

The background of the slide features a plot of Radiance (Watt/m<sup>2</sup>-cm<sup>-1</sup>-sr) on the y-axis (0 to 0.18) versus Wavenumber (cm<sup>-1</sup>) on the x-axis (0 to 3000). A grey curve represents the Planck blackbody radiation. Horizontal bars indicate the spectral ranges of various instruments: FORUM (red, ~50-200 cm<sup>-1</sup>), IASI & IASI-NG (green, ~600-2800 cm<sup>-1</sup>), MTG-IRS (blue, ~700-2000 cm<sup>-1</sup>), and SEVIRI (orange, ~1000-2500 cm<sup>-1</sup>). The plot also shows several atmospheric absorption lines with arrows pointing to them, labeled with chemical formulas: H<sub>2</sub>O, CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, CO, and N<sub>2</sub>.

# The extended All-Sky $\sigma$ -IASI Forward Model for the Next Generation IASI-NG and FORUM Infrared Atmospheric Sounders: Towards the Analysis and Retrieval of Cloud Microphysical Properties

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- The forward model we developed in the last 25 years is called  $\sigma$ -IASI
- We first developed it in the framework of EUMETSAT programs
- Assessment of IASI data for the Atmosphere (1996-2004) , grants
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- FORUM-Scienza Program of Italian Space Agency
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# Summary

## The Model

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

## Its Applications

- Validation of Forward Model
- Validation of Inverse Model

# $\sigma$ -IASI



- $\sigma$ -IASI is a general purpose monochromatic radiative transfer model
- It is designed for fast computation of radiance and its derivatives (Jacobian) with respect to a given set of geophysical parameters
- It adopts a grid of 61 (60) pressure levels (Layers) [1050.00-0.005 hPa].
- It is based on look-up table of monochromatic optical depth + an interpolation procedure.
- The 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
- The model also includes a proper treatment of H<sub>2</sub>O self-broadening
- For the clouds and aerosols we adopt a Chou parameterization
- It is a FORTRAN90 Code running on LINUX and Windows platform with Intel Compiler.

# Milestones



**2000** - First Publication

**2002** - Main reference Paper

**2003** - Water Vapor Self Broadening

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

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

**2015** - Application to Mars (TES)

**2017** – Aerosols

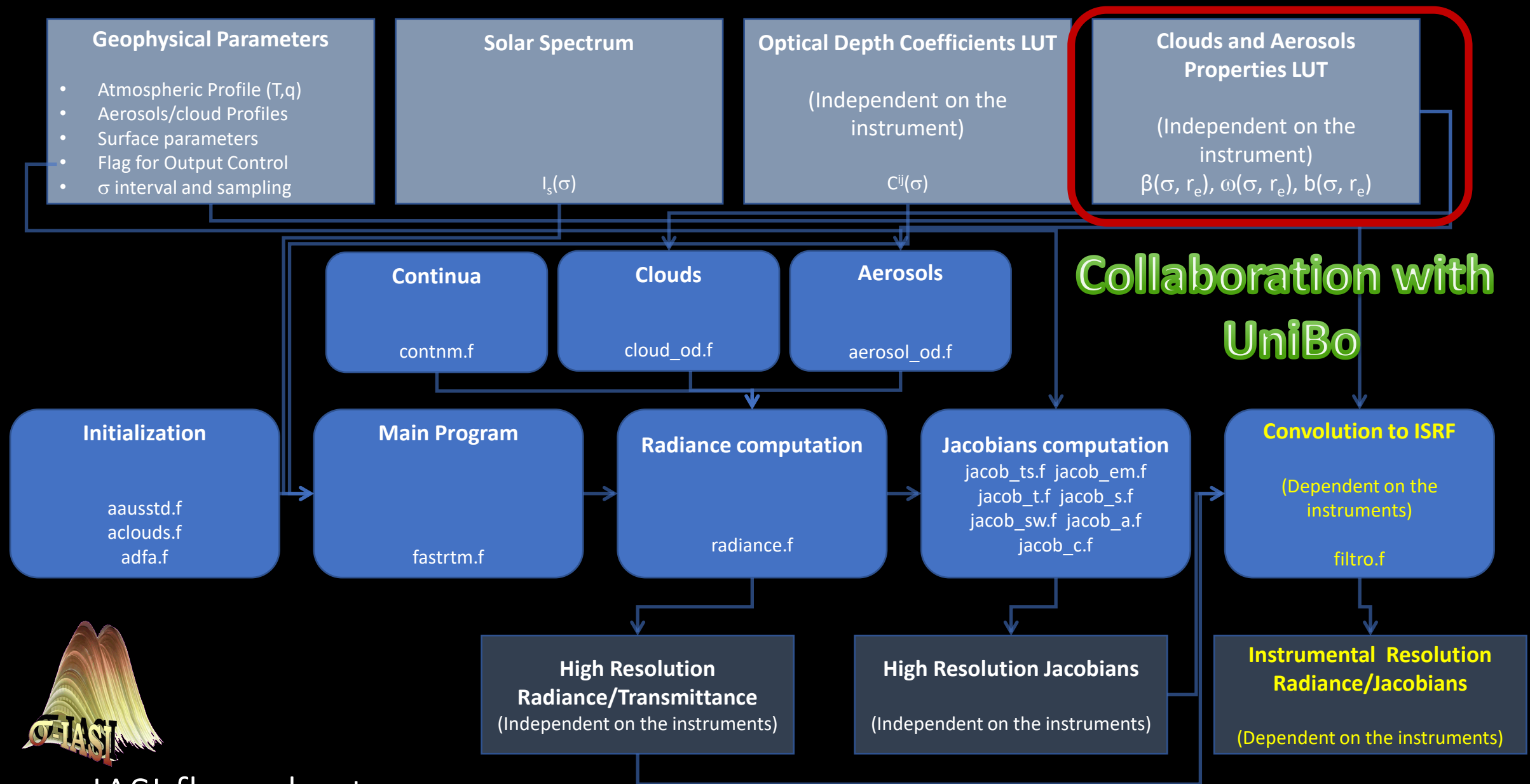
**2021** - New Clouds Parametrization

- Masiello et al. (2000) Fast wavelet radiative transfer model for inversion of IASI radiances. Proceedings IGARSS 2000. [doi: 10.1109/IGARSS.2000.859719](https://doi.org/10.1109/IGARSS.2000.859719)
- Amato et al (2002) The  $\sigma$ -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](https://doi.org/10.1016/S1364-8152(02)00027-0)
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- Serio et al. (2008). Retrieval of foreign-broadened water vapor continuum coefficients from emitted spectral radiance in the H<sub>2</sub>O rotational band from 240 to 590 cm<sup>-1</sup>. OptExp, vol. 16,20; p. 15816-15833, [doi:10.1364/OE.16.015816](https://doi.org/10.1364/OE.16.015816)
- Liuzzi et al. (2015). Simultaneous physical retrieval of Martian geophysical parameters using Thermal Emission Spectrometer spectra: the  $\phi$ -MARS algorithm. ApplOpt, Vol. 54/9, pp. 2234-2246, [doi:10.1364/AO.54.002334](https://doi.org/10.1364/AO.54.002334)
- 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](https://doi.org/10.5194/amt-10-599-2017)
- 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](https://doi.org/10.1016/j.jqsrt.2021.107739)

Input

Model

Output



σ-IASI flow chart

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

Variable	Fixed		
H <sub>2</sub> O	O <sub>2</sub>	NO	NO <sub>2</sub>
HDO	OH	HF	HCL
CO <sub>2</sub>	HBR	HI	CLO
O <sub>3</sub>	H <sub>2</sub> CO	HOCL	N <sub>2</sub>
N <sub>2</sub> O	HCN	CH <sub>3</sub> CL	H <sub>2</sub> O <sub>2</sub>
CO	C <sub>2</sub> H <sub>2</sub>	C <sub>2</sub> H <sub>6</sub>	PH <sub>3</sub>
CH <sub>4</sub>			
SO <sub>2</sub>	CFCs		
NH <sub>3</sub>	CCl <sub>3</sub> F (CFC-11)		
HNO <sub>3</sub>	CCl <sub>2</sub> F <sub>2</sub> (CFC-12)		
OCS	CCl <sub>4</sub>		
CF <sub>4</sub>	CHClF <sub>2</sub>		

Clouds
Liquid Water Clouds
Ice Water Clouds

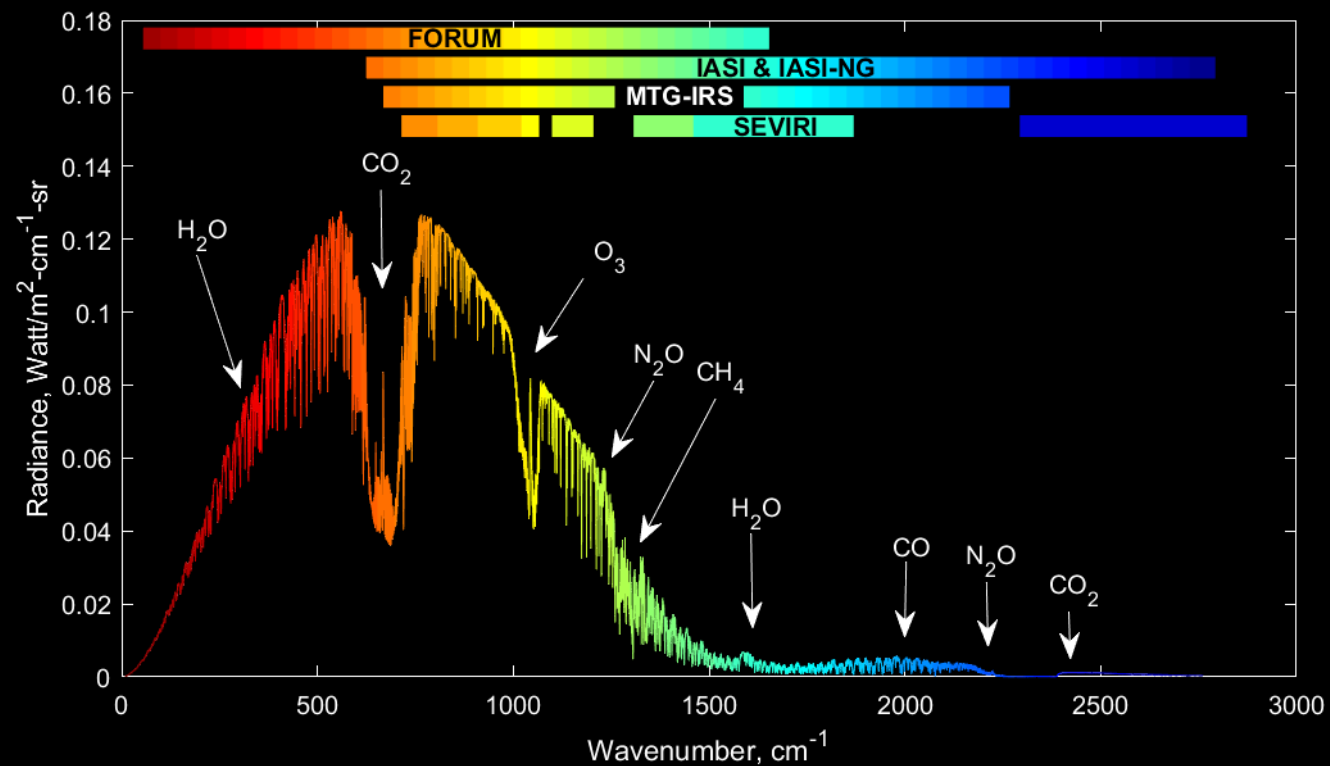
Aerosol
Sea Salt Aerosol
Dust Aerosol
Organic Matter
Black Carbon
Sulphate Aerosol
Volcanic Ash

# More details about Radiative Transfer Calculations

- Spectral Range : 5-3000  $\text{cm}^{-1}$
- Surface Type: Lambertian or Specular
- Radiance
- Jacobian with respect to
  - Temperature,
  - H<sub>2</sub>O, HDO, CO<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, CO, CH<sub>4</sub>, SO<sub>2</sub>, NH<sub>3</sub>, HNO<sub>3</sub>, OCS, CF<sub>4</sub> concentrations
  - Surface Temperature and Emissivity
  - Liquid cloud re, and concentrations
  - Ice cloud re, and concentrations
  - Aerosols re, and concentrations
  - H<sub>2</sub>O self and foreign continua coefficients, CO<sub>2</sub> foreign continuum coefficients
- High resolution  $10^{-2} \text{ cm}^{-1}$



# Spectral coverage of FORUM, IASI and MTG-IRS



# Gases OD Look-Up-Table: Parametrization

Low order (2) Polynomial Interpolation

## 1) For the trace gases ( $N$ )

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

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

## 2) For the Water Vapour ( $W$ )

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

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

# Analytical Derivatives

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

1) For the trace gases ( $N$ )

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

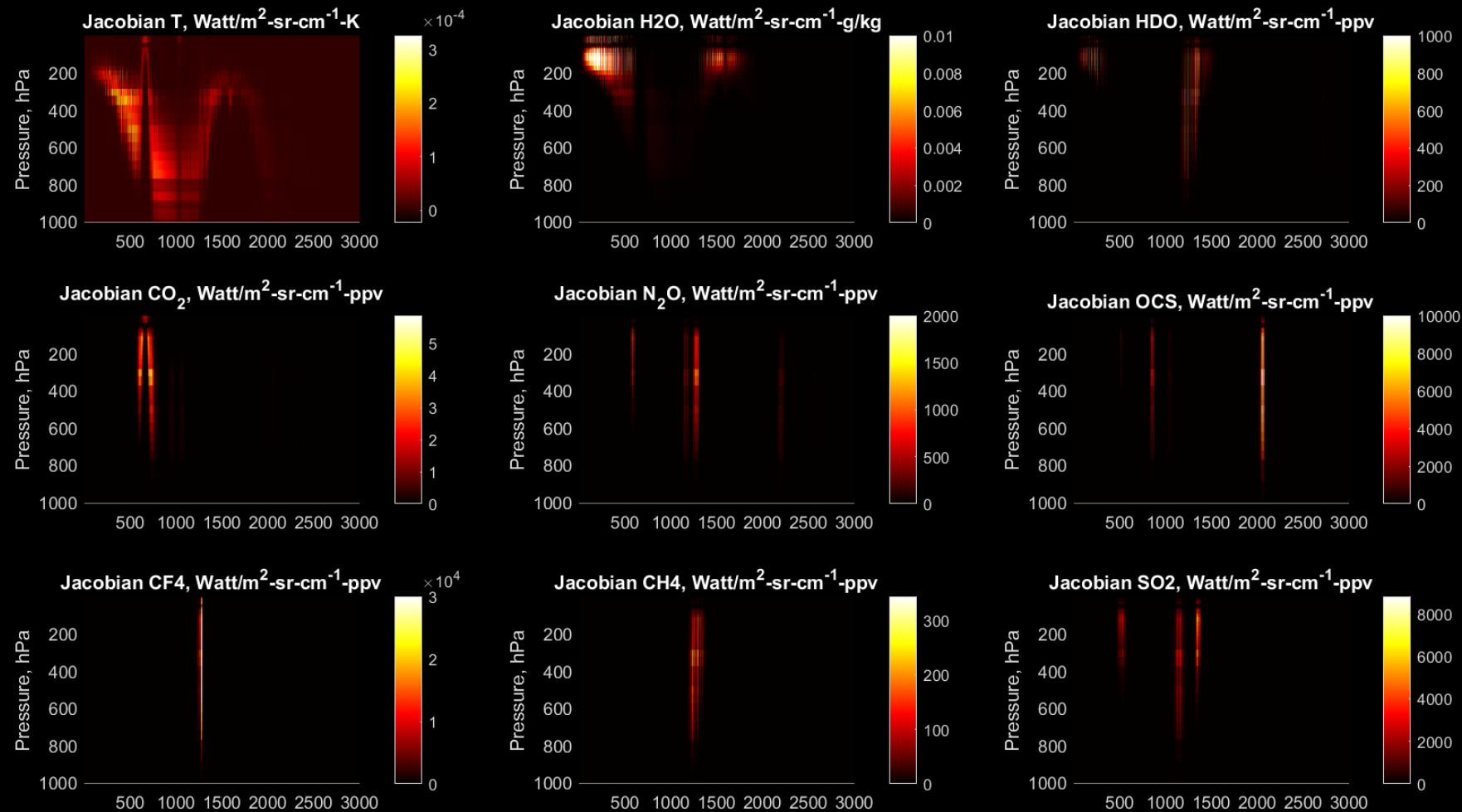
2) For the Water Vapour ( $W$ )

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

**With respect to the temperature  $T_i$**

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

# Jacobians



# 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](https://doi.org/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:

$$\chi = \frac{3}{4} \frac{x_{pc}}{r_e \rho_p} \tilde{\beta} \Delta z$$
$$\tilde{\beta} = \beta [(1 - \omega) + b\omega]$$

Collaboration with UniBO, provides new and accurate parametrization of  $\beta$ ,  $b$ ,  $\omega$  as a function of  $r_e$ ,

if  $Y$  is one among  $\beta, b, \omega$

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

With  $P_i$ ,  $t$  function of wavenumber

# 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  $r_e$

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

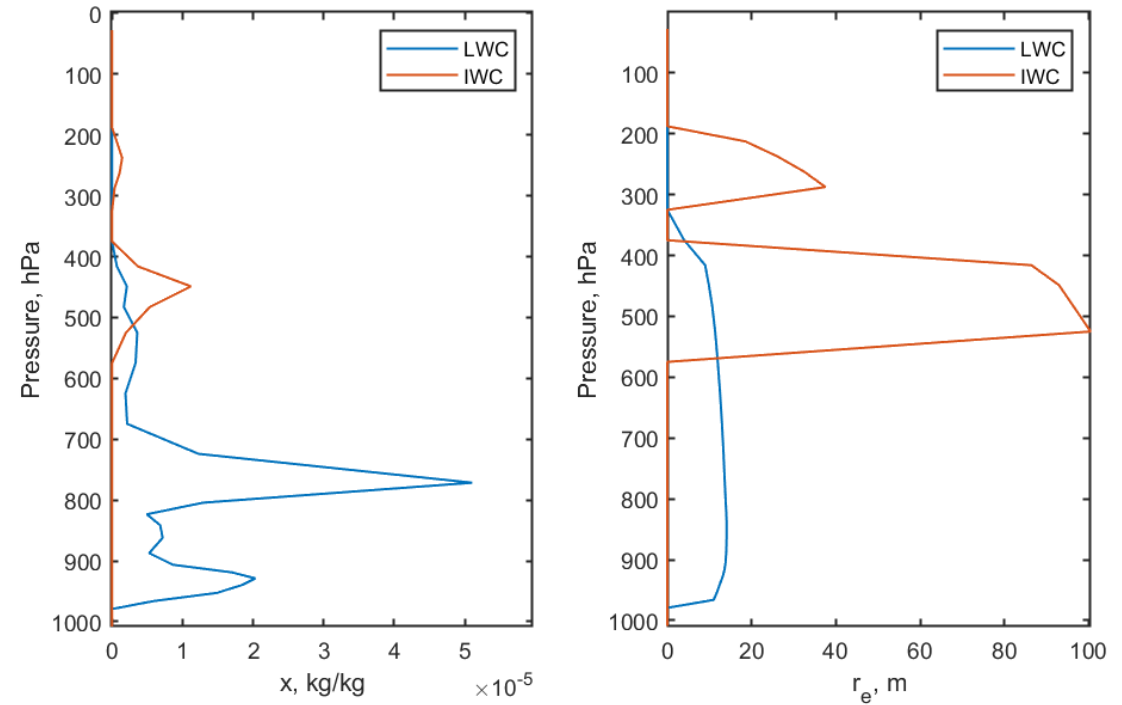
$$\frac{\partial \tilde{\beta}}{\partial r_e} = \frac{\partial \beta}{\partial r_e} [(1 - \omega) + b\omega] + \beta \left[ \frac{\partial \omega}{\partial r_e} (b - 1) \right] + \beta \omega \frac{\partial b}{\partial r_e}$$

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

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

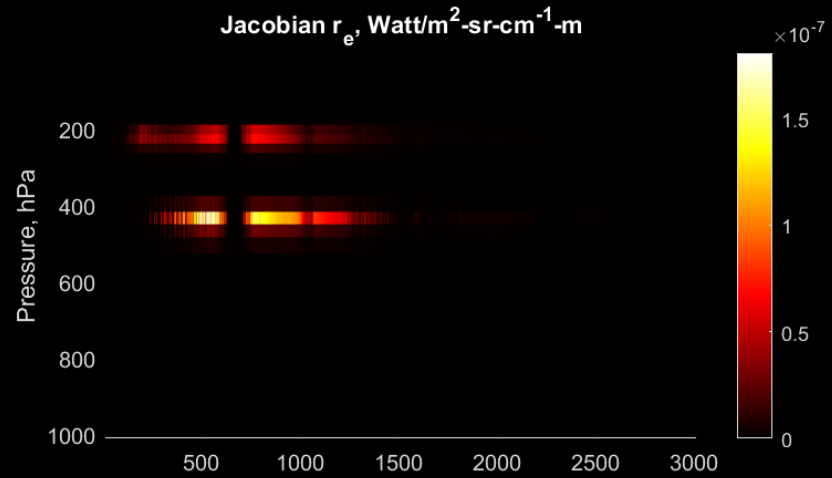
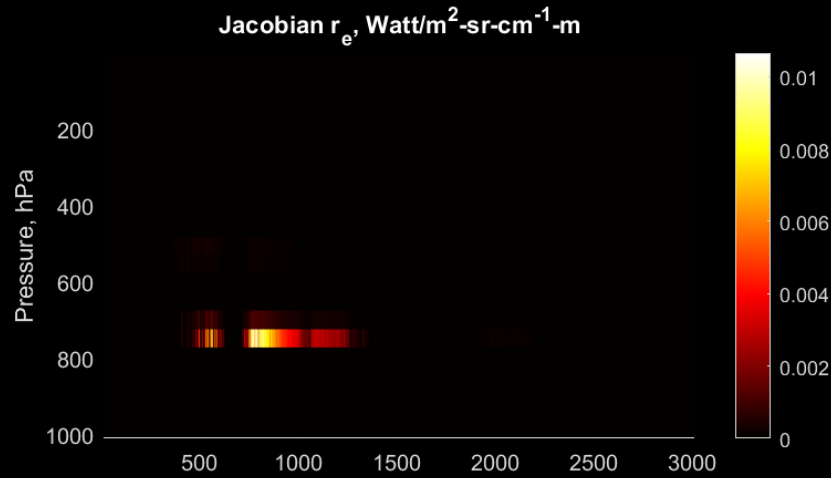
# Clouds and aerosol Profiles

- In input
  - effective radii of particles
  - and concentrations

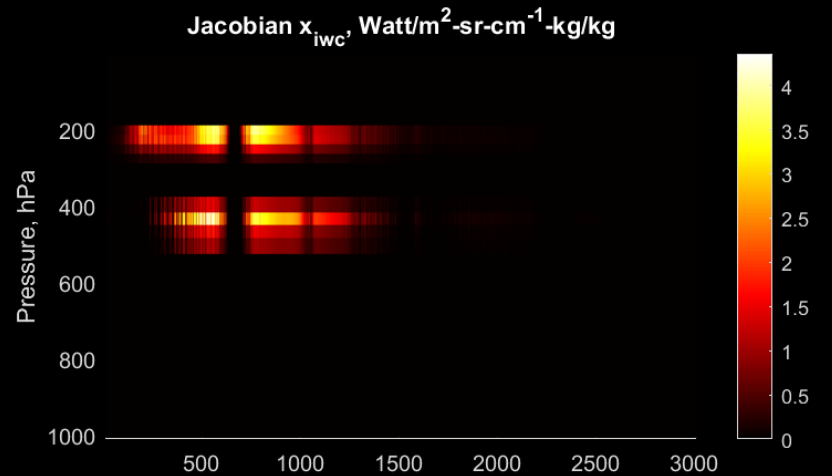
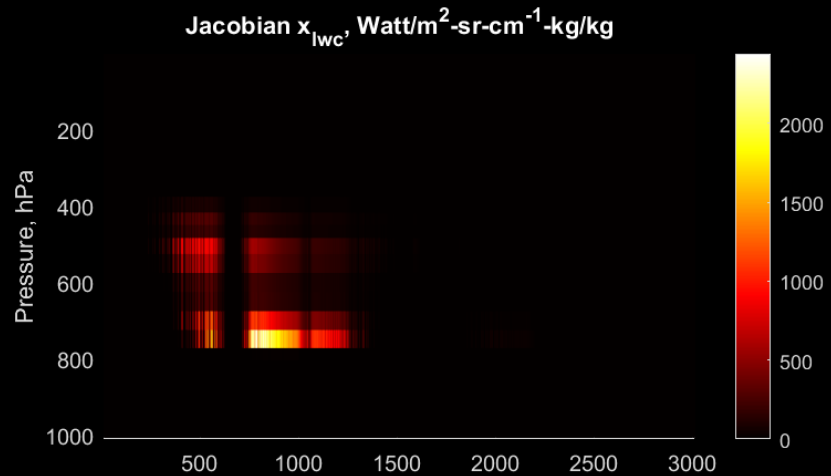


# Clouds Jacobians

$Jr_e$



$Jx_p$



Liquid water

Ice water



# Forward Model Validation

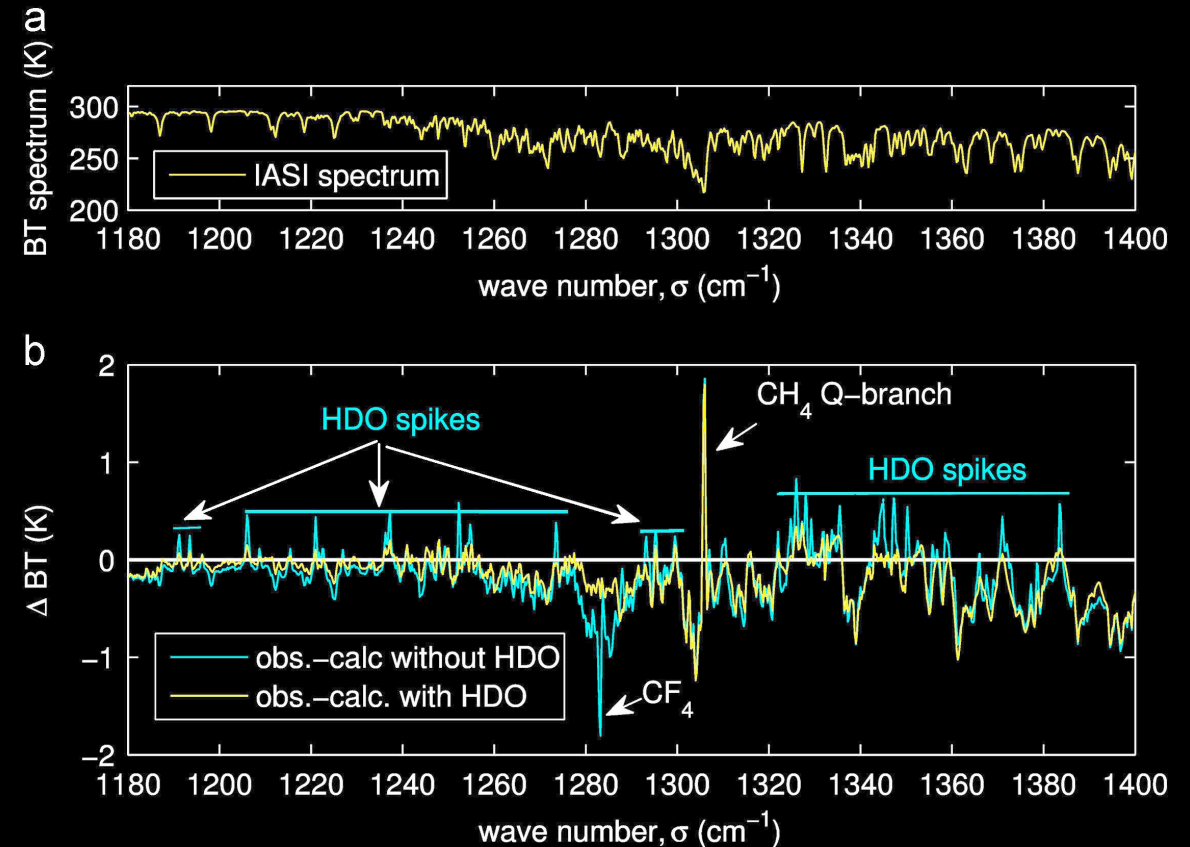
# The case of HDO and CF<sub>4</sub>

- Results have been averaged on 1000 IASI soundings over the target of Hawaii Island
- Ancillary data from ECMWF
- Liuzzi et al JQSRT 2016  
[doi:10.1016/j.jqsrt.2016.05.022](https://doi.org/10.1016/j.jqsrt.2016.05.022)



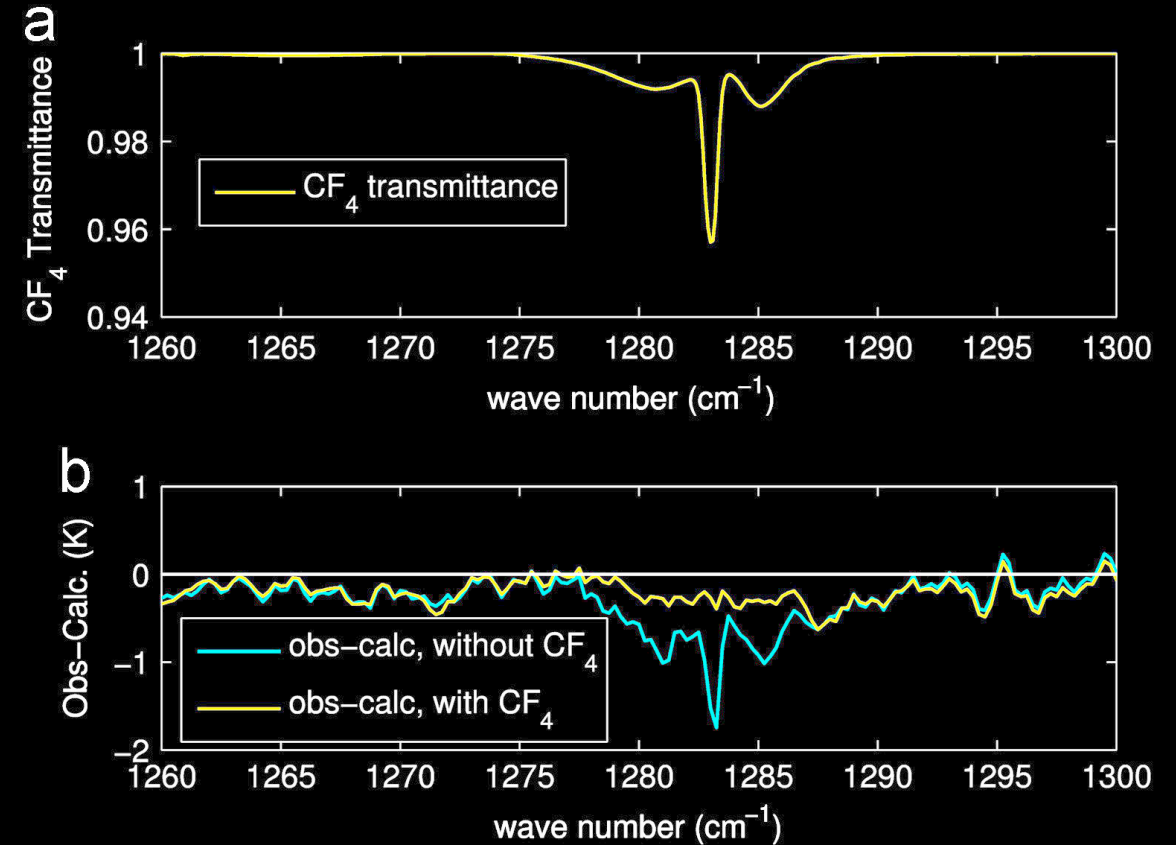
# HDO, $\nu_2$ Band

- Forward models use the standard isotopologues ratio.
- It is now well-known that upper tropical atmosphere processes of condensation/sublimation can deplete water vapor in its heavier isotopologues
- Figure shows typical spectral residuals within the intense  $\nu_2$  HDO band obtained **with** and **without** HDO retrieval.
- When **HDO is set to its standard abundance**, positive spikes appear at wavenumbers of intense HDO absorption.
- **HDO retrieval reduce sensitively these spikes.**





- In the spectral region of previous figure large negative spike appears at 1283 cm<sup>-1</sup>
- It has been identified in CF<sub>4</sub>.
- The figure In the upper panel shows the CF<sub>4</sub> transmittance, convolved to IASI spectral resolution,
- Lower panel showing the IASI spectral residuals obtained **retrieving or not** CF<sub>4</sub>.



# Level 2 Validation

# Our Retrieval Scheme

State vector simultaneously retrieved

$\mathbf{V}$

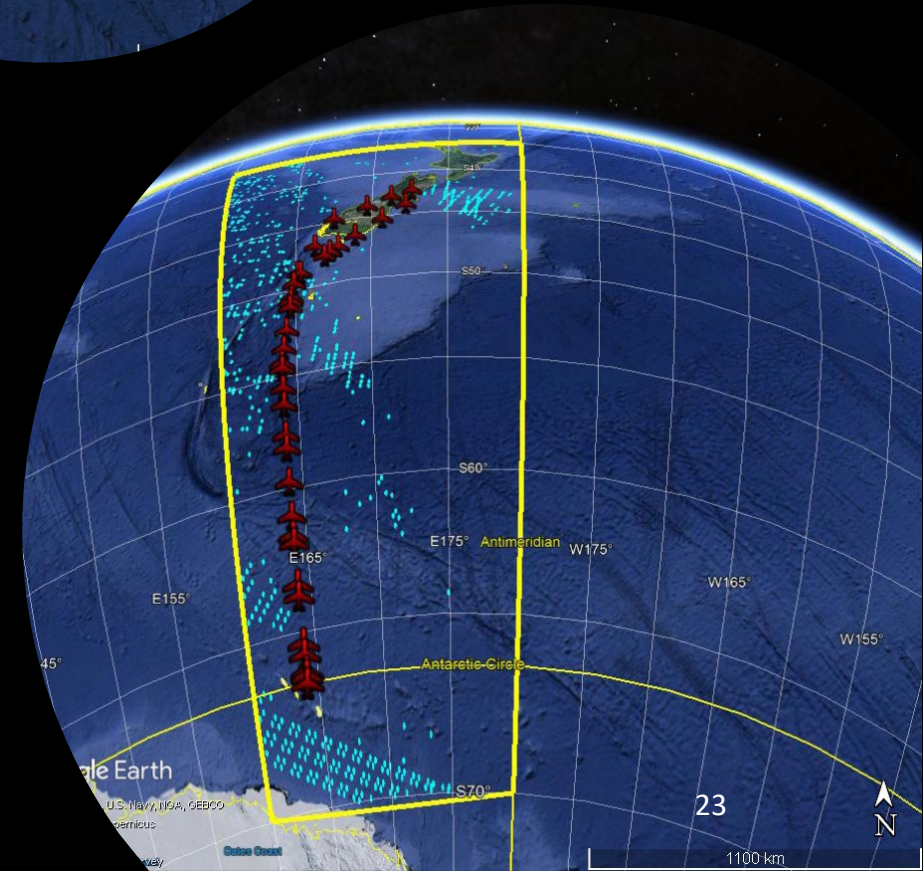
$$= (T_s, \mathbf{T}, \mathbf{Q}, \mathbf{O}, \mathbf{D}, \mathbf{q}_{\text{CO}_2}, \mathbf{q}_{\text{OCS}}, f_{\text{N}_2\text{O}}, f_{\text{CO}}, f_{\text{CH}_4}, f_{\text{SO}_2}, f_{\text{HNO}_3}, f_{\text{NH}_3}, f_{\text{CF}_4}, p_{\text{C}_\epsilon})$$

- Surface temperature, ( $T_s$ ), Atmospheric profiles of Temperature, Water vapour, Ozone, HDO, CO<sub>2</sub>, and OCS;
- Scalar scaling factors for the column amount of CO, N<sub>2</sub>O, CH<sub>4</sub>, SO<sub>2</sub>, HNO<sub>3</sub>, NH<sub>3</sub>, and CF<sub>4</sub>
- PC scores for surface emissivity

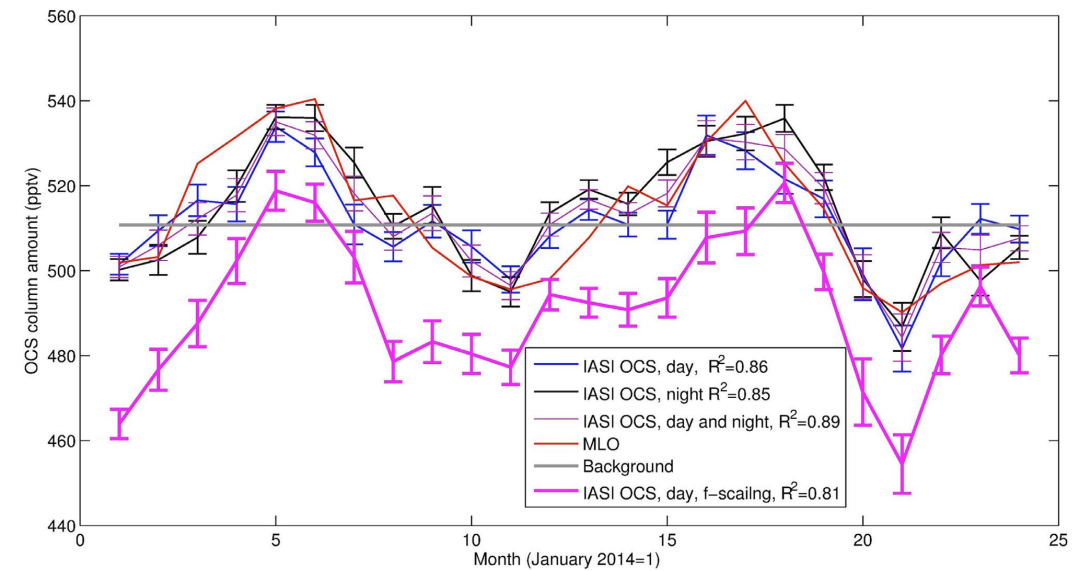
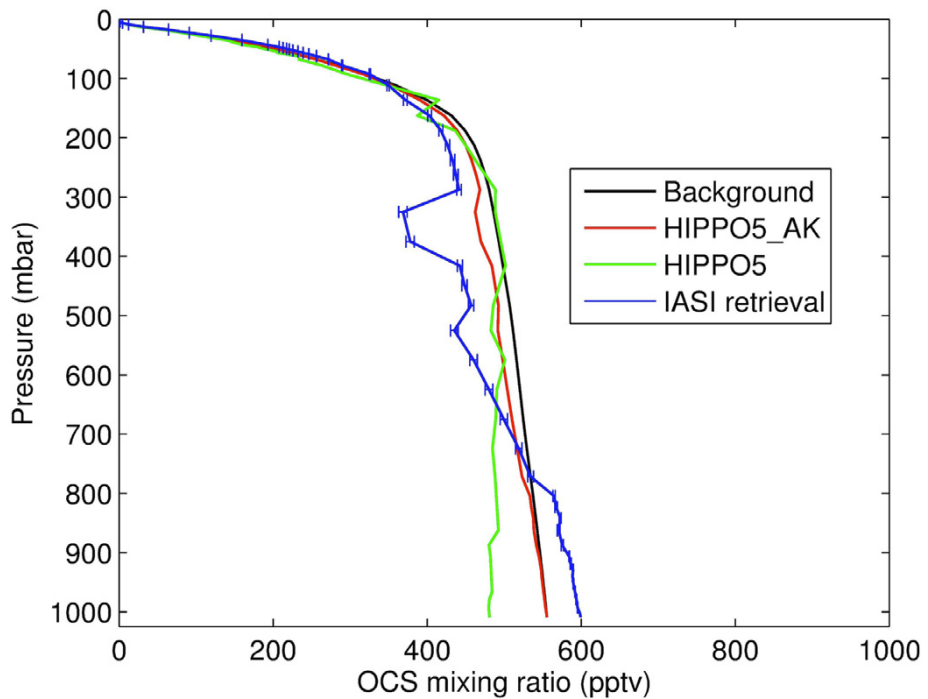


# The case of OCS

- 2 years of IASI soundings over the target of Hawaii Island
- Ancillary data from ECMWF,
- OCS ground-based
- IASI soundings co-located with hiaper pole-to-pole observations (hippo):
- OCS from hippo
- Camy-Peyret et al JQSRT, 2017 [doi: 10.1016/j.jqsrt.2017.07.006](https://doi.org/10.1016/j.jqsrt.2017.07.006)



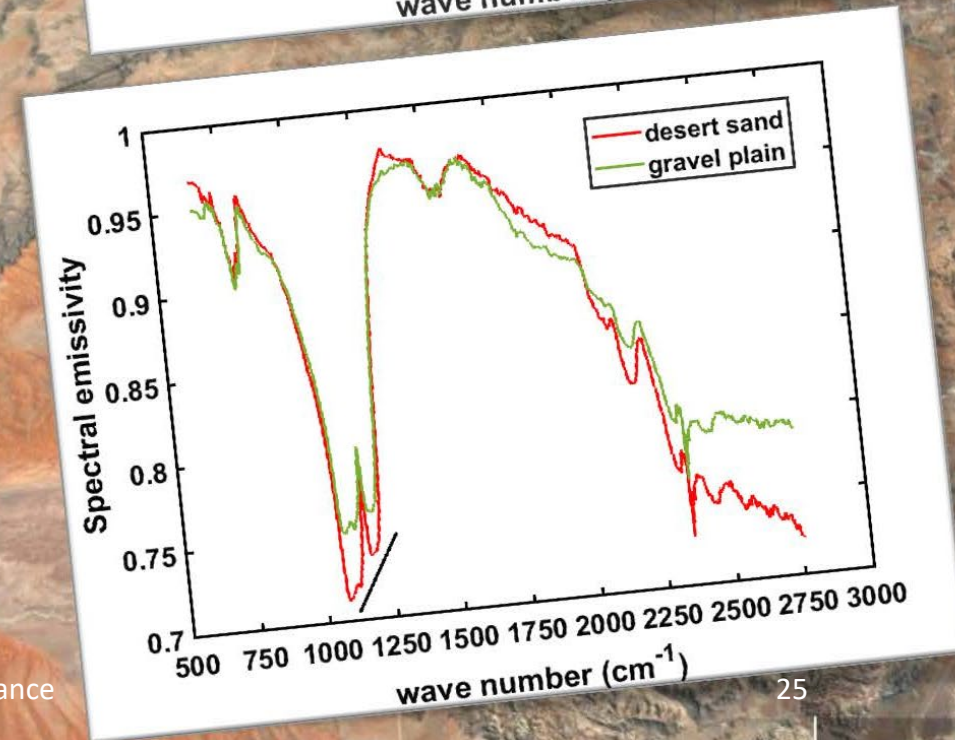
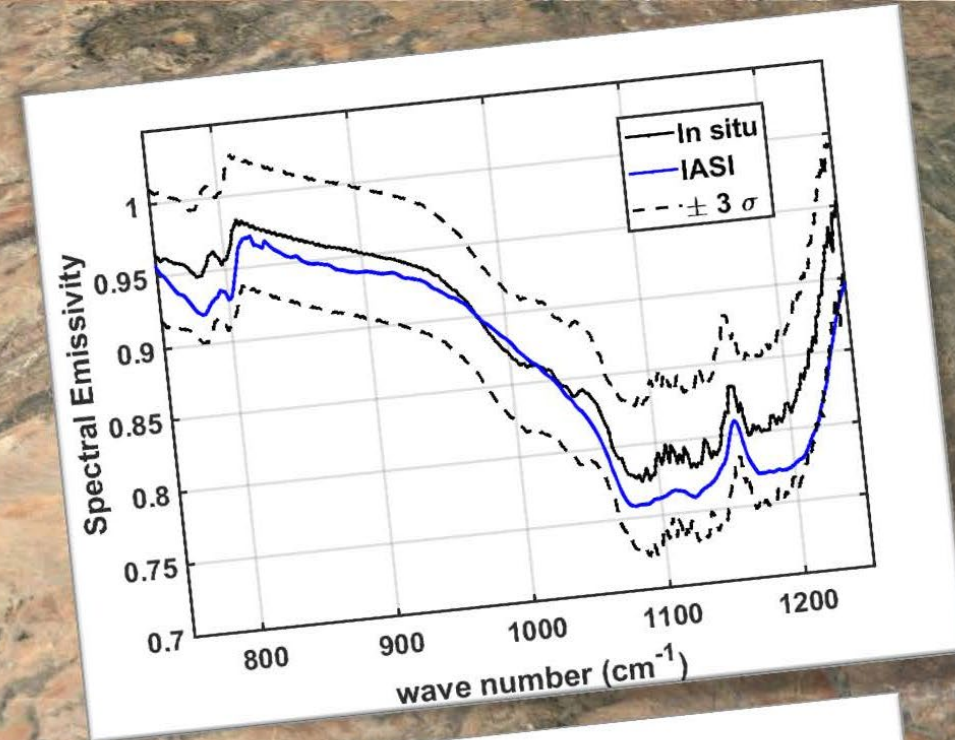
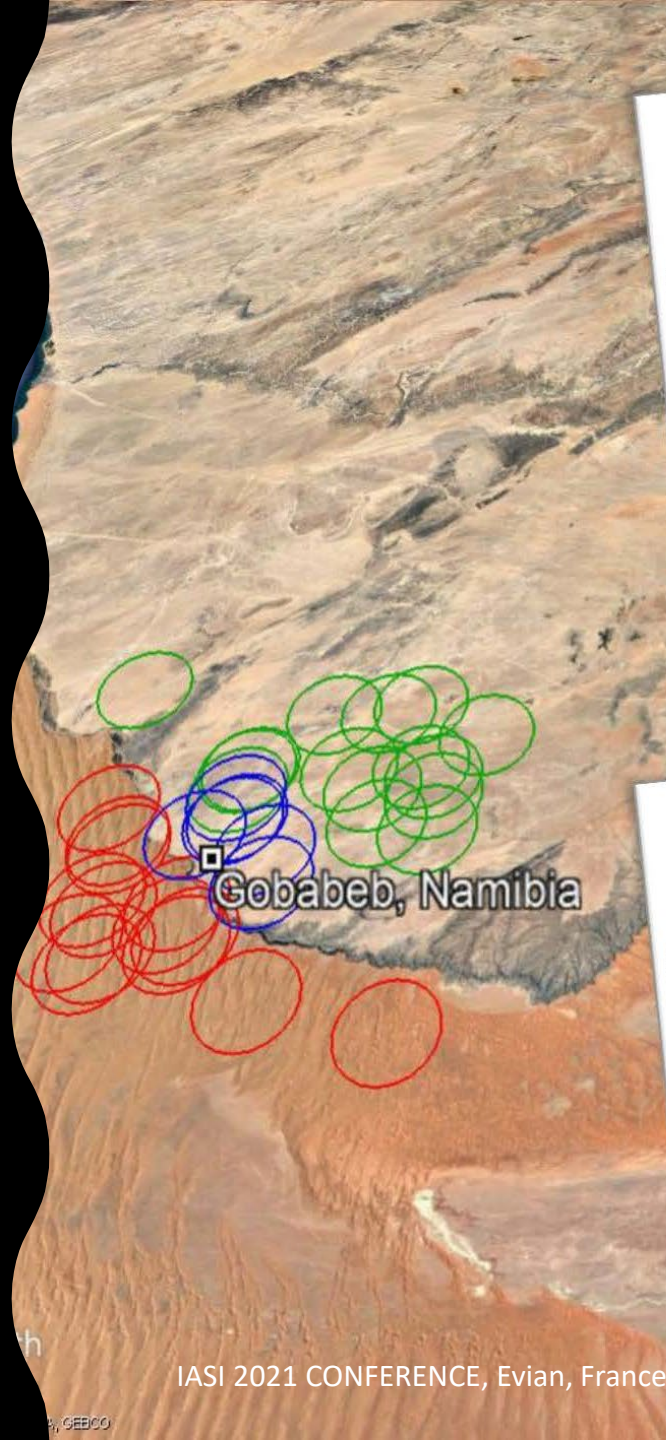
# OCS Profiles and Time series





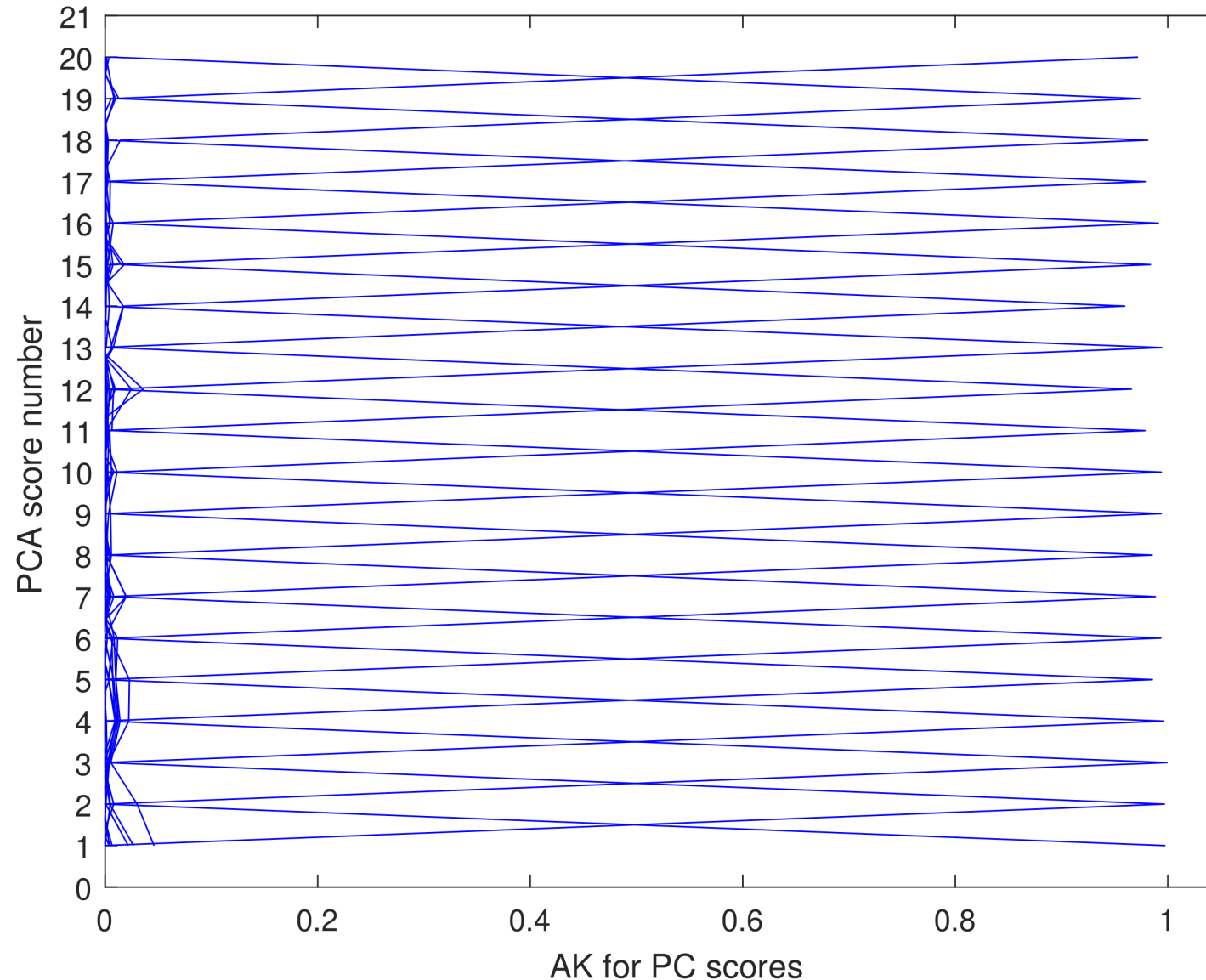
# Emissivity spectrum

- IASI spectrum co-located with Gobabeb, Namibia station.
- Ancillary information ECMWF
- Masiello et al. Remote Sens. 2018  
<https://doi.org/10.3390/rs10060976>



# Averaging Kernel

- Emissivity spectrum is retrieved simultaneously using 20 PCA scores.
- Figure shows the Averaging Kernels (AK) for the  $t = 20$  PC scores used to represent the emissivity spectrum.
- AK is that it is nearly one at each PC score. The degrees of freedom are in fact 19.71, very close to the value of 20, which corresponds to a retrieval for which the twenty PC score were fully resolved by the data.
- **20 DOF**



# Conclusions

- $\sigma$ -IASI is a flexible and accurate fast RTM for retrieval of geophysical parameters
  - Unlike other fast RTM, it is Flexible with respect to line parameters and ISRF
  - Can exploit the synergy among FORUM, IASI-NG, MTG-IRS and HIRAS
- It covers the entire infrared range (5-3000  $\text{cm}^{-1}$ )
- It computes analytical derivatives with respect to thermodynamics and surface parameters, atmospheric gases, clouds and aerosol
  - Unlike other fast RTM, it can perform calculations taking into account the microphysical properties of clouds and aerosol (shape and effective radii)