Volcanic SO_2 Height Retrieval From UV Satellite Measurements

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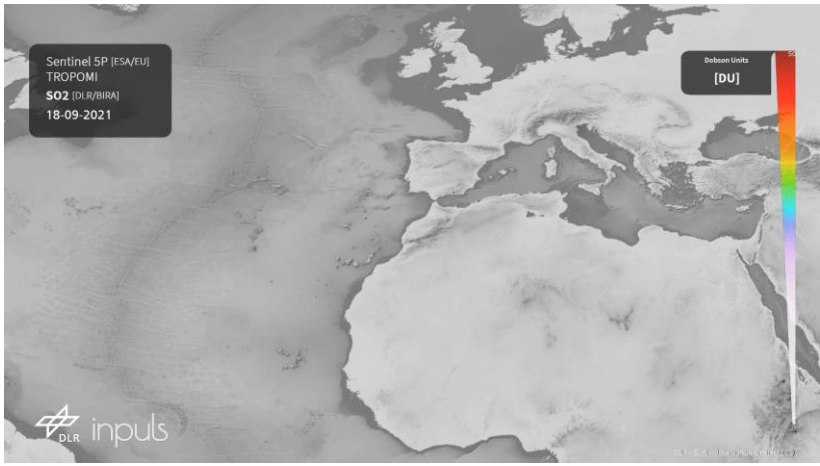
SO_2 column retrieval

- Based on UV earthshine measurements:
  - *Easy* retrieval of SO_2 SCD (DOAS, PCA, etc)
  - Calculation of VCD via AirMassFactor (AMF)
- AMF requires assumption about SO_2 profile
  - Plume height unknown, depending on emission source & strength
  - → Operational products provide SO_2 VCDs for different eruption/emission scenarios
- E.g. S5p & GOME2 SO_2 product: **4 VCDs**
  - Explosive eruption (i.e. @15km)
  - Moderate eruption (i.e. @~7km)
  - Weak eruption & degassing (i.e. @~2km)
  - Anthropogenic pollution (i.e. @PBL)



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SO_2 LH retrieval algorithm
FP_ILM: Full Physics Inverse Learning Machine

- Full-Physics Inverse Learning Machine (FP_ILM)
  - **Extremely fast** and **accurate UV SO_2 layer height retrieval**
  - **Combined PCA & NN algorithm**
  - **Processing speed: ~3ms / pixel (TROPOMI)**
  - **Accuracy: <2km (SO$_2$ VCD > 20 DU)**
  - **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
- **DLR INPULS: Semi-operational NRT** S5p SO_2 LH **retrieval** every hour
  - Assimilated by ECMWF/CAMS

- *D. Efremenko, et al. (2017):* **Volcanic SO_2 plume height retrieval from UV sensors using inverse learning machines** IJRS, Vol 38
- *P. Hedelt, et al. (2019):* **SO_2 Layer Height retrieval from Sentinel-5 Precursor/TROPOMI using FP_ILM,** AMT-2019-13, Vol. 12, No. 10
- *N. M. Fedkin, et al. (2020)*: **Volcanic SO_2 Effective Layer Height Retrieval for OMI Using a Machine Learning Approach**, AMT, Vol14

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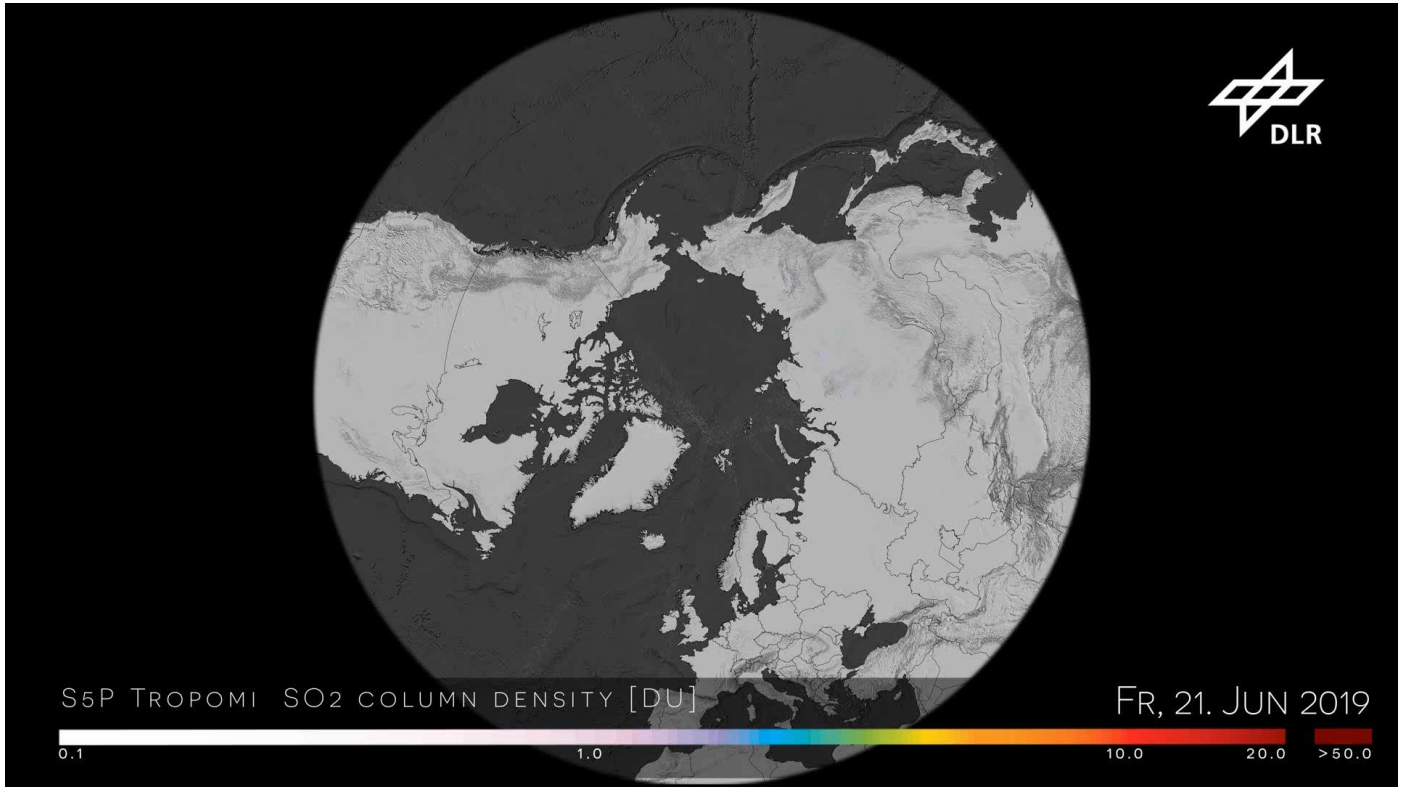
Raikoke eruption in June/July 2019



- Massive eruption on 21/22 June 2019
- High-altitude ash & SO_2 plume reaching stratosphere
- SO_2 plume detectable until September 2019

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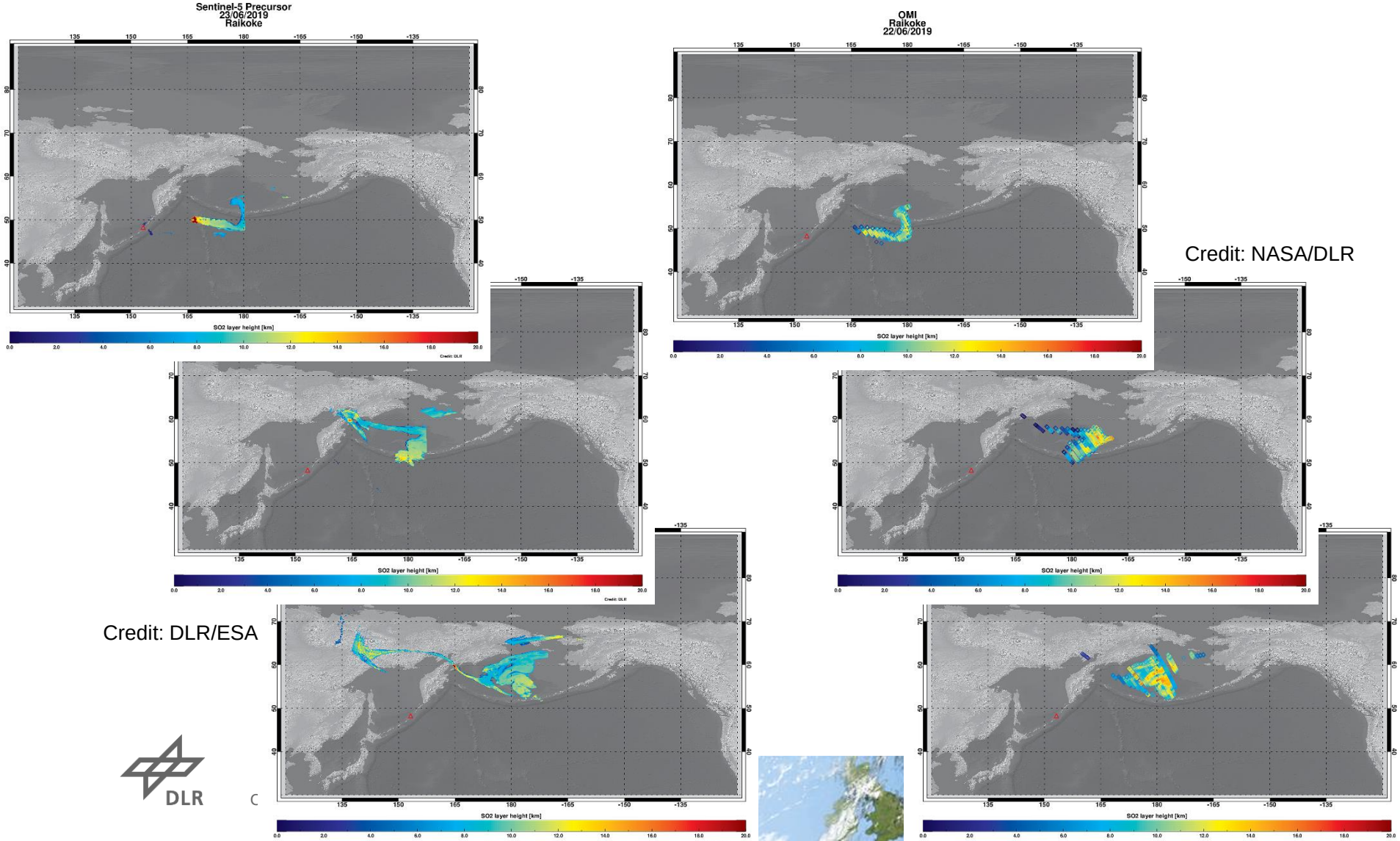
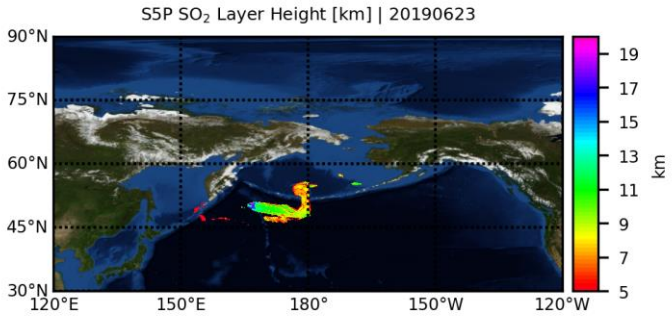
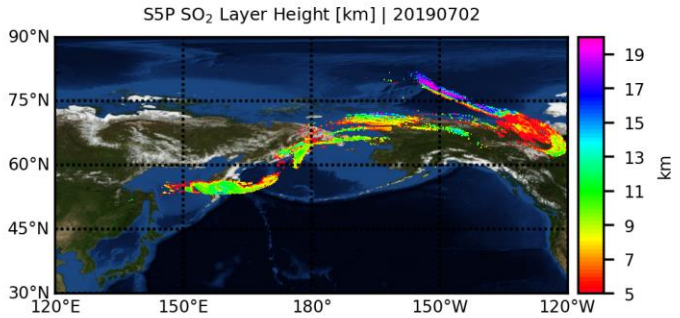
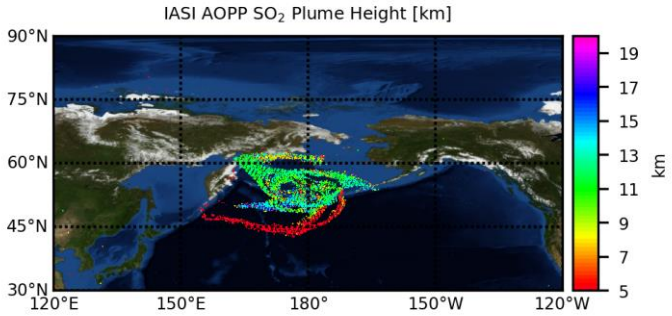
Raikoke 2019:
Comparison S5P LH vs OMI LH

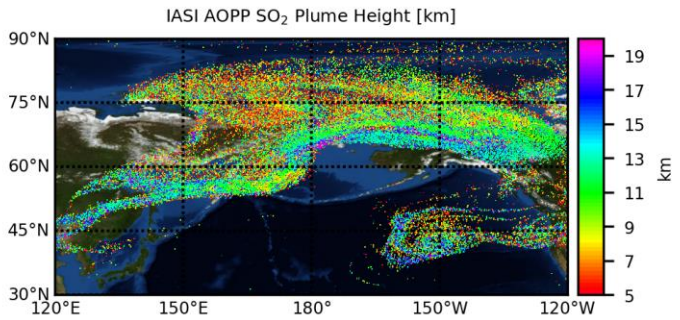


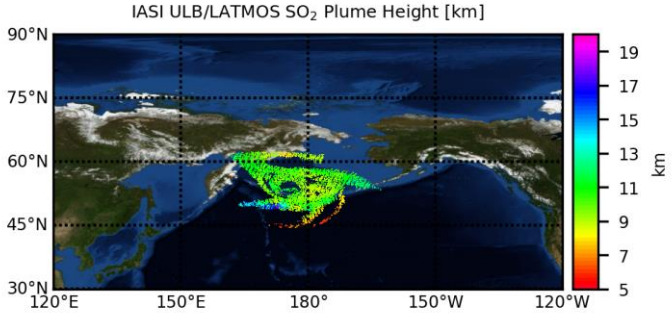
Raikoke 2019:
Validation against IASI SO_2 LH products

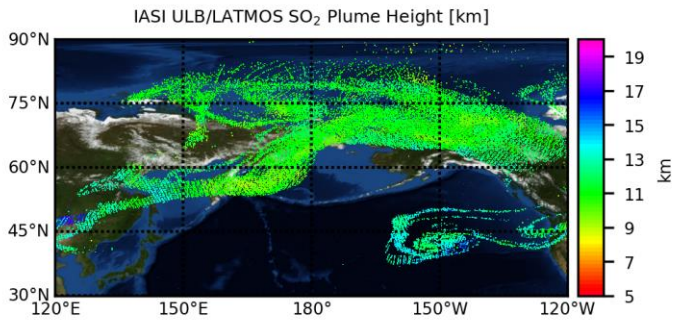












Koukouli et al. (2021, submitted to ACP)

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Raikoke 2019:
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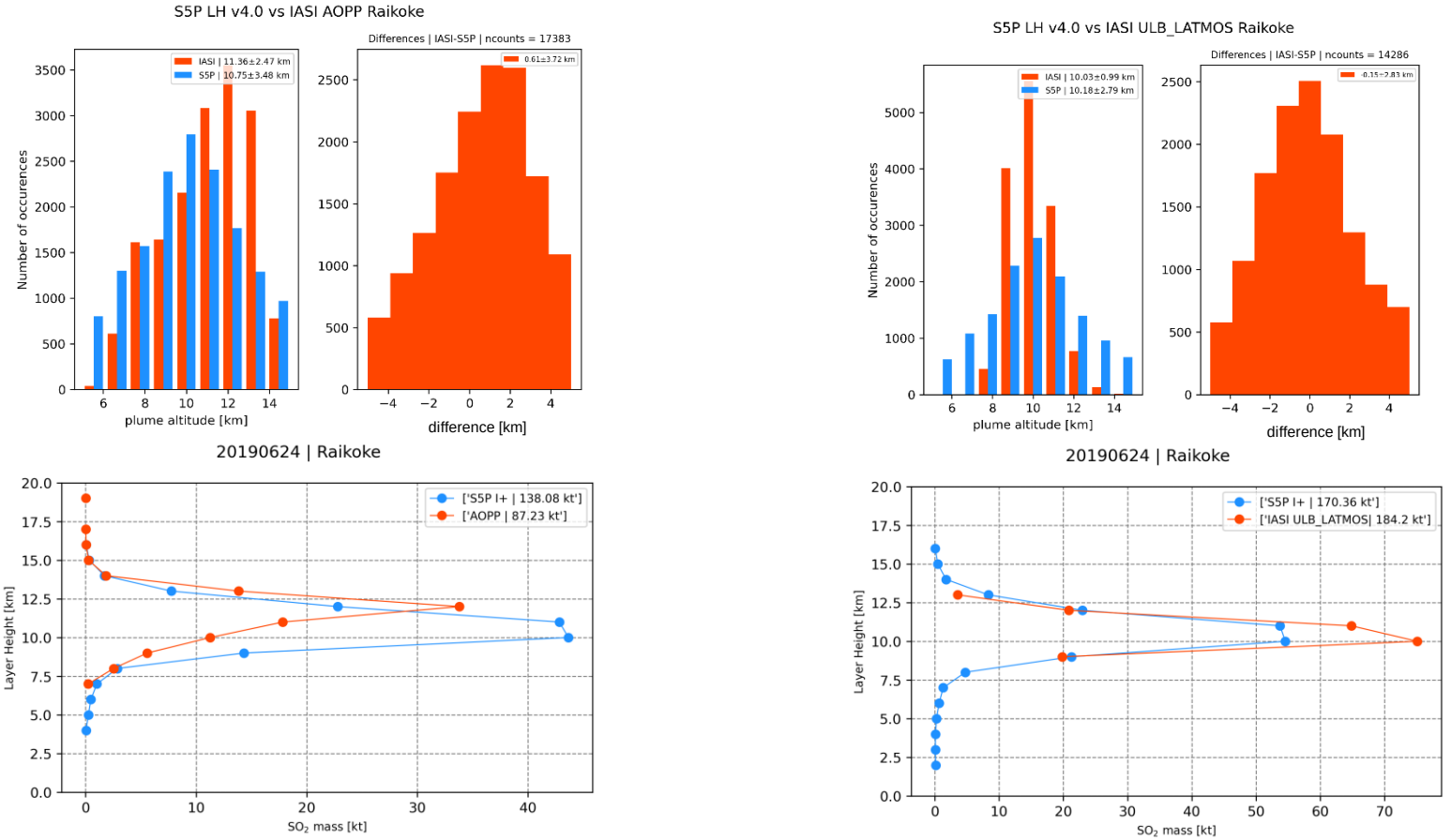
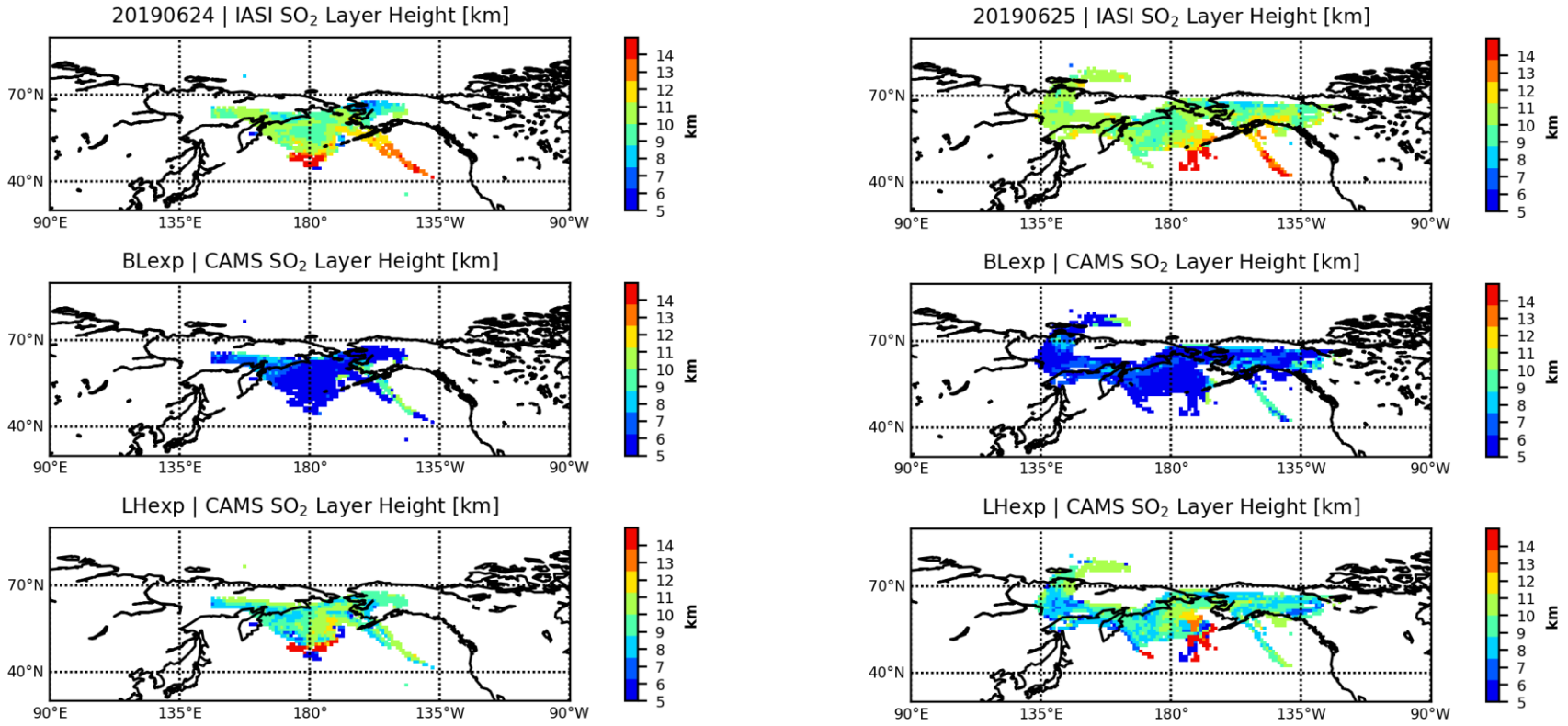


→ Mean LH difference between sensors ~ ±0.5±3km

→ Koukouli et al. (2021, submitted to ACP)

Raikoke 2019:
ECMWF/CAMS assimilation



→ Active assimilation of SO_2 LH product by CAMS

→ Vast improvement of CAMS forecast when S5P SO_2 LH data is used

→ CAMS forecast vs IASI: -1.5 ± 2.5km (Blexp: -5 ± 2km)

→ See Inness et al. (2021, GMD, accepted)

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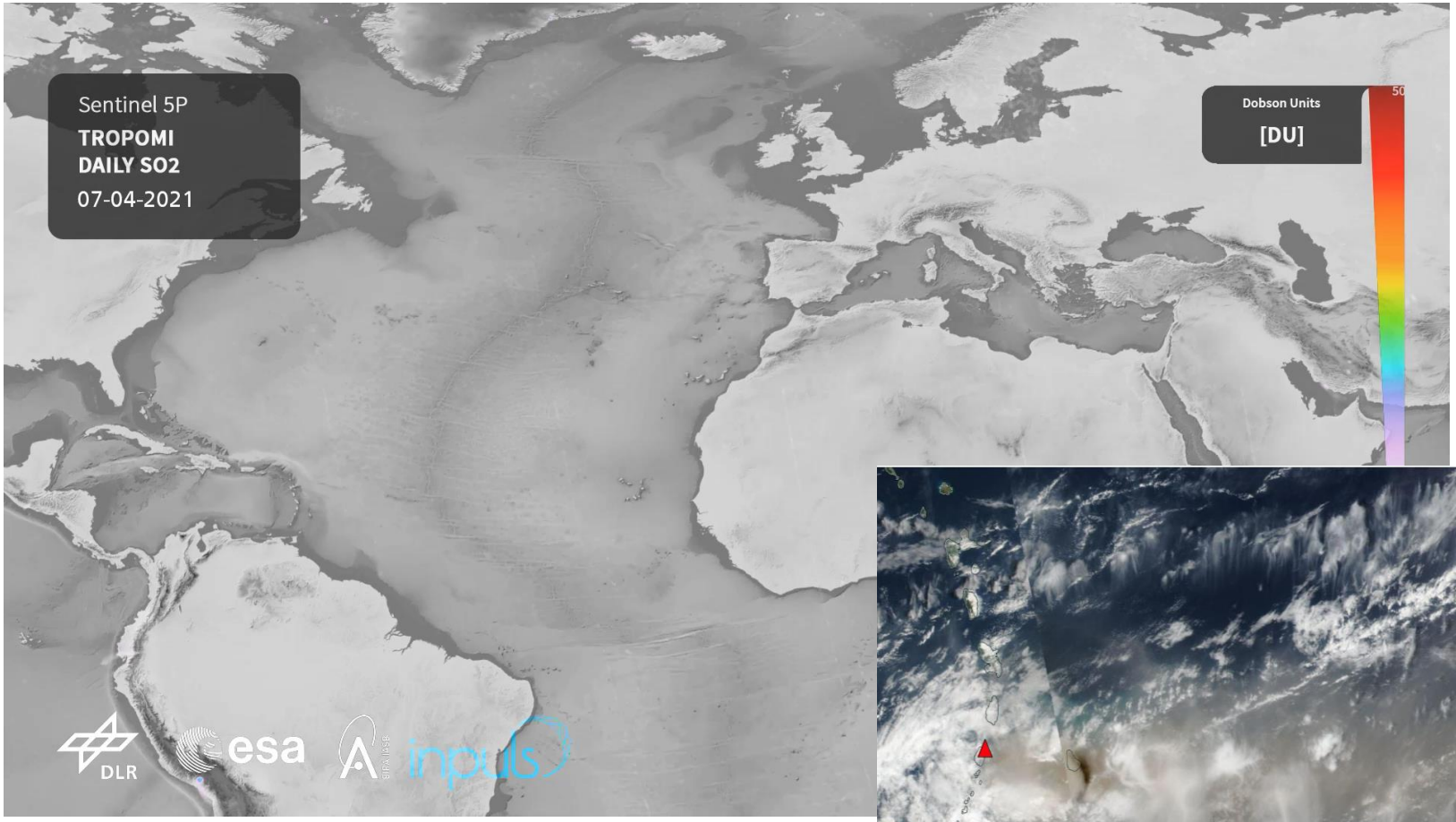
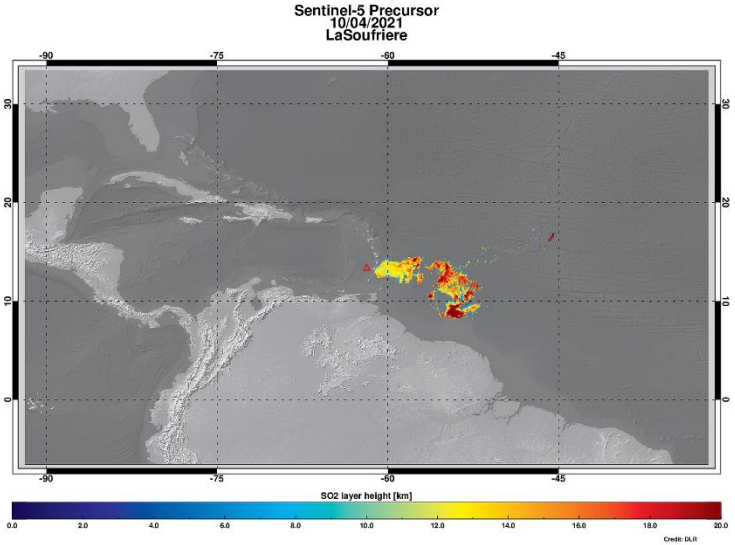
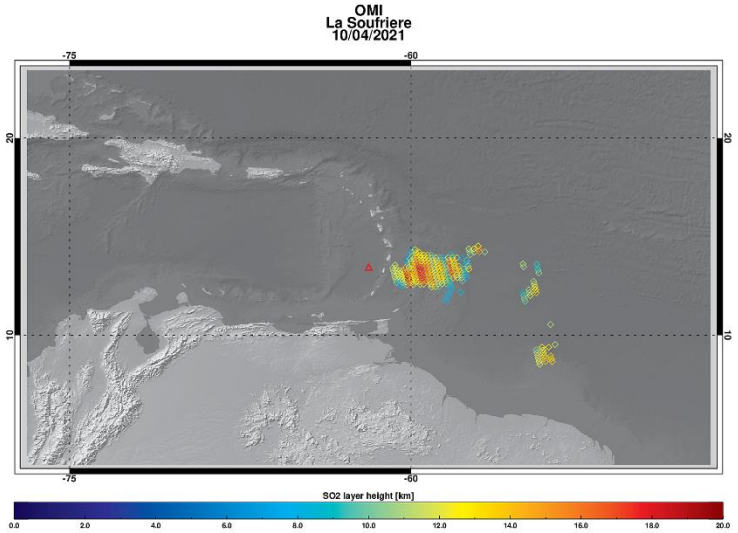
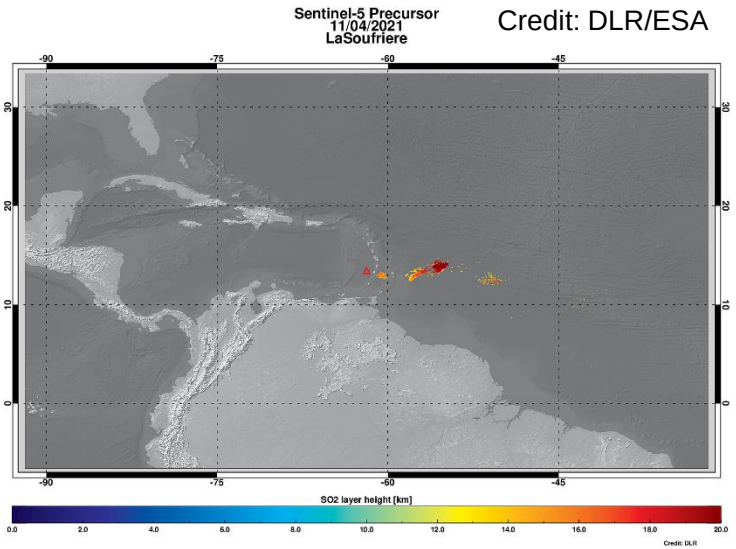
La Soufriere eruption in April 2021



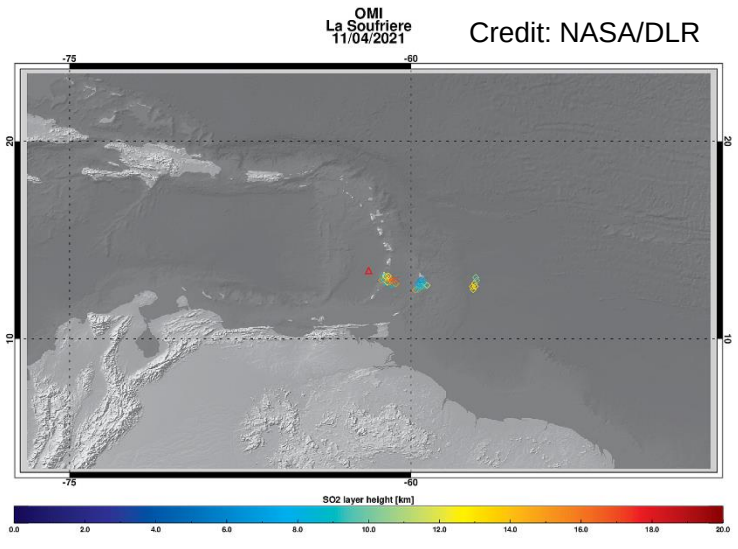
La Soufriere eruption in April 2021
TROPOMI vs OMI





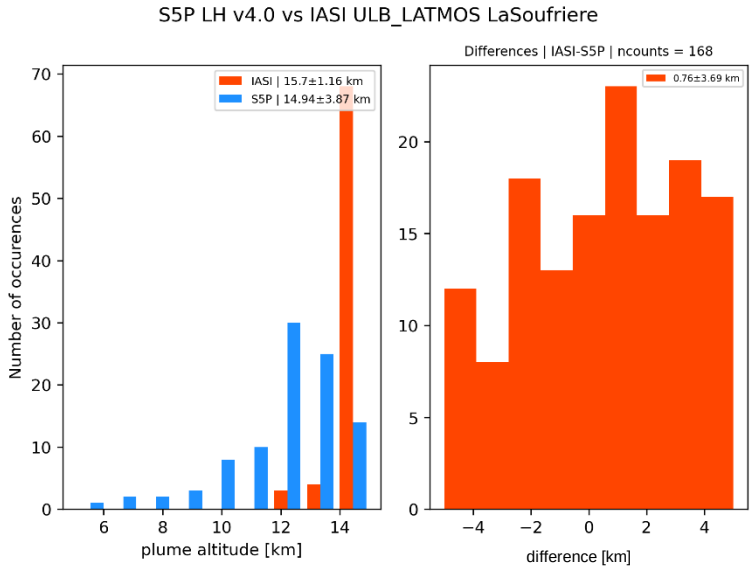


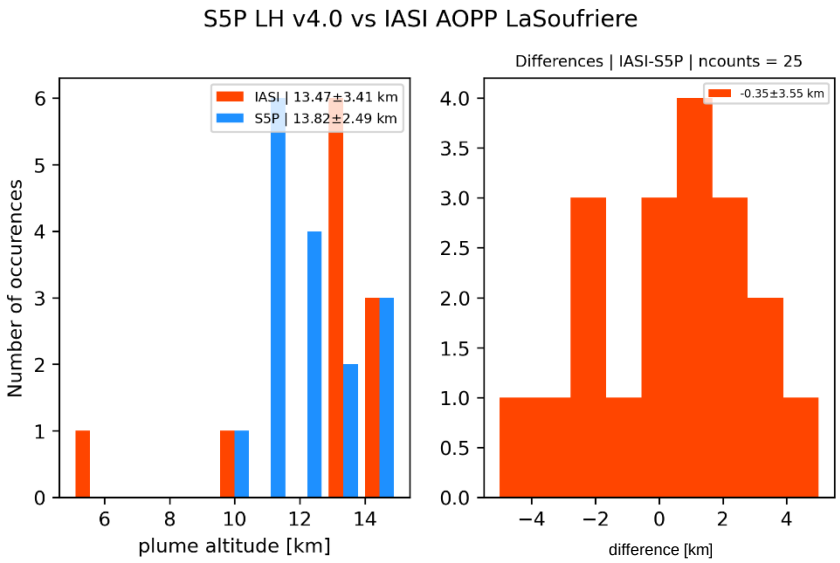
Credit: DLR/ESA



Credit: NASA/DLR

La Soufriere eruption in April 2021
Validation against IASI SO_2 LH





→ Mean LH difference between sensors ~ ±0.6±3.6km

→ See Koukouli et al. (2021, submitted to ACP)

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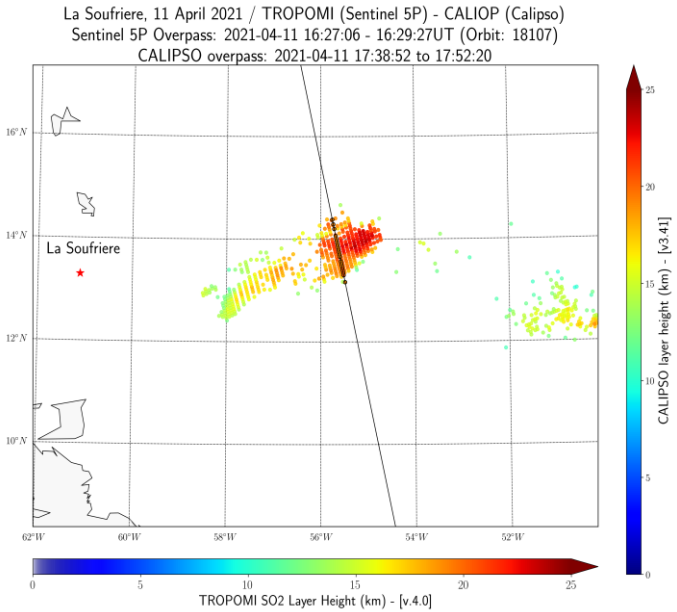
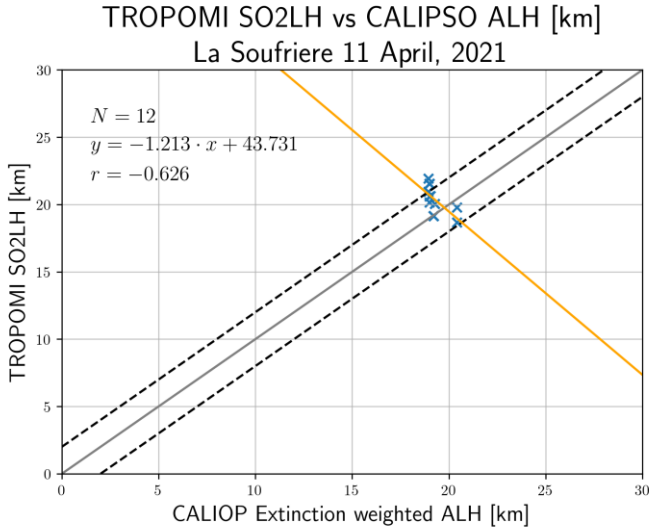
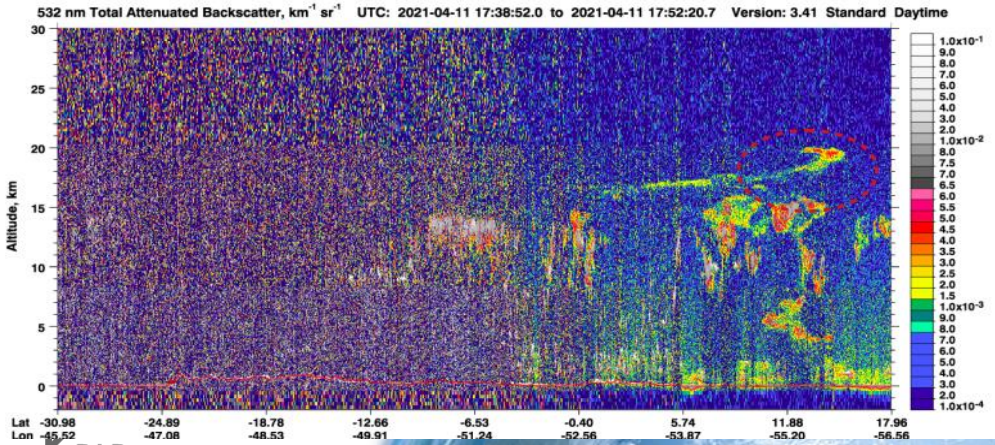
La Soufriere eruption in April 2021
Validation against CALIPSO ALH







→ Height difference within ~1.0km

→ See Koukouli et al. (2021, submitted to ACP)

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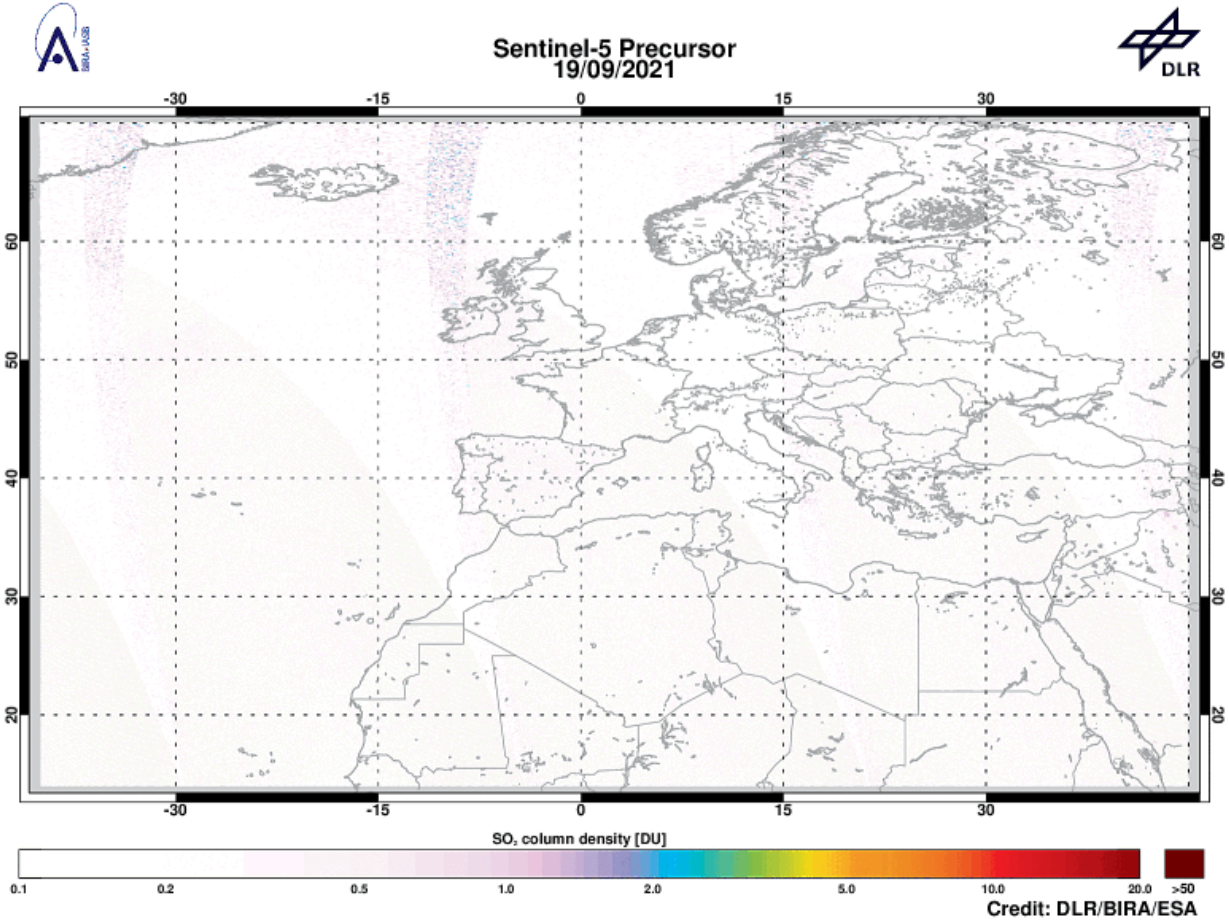
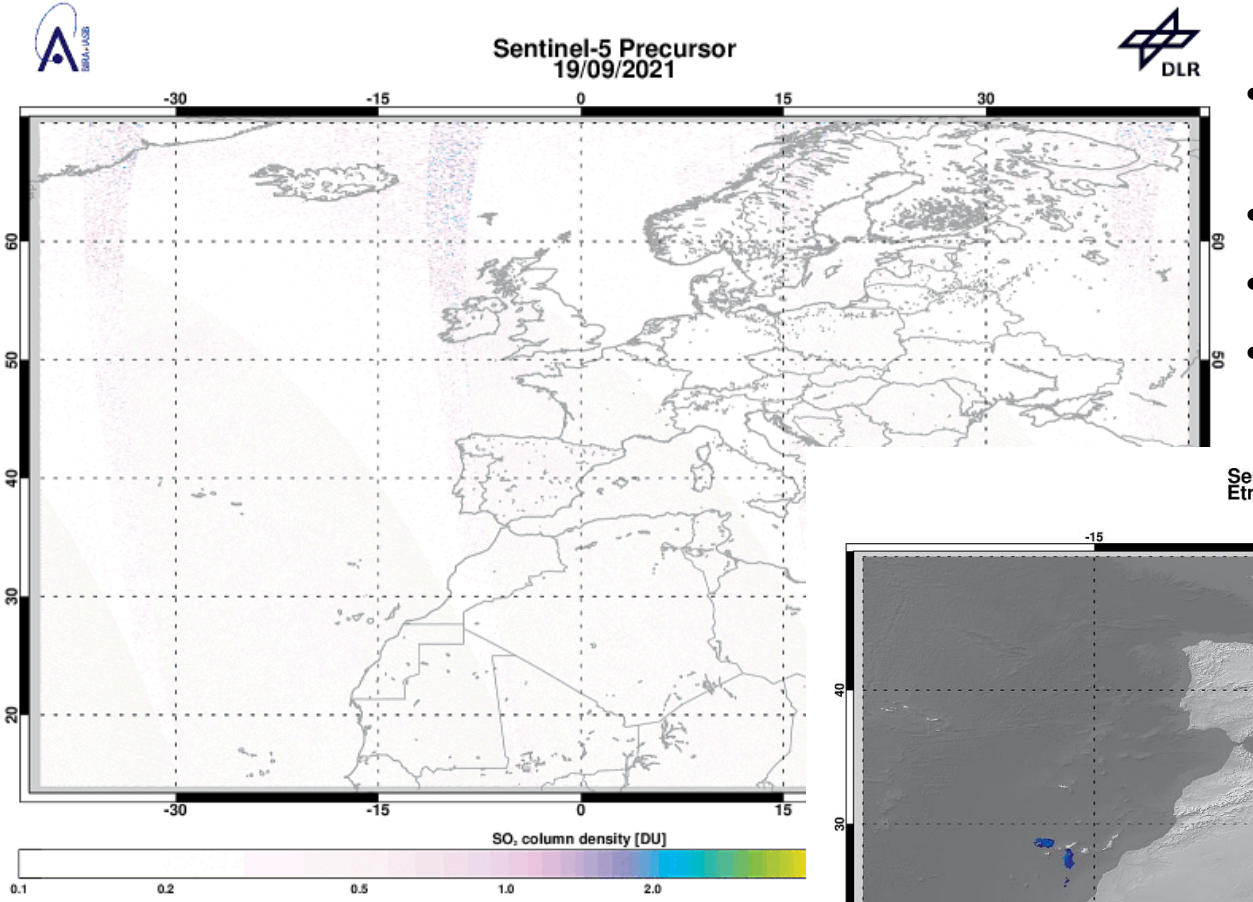
Cumbre Vieja eruption Sept - ?? 2021



- Volcano erupted on 19 Sept. 2021
- Eruption still ongoing
- Low altitude ash & SO_2
- SO_2 LH between 2-5km

Cumbre Vieja eruption Sept - ?? 2021



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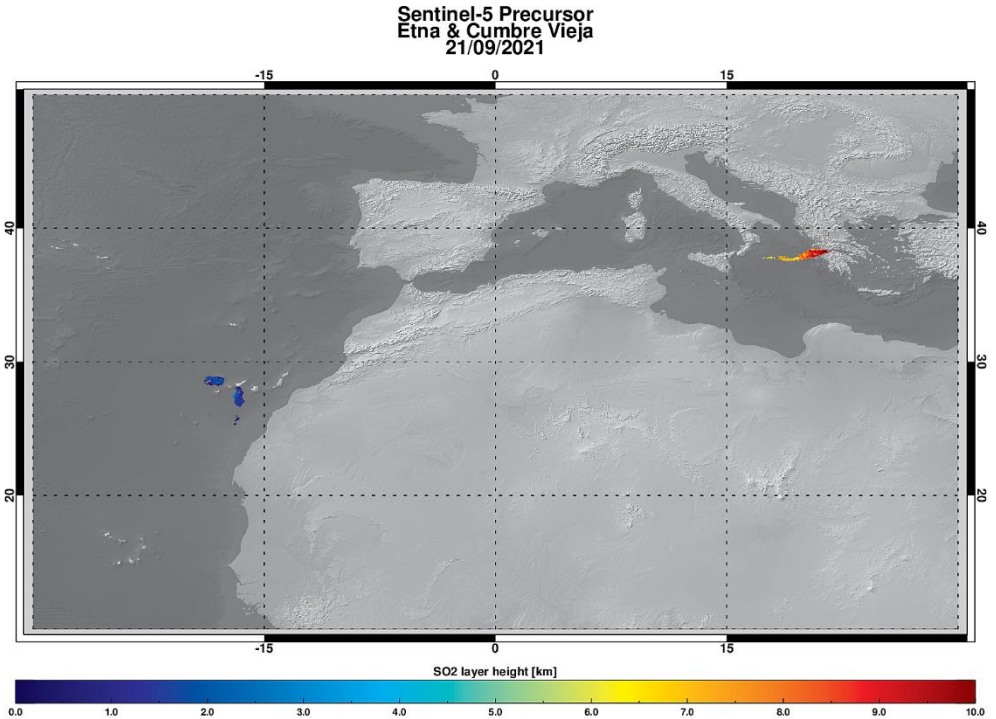
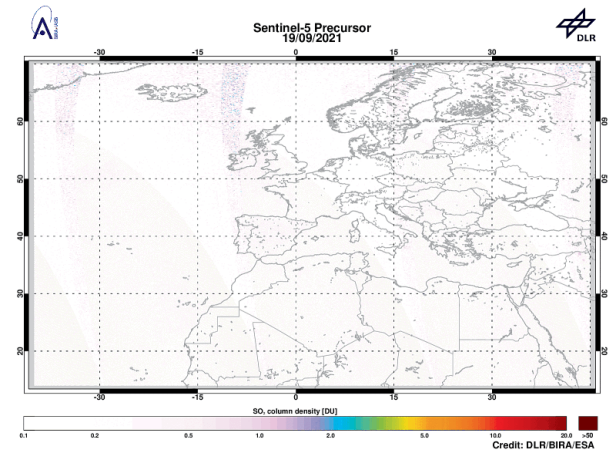


Conclusion & Outlook

- FP_ILM SO_2 LH algorithm developed for GOME-2, OMI, S5p
- **Extremely fast** and **accurate UV SO_2 layer height retrieval**
- S5p SO_2 LH prototype product developed in **S5P+I: SO2LH project**
- S5p SO_2 LH product **successfully validated** against IASI, OMI, CALIPSO
  - Very good agreement for most volcanic cases considered
  - See Koukouli et al. (2021, submitted to ACP)
- S5p SO_2 LH product is actively **assimilated by ECMWF/CAMS**
  - Significant improvement in SO_2 forecast
  - See Inness et al. (2021, accepted in GMT)
- Quasi-NRT SO_2 LH products are generated in **DLR INPULS project**
- Application to Sentinel-4, Sentinel-5, GEMS, etc. is foreseen

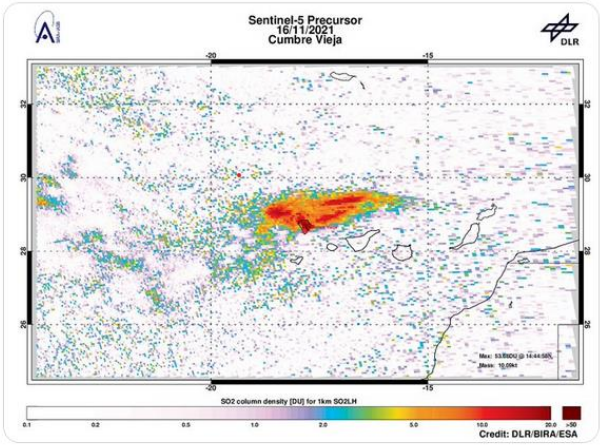
SO_2 LH: Outreach

- S5P+I: SO_2 LH **project website**: https://atmos.eoc.dlr.de/so2-lh
- **Semi-operational quasi-NRT** SO_2 LH retrieval from S5p data **once per hour**
  - Push-ftp to ECMWF/CAMS for assimilation & forecast
- Immediate **Twitter** publication @DlrSO2
  - https://twitter.com/DlrSo2
  - Name of volcano erupted, SO_2 VCD, SO_2 LH, SO_2 mass



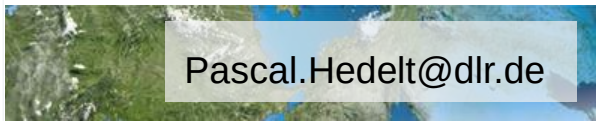
TROPOMI SO2
@DlrSo2

On 2021-11-16 #TROPOMI has detected a strong SO2 signal at a distance of 7.3km to #CumbreVieja with 48.38DU of SO2 at an altitude of ~1km. Estimated mass within 300km: 10.1ktons. @tropomi #S5p #Sentinel5p @DLR_en @BIRA_IASB @ESA_EO #SO2LH



5:11 nachm. · 16. Nov. 2021 · TROPOMISO2

TROPOMI SO2 @DlrSo2 · 15. Nov.
Antwort an @DlrSo2
Updated animation of #S5p #tropomi SO2 measurements of the #CumbreVieja volcanic eruption from 19 Sept - 14 Nov. Note the extended plume from #Etna on 24 Oct!



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