

# Volcanic SO<sub>2</sub> Height Retrieval From UV Satellite Measurements

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K. Michailidis<sup>3</sup>, D. Balis<sup>3</sup>, C. Li<sup>2</sup>, N. Krotkov<sup>2</sup>, D. Loyola<sup>1</sup>

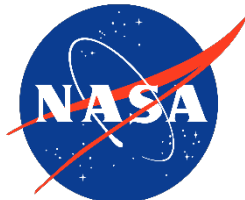
<sup>1</sup>DLR-IMF, Germany

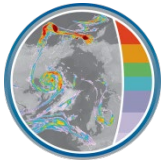
<sup>2</sup>NASA, University of Maryland, College Park, MD, USA

<sup>3</sup>Aristotle University of Thessaloniki, Greece

<sup>4</sup>ECMWF/CAMS, UK

24 May 2022





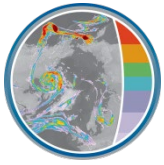
# SO<sub>2</sub> column retrieval

- Based on UV earthshine measurements:
  - SO<sub>2</sub> SCD via DOAS, PCA, etc
  - SO<sub>2</sub> VCD via AirMassFactor (AMF)
- AMF requires assumption about SO<sub>2</sub> profile
  - **Unknown**, depends on source
  - Operational products contain multiple SO<sub>2</sub> VCDs for different scenarios

## TROPOMI & GOME2 SO<sub>2</sub> product: **4 VCDs**

- SO<sub>2</sub> at 15km (Explosive eruption)
  - SO<sub>2</sub> at 7km (Moderate eruption)
  - SO<sub>2</sub> at 1km (Weak eruption & degassing)
  - SO<sub>2</sub> in PBL (Anthropogenic pollution)
- 
- **SO<sub>2</sub> LH required to determine true VCD**

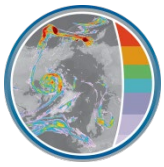




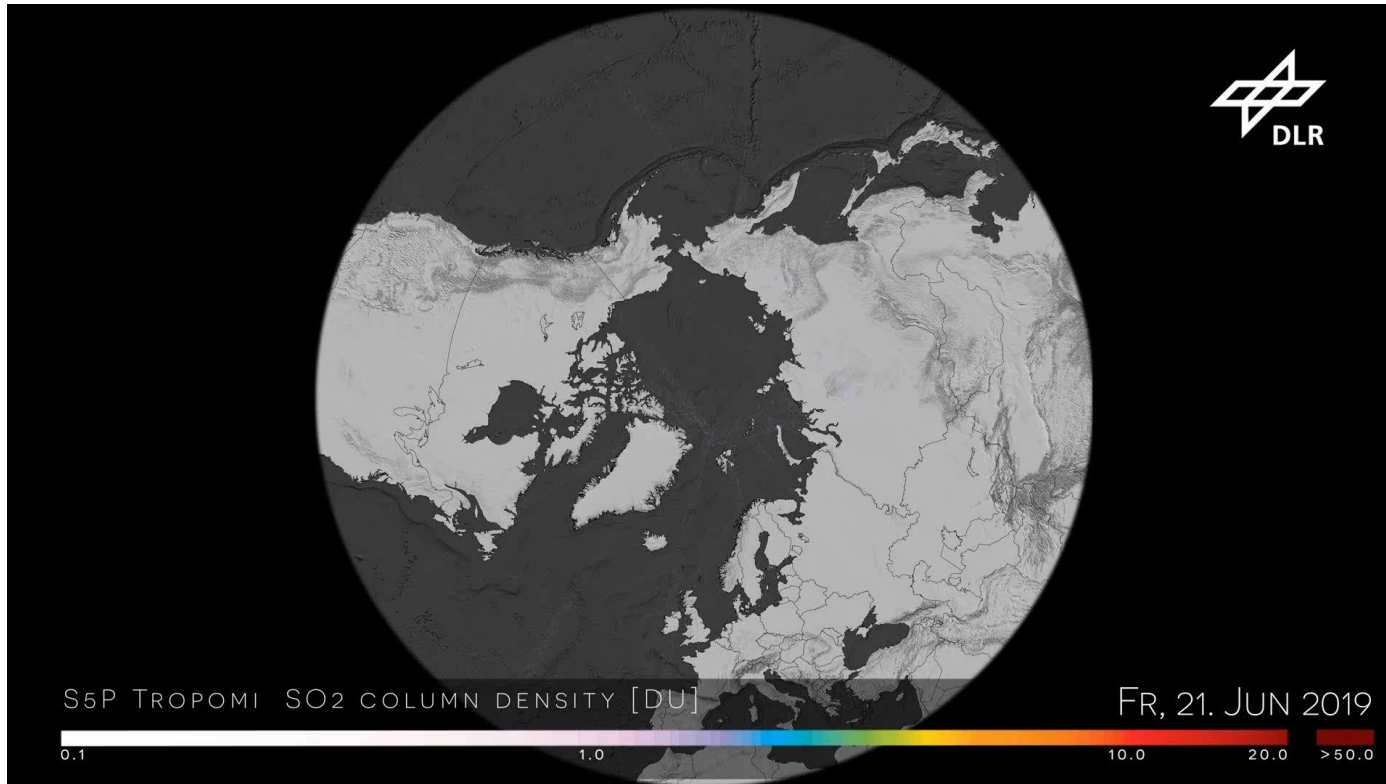
# SO<sub>2</sub> LH retrieval algorithm

## Full-Physics Inverse Learning Machine (FP\_ILM)

- **Combined PCA & NeuralNetwork regression**
  - Trained with simulated UV spectra (310-340nm, LIDORT RRS, Spurr 2008)
- **Extremely fast:** 3min per TROPOMI orbit
- **Accurate:**  $\sigma_{LH} < 2\text{km}$  (SO<sub>2</sub> VCD > 20 DU)
- **Versatile:** Easily applicable to any UV instrument (GEMS, S4, S5, ...)
  - Metop/GOME-2 (Efremenko et al. 2017)
  - S5p/TROPOMI (Hedelt et al. 2019)
  - AURA/OMI (Fedkin et al. 2020)
- **Optimized** in framework of **ESA S5P+I: SO2LH** project
- **Validated** against IASI / CALIPSO (Koukouli et al. 2022)
- **Semi-operational SO<sub>2</sub> LH retrieval (hourly):** DLR-INPULS project
- **Assimilation** by ECMWF/CAMS (Inness et al. 2022)



# Raikoke eruption in June/July 2019



- Massive eruption on 21/22 June 2019
- High-altitude ash & SO<sub>2</sub> plume reaching stratosphere
- SO<sub>2</sub> plume detectable until September 2019

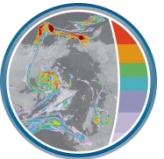


Chart 4

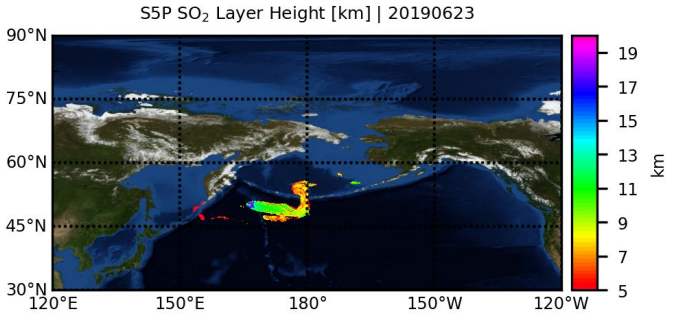


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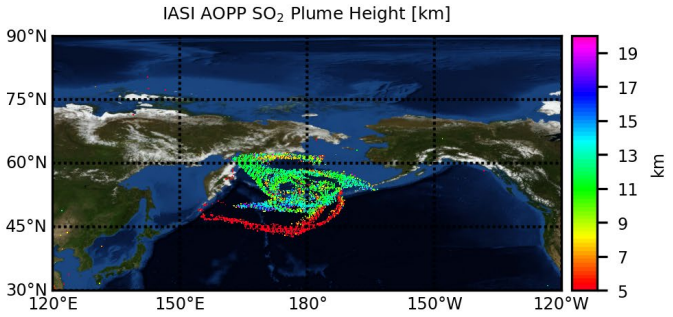
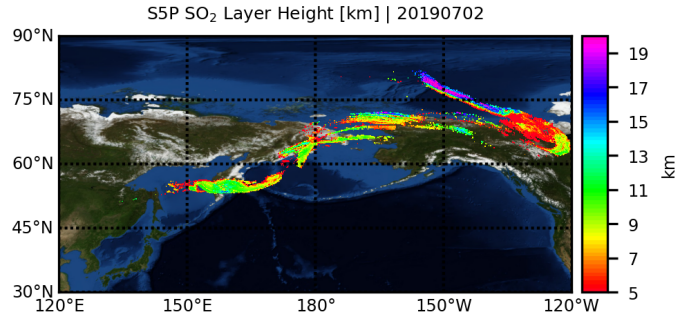




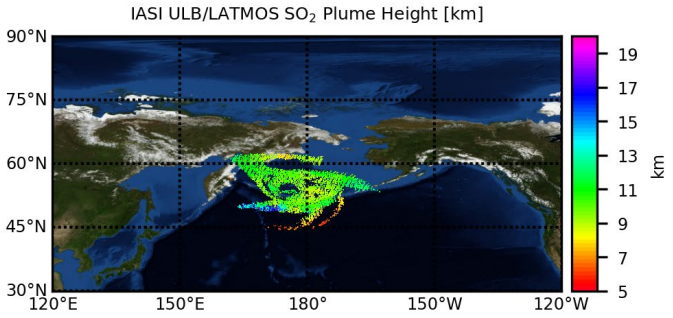
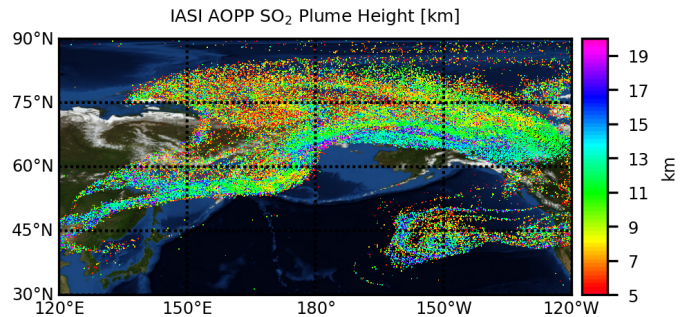
# Raikoke 2019: Validation against IASI SO<sub>2</sub> LH products



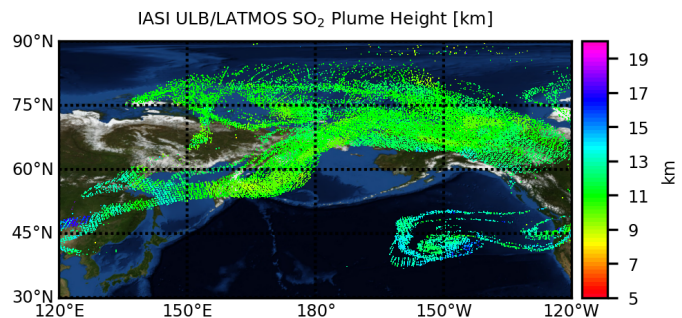
S5P

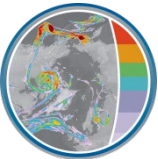


IASI AOPP



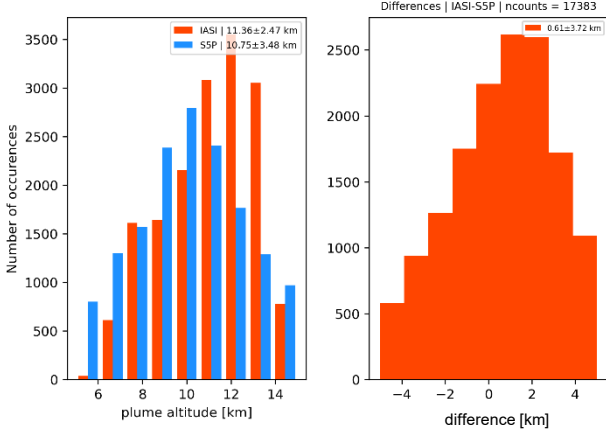
IASI ULB



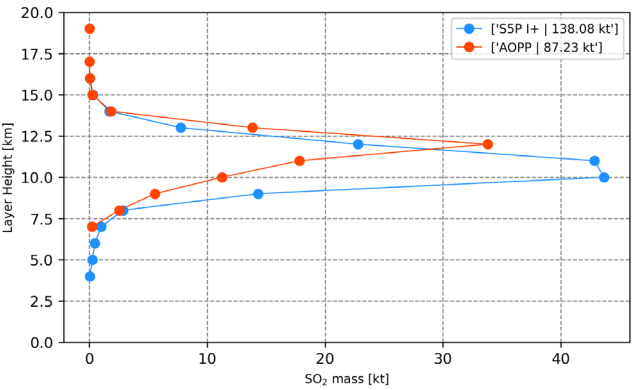


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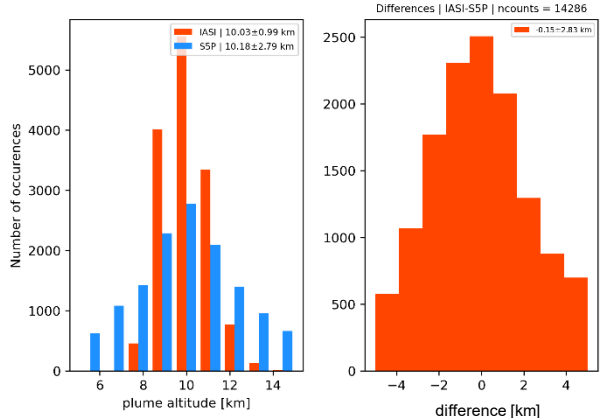
S5P LH v4.0 vs IASI AOPP Raikoke



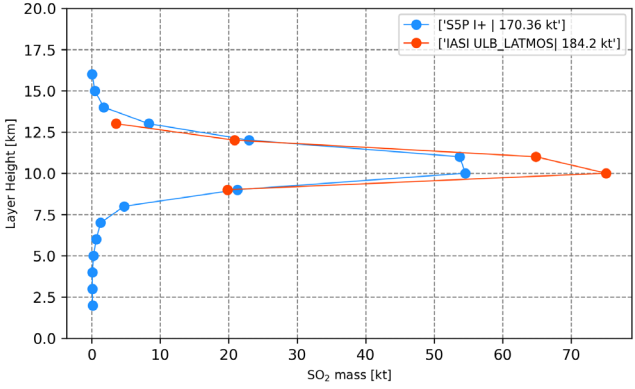
20190624 | Raikoke



S5P LH v4.0 vs IASI ULB\_LATMOS Raikoke

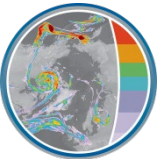


20190624 | Raikoke

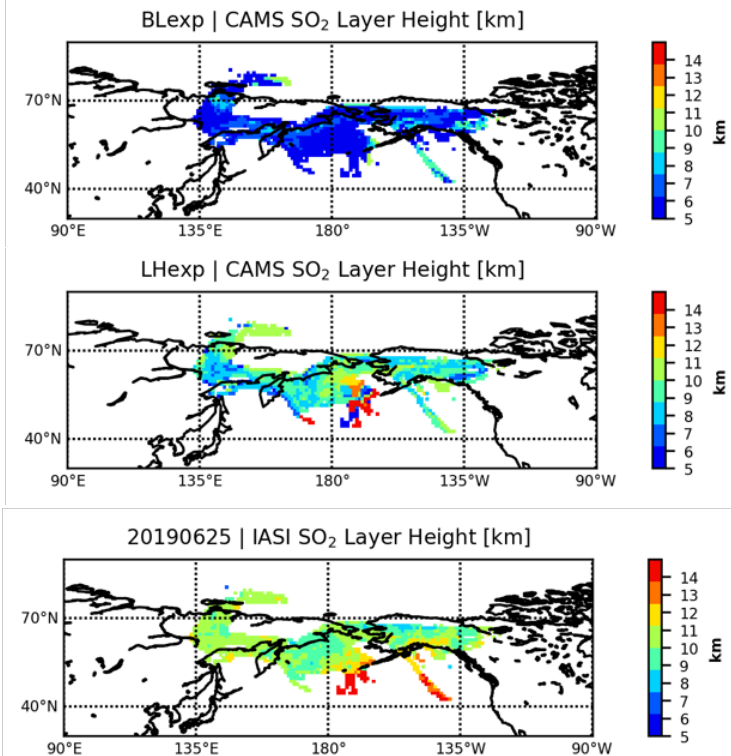
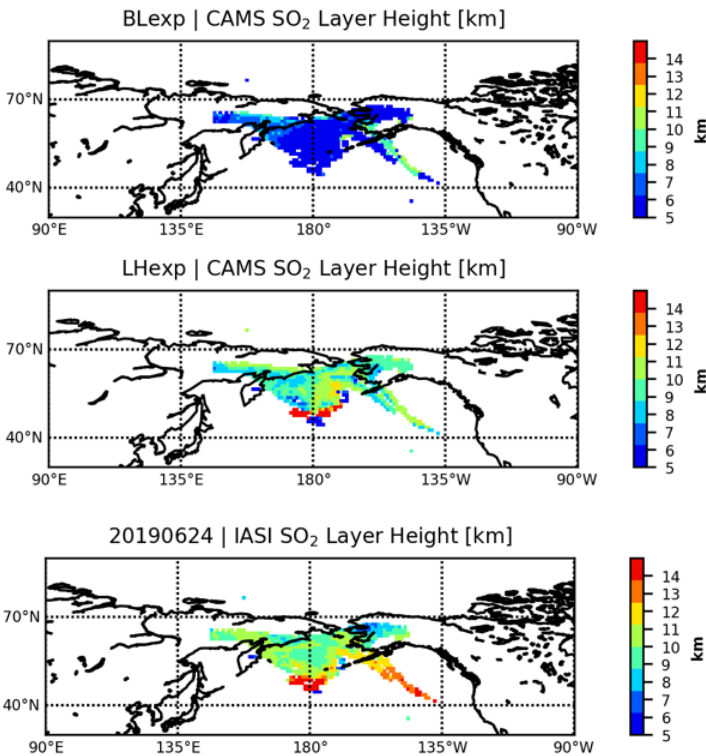


→ Mean LH difference between sensors ~ ±0.5±3km (Koukouli et al. 2022)





# Raikoke 2019: ECMWF/CAMS assimilation



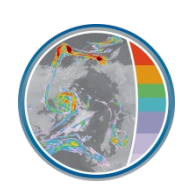
Assimilation of S5P SO<sub>2</sub> LH product by CAMS (Inness et al. 2022)

→ Vast improvement of CAMS forecast when S5P SO<sub>2</sub> LH data is used (LHexp)

→ CAMS forecast vs IASI:  $-1.5 \pm 2.5\text{km}$  (BLexp:  $-5 \pm 2\text{km}$ )







# Cumbre Vieja eruption Sept - Dec 2021



- Eruptive phase: 19 Sept to 12 Dec 2021
- Low altitude ash & SO<sub>2</sub>



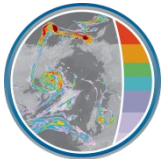
Chart 8



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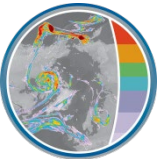




# Cumbre Vieja eruption Sept - Dec 2021

## TROPOMI SO<sub>2</sub> VCD



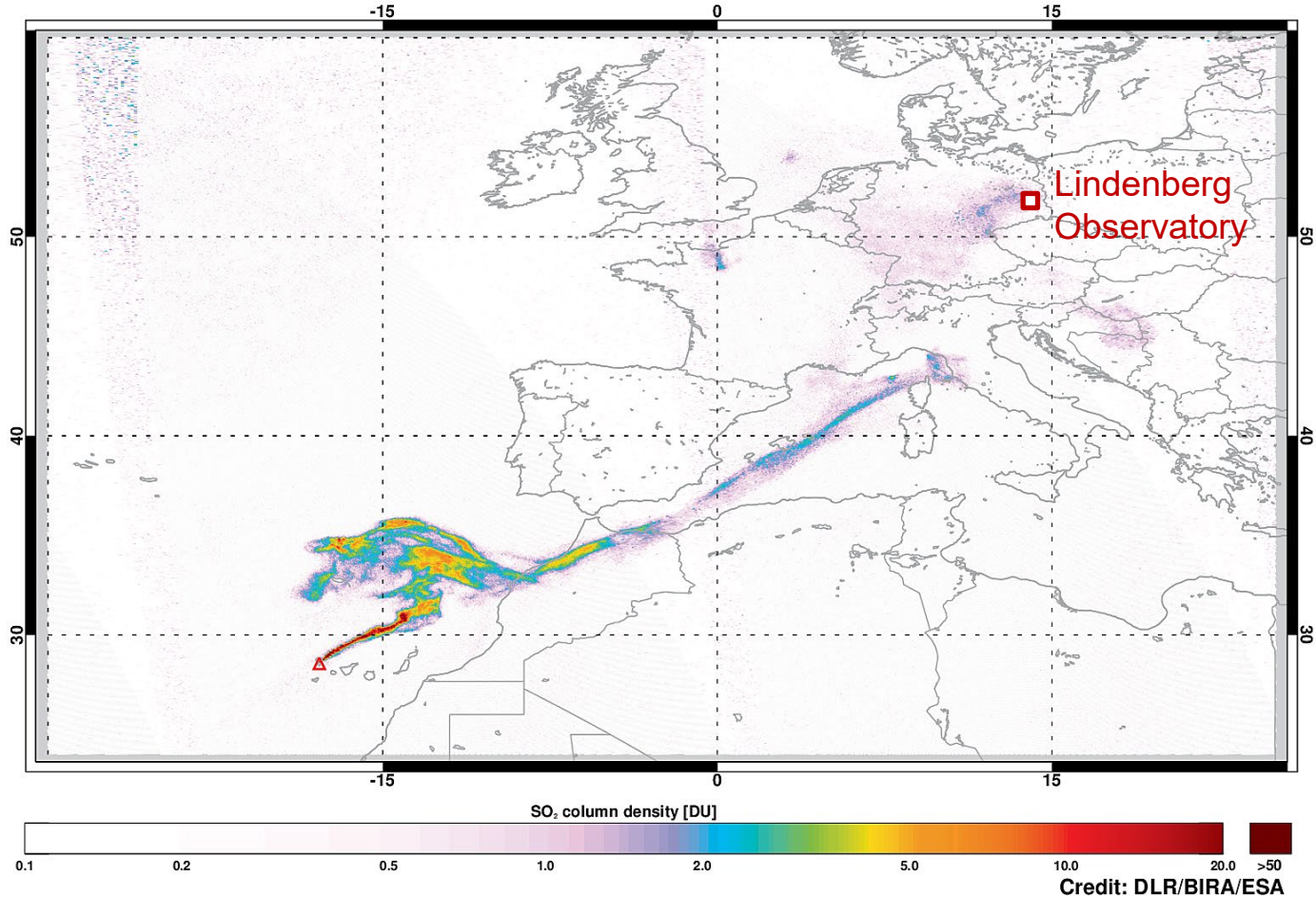


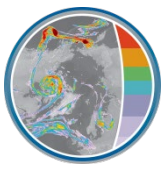
# Cumbre Vieja eruption 26 Sept 2021

## TROPOMI SO<sub>2</sub> VCD



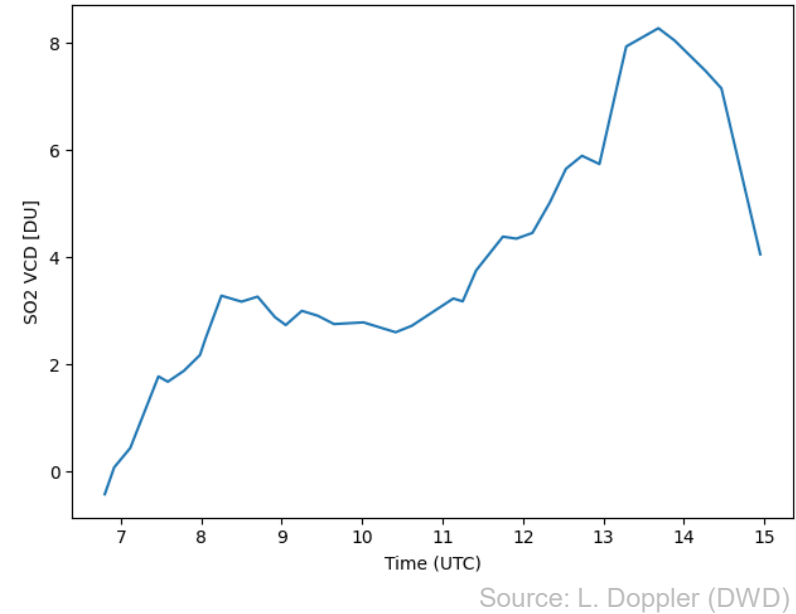
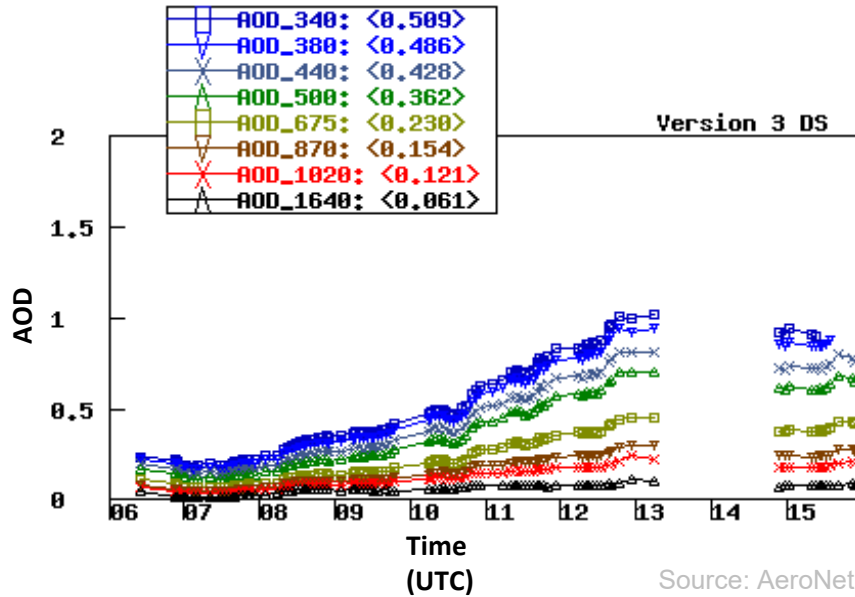
Sentinel-5 Precursor  
26/09/2021  
Cumbre Vieja





# Lindenberg Observatory (Germany)

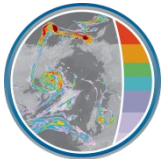
## Brewer measurements on 26 Sept. 2021



- Detection of increased AOD and SO<sub>2</sub> on 26 Sept. 2021
- Maximum at about 14:00 UTC

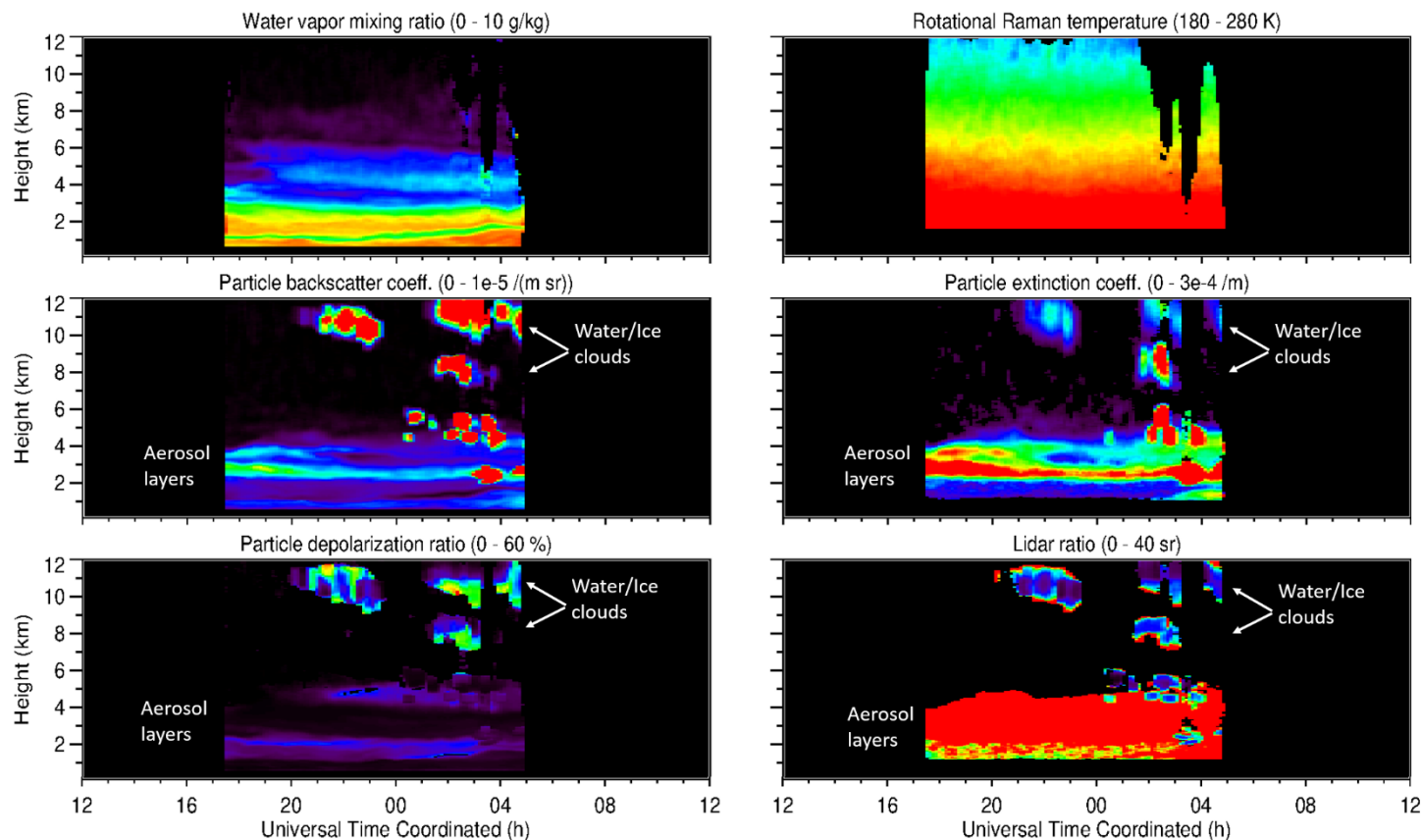






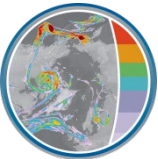
# Lindenberg Observatory (Germany)

## Raman-LIDAR measurements 26/27 Sept. 2021



- Detection of aerosol layers at 2-5km below patchy water/ice clouds
- Volcanic aerosol: Strong extinction, low depolarization ratio, high Lidar ratio

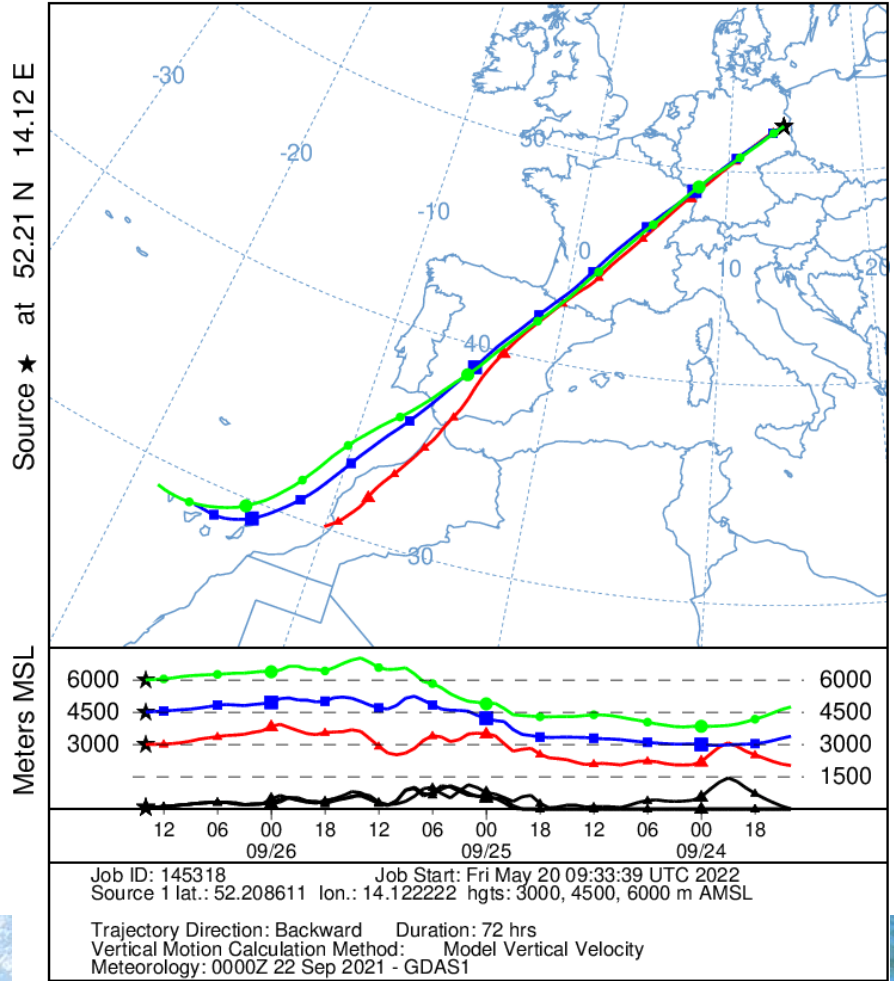


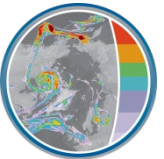


# Cumbre Vieja eruption Backward trajectories

- HySplit back-trajectories from Lindenberg Observatory
- Starting altitude: 4 – 6 km
- Starting time: 14:00 UTC
- Injection at Cumbre Vieja: 23 September 2021
- Injection height @ CumbreVieja 3 – 5 km

NOAA HYSPLIT MODEL  
Backward trajectories ending at 1400 UTC 26 Sep 21  
GDAS Meteorological Data

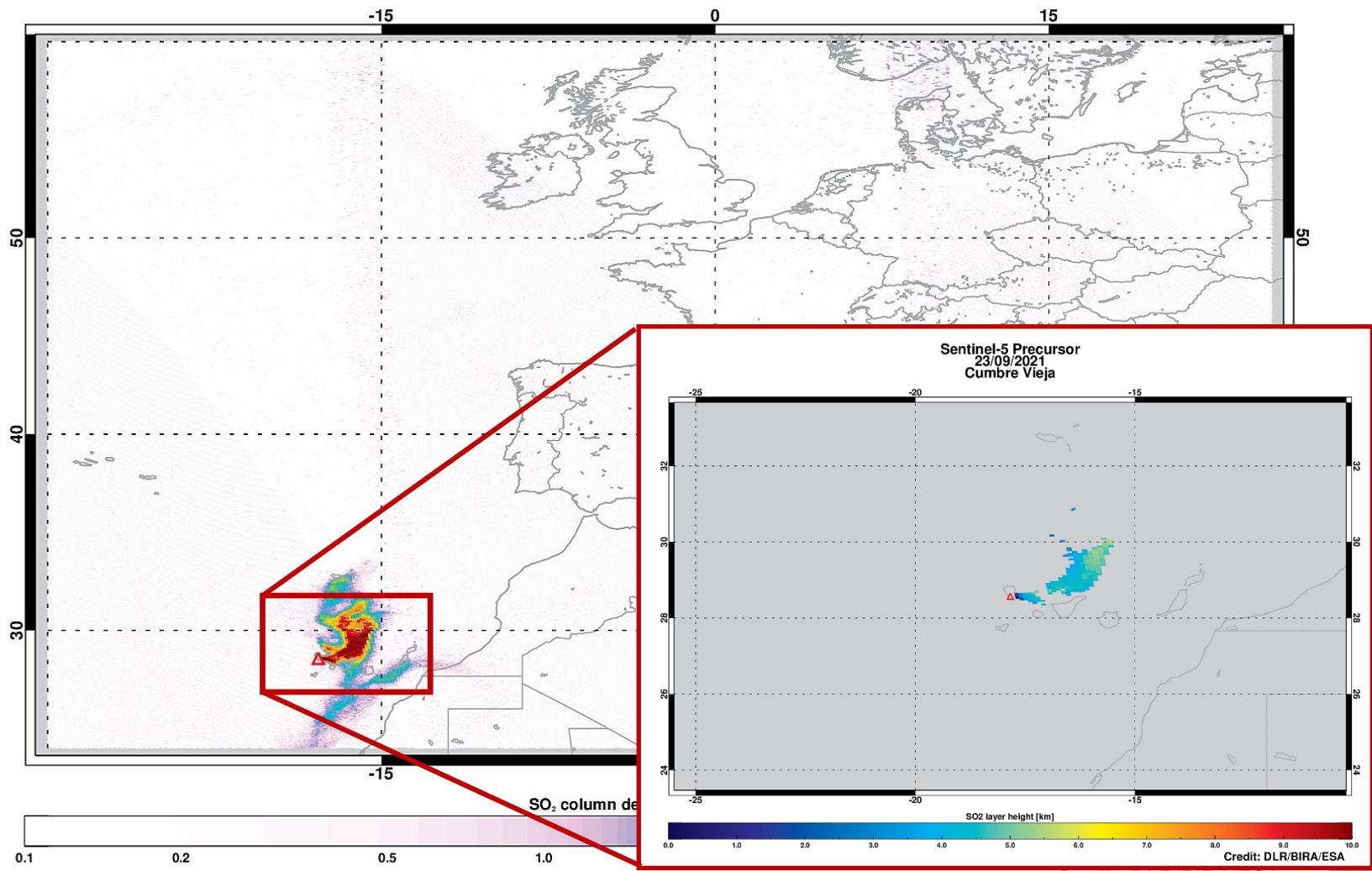




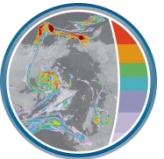
# Cumbre Vieja eruption 23 Sept. 2021

## TROPOMI SO<sub>2</sub> VCD & LH

Sentinel-5 Precursor  
23/09/2021  
Cumbre Vieja





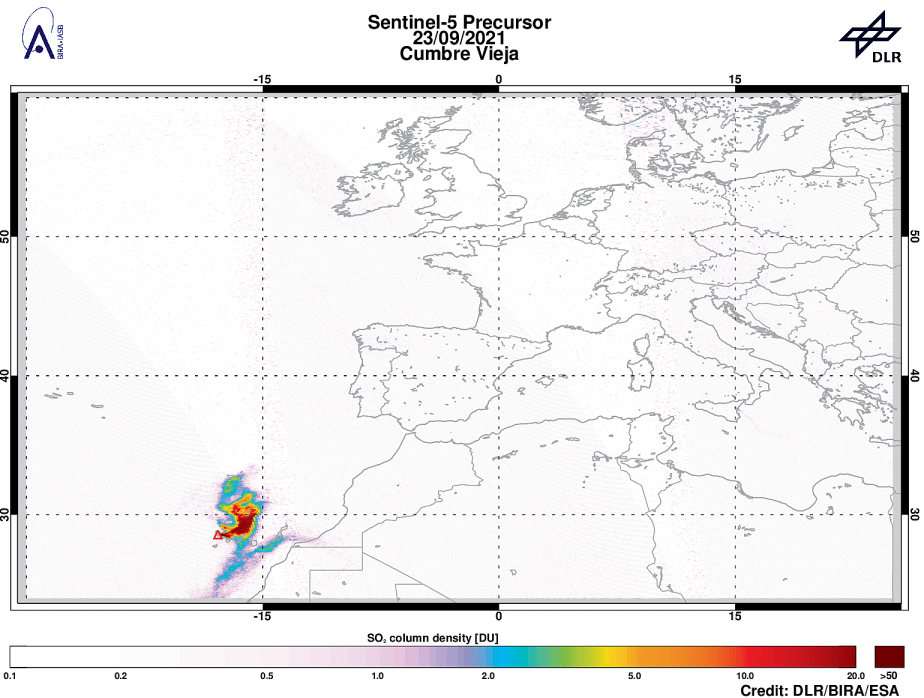
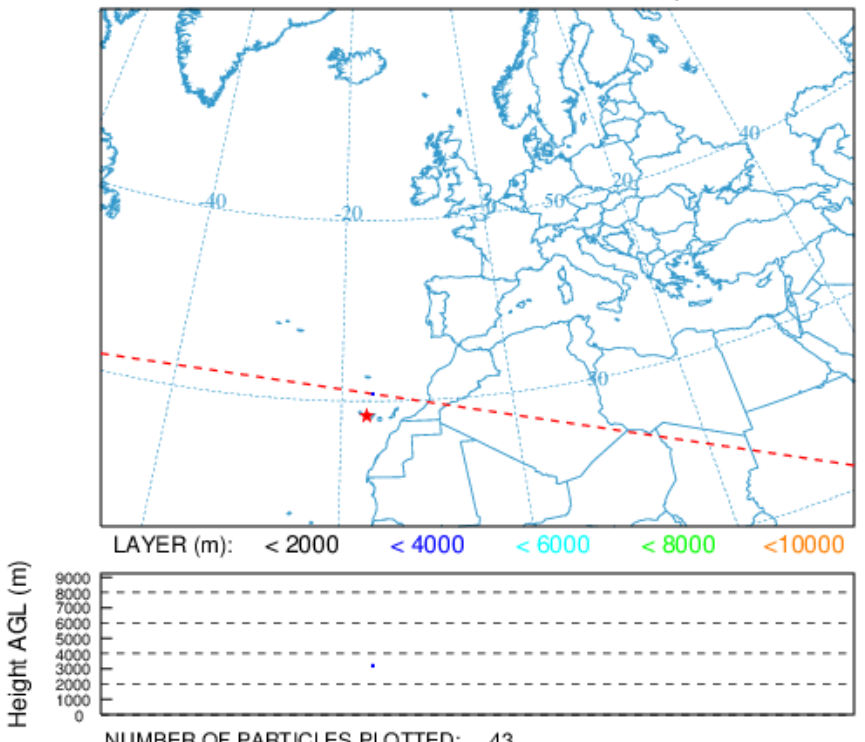


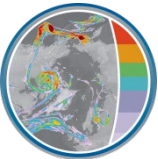
# Cumbre Vieja eruption 2021

## HySplit simulations

- HySplit forward calculations starting from Cumbre Vieja
- Run duration: 23 – 26 September 2021
- Particles launched at TROPOMI SO<sub>2</sub> pixel locations / time / SO<sub>2</sub> LH

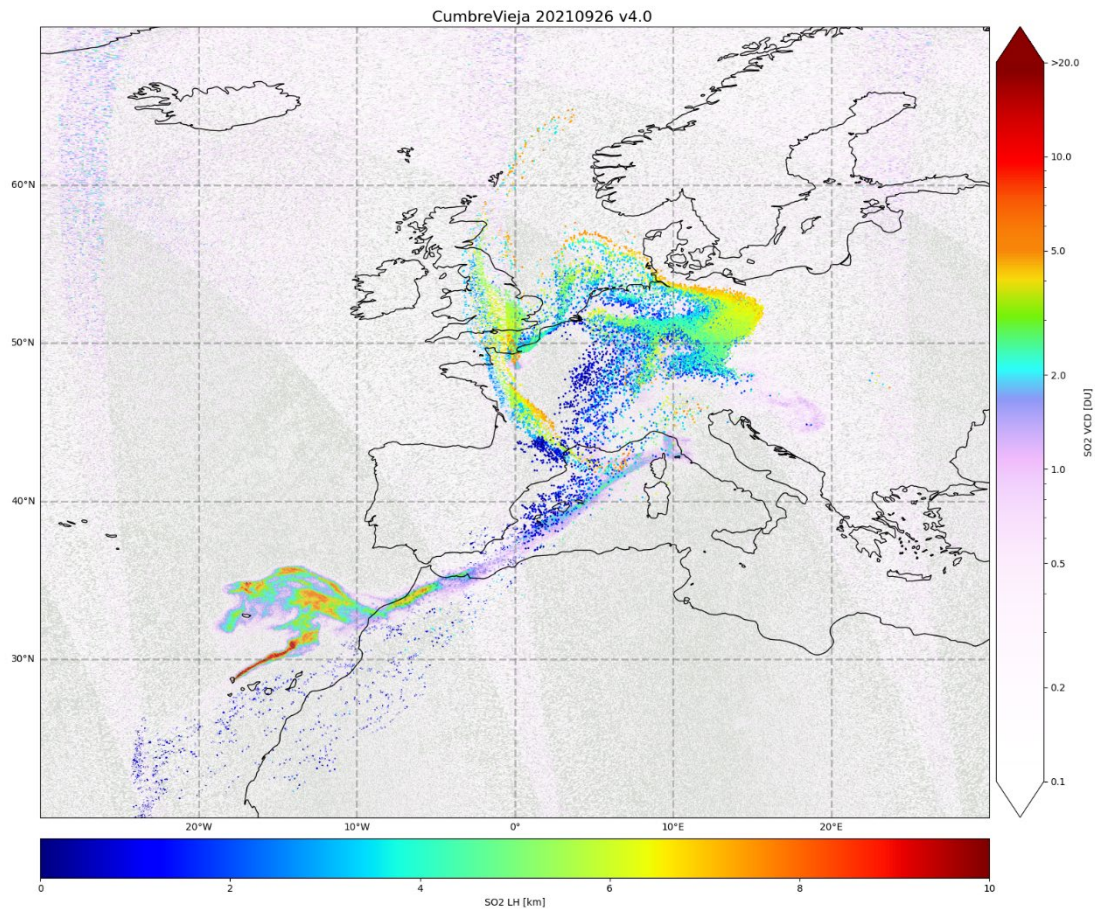
NOAA HYSPLIT MODEL  
PARTICLE CROSS-SECTIONS  
PARTICLE POSITIONS AT 14 00 23 Sep 21





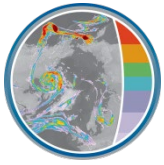
# Cumbre Vieja eruption – 26 Sept 2021

## TROPOMI VCD vs HySplit simulations



Very good agreement of particle positions and TROPOMI measurements



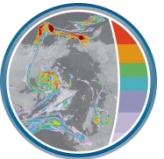


## Conclusion & Outlook

- FP\_ILM algorithm is able to retrieve SO<sub>2</sub> LH from UV satellite data
  - **Extremely fast and accurate**
  - **Versatile** (TROPOMI, GOME-2, OMI)
  - **Quasi-operational** retrieval of SO<sub>2</sub> LH
  - Public dataset available on SO<sub>2</sub> LH **project website**:  
<https://atmos.eoc.dlr.de/so2-lh> (Google: Search for “SO2LH”)
- S5p SO<sub>2</sub> LH product is actively **assimilated by ECMWF/CAMS**
- **Raikoke**: Very good agreement with IASI SO<sub>2</sub> LH and CALIPSO
- **Cumbre Vieja**: Preliminary analysis shows very good agreement with ground-based measurements




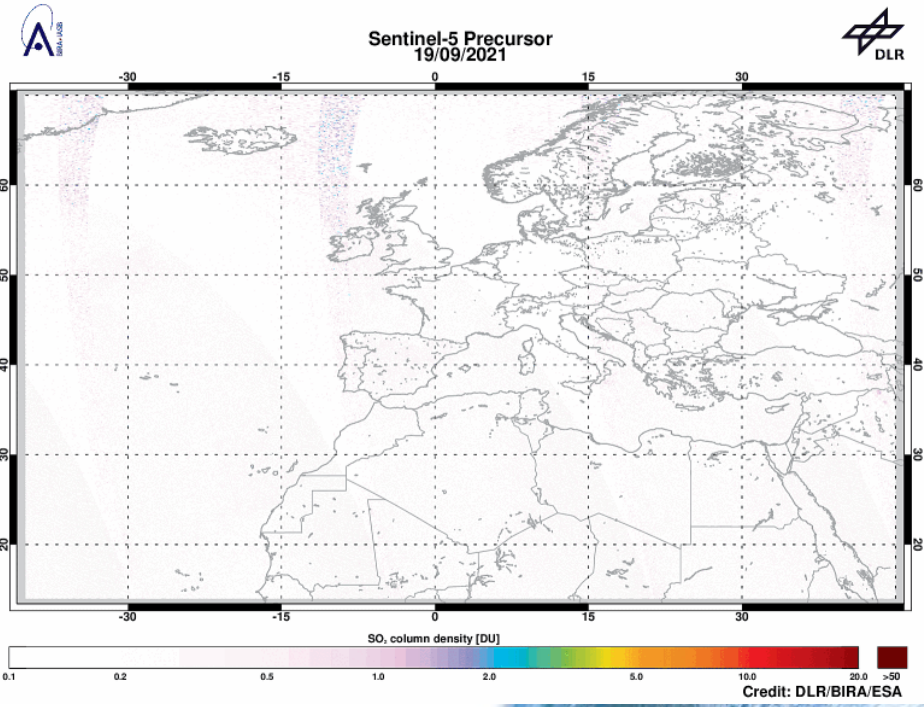




# SO<sub>2</sub> LH: Outreach

- **Twitter** account @DlrSO2: <https://twitter.com/DlrSo2>
- Automatic detection of volcanic eruptions & immediate twitter notification
  - Name of volcano erupted, SO<sub>2</sub> VCD, SO<sub>2</sub> LH, SO<sub>2</sub> mass

 TROPOMI SO2 @DlrSo2 · 23. Nov. Updated animation of #S5p #tropomi SO2 measurements of the #CumbreVieja volcanic eruption from 19 Sept - 22 Nov. Note the extended plume from #Etna on 24 Oct!



 TROPOMI SO2 @DlrSo2

On 2022-04-24 #TROPOMI has detected a strong SO2 signal of 27.10DU at a distance of 130.8km to #Krakatau. @tropomi #S5p #Sentinel5p @DLR\_en @BIRA\_IASB @ESA\_EO #SO2LH

