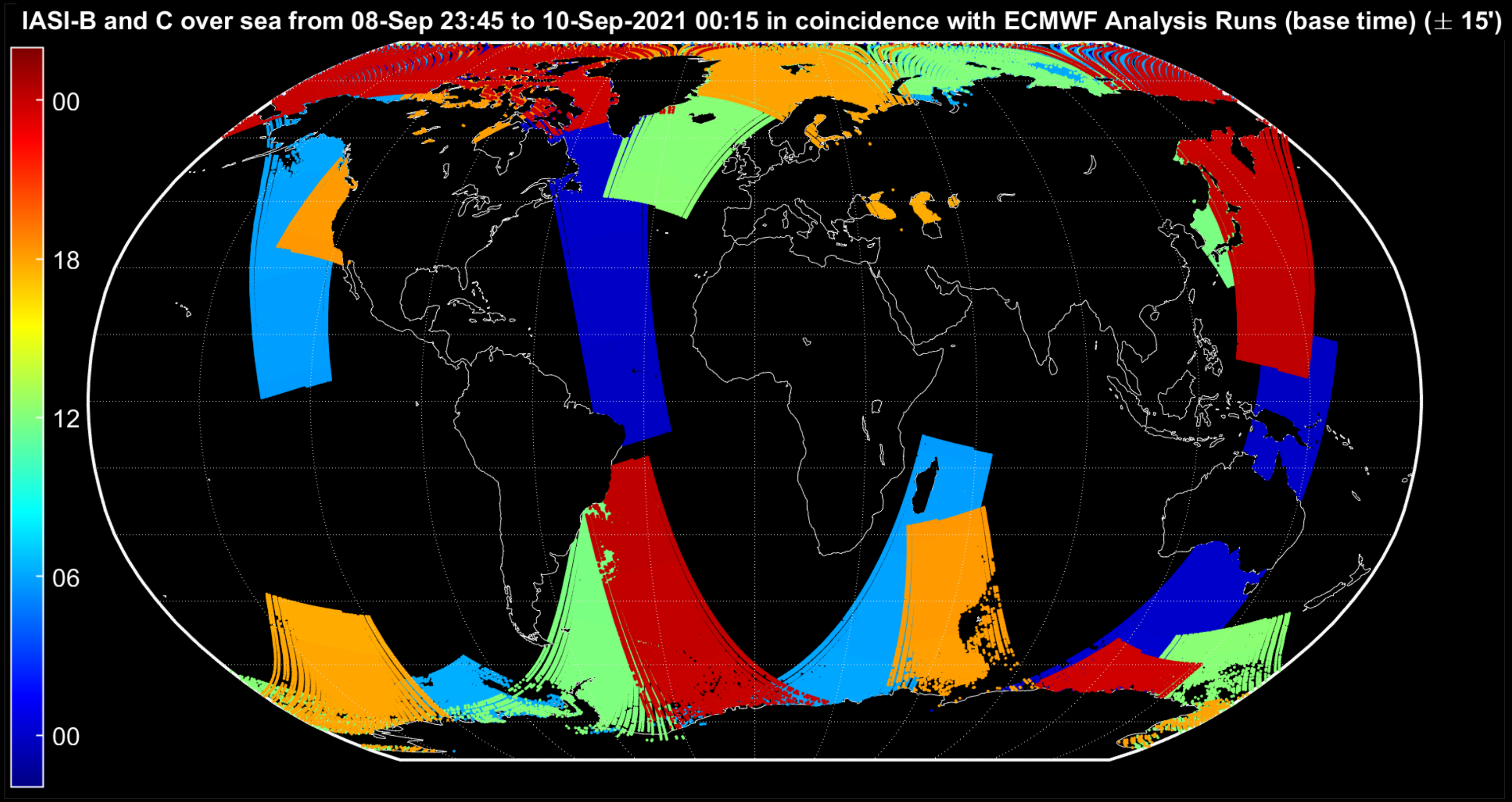
Forward Model Validation

The rationale behind the comparison is to check the capability of σ-IASI/F2N to reproduce cloud patterns and provide the correct spectral radiances observed by the IASI instrument.

Masiello et al 2023, to be submitted to JQSRT

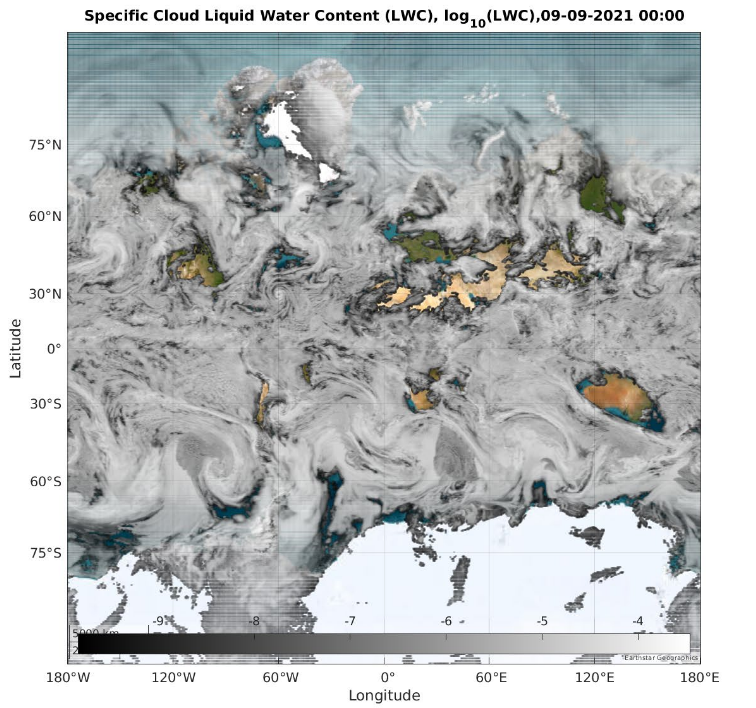
IASI B and C spectra co-located with ECMWF

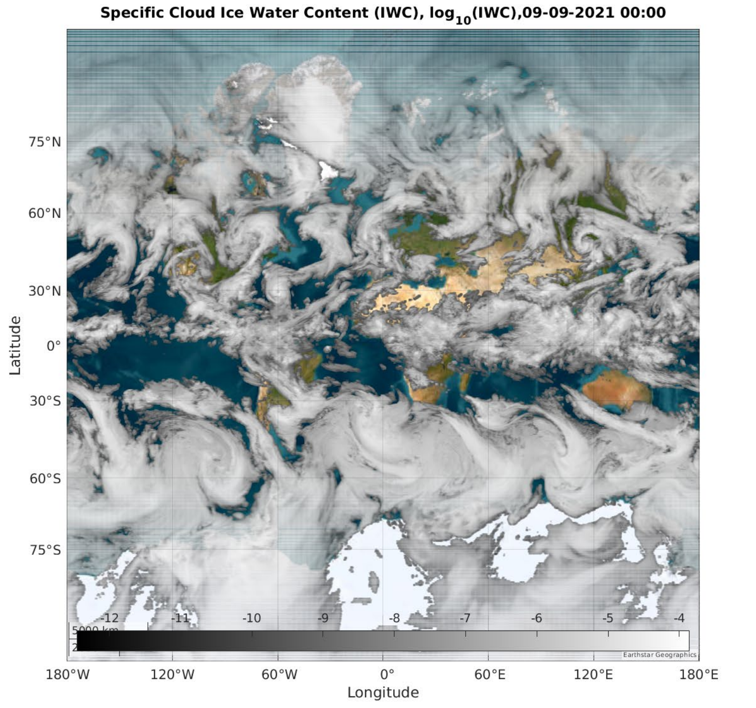
- Among IASI spectra of 9 September 2021, we selected those in temporal coincidence with ECMWF analysis with a range +/-15' over sea.
- Base Time 00, 06, 12, 18, 00
- 167244 IASI-B and C spectra
- Each Spectra co-located with nearest ECMWF analysis



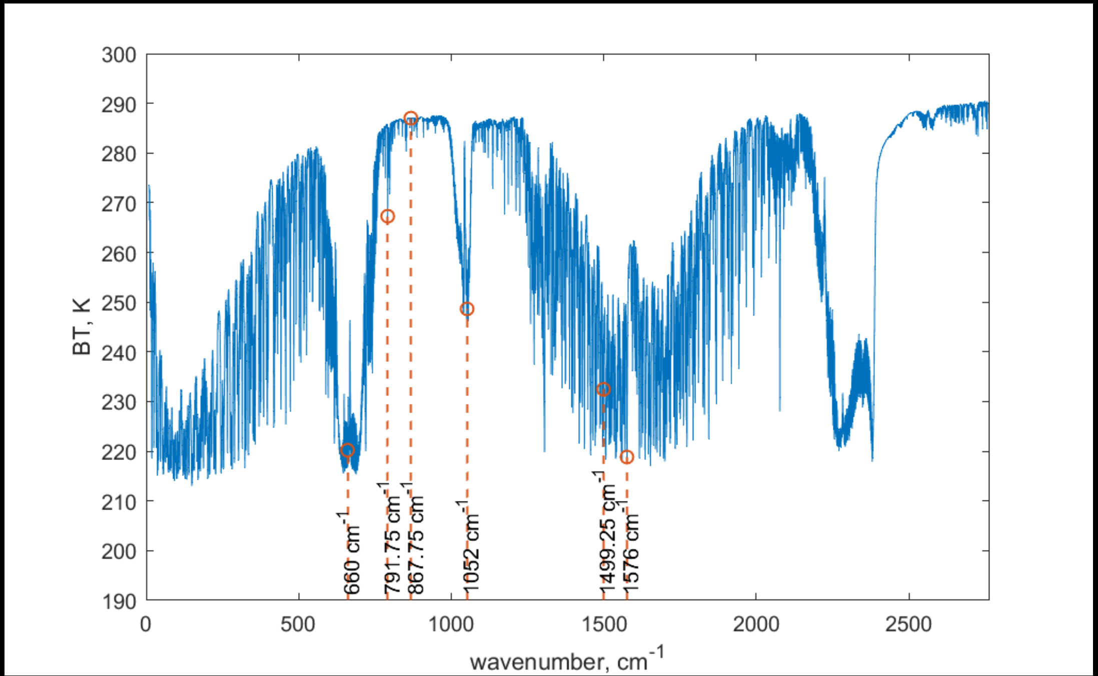
State Vector: ECMWF Analysis

- The state vector provided by ECMWF includes some of the basic parameters to simulate IASI spectra, that is
- $\boldsymbol{v}_{ECMWF} = (T, T_s, Q, O, LWC, IWC)$
- Radius, r_e from Martin formula (Martin et al., 1994)
- Dimension, D_e from Wyser approach (Wyser, 1998).
- Other gases from Climatology
- No retrieval!



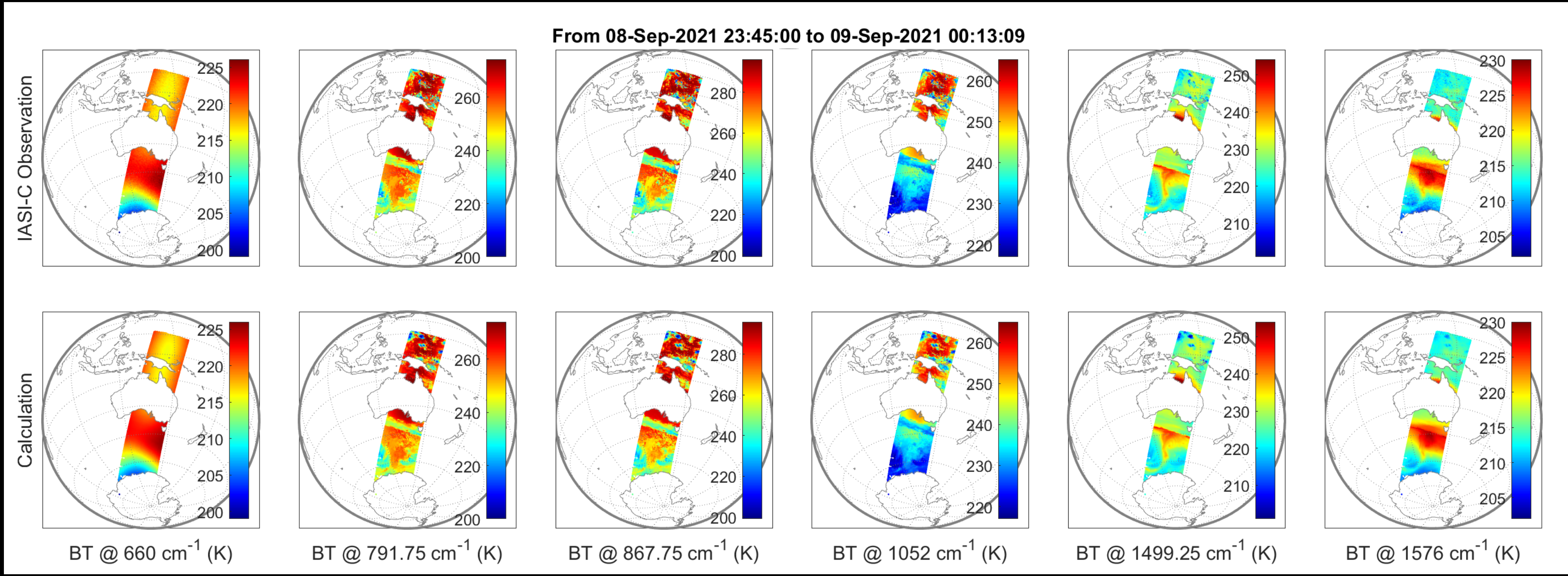


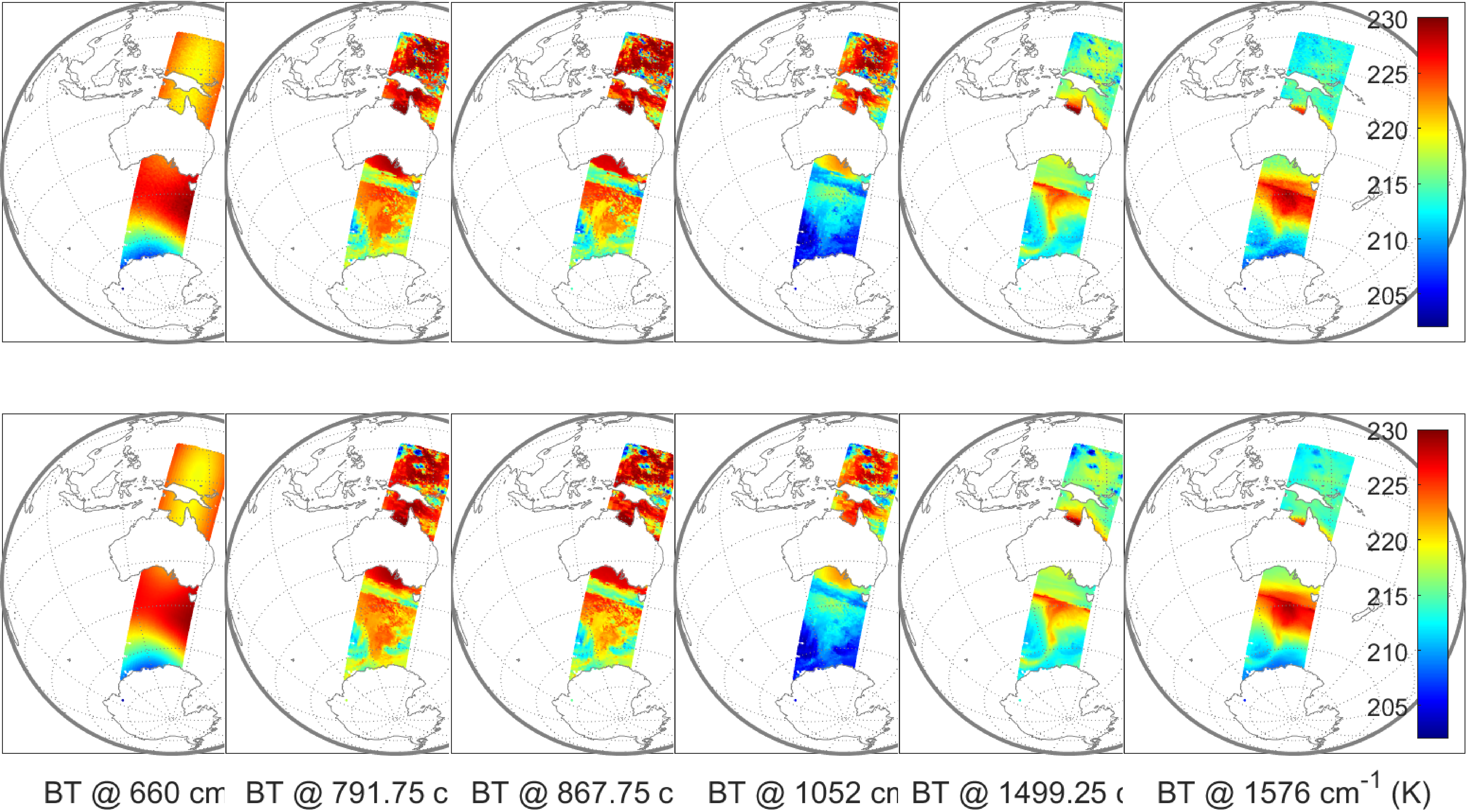
Six channels



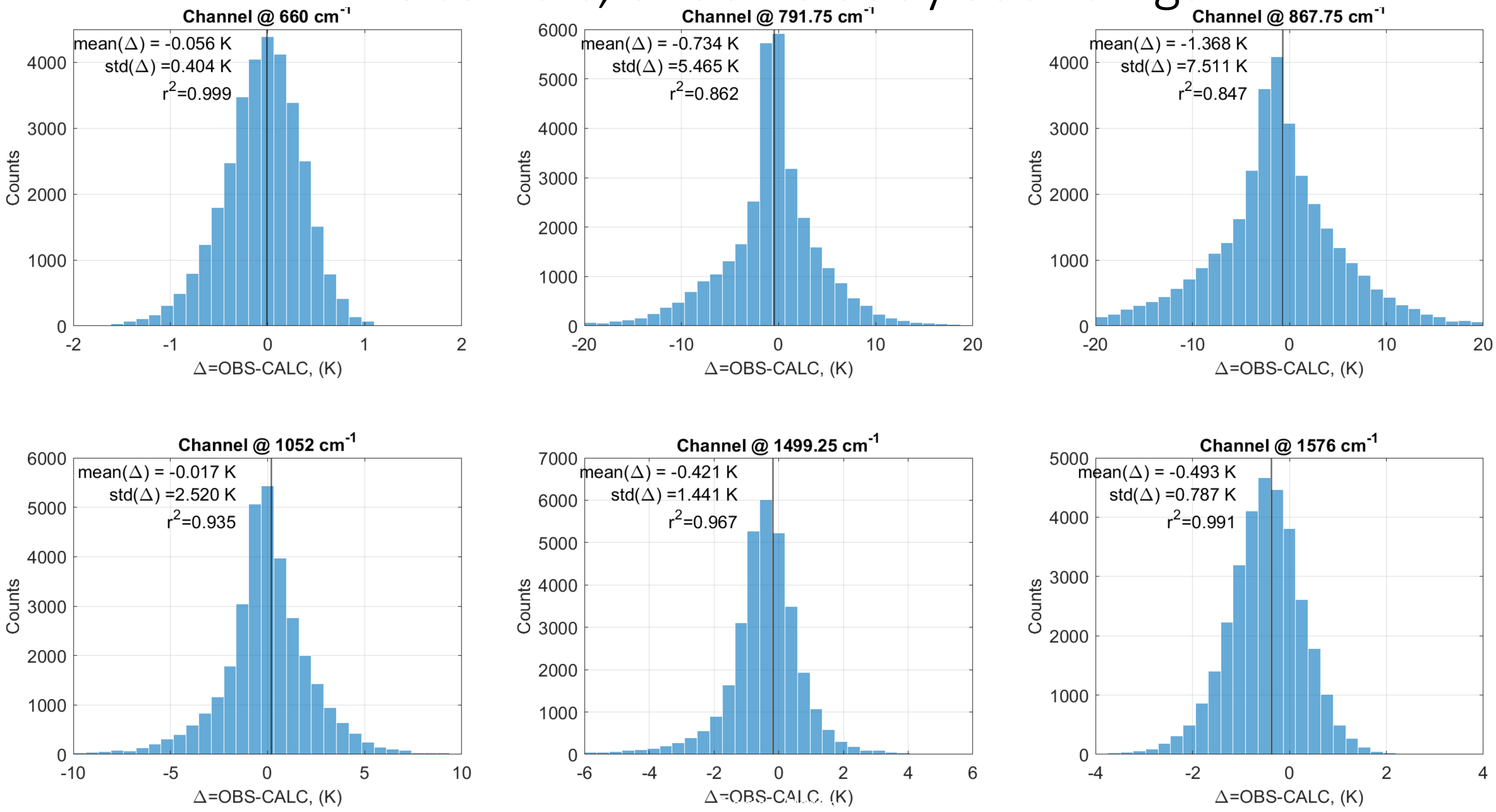
- 660 cm^{-1}
  - CO_2 v_2 band (upper atmosphere)
- 791.75 cm^{-1}
  - weaker Q-branch of CO_2 (middle troposphere)
- 867.75 cm^{-1}
  - Atmospheric window (Surface)
- 1052 cm^{-1}
  - O_3 band at 9.7 µm
- 1499.25 cm^{-1}
  - H_2O at 6.7 µm (Humidity in the middle of the troposphere)
- 1576 cm^{-1}
  - H_2O at 6.7 µm (Humidity in the upper troposphere)

IASI-C from 08-Sep-2021 23:45 to 09-Sep-2021 00:15

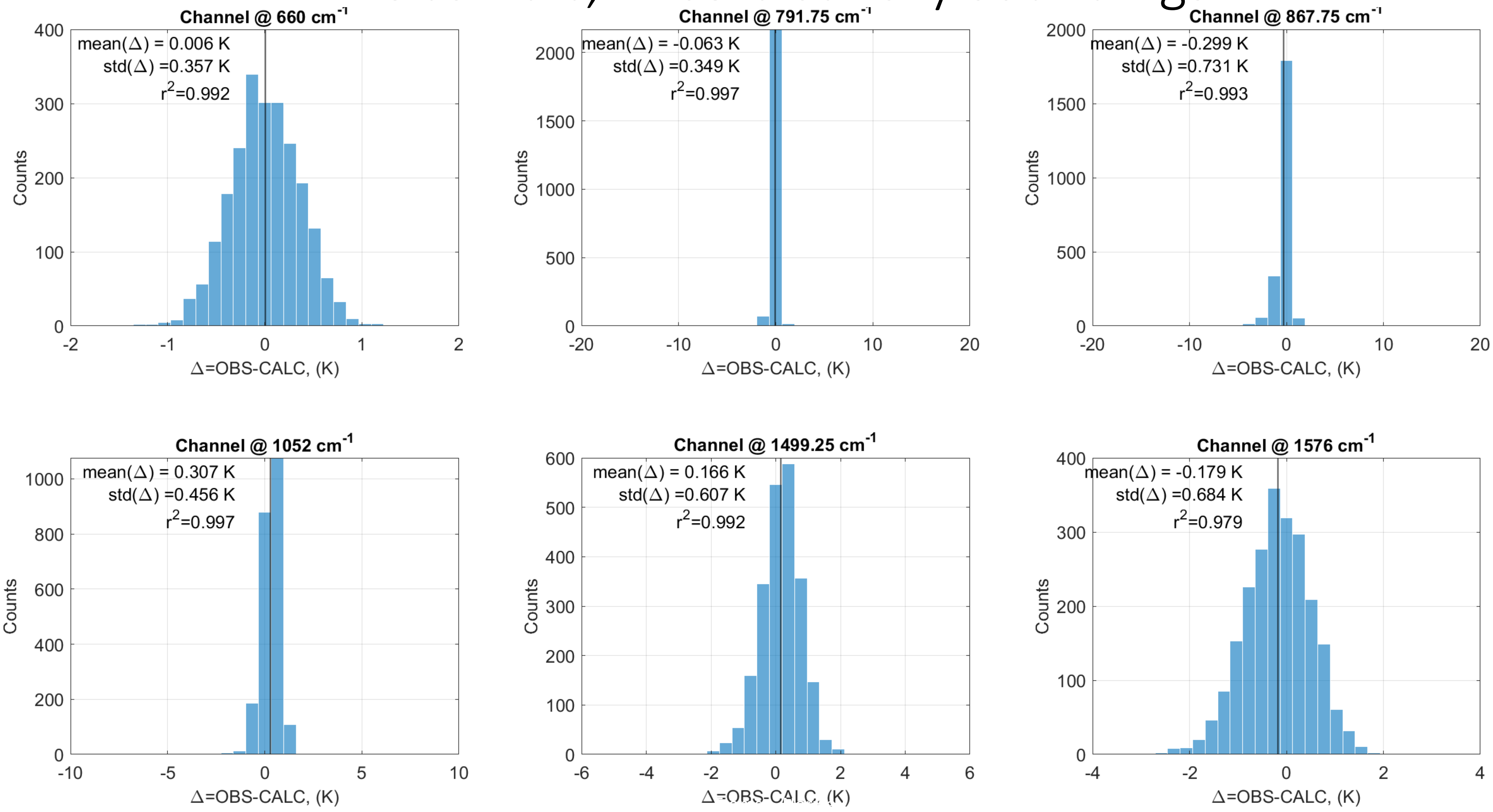



230
225
220
215
210
205
BT @ 660 cm
BT @ 791.75 c
BT @ 867.75 c
BT @ 1052 cn
BT @ 1499.25
BT @ 1576 cm^{-1} (K)

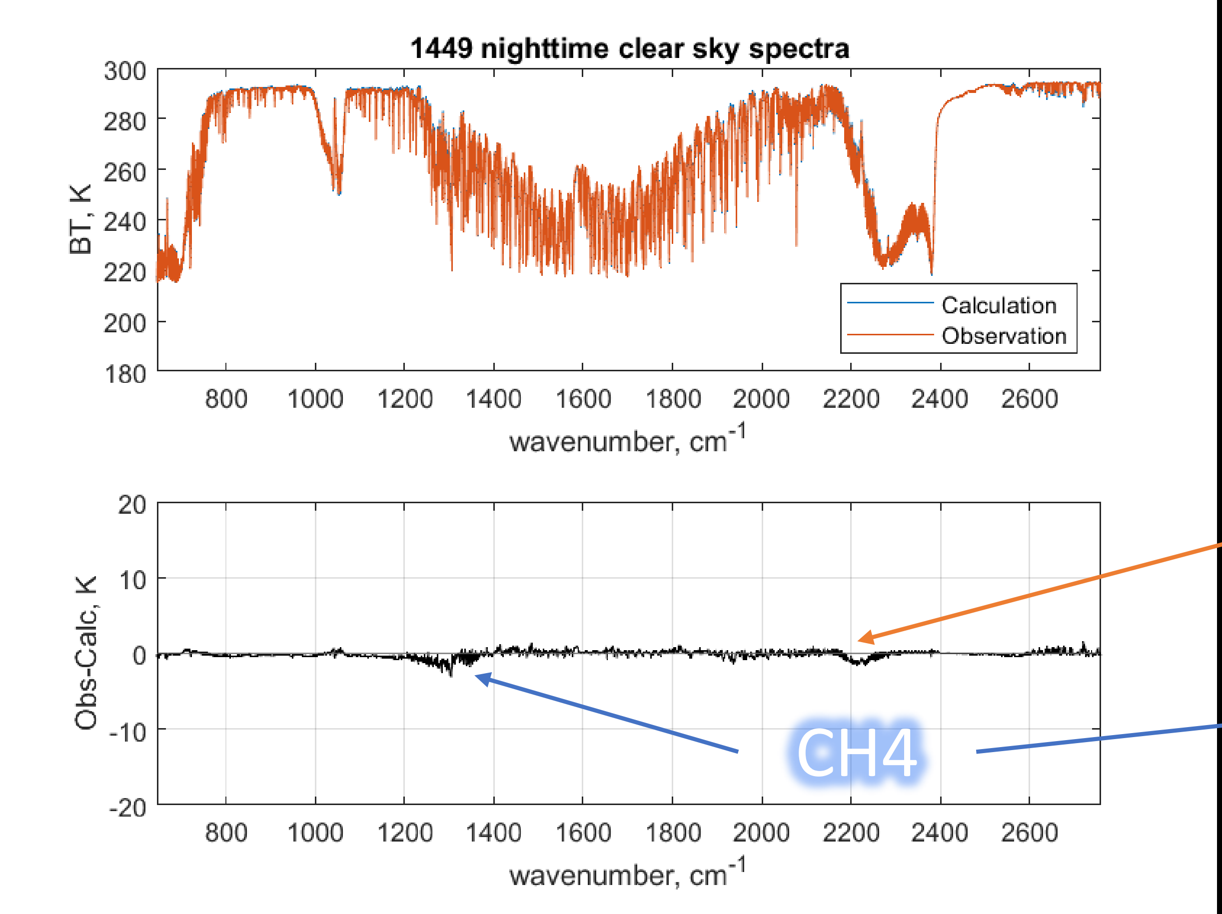
Obs-Calc, 32364 cloudy soundings

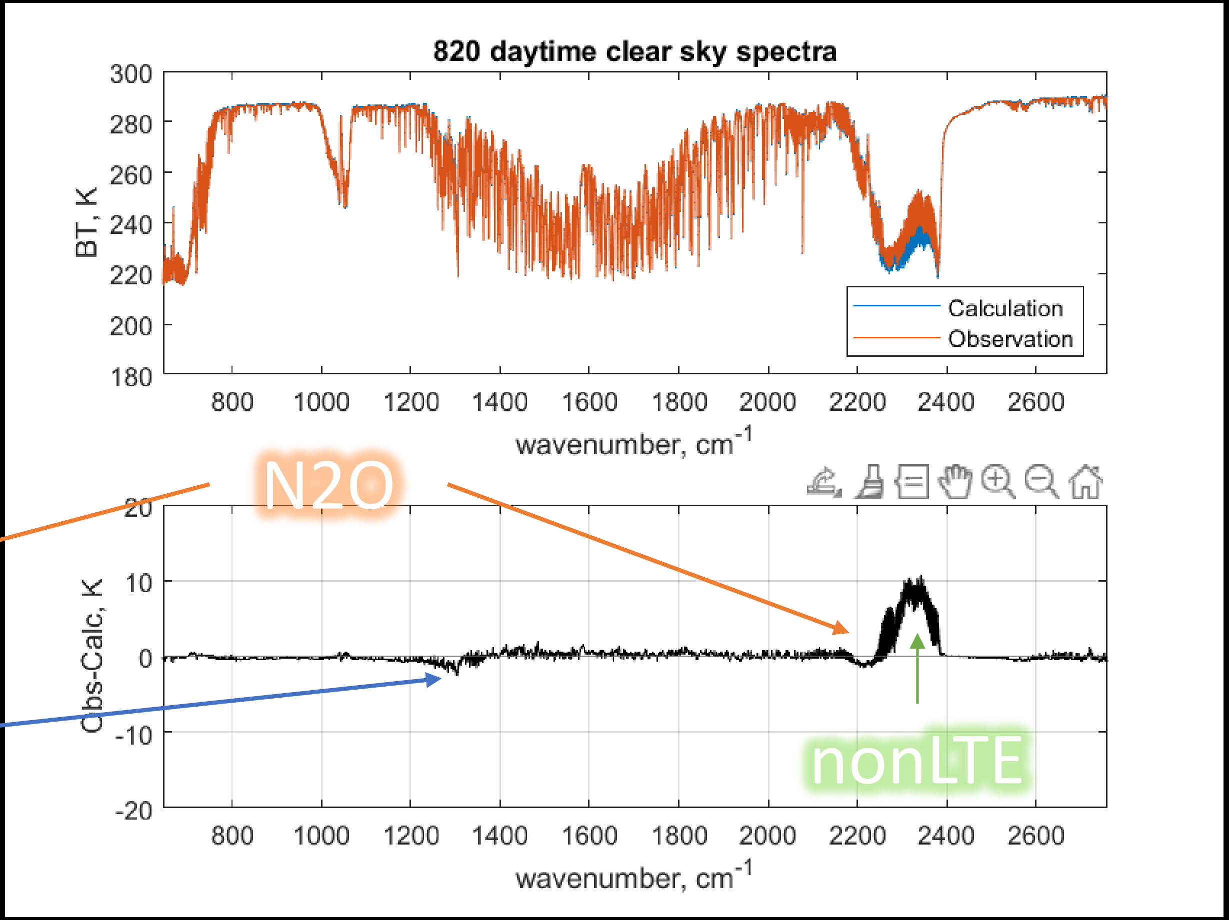


Obs-Calc, 2269 clear sky soundings

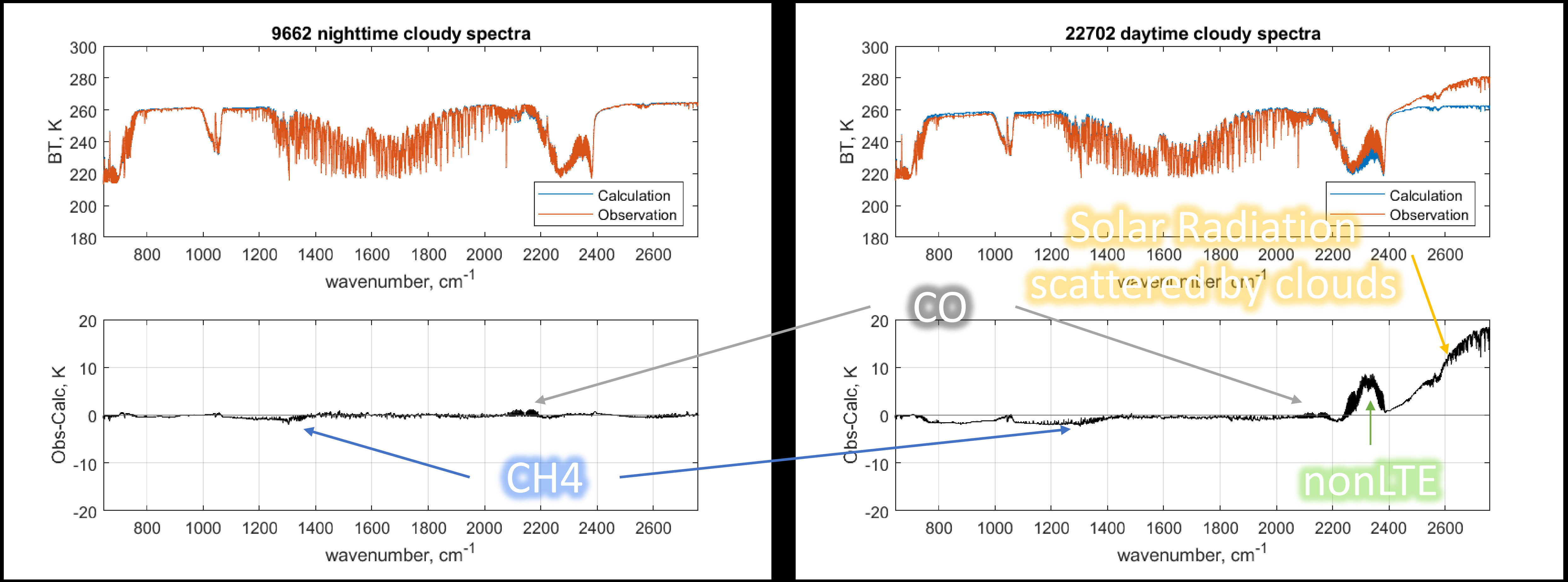


IASI whole spectral range, Clear Sky, Nigh and Day





IASI whole spectral range, Cloudy Sky, Nigh and Day



Conclusions

- σ-IASI/F2N is a flexible and accurate fast RTM for retrieval of geophysical parameters
  - it is Flexible with respect to ISRF
  - It covers the entire infrared range, From FAR to NEAR
  - Can exploit the synergy among FORUM, PREFIRE, IASI-NG, MTG-IRS and HIRAS
- It computes analytical derivatives with respect to thermodynamics and surface parameters, atmospheric gases, clouds and aerosol
  - it can perform calculations considering the microphysical properties of clouds and aerosol (shape and effective radii)
- σ-IASI/F2N shows differences below 1 K in cloudy condition in the 8-12 µm atmospheric window.
- It can reproduce with high accuracy cloud patterns
- For clear sky, differences below 0.3 K when considering spectral ranges, which are not affected by intense molecules absorption.

Back-Up

Milestones

2000 - First Publication

- Masiello et al. (2000) Fast wavelet radiative transfer model for inversion of IASI radiances. Proceedings IGARSS 2000. doi: 10.1109/IGARSS.2000.859719

2002 - Main reference Paper

- Amato et al (2002) The σ-IASI code for the calculation of infrared atmospheric radiance and its derivatives. Environ. Model. Softw., 17/7. doi: 10.1016/S1364-8152(02)00027-0

2003 - Water Vapor Self Broadening

- Masiello e Serio (2003) An effective water vapor self-broadening scheme for look-up-table-based radiative transfer. Proceedings of the SPIE, vol. 4882, p. 52-61, doi: 10.1117/12.462580

2007 - Validation with Airplane based Measurements (NAST-I)

- Grieco et al. (2007). Demonstration and Validation of the φ-IASI Inversion Scheme with NAST-I Data. QJRMetS, vol. 133,s3; p. 217-232, doi:10.1002/qj.162

2008 - Extension in the far Infrared, Validation with ground-based measurements (REFIR, I-BEST)

- Serio et al. (2008). Retrieval of foreign-broadened water vapor continuum coefficients from emitted spectral radiance in the H_2O rotational band from 240 to 590 cm^{-1}. OptExp, vol. 16,20; p. 15816-15833, doi:10.1364/OE.16.015816

2015 - Application to Mars (TES)

- Liuzzi et al. (2015). Simultaneous physical retrieval of Martian geophysical parameters using Thermal Emission Spectrometer spectra: the φ-MARS algorithm. ApplOpt, Vol. 54/9, pp. 2234-2246, doi:10.1364/AO.54.002334

2017 – Aerosols

- Liuzzi et al. (2017). Consistency of dimensional distributions and refractive indices of desert dust measured over Lampedusa with IASI radiances. AMT, Vol. 10, 599-615, doi:10.5194/amt-10-599-2017

2021 - New Clouds Parametrization

- Martinazzo et al. (2021) Assessment of the accuracy of scaling methods for radiance simulations at far and mid infrared wavelengths, JQSRT, Vol. 271, 107739, doi: 10.1016/j.jqsrt.2021.107739

More details about molecules and particles included in the Radiative Transfer Calculations

Variable	Fixed		
H_2O	O_2	NO	NO_2
HDO	OH	HF	HCL
CO_2	HBR	HI	CLO
O3	H_2CO	HOCL	N_2
N_2O	HCN	CH_3CL	H_2O_2
CO	C_2H_2	C_2H_6	PH_3
CH_4			
SO_2	**CFCs**		
NH_3	CCl_3F (CFC-11)		
HNO_3	CCl_2F_2 (CFC-12)		
OCS	CCl_4		
CF_4	$CHClF_2$		

Clouds
Liquid Water Clouds
Ice Water Clouds

Aerosol
Sea Salt Aerosol
Dust Aerosol
Organic Matter
Black Carbon
Sulphate Aerosol
Volcanic Ash

More details about Radiative Transfer Calculations

- Spectral Range : 5-3000 cm^{-1}
- Surface Type: Lambertian or Specular
- Radiance
- Jacobian with respect to
  - Temperature,
  - H2O, HDO, CO2, O3, N2O, CO, CH4, SO2, NH3, HNO3, OCS, CF4 concentrations
  - Surface Temperature and Emissivity
  - Liquid cloud re, and concentrations
  - Ice cloud re, and concentrations
  - Aerosols re, and concentrations
  - H2O self and foreign continua coefficients, CO2 foreign continuum coefficients
- High resolution 10^{-2} cm^{-1}

IASI-B from 08-Sep-2021 23:45 to 09-Sep-2021 00:15