# Comprehensive Infrared forward-Inverse Analysis of the Ozone hole with IASI

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# Anknowledgements


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# Foreword

- 2021 and 2023 have been two years with the most spatially extensive, and deep ozone hole.
- Formation of Polar stratospheric clouds (PSCs) is the fundamental catalytic mechanism that accelerates ozone destruction
- PSC formation involves $HNO_3$ and $H_2O$ initially in the gas phase, which condenses into the solid phase (giving rise to crystals of $HNO_3$-$3H_2O$ or NAT) at $T<195$ K
- The phenomenon is continuously monitored by satellite instruments, (Ozone Monitoring Instrument, OMI,  TROPOspheric Monitoring Instrument, TROPOMI)
- They need daylight
- They have no sensitivity to the thermodynamic conditions of UT/LS region, and they don't sense nitric acid and water in the gas phase.

# Outline

- Data & Method
- Results
- Conclusions

12/05/2025

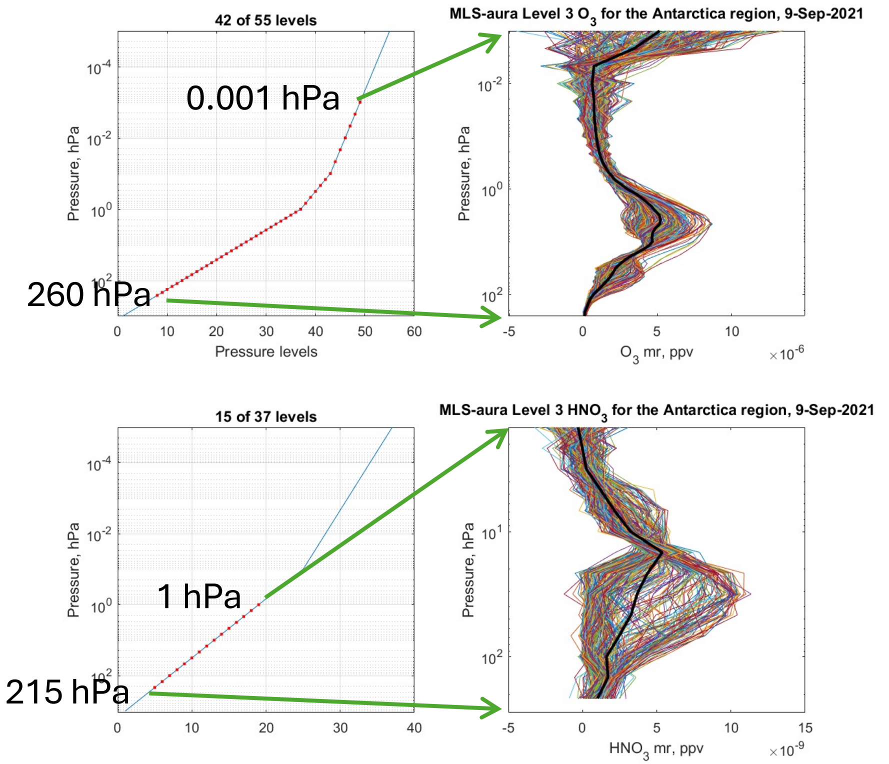
| | TROPOMI | OMI | IASI | MLS-AURA |
|---|---|---|---|---|
| Ozone | X | X | X | X |
| HNO3 | | | X | X |
| Temperature | | | X | |
| Water Vapour | | | X | |

# The “Ingredients” of the Ozone Depletion

- We collect data for
  - the 9th of July, Sept and Oct 2021 and 2023
  - 90°<Lat<-60°

# Microwave Limb Sounder (MLS) on NASA's EOS AURA Satellite

- Level 3 observations of the O3 and HNO3 profiles for MLS.
- https://disc.gsfc. nasa.gov/
- Sept. 9, 2021, and 2023.
- Level 3 data available on a 4°×5° longitude/latitude grid
- O3 pressure range: 260–0.001 hPa (42 of 55 levels)
- HNO3 pressure range: 215–1 hPa (15 of 37 levels)
- O3 profile -> Columnar Amount
- $\bar{X}_{O3} = \frac{N_A}{n_0 m_{air}} \int_{p_l}^{p_u} q_{O_3}(p)dp$ [D.U.]
- HNO3 Profiles-> Columnar Amount
- $\bar{X}_{HNO3} = \frac{1}{p_l - p_u} \int_{p_l}^{p_u} q_{HNO_3}(p)dp$ [PPV]



# OMI and TROPOMI

TROPOspheric Monitoring Instrument (TROPOMI)

Level 2 data (flag q <0.75)

Ozone Measurements Instruments (OMI)

Level 3 gridded data

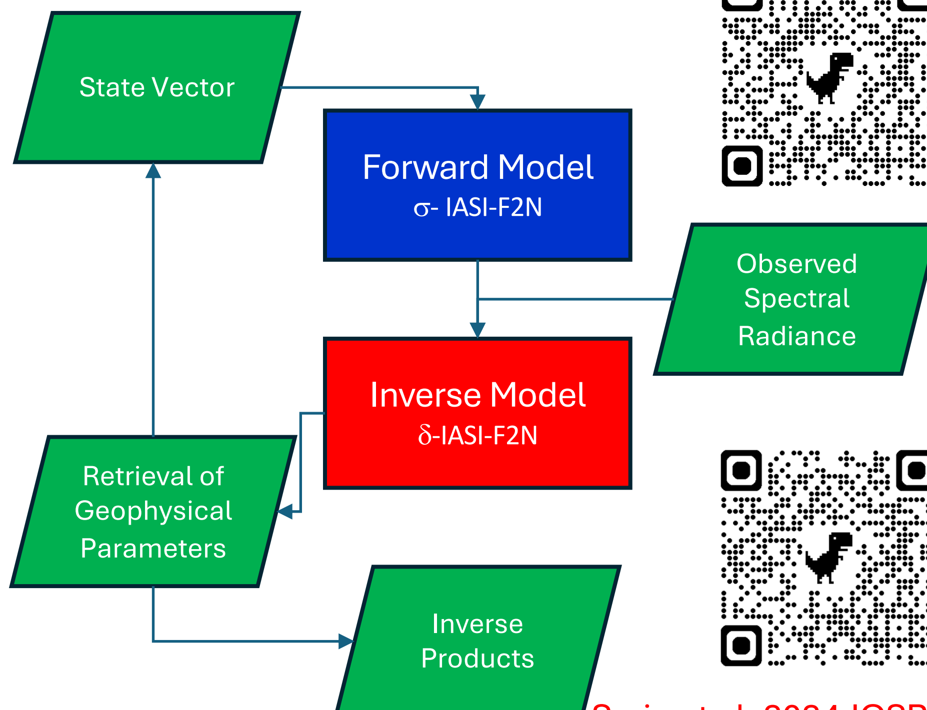
# $\varphi$-IASI-F2N: forward/inverse package from the far to near infrared

$\varphi$-IASI-F2N is a forward/inverse for all-sky (clear and cloudy conditions) calculations of forward (L1) and inverse (L2) products

The system includes
- $\sigma$- IASI-F2N
- $\delta$-IASI-F2N

To sum up
- $\varphi$ stands for *φυσικά* physical
- $\sigma$ stands for wavenumber and for s - Spectrum
- $\delta$ stands for increment

Masiello et al. 2024 JQSRT




Serio et al. 2024 JQSRT

# $\delta$-IASI/F2N State Vector

| Atmosphere (profiles of size $N_L$=60) | | Surface |
|---|---|---|
| • Temperature (K) | • $CH_4$ (ppv) | • Ts (scalar, K) |
| • $H_2O$ (g/kg) | • $SO_2$ (ppv) | • Emissivity spectrum, $\varepsilon(\sigma)$ |
| • HDO (ppv) | • $NH_3$ (ppv) | Cloud parameters (profiles of size, $N_L$=60) |
| • $CO_2$ (ppv) | • $HNO_3$ (ppv) | • LWC (kg/kg) |
| • $O_3$ (ppv) | • $CF_4$ (ppv) | • IWC (kg/kg) |
| • $N_2O$ (ppv) | • OCS (ppv) | • $r_e$ (µm) |
| • CO (ppv) | | • $D_e$ (µm) |
| | | • Cloud fraction, cf (scalar) |

$$\mathbf{v} = \left( \begin{array}{c} \varepsilon(\sigma), cf, T_s, \mathbf{T}, \mathbf{Q}, \mathbf{O}, \mathbf{HDO}, \mathbf{q}_{CO_2}, \\ \mathbf{q}_{CH_4}, \mathbf{q}_{N_2O}, \mathbf{q}_{CO}, \mathbf{q}_{SO_2}, \mathbf{q}_{NHO_3}, \mathbf{q}_{HNO_3}, \mathbf{q}_{OCS}, \mathbf{q}_{CF_4}, \\ \mathbf{q}_{LWC}, \mathbf{q}_{IWC}, \mathbf{q}_{r_e}, \mathbf{q}_{D_e}, w \end{array} \right)$$

# Outline

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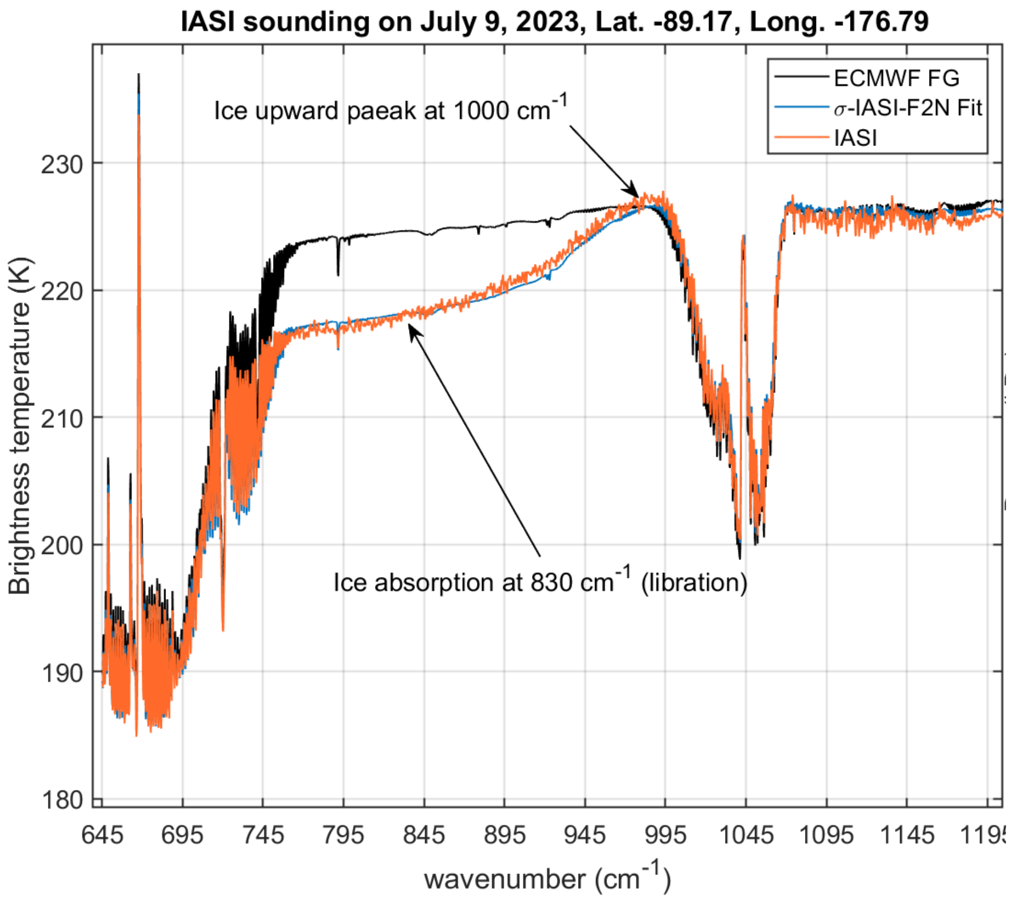
# Retrieval of Polar Stratospheric Cloud




**Orange – IASI Measurement**

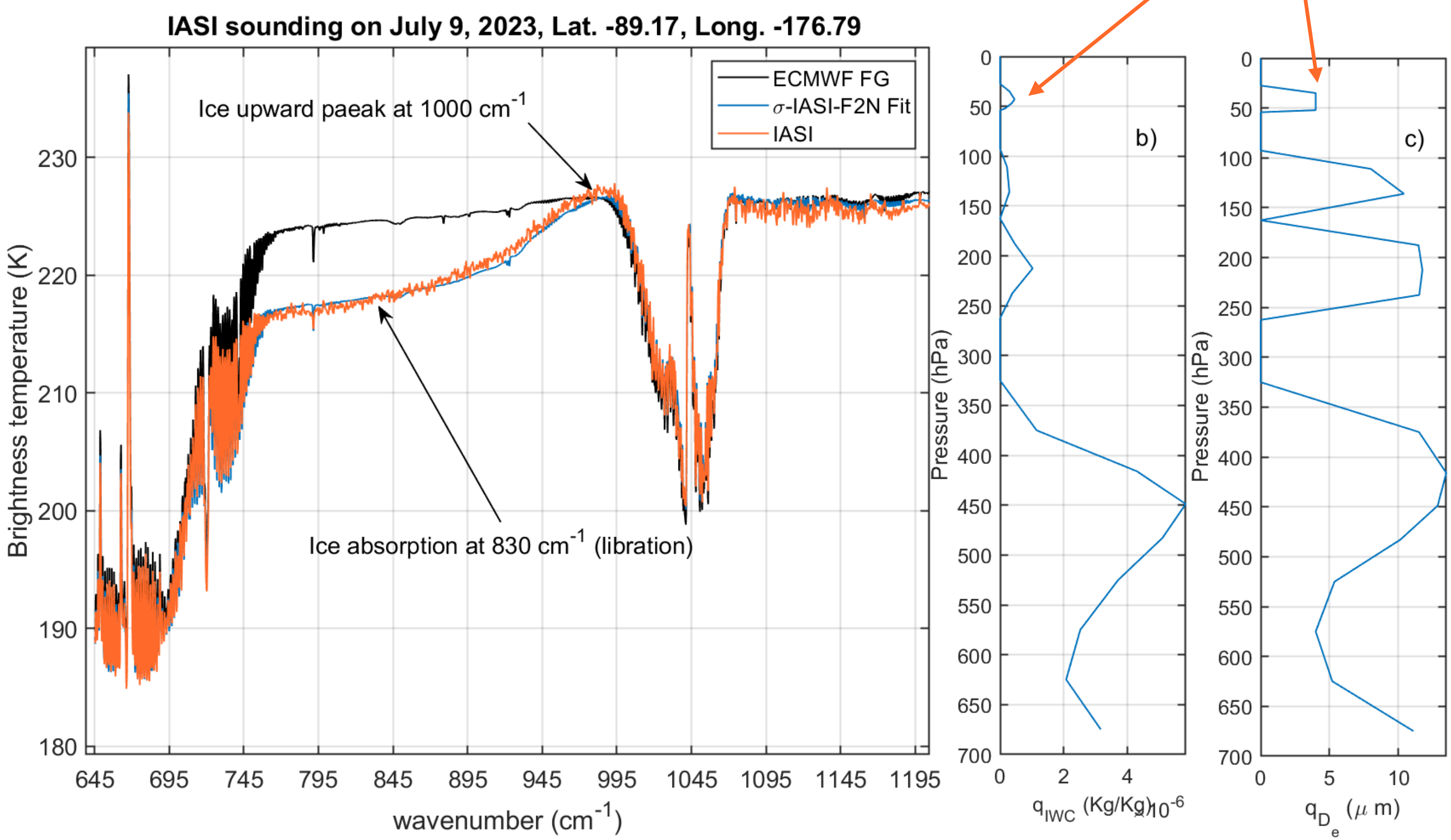
**Black – Computed with ECWMF profile**

**Blue – Computed with IASI retrieved profile**

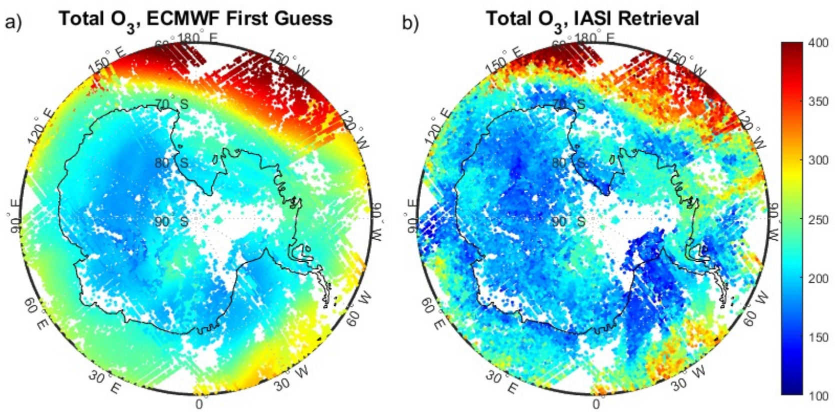
# Retrieval of Polar Stratospheric Cloud

International TOV

P = 43 hPa (~20 km)
T(p) = 182 K
IWC = 4.5 $10^{-7}$ kg/kg
$D_e$= 4 um



# Retrieval of Ozone, 09/09/2021



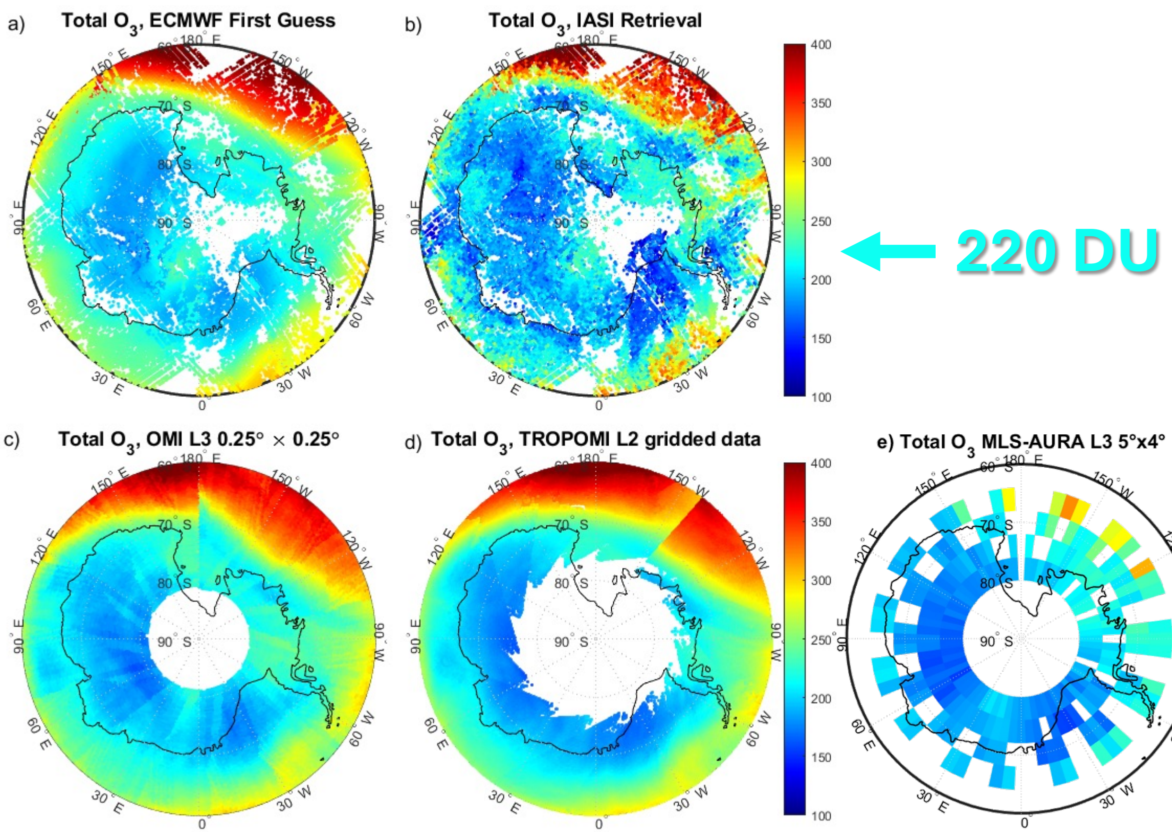

220 DU

a) O3 map from ECMWF (background),

b) O3 map retrieved by IASI data (un-gridded level 2 product)

➢ IASI see a deeper and wider Ozone hole with respect ECMWF

# Retrieval of Ozone, 09/09/2021




a) O3 map from ECMWF (background),

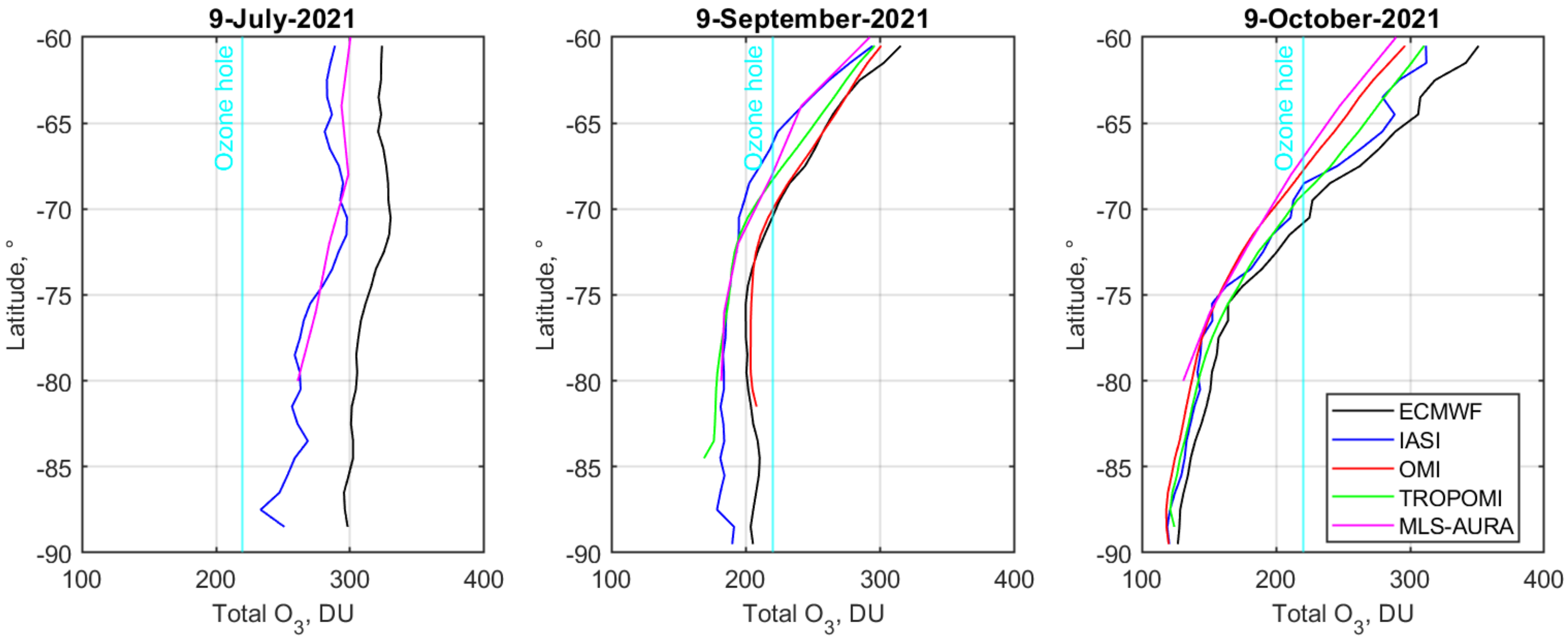
b) O3 map retrieved by IASI data (un-gridded level 2 product)

c) OMI level 3 gridded and smoothed product.

d) TROPOMI level 2 gridded product,(QF>0.75)

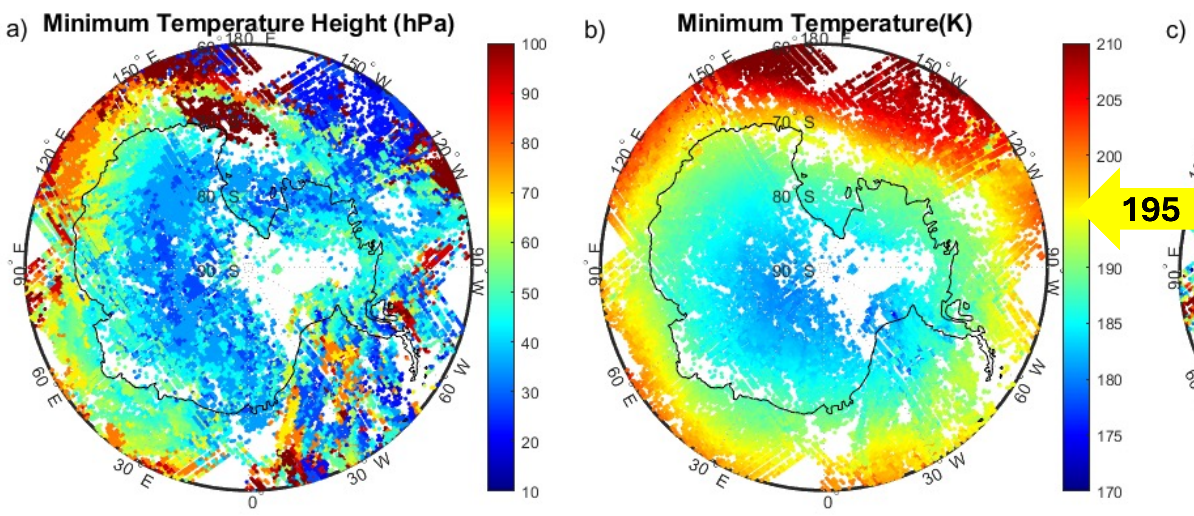
e) MLS-AURA level 3 gridded data

- IASI see a deeper and wider Ozone hole with respect ECMWF
- OMI and TROPOMI don't cover the pole (Night)
- MLS-AURA with a coarser spatial resolution captures the same features of IASI



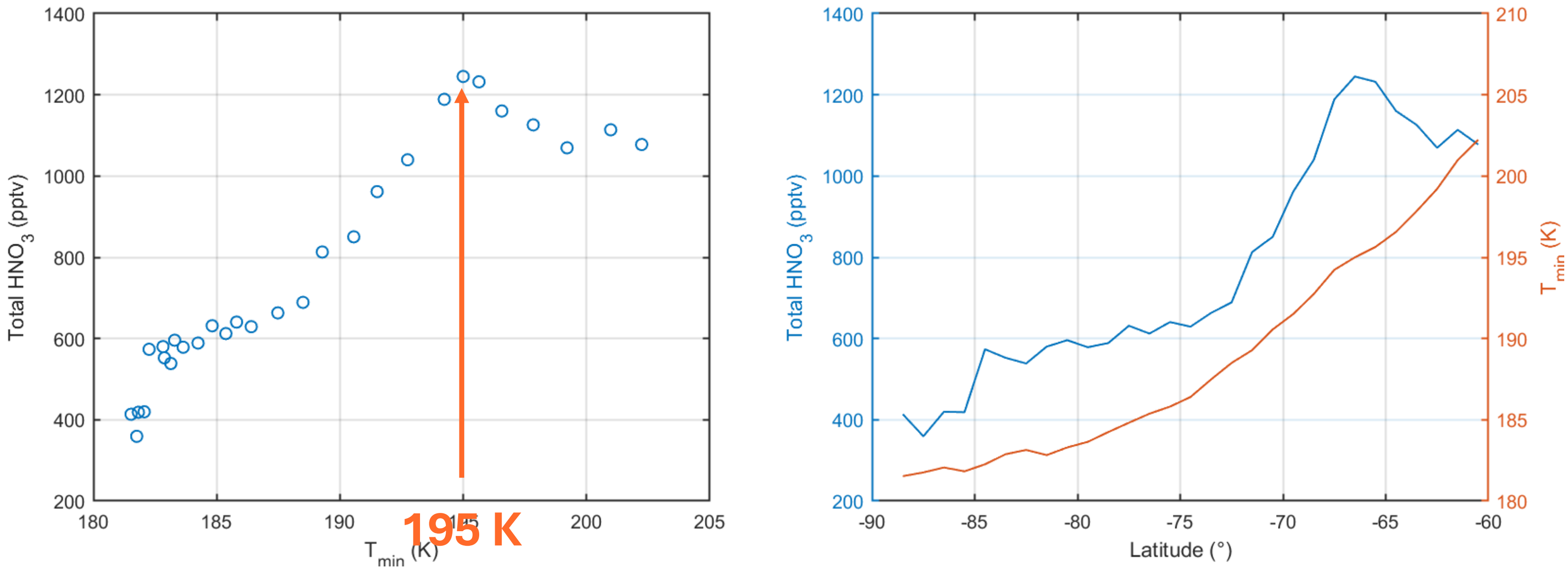

# 2021 Total Ozone zonal mean

- OMI and TROPOMI don't cover the pole (Night)
- IASI see a deeper and wider Ozone hole with respect ECMWF.
- Overall, our IASI level 2 data compare better with TROPOMI and MLS-AURA than OMI.
- OMI tends to be more coherent with the ECMWF analysis, could be just the results that OMI total ozone is of the level 3 type.

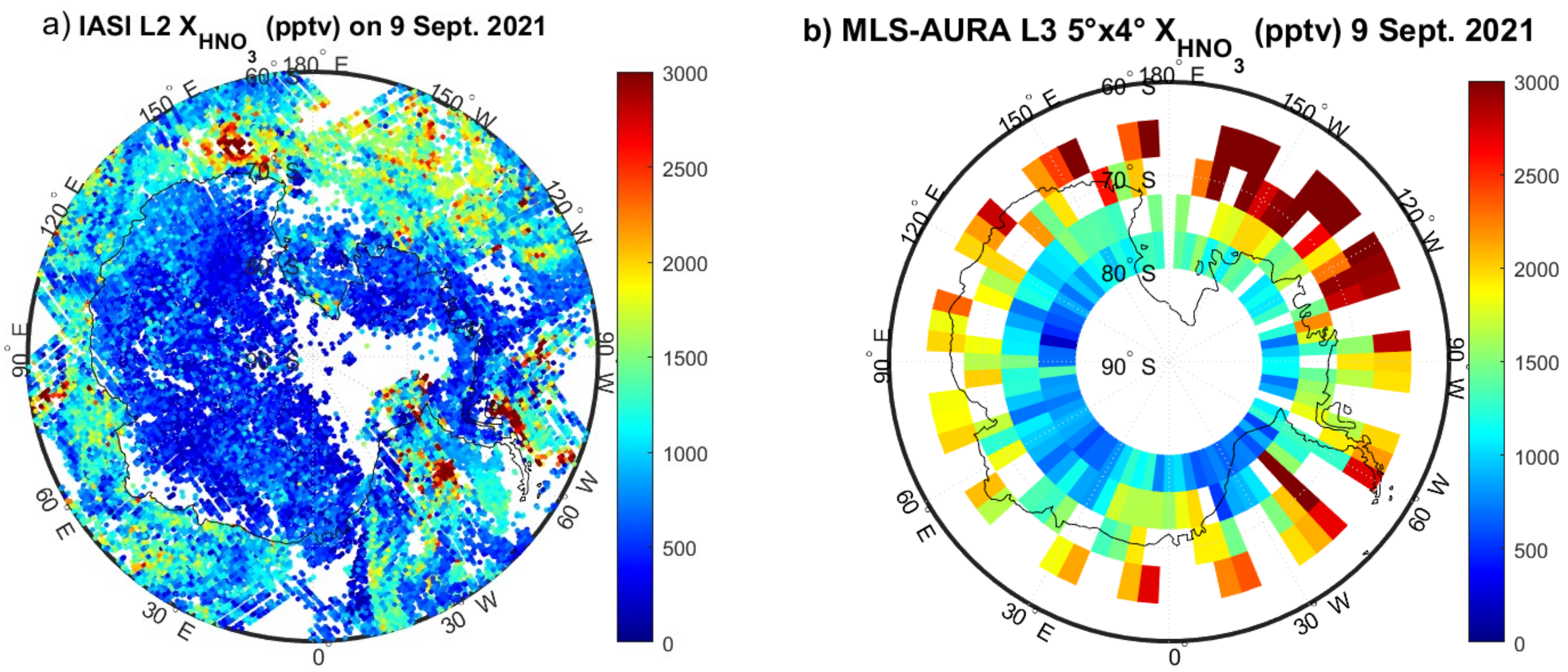



# $P_{min}$, $T_{min}$ & $HNO_3$

- In the inner continent, the temperature is well below 195 K (b)
- Pressure at Temperature inversion ranges 30-60 hPa (a)
- Low amount of HNO3 < 500 pptv in the inner continent (c)
- PSCs formation may lead to the removal of nitric acid from the gas phase.

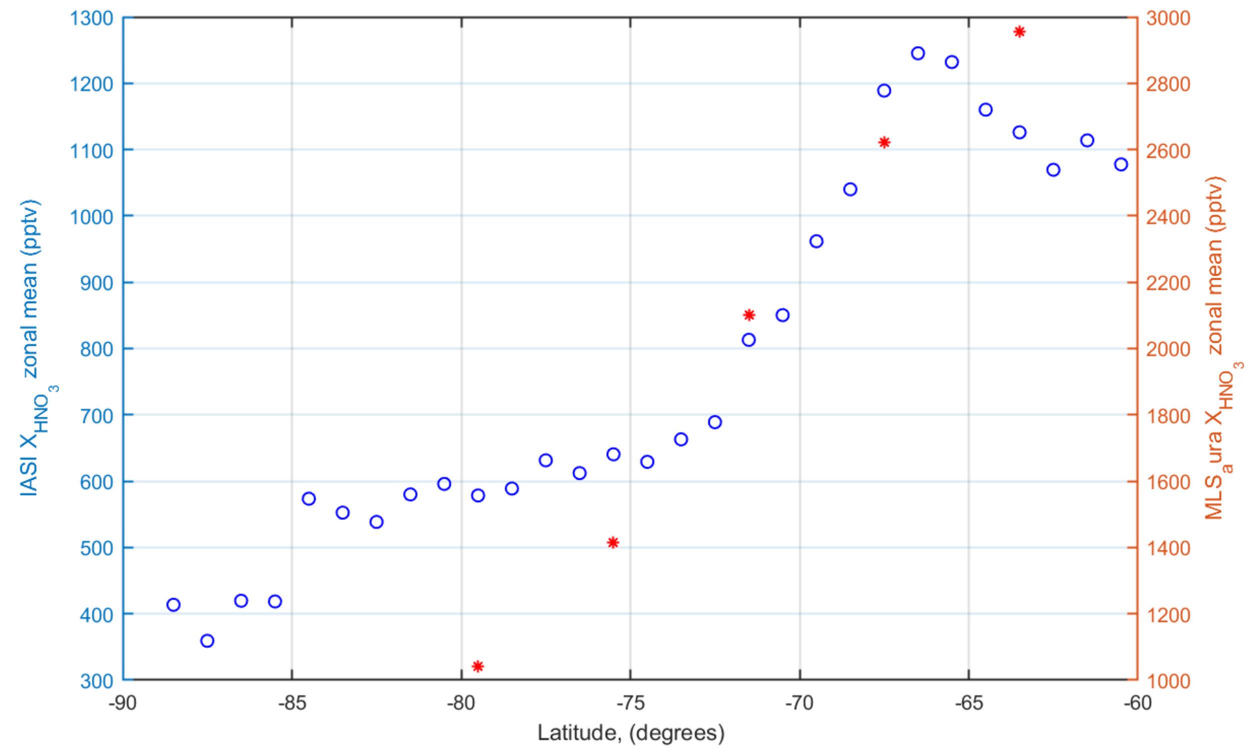



# Zonal Mean of $T_{min}$ & $HNO_3$




# HNO3 (IASI v/s MLS)

- Despite their different viewing geometries and spectral ranges and although the columnar contents are calculated on different columns, IASI and MLS see the same patterns for HNO3.
- Both IASI and MLS instruments observed denitrification over the Antarctica plateau




# HNO3 Zonal average of on 9 Sept. 2021

- left y-axis IASI;
- right y-axis MLS_aura
- Both IASI and MLS instruments observed denitrification over the Antarctica plateau

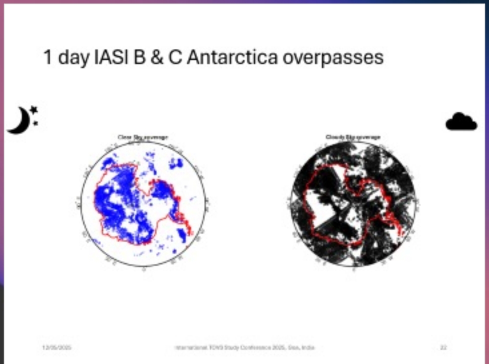
# Conclusions

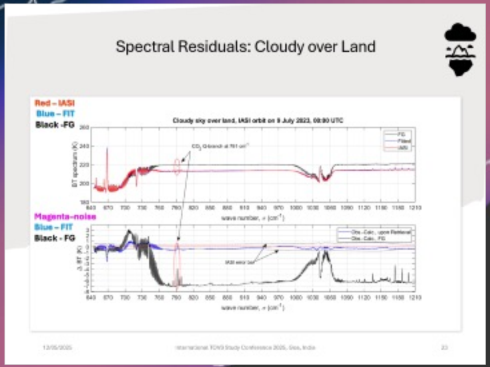
- **ϕ-IASI-F2N:** we developed a system integrating a direct and inverse models. The scheme simultaneously retrieve cloud optical properties, the atmosphere's thermodynamic, and composition state for the clear-cloudy sky
- **Infrared Instrument Importance**: Infrared instruments like IASI are crucial for improving the night/day coverage and spatial resolution of trace gases, enhancing our understanding of ozone depletion in the polar atmosphere.
- **Ozone Hole and Denitrification**: The onset of the ozone hole in September 2021 and 2023 (not shown here) was accompanied by significant denitrification of the polar atmosphere.
- **Instrument Agreement**: Both IASI (infrared) and MLS_aura (microwave) instruments observed this denitrification, despite their different viewing geometries and spectral ranges.
- **NAT/PSC Clouds**: NAT PSC clouds catalyzed ozone destruction, contributing to the overall ozone hole.

ozone hole

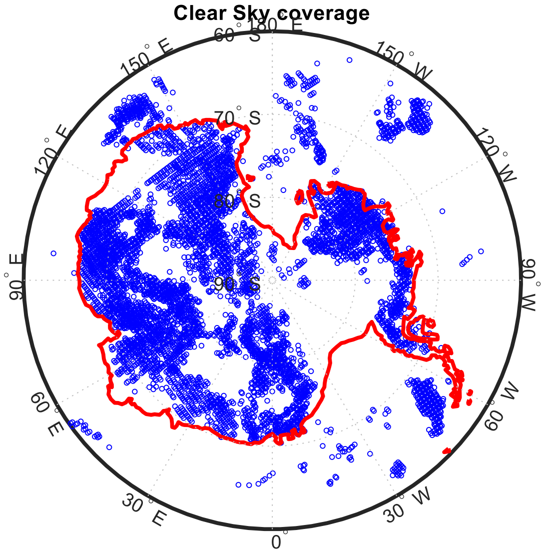
Antarctica

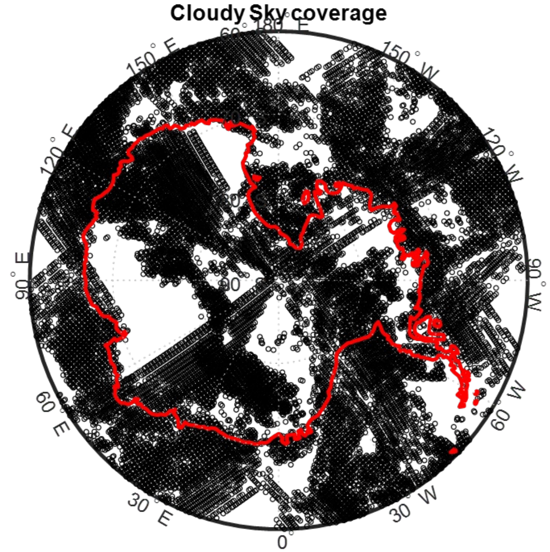
# Back-up Slides



# 1 day IASI B & C Antarctica overpasses



# Spectral Residuals: Cloudy over Land