EPIC observations of volcanic eruptions: SO_2 data validation and development of UV ash mass retrievals

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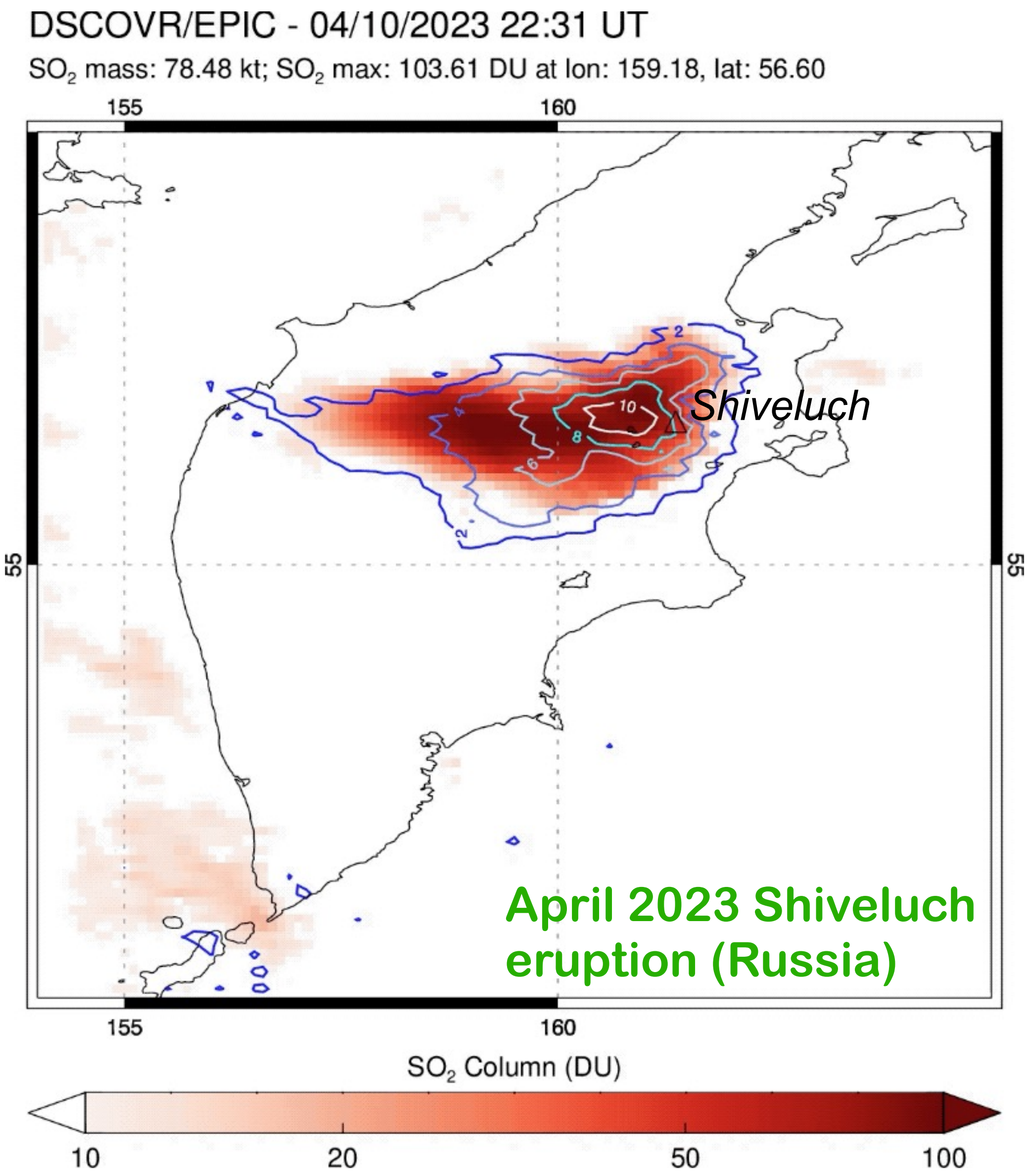
EPIC L2 volcanic SO_2 algorithm (MS_SO2) and product

- State vector [*Fisher et al.*, AMT, 2019]

$$\boldsymbol{x} = \begin{pmatrix} SO_2 \\ O_3 \\ dR/d\lambda \\ R \end{pmatrix} \longrightarrow \text{UV Aerosol Index (UVAI)}$$

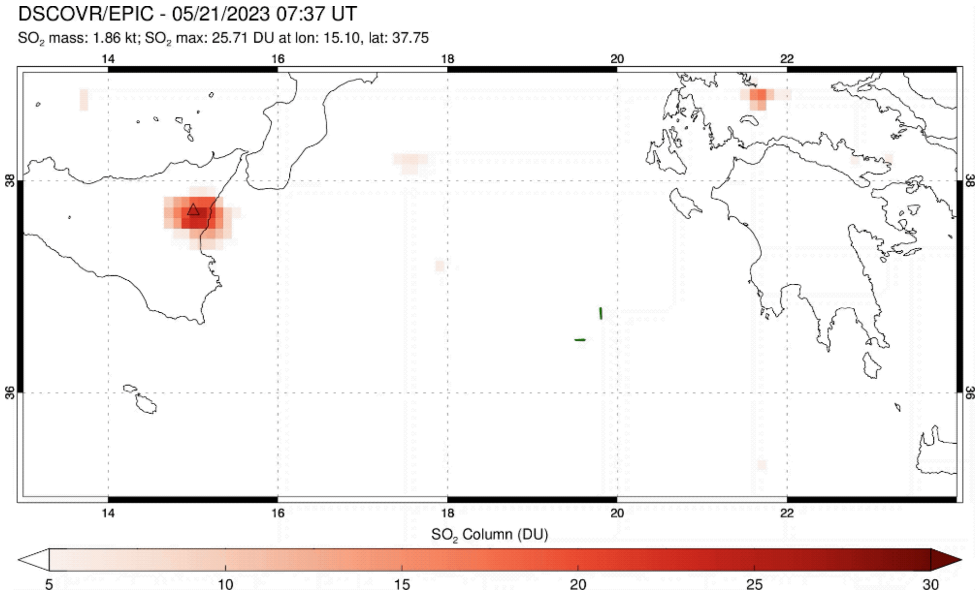
- Uses 4 EPIC UV channels
- Step 1 -> initial estimates
- Step 2 -> reduce artifacts
    - Earth rotation
    - Geolocation errors
    - Cloud noise
    - Ozone variability
- We process the EPIC volcanic SO_2 product 'on demand' after significant eruptions (4,092 granules on ASDC)
- Radiance LUTs generated for SO_2 center of mass altitudes (CMAs) of 3, 5, 8 and 18 km for research use (L2 product = 13 km)



[*Carn et al.*, *GRL*, 2018; *Gorkyavi et al.*, *Frontiers Rem. Sens.*, 2021; *Carn et al.*, *Frontiers Earth Sci.*, 2022]

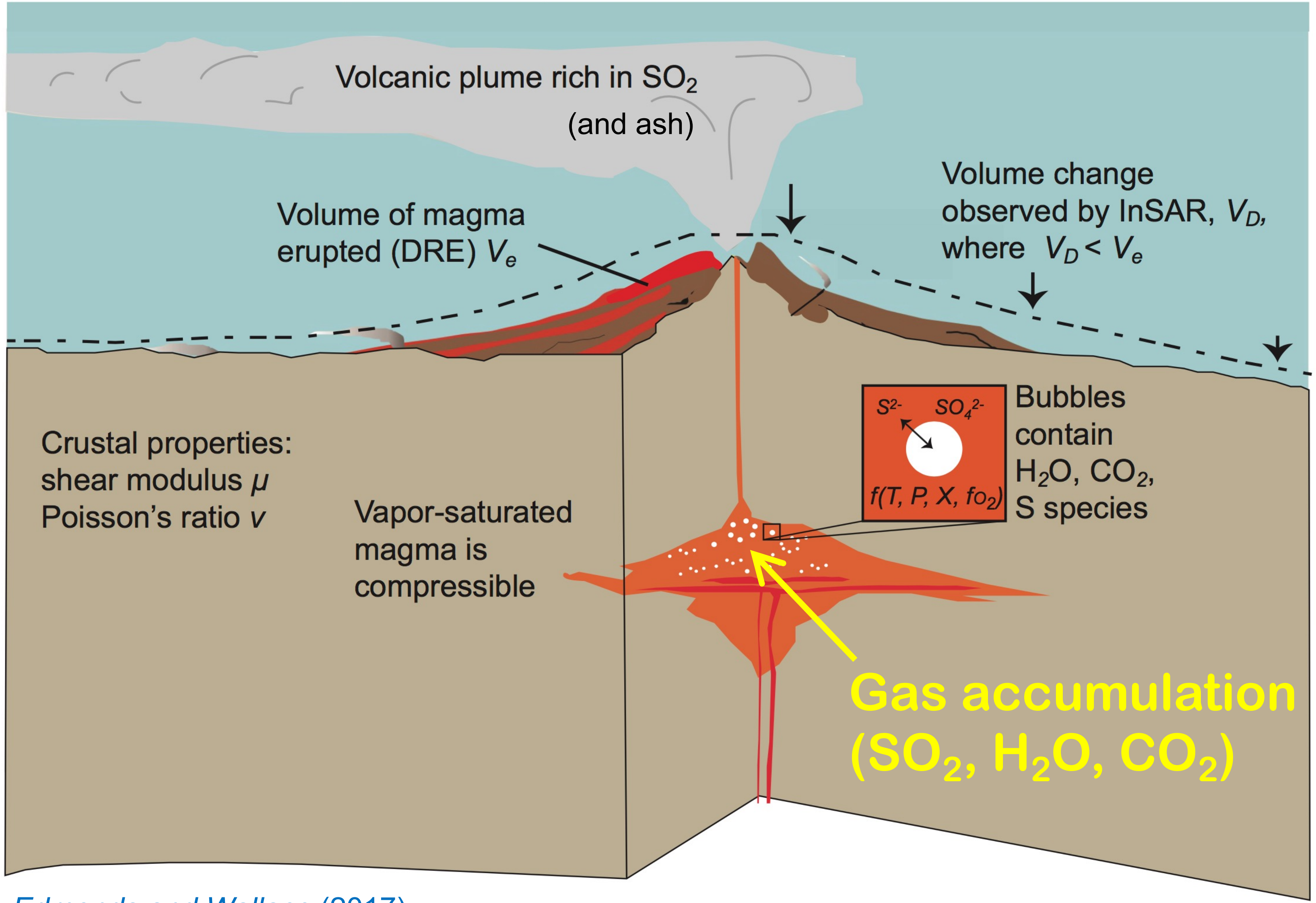
Recent volcanic eruptions detected by EPIC (2021 -)

Volcano	Eruption time (UTC)	First EPIC detection (UTC)	Difference (hours)[1]	EPIC exposures[2]	Max. SO_2 column (DU)
Lewotolo (Indonesia)	Nov 29, 2020, 01:45	Nov 29, 02:52	1.12	4	192
Etna (Italy)	Feb 19, 2021, 07:50	Feb 19, 09:27	1.78	3	20
Etna (Italy)	Feb 24, 2021, 17:00	Feb 25, 07:20	14.3	4	31
Etna (Italy)	Feb 28, 2021, 07:02	Feb 28, 10:04	3.03	3	71
Sangay (Ecuador)	Mar 11, 2021, 08:15	Mar 11, 12:44	4.48	5	70
Etna (Italy)	Mar 12, 2021, 06:41	Mar 12, 09:27	2.77	4	52
Etna (Italy)	Apr 1, 2021, 07:40	Apr 1, 09:08	1.47	4	27
La Soufrière (St. Vincent)	Apr 9, 2021, 19:00	Apr 9, 20:15	1.25	~20	154
Sangay (Ecuador)	May 7, 2021, 15:00	May 7, 16:49	1.82	3	28
Etna (Italy)	Jun 22, 2021, 04:00	Jun 22, 10:25	6.42	3	14
Etna (Italy)	Jun 23, 2021, 02:00	Jun 23, 09:01	7.02	4	17
Etna (Italy)	Jun 24, 2021, 10:00	Jun 24, 11:03	1.05	5	37
Etna (Italy)	Jun 27, 2021, 09:00	Jun 27, 09:48	0.80	2	24
Etna (Italy)	Aug 9, 2021, 00:30	Aug 9, 06:22	5.87	9	39
Fukutoku-Oka-no-Ba	Aug 12, 2021, 21:20	TBD			
La Palma (Canary Is)	Sep 19, 2021, 14:00	Sep 20, 09:55	19.9	>50	74
Etna (Italy)	Sep 21, 2021, 06:15	Sep 21, 09:36	3.4	1	48
Etna (Italy)	Oct 23, 2021, 08:40	Oct 23, 09:46	1.1	3	54
Hunga Tonga-Hunga Ha'apai (Tonga)	Dec 19, 2021, 20:30	Dec 19, 20:53	0.38	2	23
Wolf (Ecuador)	Jan 7, 2022, 05:15	Jan 7, 14:51	9.6	>15	71
Hunga Tonga-Hunga Ha'apai (Tonga)	Jan 13, 2022, 15:30	Jan 13, 19:56	4.43	4	26
Hunga Tonga-Hunga Ha'apai (Tonga)	Jan 15, 2022, 04:00	Jan 15, 18:46	14.8	3	30
Etna (Italy)	Feb 10, 2022, 19:40	Feb 11, 09:27	13.8	3	30
Etna (Italy)	Feb 21, 2022, 10:00	Feb 21, 13:31	3.5	1	33
Karymsky (Russia)	Apr 19, 2022, 20:05	Apr 19, 22:13	2.13	4	40
Mauna Loa (USA)	Nov 28, 2022, 09:30	Nov 28 18:55	9.42	~25	136
Shiveluch (Russia)	Apr 10, 2023, 13:10	Apr 10, 20:43	7.55	>20	157
Etna (Italy)	May 21, 2023, 07:20	May 21, 07:37	0.28	8	83
Etna (Italy)	Aug 13, 2023, 21:33	Aug 14, 07:27	9.9	9	40
Shishaldin (USA)	Sep 16, 2023, 01:10	Sep 16, 02:33	1.38	4	tbd
Shishaldin (USA)	Sep 25, 2023, 13:42	Sep 25, 18:55	5.22	5	73



- Significant EPIC L2 SO_2 data processing effort in 2023 – identified many eruptions of Etna volcano (Italy).
- Largest eruption of 2023 (to date) is Shiveluch (Russia) in April.
- Prepared protocols for higher-cadence (~20 minute) EPIC imaging of a future volcanic eruption (requires 1-2 days advance warning).

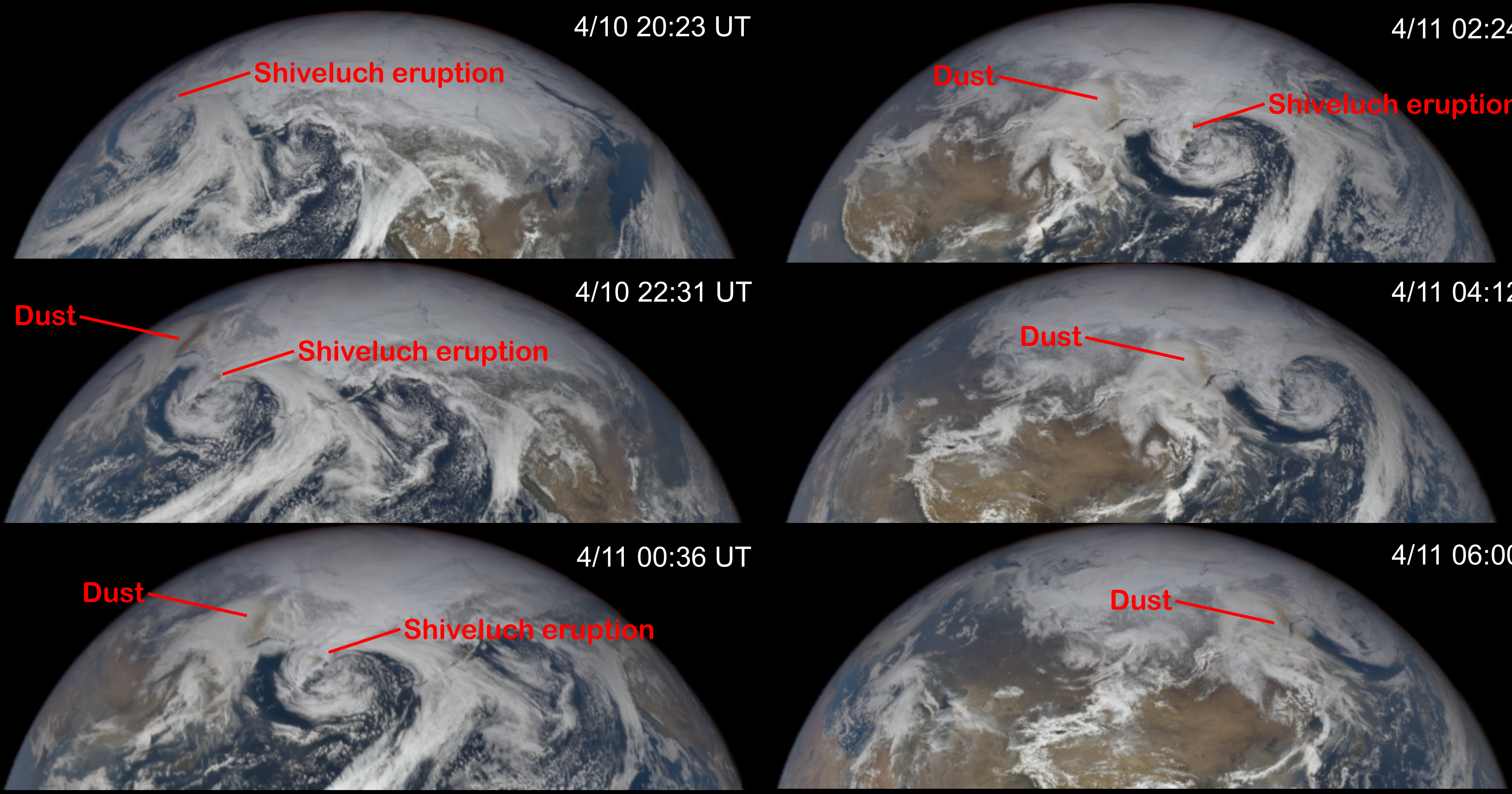
Pre-eruptive gas accumulation in magma reservoirs



Edmonds and Wallace (2017)

- Pre-eruptive accumulation of volcanic gases in magma reservoirs may trigger some eruptions.
- Usually not possible to detect accumulated gases before eruptions.
- Accumulated gas 'gradients' could be manifested in volcanic emissions during eruptions (high-cadence imaging of fresh eruption plumes required).
- Volcanic ash measurements also needed, to quantify erupted mass and assess impact of ash on SO_2 data.

Shiveluch eruption (April 2023) – volcanic SO_2, ash and dust



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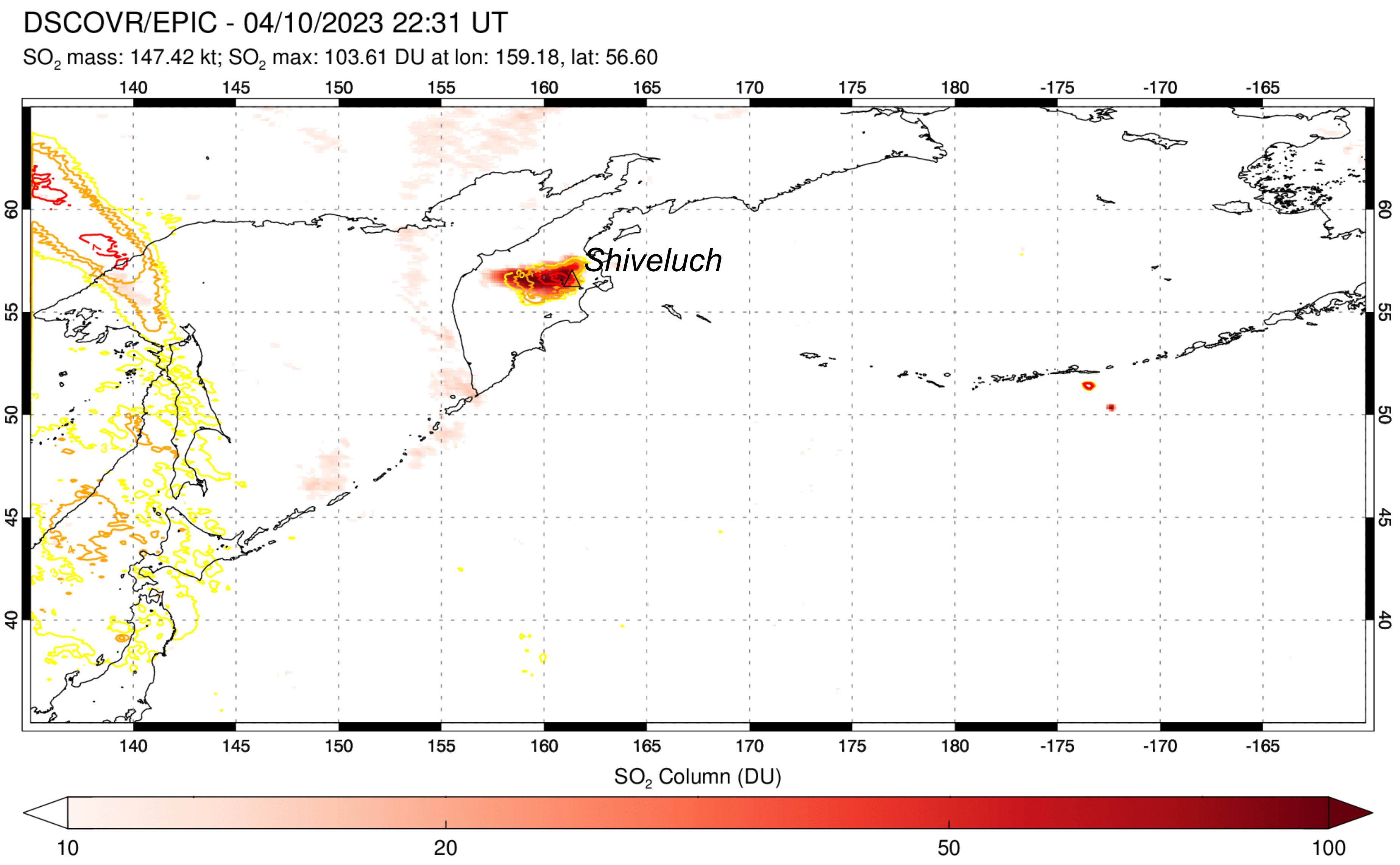
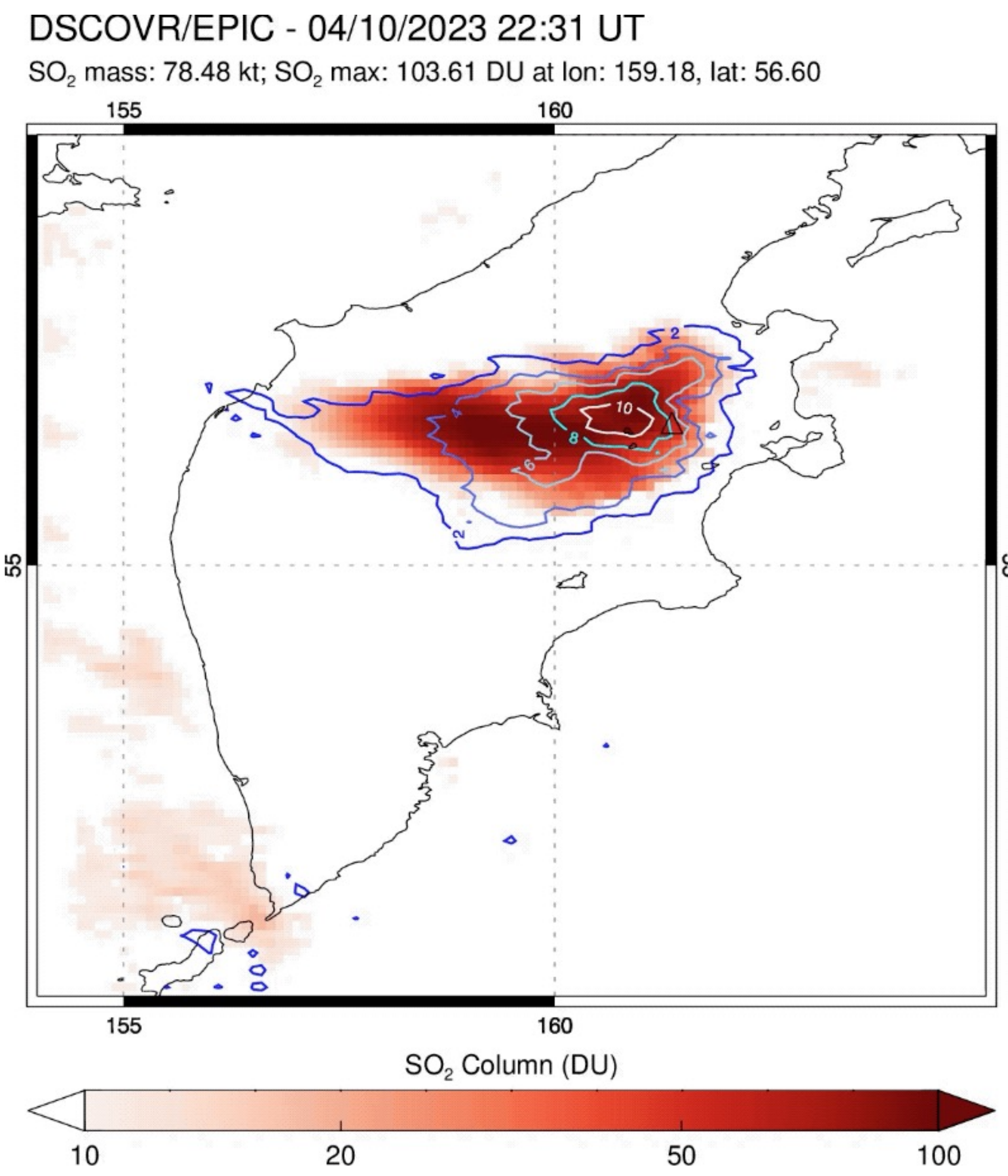
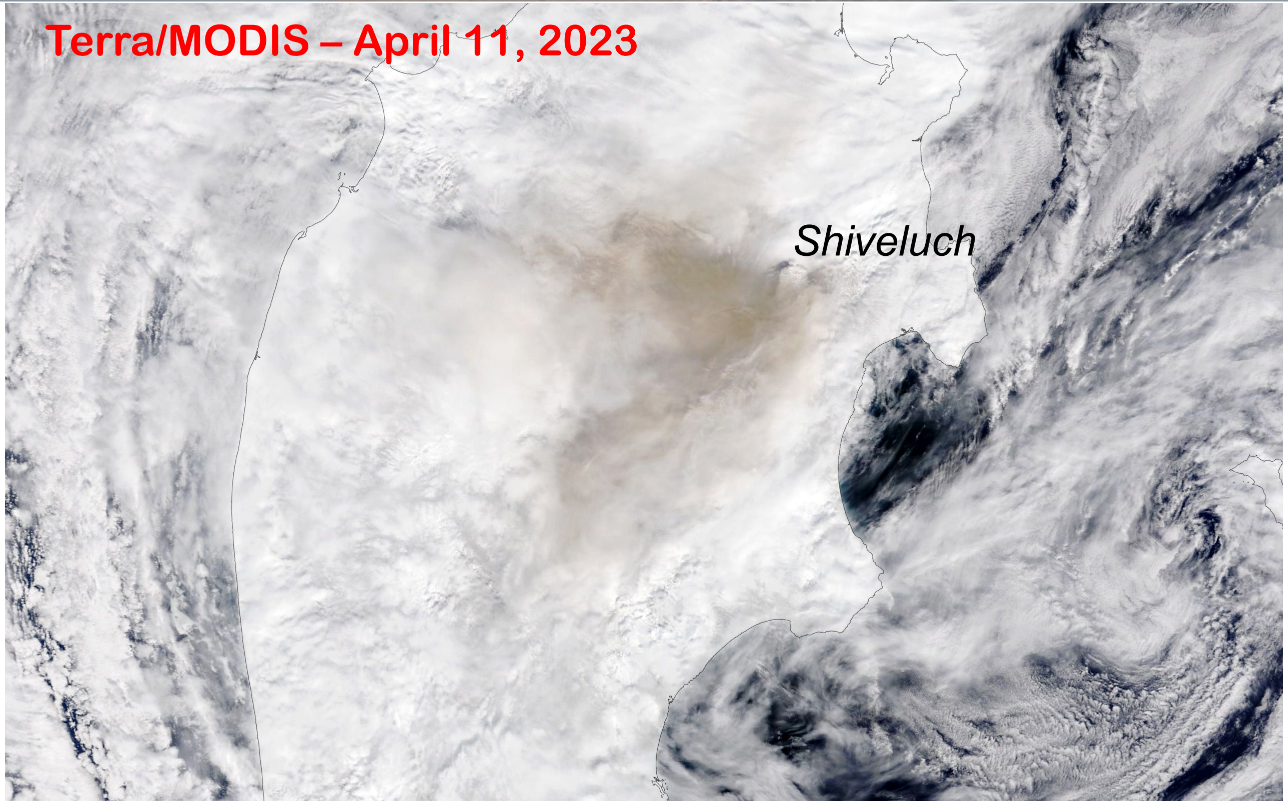


- EPIC SO_2 and UV Aerosol Index (UVAI)
- April 10-12, 2023
- Simultaneous observations of volcanic SO_2, ash and Asian dust transport.
- ‘Volcanic ash’ later reported (Apr 14) over Pacific NW, causing flight cancelations, but may have been dust?

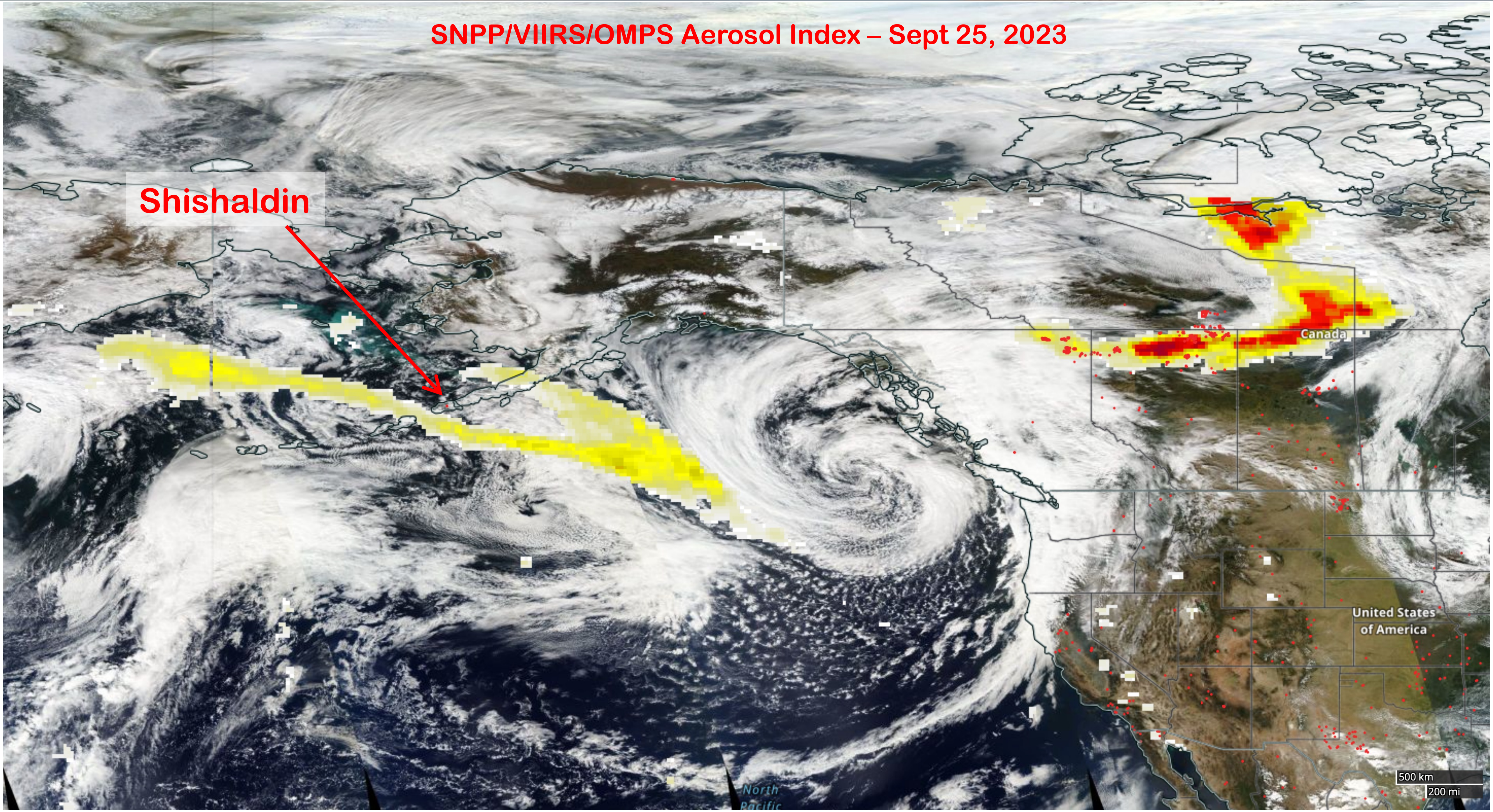
2023 Sheveluch eruption (Kamchatka, Russia)



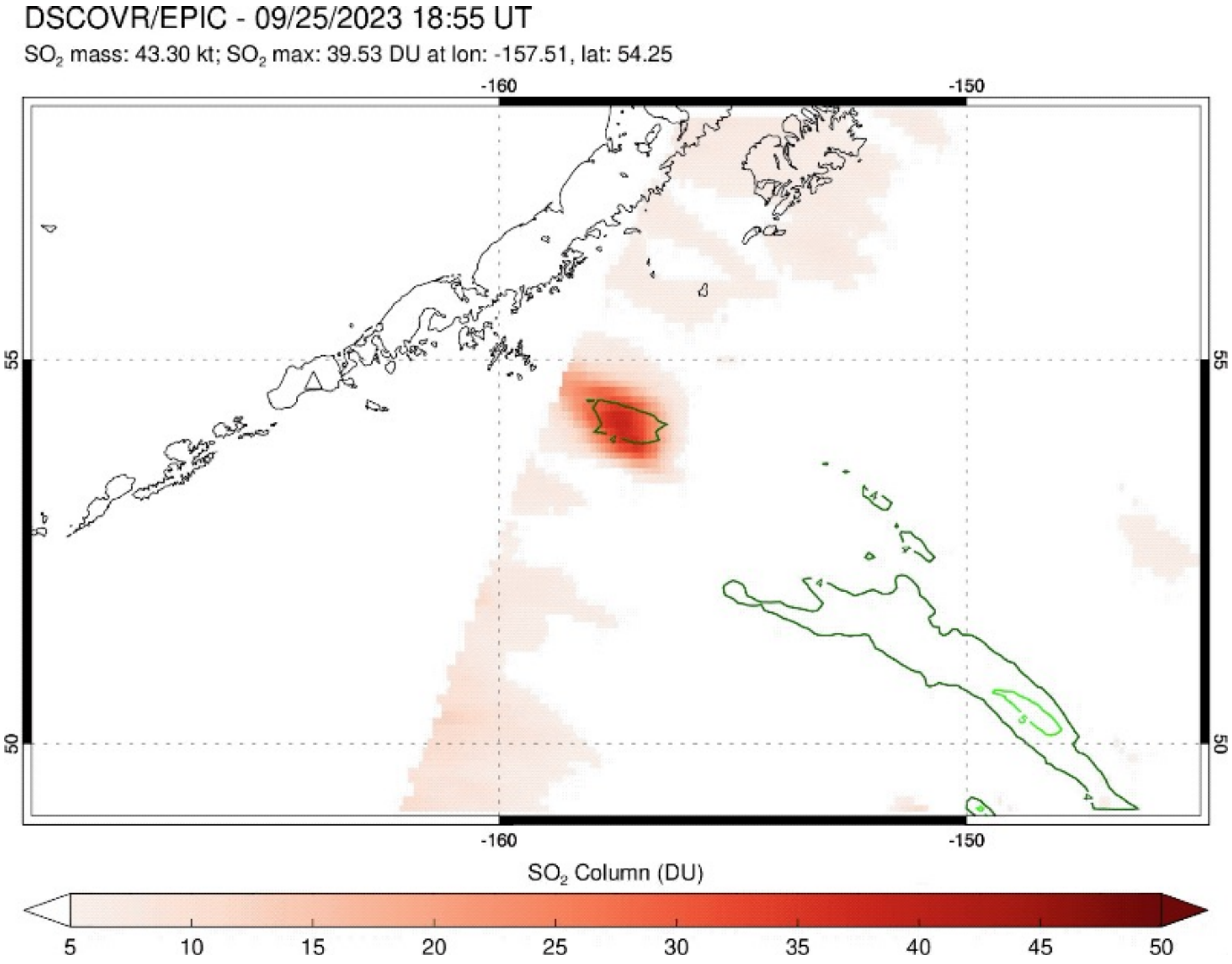


- EPIC UVAI decreases quickly after eruption
- Consistent with heavy fallout of volcanic ash in Kamchatka
- Volcanic ash interference on SO_2 measurements possible

Shishaldin eruption (Sept 2023) – volcanic SO_2, ash & smoke

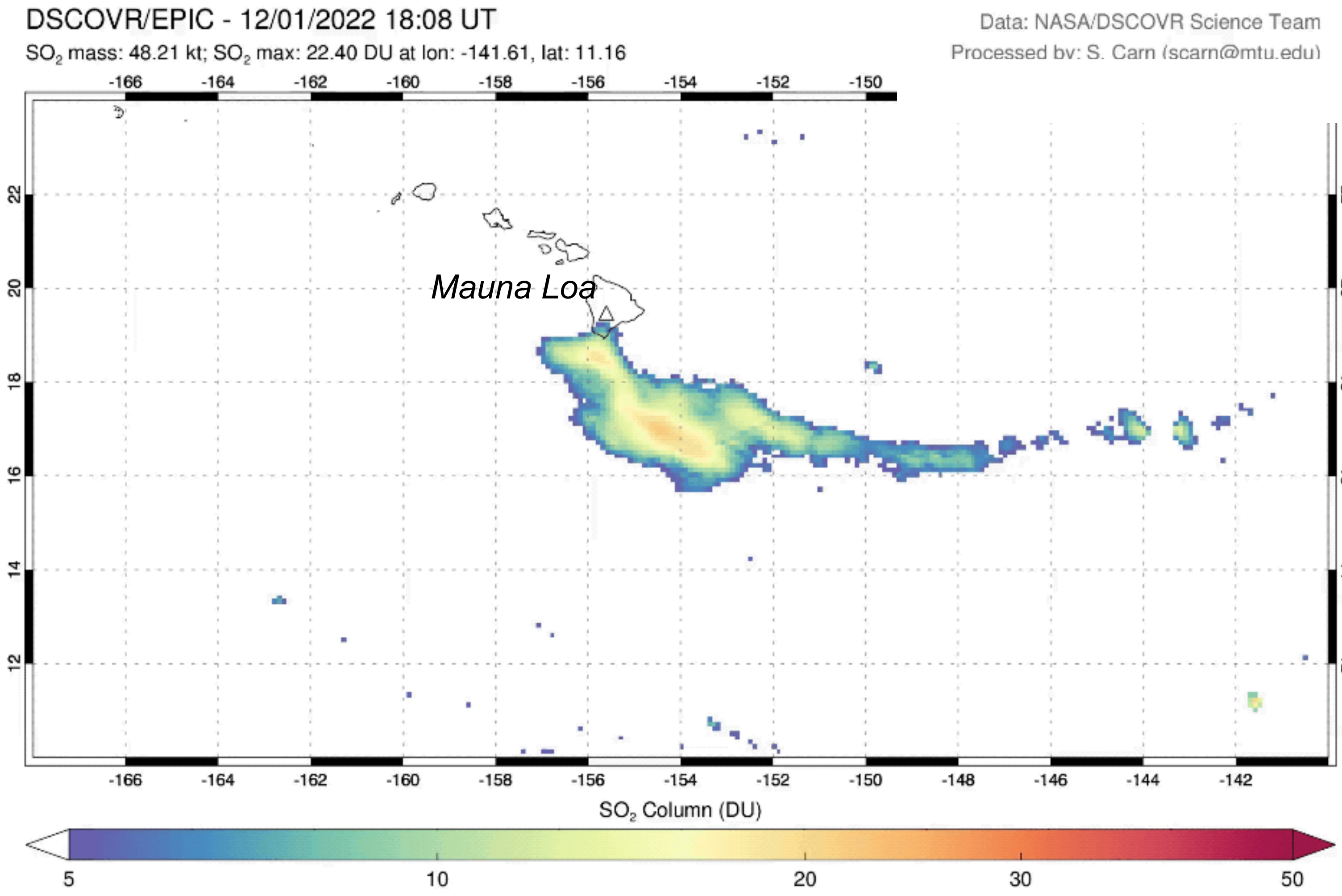


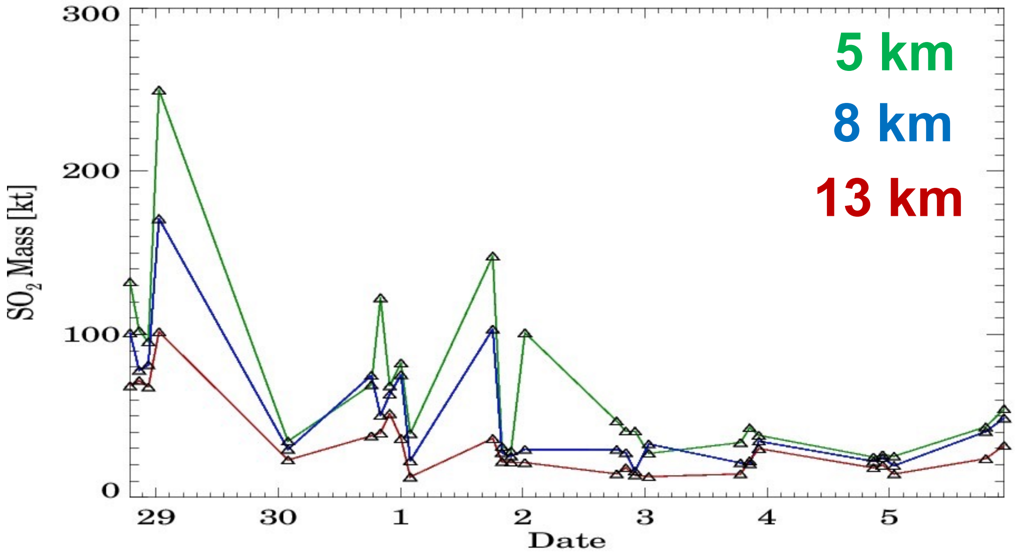
Shishaldin eruption (Sept 2023) – volcanic SO_2, ash & smoke



- EPIC SO_2 and UV Aerosol Index (UVAI)
- Sept 25, 2023
- UVAI detects smoke and volcanic ash – ash signal tracks with SO_2 in EPIC data

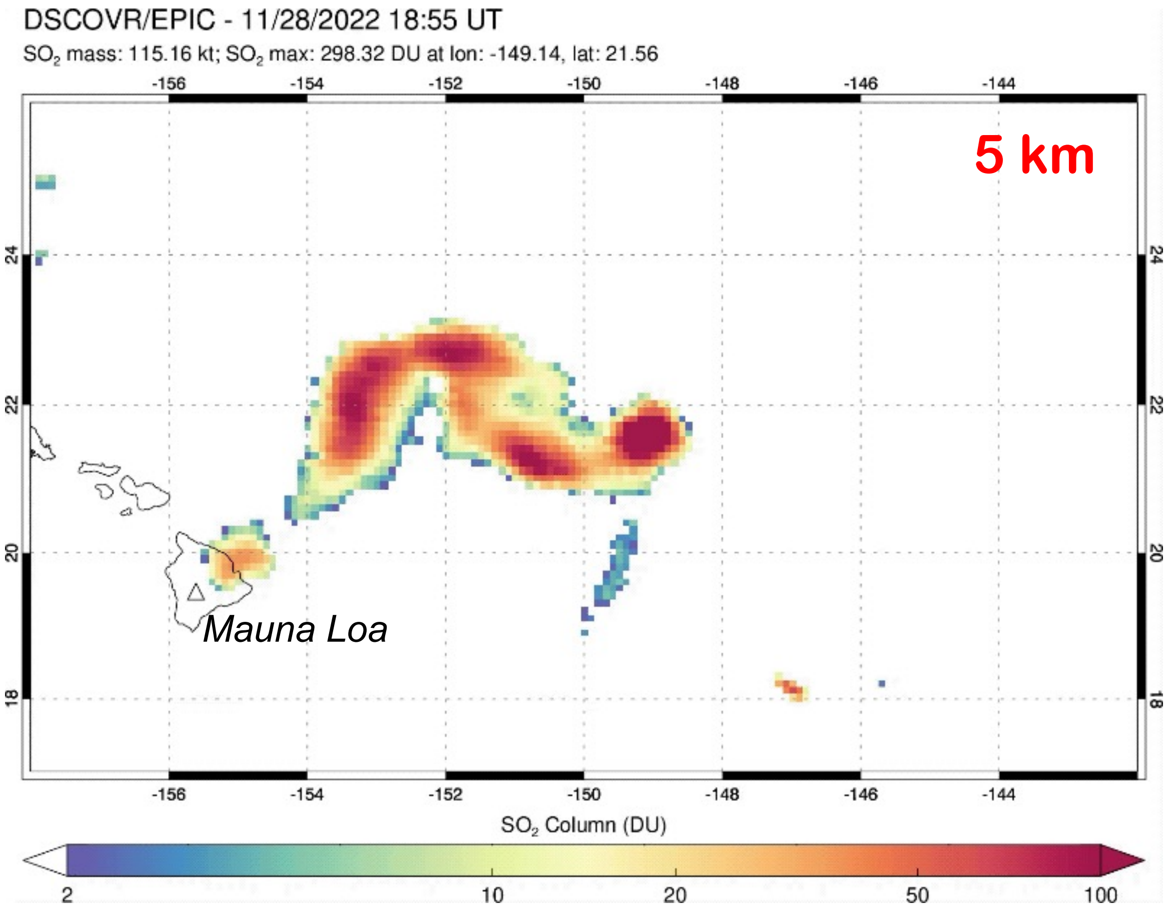
2022 Mauna Loa eruption (Hawaii)

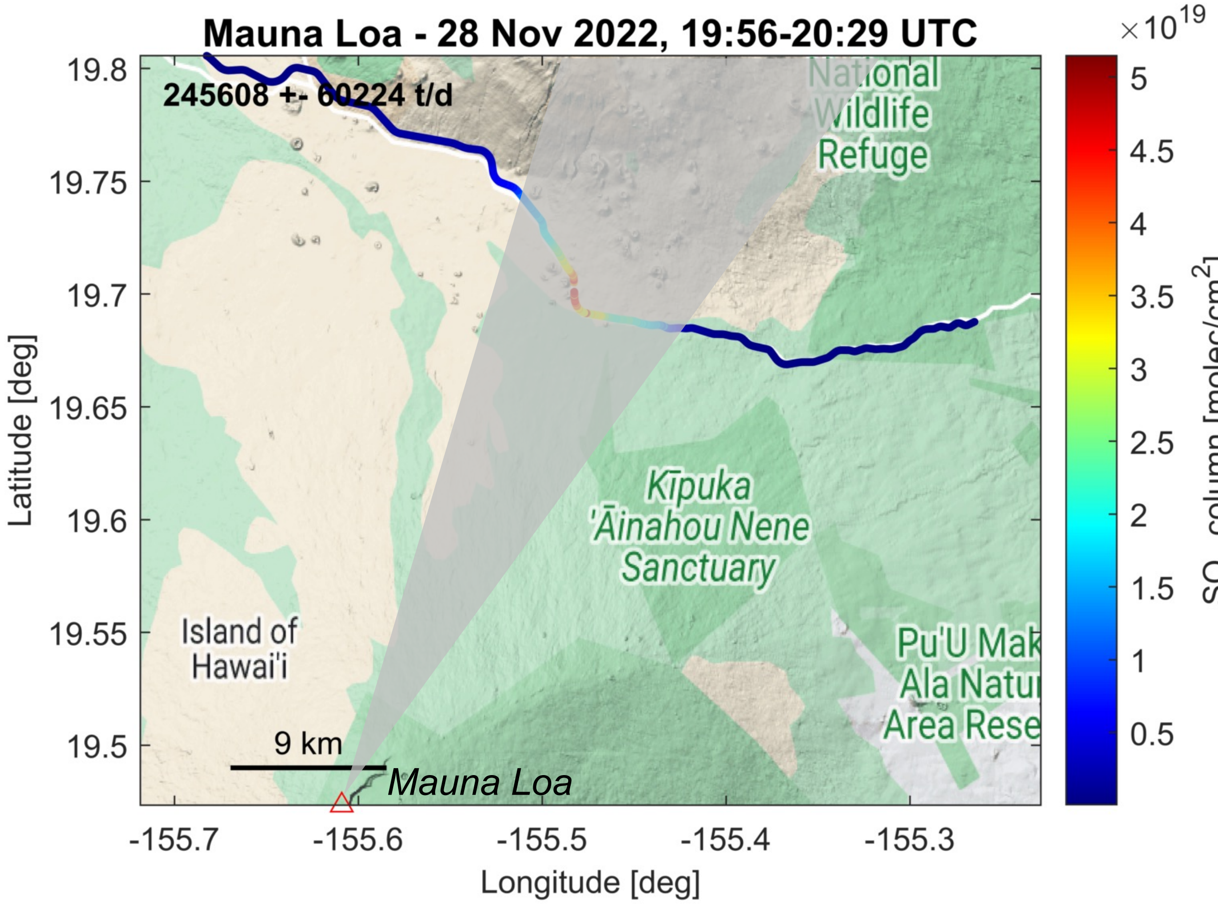




- EPIC detects exponential decrease in SO_2 emissions, as expected during effusive eruptions.
- High-cadence permits isolation of 'fresh' SO_2 emissions, improving SO_2 flux calculations.

2022 Mauna Loa eruption (Hawaii)

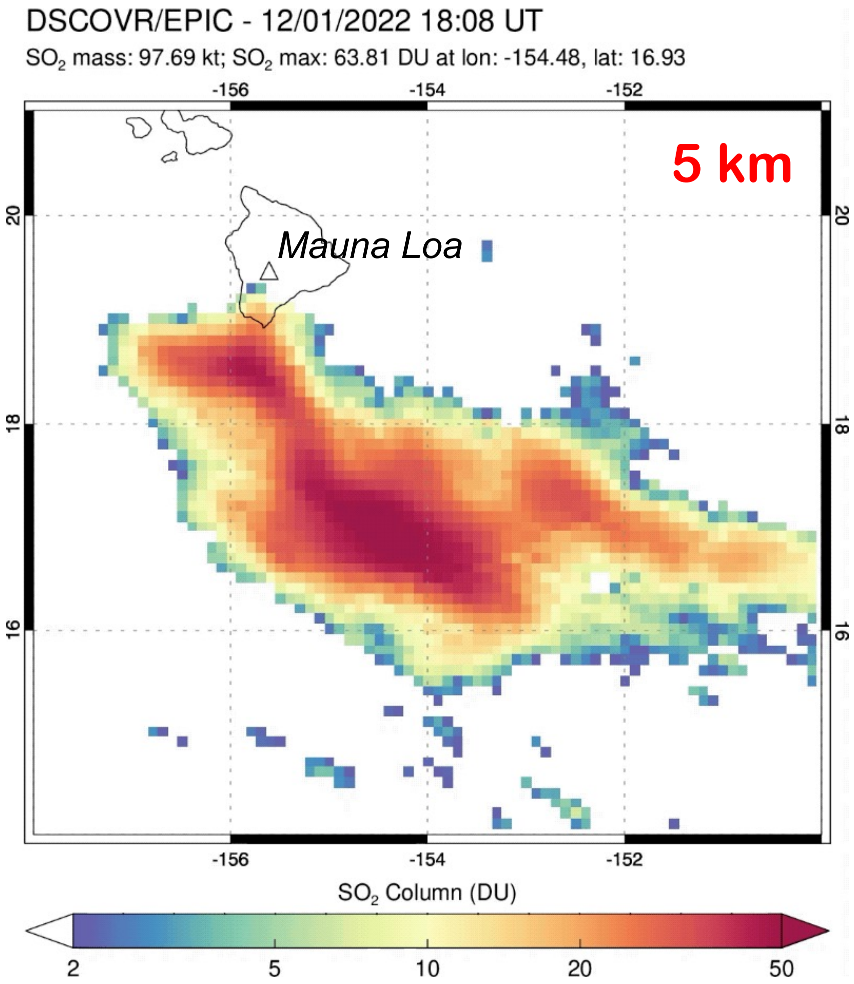


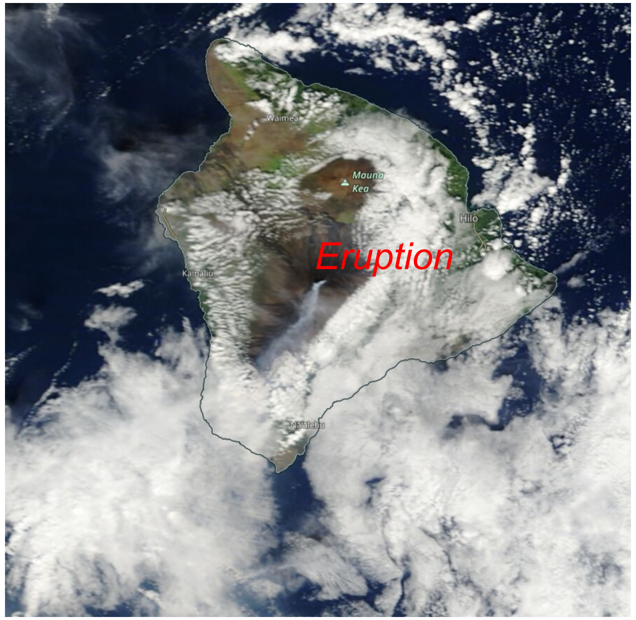


Ground-based DOAS SO_2 data (C. Kern/USGS CVO)

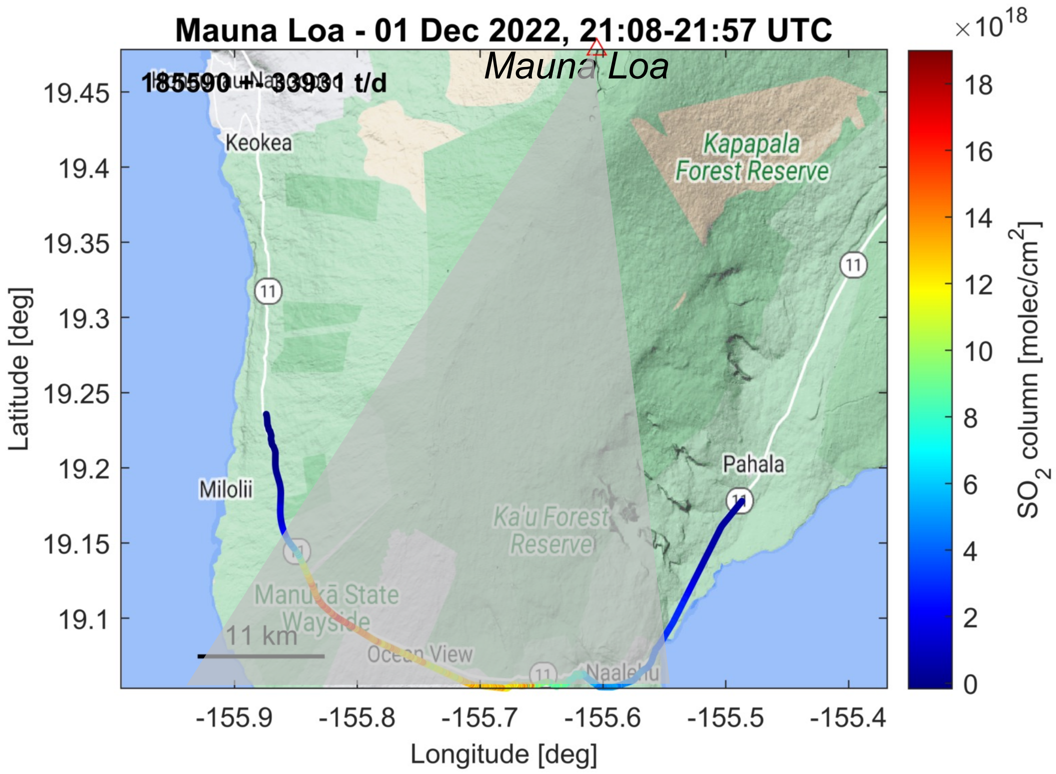
- U.S. Geological Survey (USGS) Volcanic Emissions Group measured SO_2 emissions during eruption
- EPIC L2 SO_2 products produced for appropriate plume altitudes (5 km, 8 km, 13 km)
- SO_2 mass in first EPIC exposure (Nov 28, 18:55 UT; 103.5 kt) equal to flux of 3052 kg/s (~264 kt/d).

2022 Mauna Loa eruption (Hawaii)





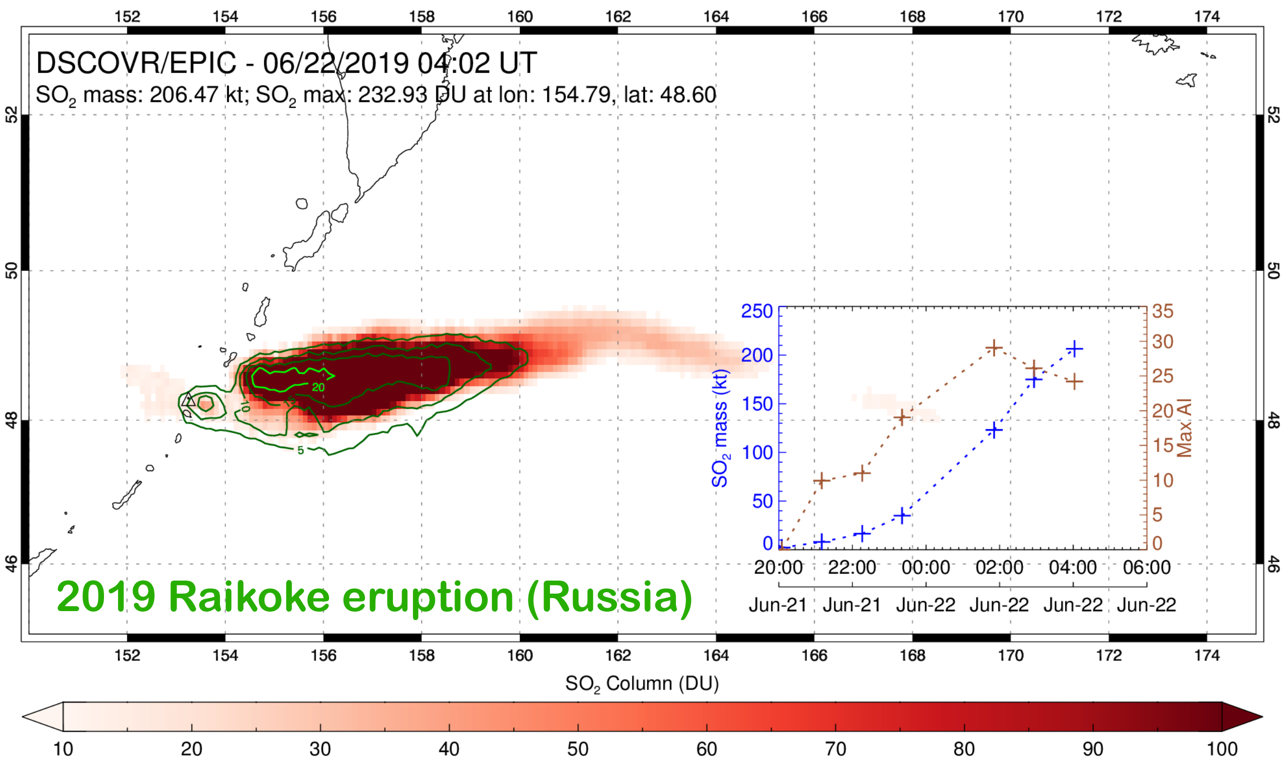
Terra/MODIS
Dec 1, 2023 (20:20 UTC)

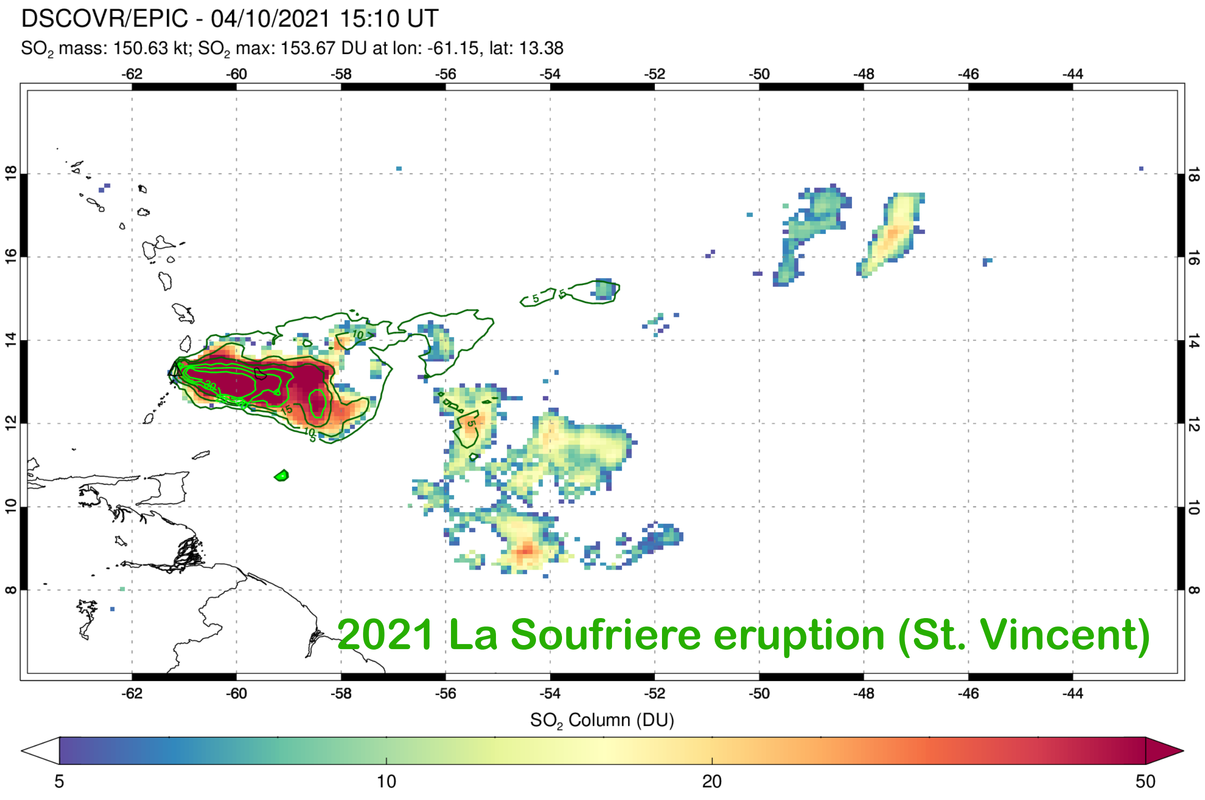


Ground-based DOAS SO_2 data
(C. Kern/USGS CVO)

- EPIC detects volcanic plume close to the source due to very high SO_2 column amounts.
- Average ground-based DOAS SO_2 columns in plume: ~300 DU; EPIC maximum: ~100 DU.
- Cloudy conditions (scattering) and plume dilution in EPIC pixel could partly explain differences.

EPIC volcanic ash and SO_2 retrievals





- Volcanic ash impacts SO_2 measurements in most (all?) explosive volcanic eruption clouds.
- Modeling volcanic ash and cloud optical properties at EPIC UV wavelengths (317, 325, 340, 388 nm).
- Testing/debugging VLIDORT 2.8.5 vs. Arizona RTM (ash particle effective radii of 4 μm and 6 μm).
- Scripts to generate aerosol-cloud LUTs are available from EPIC UV Aerosol team.
- Test using Raikoke eruption (fixed cloud and ash vertical profiles and geometry).

Summary and future plans

- EPIC volcanic SO_2 science paper in preparation.
- Continue development of EPIC UV ash-SO_2 retrievals in collaboration with EPIC UV Aerosol team.
- Improve low-end EPIC SO_2 sensitivity by applying machine learning techniques to EPIC radiances?
- Improve SO_2 retrieval for higher SZA by expanding the radiance look-up tables.
- If a sufficiently large volcanic eruption occurs, attempt higher-cadence EPIC imaging (~20-30 minute repeat).
- Comparisons between EPIC and geostationary GK2B/GEMS observations of volcanic SO_2 (requires large eruption in Japan, Indonesia or the Philippines, or drifting SO_2 cloud).