Quantifying the long-term decay of Hunga stratospheric water vapour using chemistry transport modelling on ARCHER2

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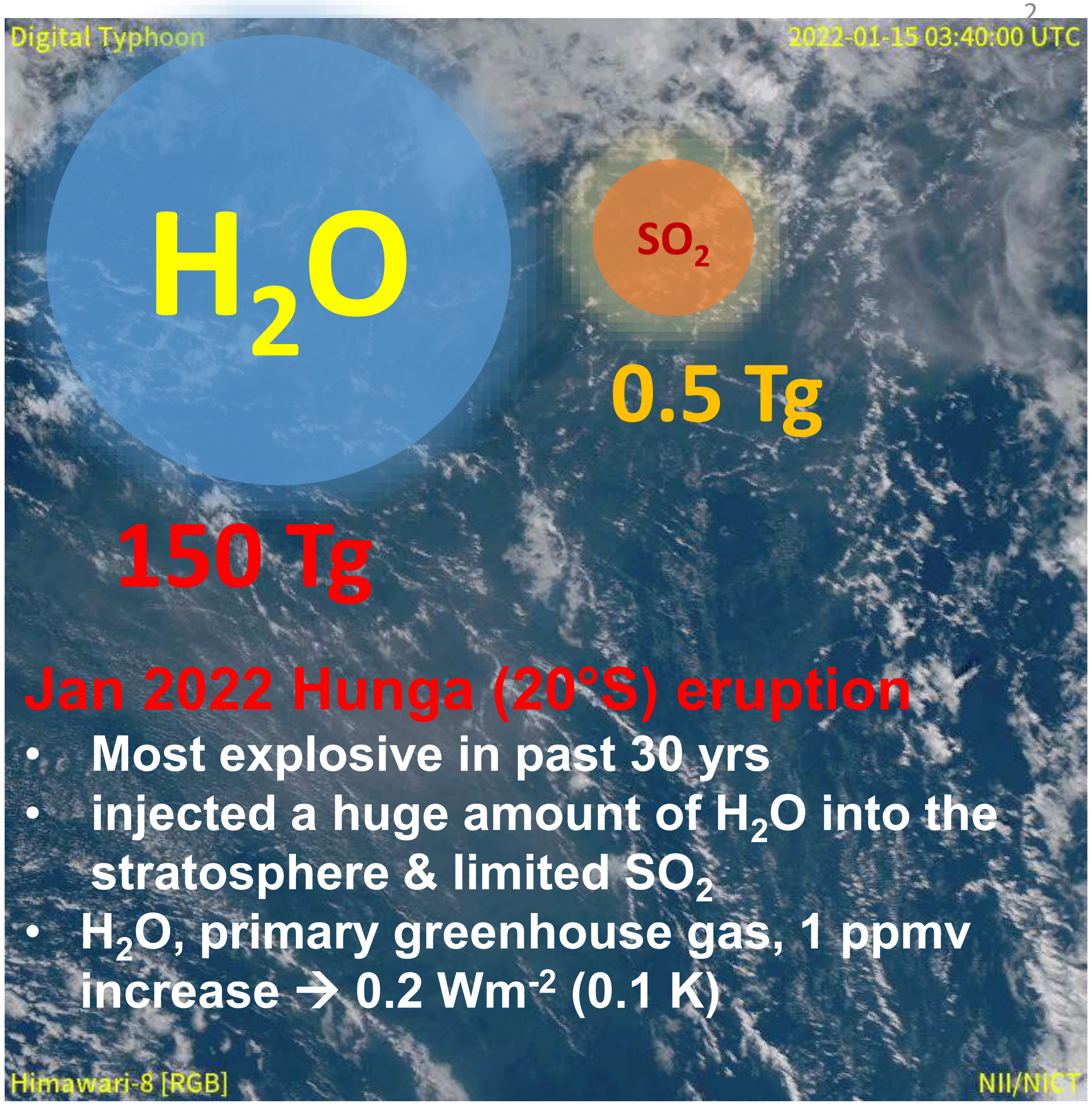
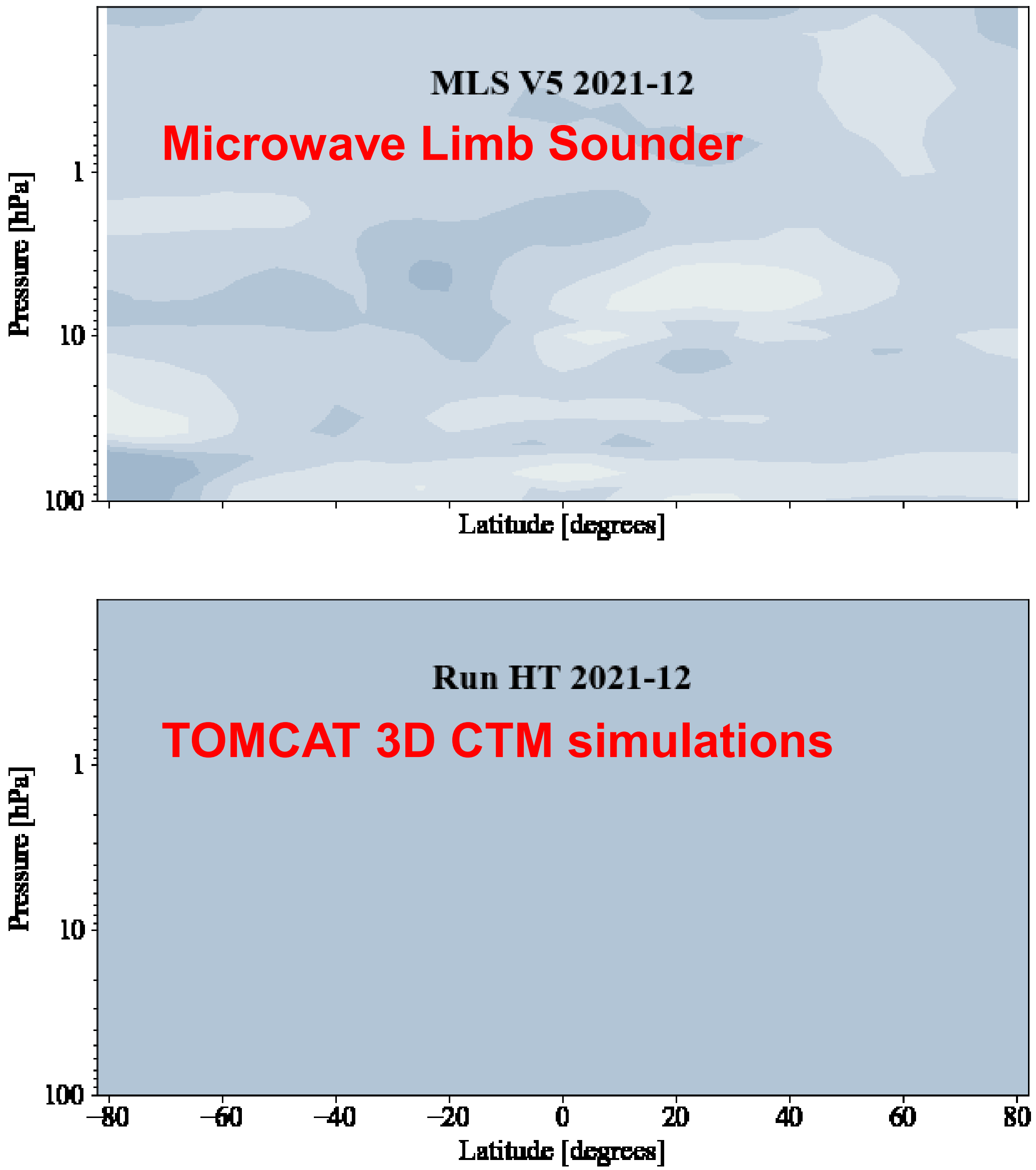
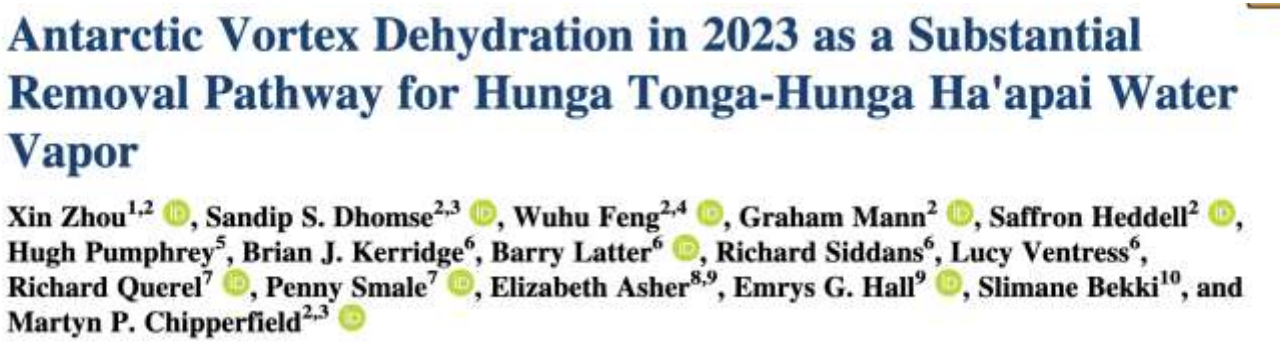


Hunga injection
in Jan 2022

First drop
in Jun-Aug 2023

NASA Microwave Limb Sounder (MLS) observed global excess H_2O mass above 68 hPa




Antarctic Vortex Dehydration in 2023 as a Substantial Removal Pathway for Hunga Tonga-Hunga Ha'apai Water Vapor

Xin Zhou[1,2], Sandip S. Dhomse[2,3], Wuhu Feng[2,4], Graham Mann[2], Saffron Heddell[2], Hugh Pumphrey[5], Brian J. Kerridge[6], Barry Latter[6], Richard Siddans[6], Lucy Ventress[6], Richard Querel[7], Penny Smale[7], Elizabeth Asher[8,9], Emrys G. Hall[9], Slimane Bekki[10], and Martyn P. Chipperfield[2,3]

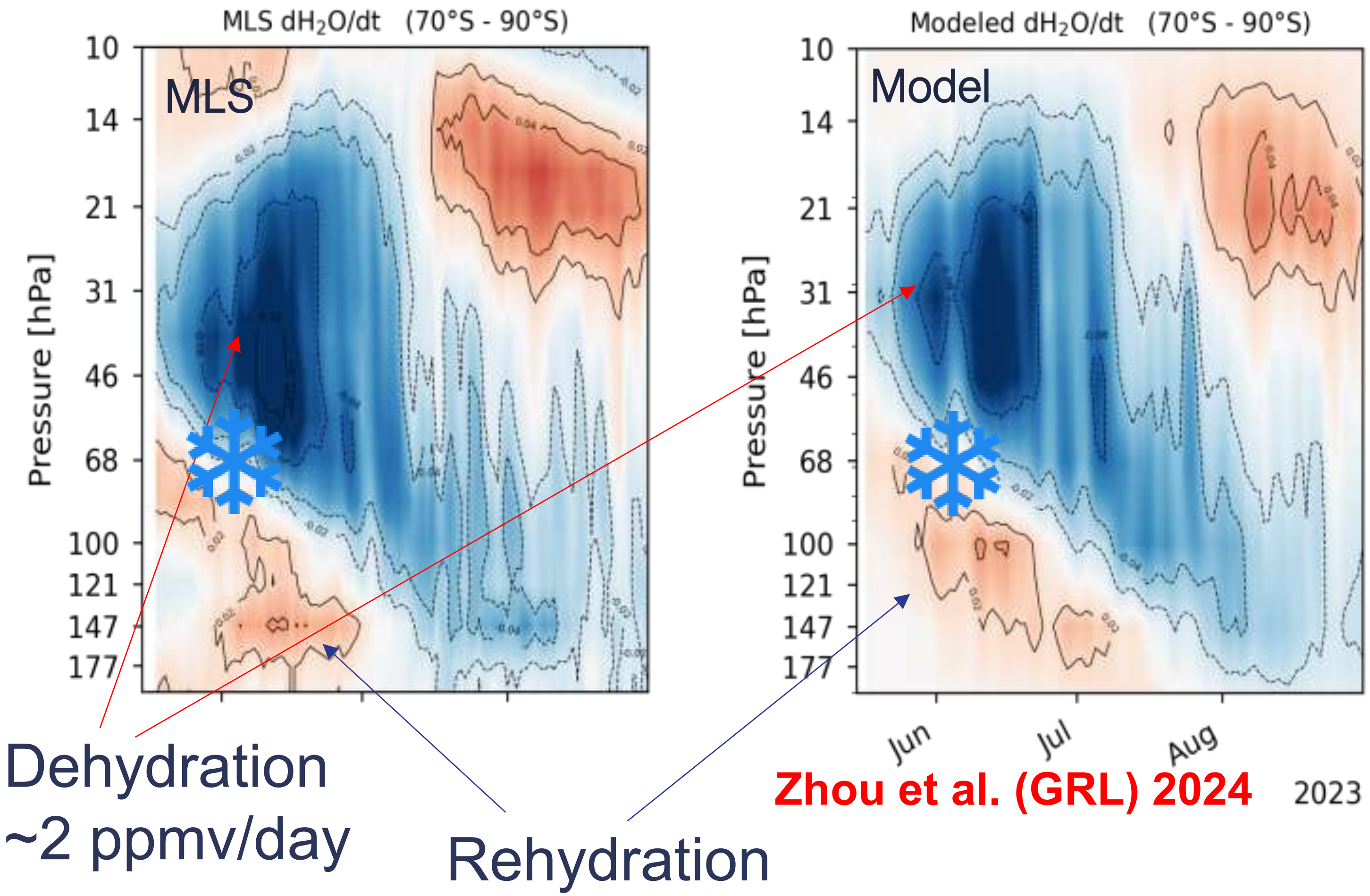
Zhou et al. (Geophys. Res. Lett.) 2024

Microwave Limb Sounder satellite observations &

Modelling Hunga H_2O with TOMCAT on ARCHER2

- a global 3D offline chemistry transport model
- 2.8° × 2.8° degrees. 32 levels from surface to ~65 km; detailed stratospheric chemistry & realistic polar stratospheric cloud (PSC) formation and dehydration
- **Hunga run (2022 onwards)**: inject 150 Tg gas-phase H_2O into the observed location (22-26 km, 2°-28°S)

Daily tendencies of the H_2O mixing ratio inside the Antarctic vortex in JJA 2023



Zhou et al. (GRL) 2024

2023 Antarctic dehydration

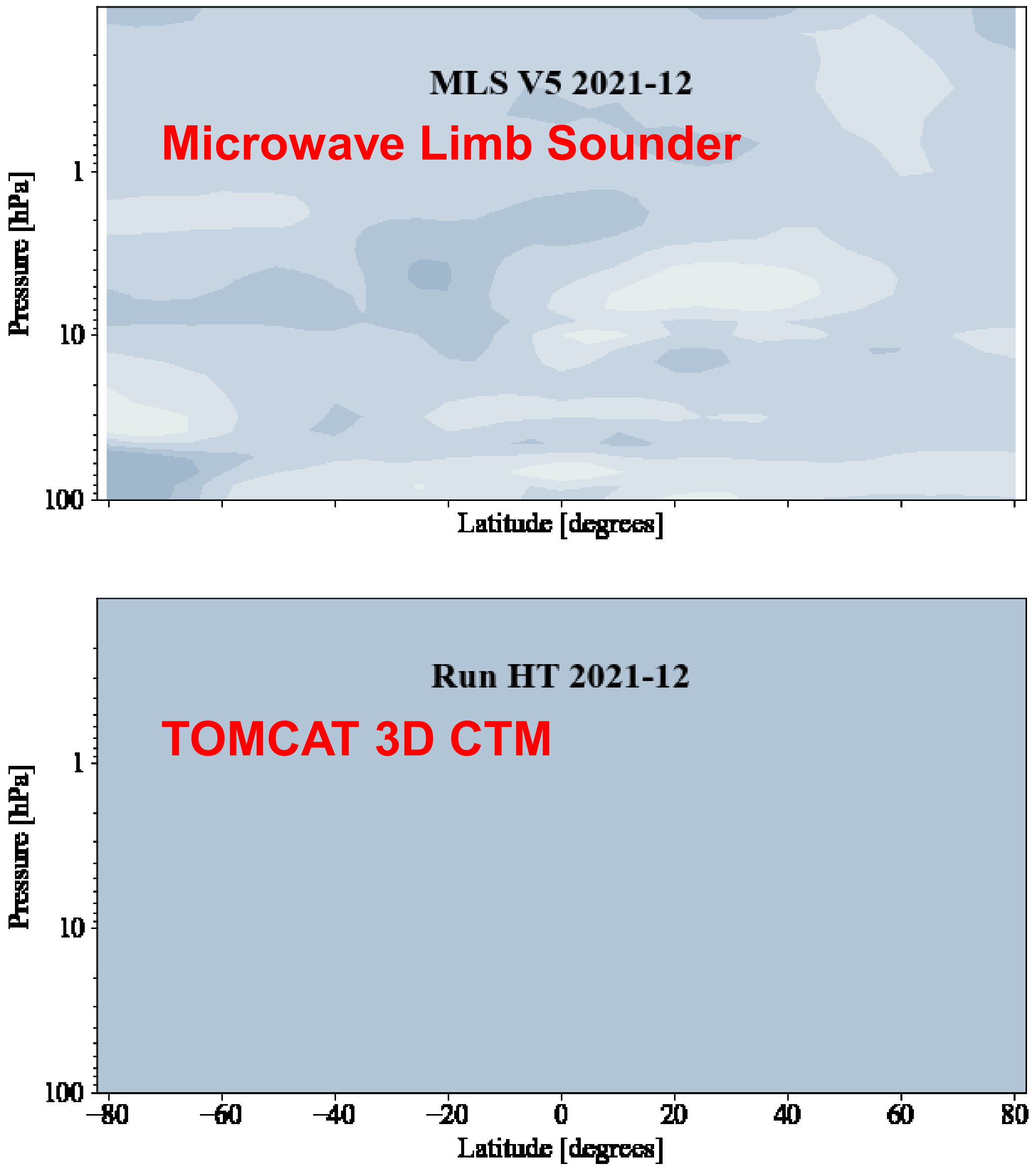
- dehydration above + rehydration below
- stronger than ever observed before
- sedimentation of the Polar Stratospheric Cloud (PSC) ice particles, causing irreversible removal of Hunga H_2O

PSCs also occur in the Arctic winter stratosphere and are sometimes visible from the UK

Image from public Facebook group 'Beautiful Edinburgh'

You can see them!

Photo of PSCs (~20 km altitude) over Edinburgh on Dec 21st 2023, when there was enhanced H_2O due to Hunga.



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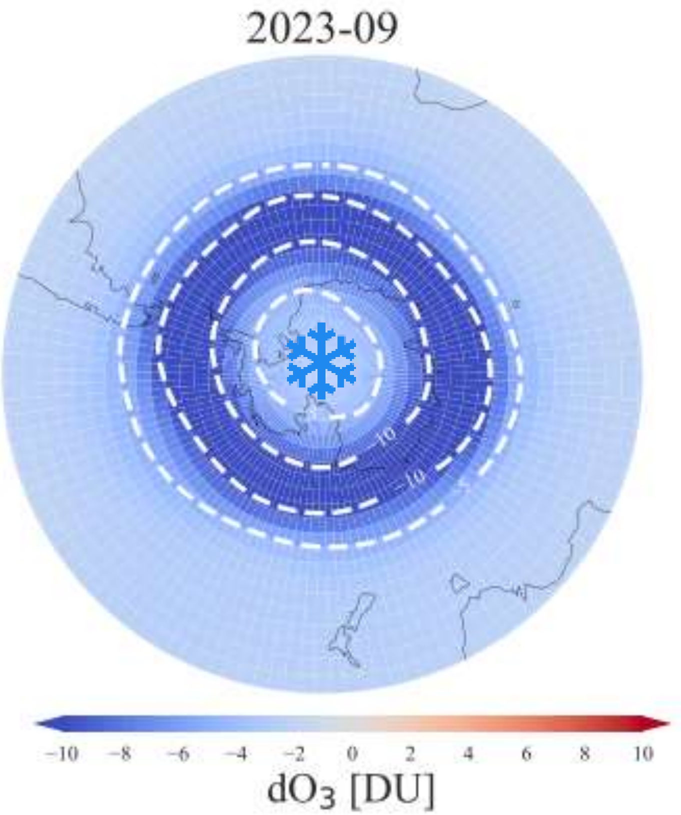
Zhou et al. (GRL) 2024

- Antarctic dehydration is a substantial removal pathway for Hunga H_2O
- Hunga H_2O caused small (~10 DU) additional chemical ozone loss in Antarctic spring, with the maximum effect on vortex edge



TOMCAT 3D chemistry transport model: dotted lines

Hunga injection in Jan 2023

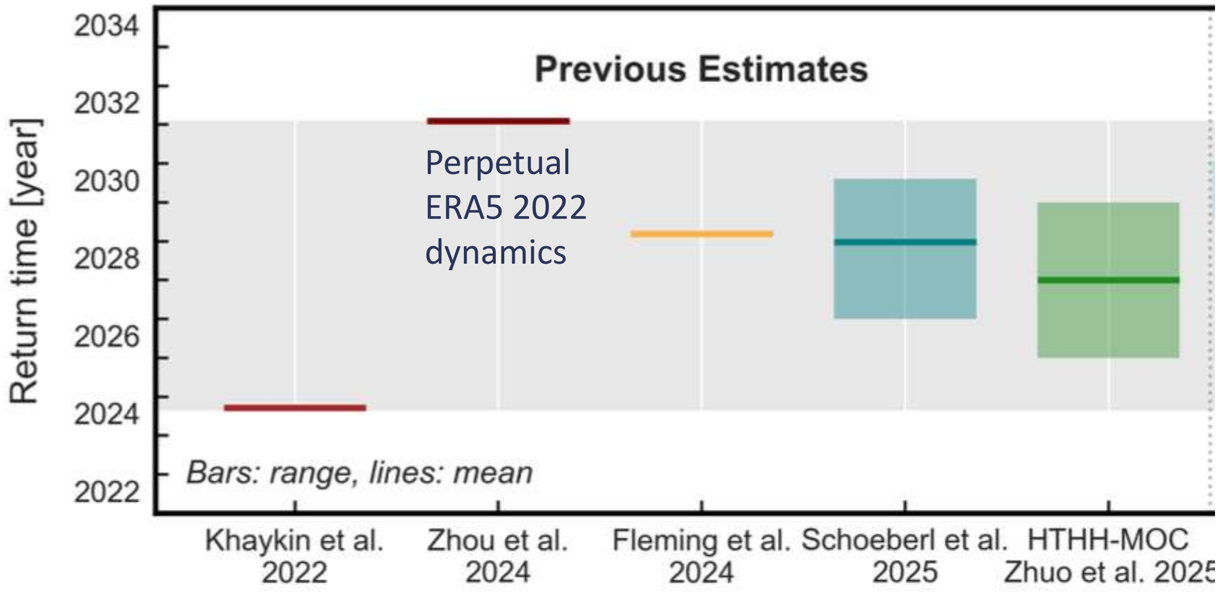
First drop in Jun-Aug 2023 (PSC dehydration)

Increased again in late 2023 (entry from tropical troposphere)

MLS global excess H_2O mass above 68 hPa

Xin Zhou | x.zhou1@leeds.ac.uk

How long will the Hunga water remain in the stratosphere?



- Without significant decline in the 2 years post eruption, it was difficult to answer
- A wide estimate: range from less than 3 years to up to a decade long

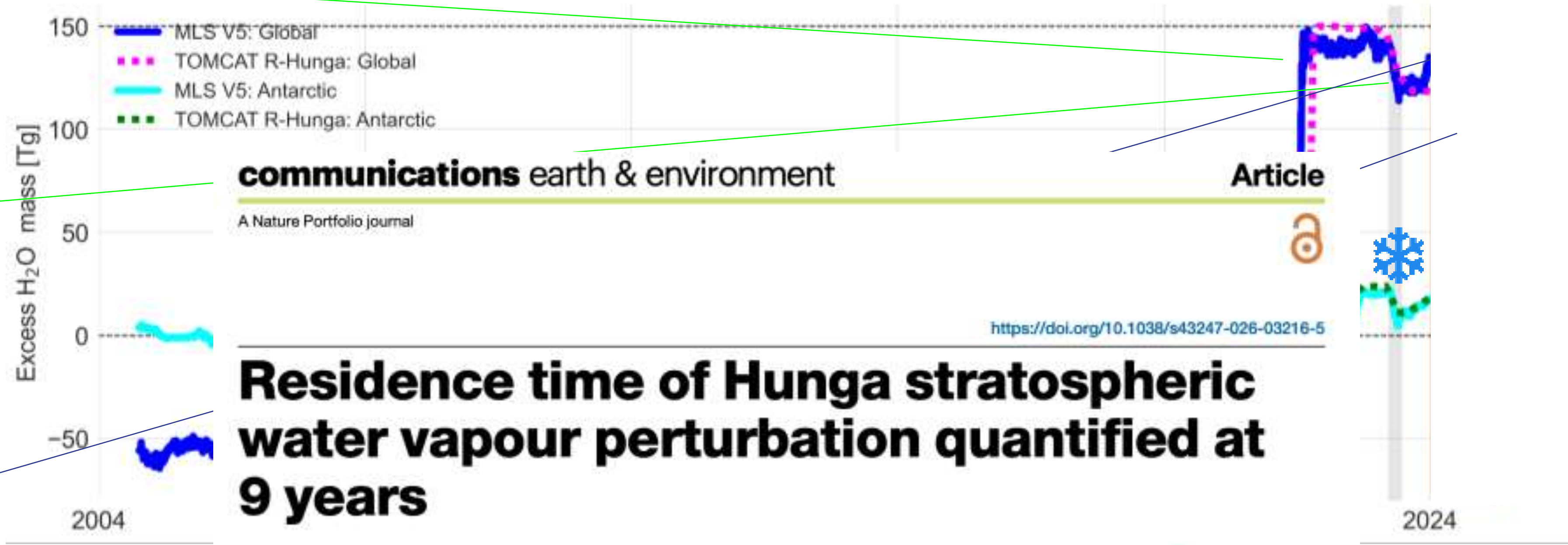
TOMCAT 3D chemistry transport model: dotted lines

Hunga injection in Jan 2023

First drop in Jun-Aug 2023 (PSC dehydration)

Increased again in late 2023 (entry from tropical troposphere)

A sudden drop in 2024



communications earth & environment
Article
A Nature Portfolio journal
https://doi.org/10.1038/s43247-026-03216-5

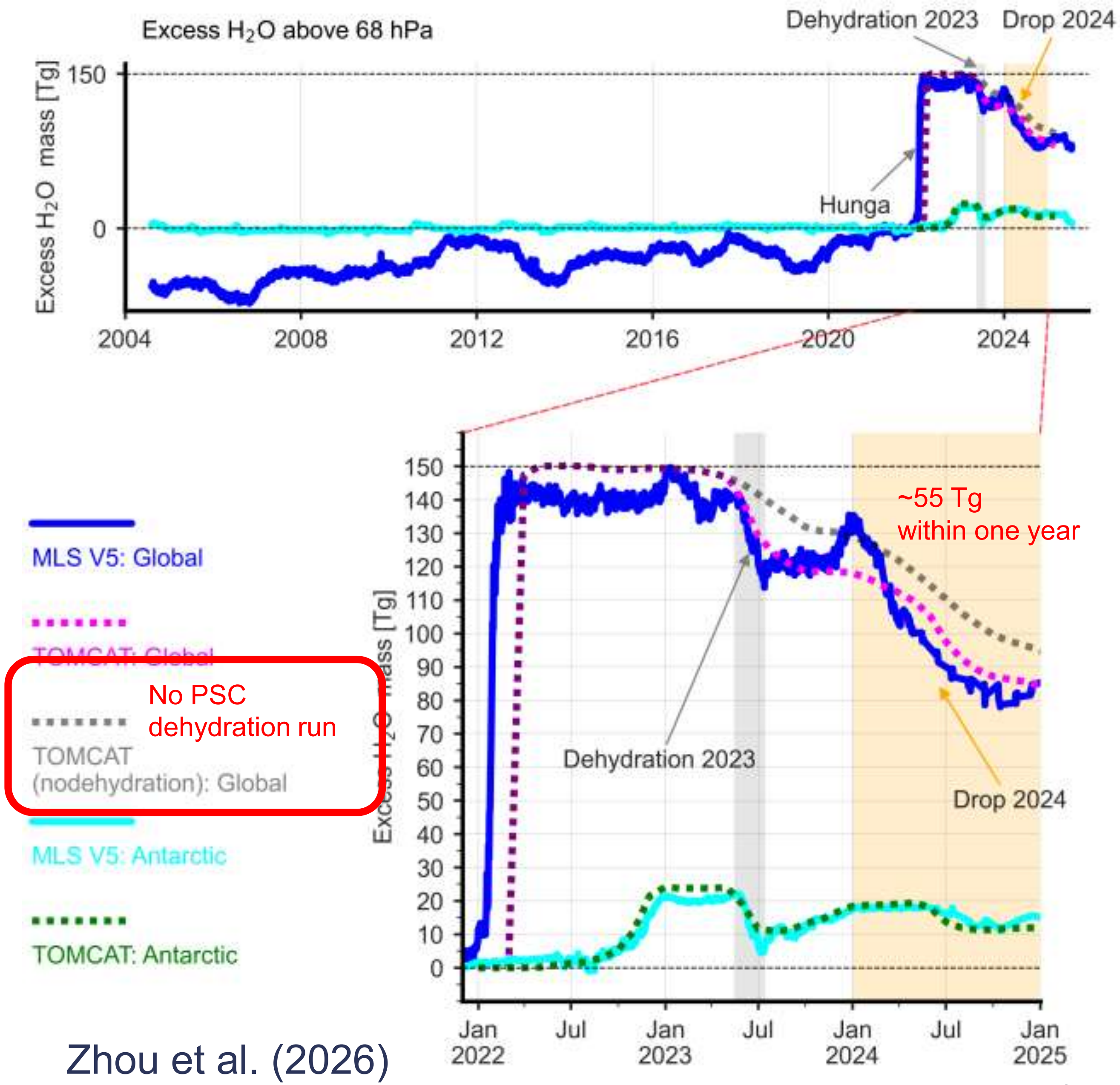
Residence time of Hunga stratospheric water vapour perturbation quantified at 9 years

Check for updates

Xin Zhou[1,2], Quanliang Chen[1], Wuhu Feng[2,3], Saffron Heddell[2], Sandip S. Dhomse[2,4], Graham Mann[2,3], Hugh C. Pumphrey[5], Luis Millán[6], Michelle L. Santee[6] & Martyn P. Chipperfield[2,4]

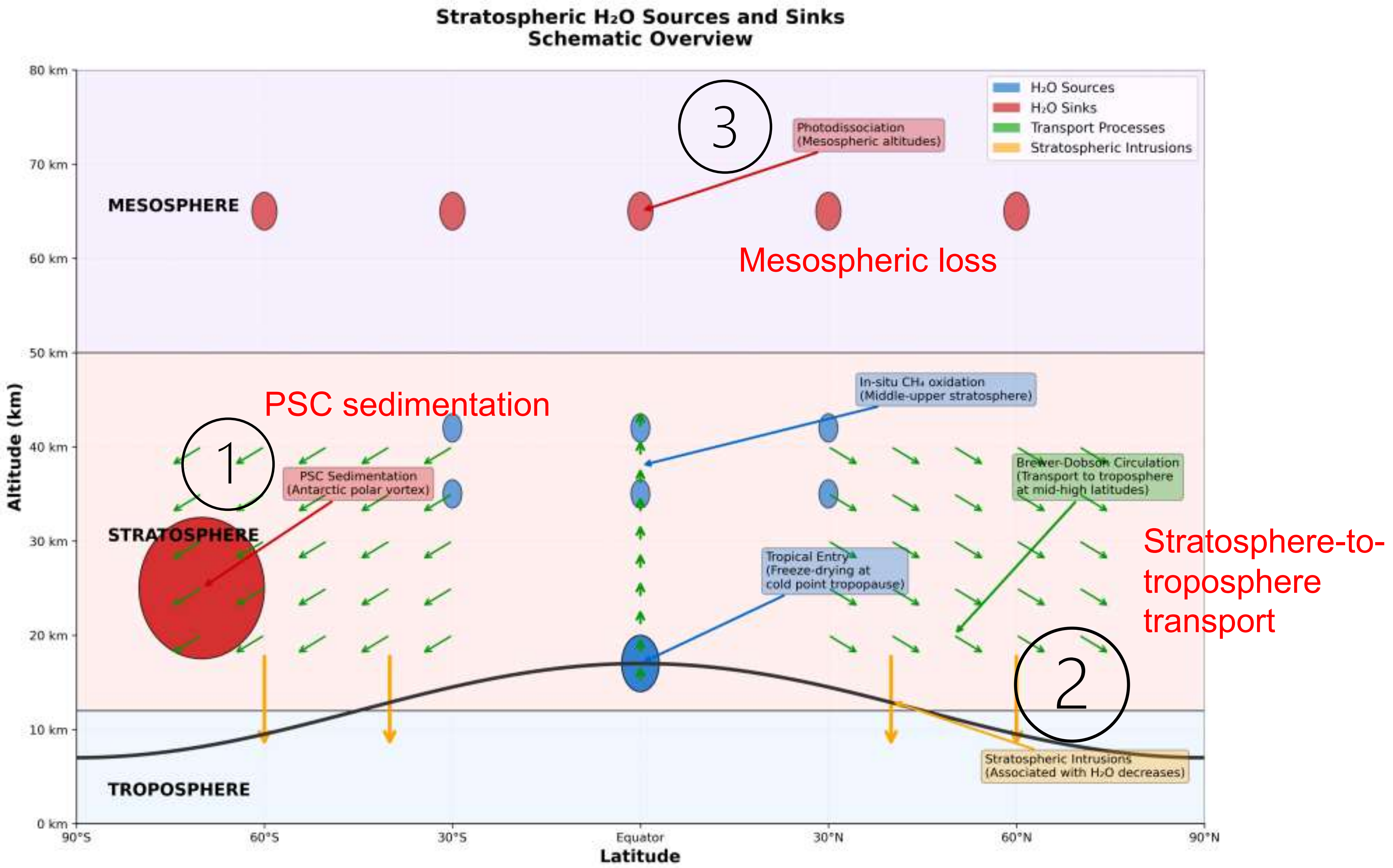
Zhou et al., Communications E. & E., 2026

We now have sufficient observations to characterise the decay in the Hunga H_2O, and interpret it with model.

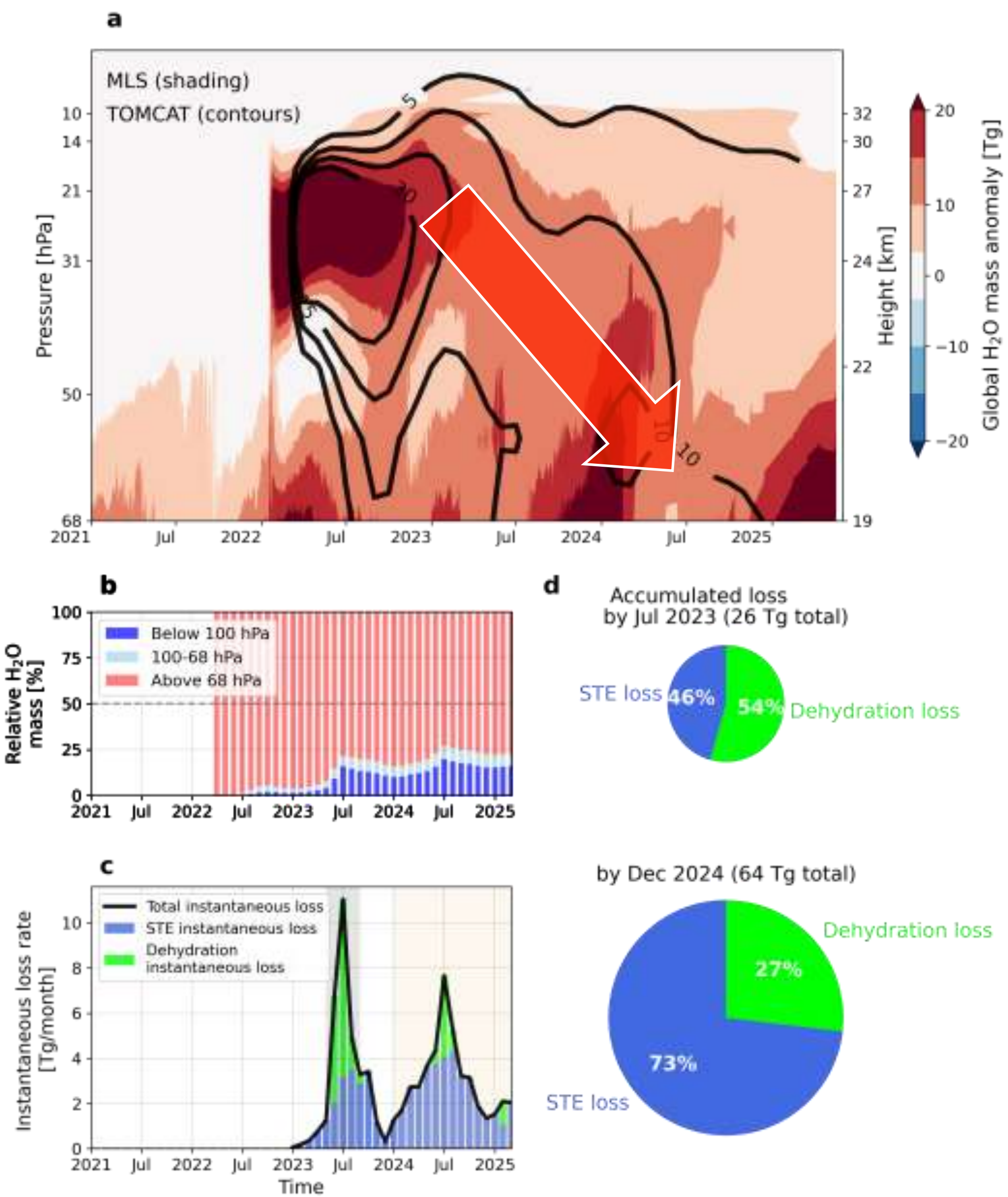


Zhou et al. (2026)

- A sudden drop in 2024, reducing Hunga H_2O by ~55 Tg within just one year.
- The initial injection is diminished by almost half.
- ~~PSC ice dehydration, again?~~
- No PSC dehydration run still captures most of the drop.
- A new decaying phase



Stratospheric H₂O Sources and Sinks
Schematic Overview
80 km
70 km
60 km
50 km
40 km
30 km
20 km
10 km
0 km
Altitude (km)
H₂O Sources
H₂O Sinks
Transport Processes
Stratospheric Intrusions
3
Photodissociation
(Mesospheric altitudes)
MESOSPHERE
Mesospheric loss
PSC sedimentation
In-situ CH₄ oxidation
(Middle-upper stratosphere)
1
PSC Sedimentation
(Antarctic polar vortex)
Brewer-Dobson Circulation
(Transport to troposphere
at mid-high latitudes)
STRATOSPHERE
Tropical Entry
(Freeze-drying at
cold point tropopause)
Stratosphere-to-
troposphere
transport
2
Stratospheric Intrusions
(Associated with H₂O decreases)
TROPOSPHERE
90°S
60°S
30°S
Equator
30°N
60°N
90°N
Latitude

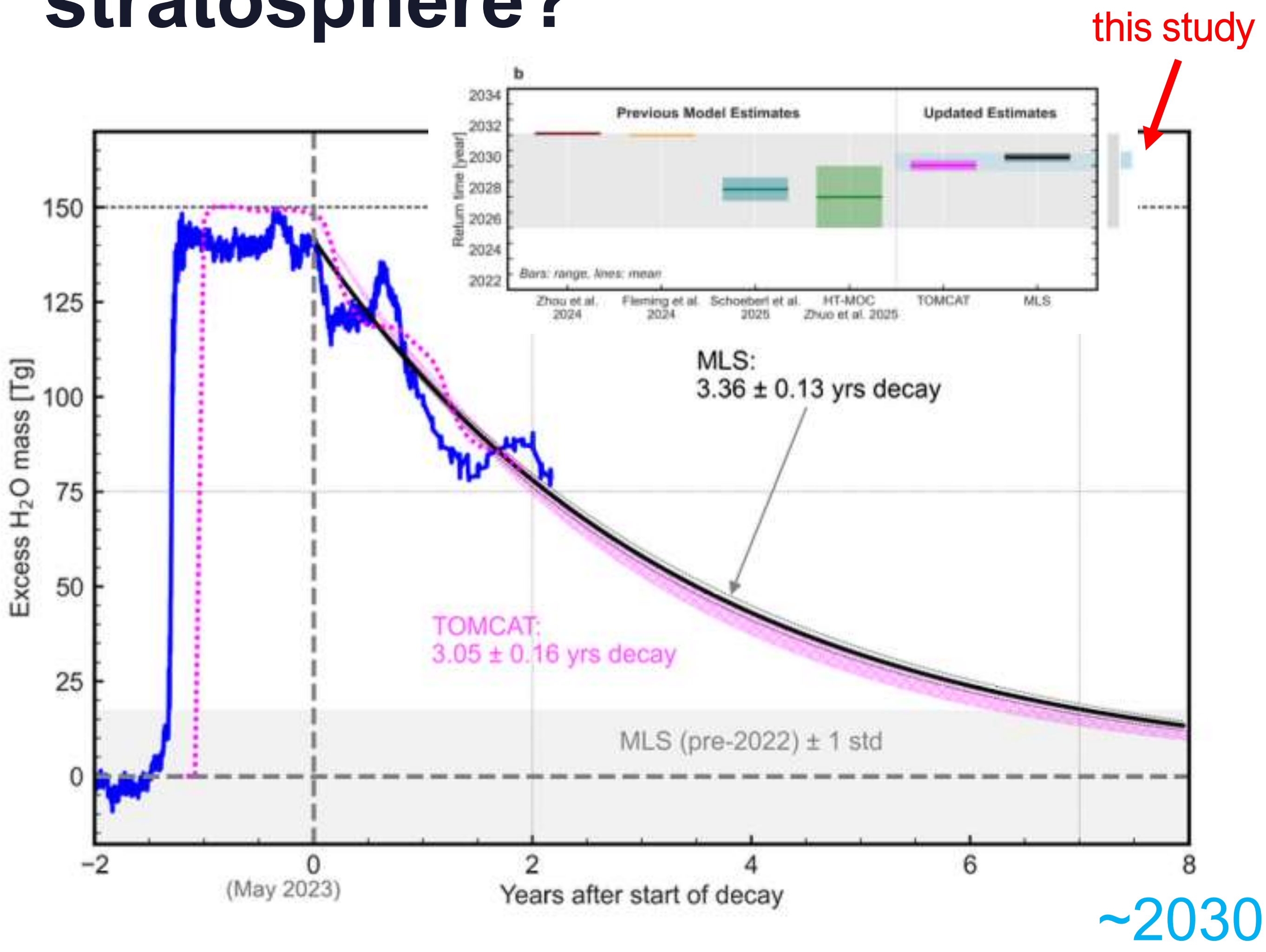


Zhou et al. (2026)

- Above 1 hPa: 1.7% → mesospheric loss is minor.
- Since 2023, Hunga H_2O has been transported downward with the descent of Brewer-Dobson circulation.

- A large fraction (~18%) is now arriving the lower stratosphere below 100 hPa, where it fluxes out.
- Contribution from transport exceeds dehydration loss and becomes dominant by 2024.

How long will the Hunga water remain in the stratosphere?

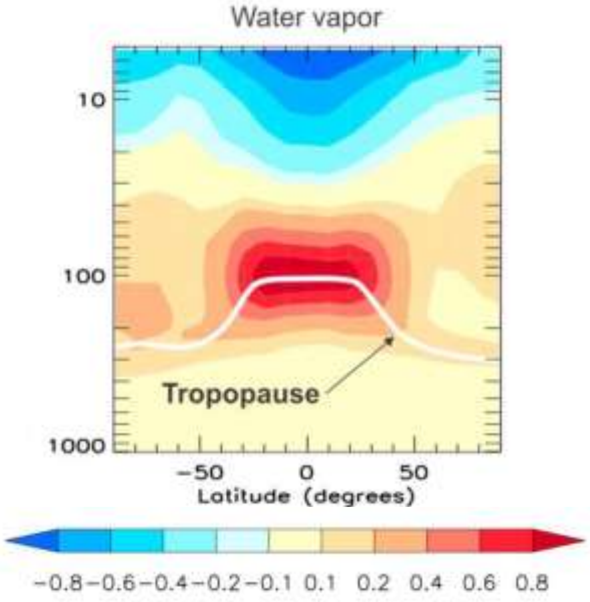


Zhou et al. (2026)

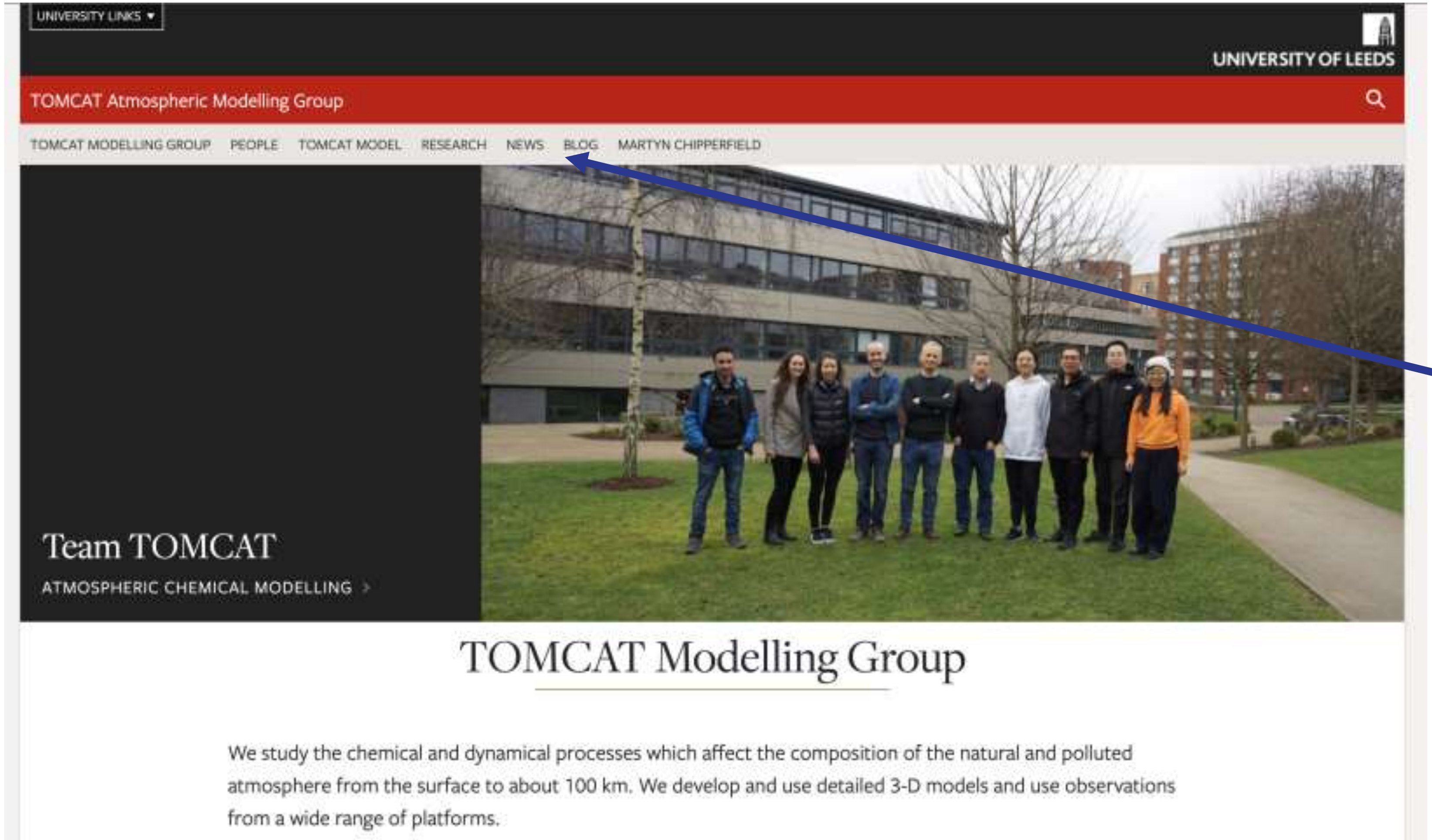
- After 7 yrs of decay, it drops to pre-Hunga condition **around 2030**.
- For the first time, we are able to reduce the uncertainty in Hunga H_2O timescale sufficiently.

What's next?

The descent of Hunga water to the lower stratosphere could enhance its climate impact.

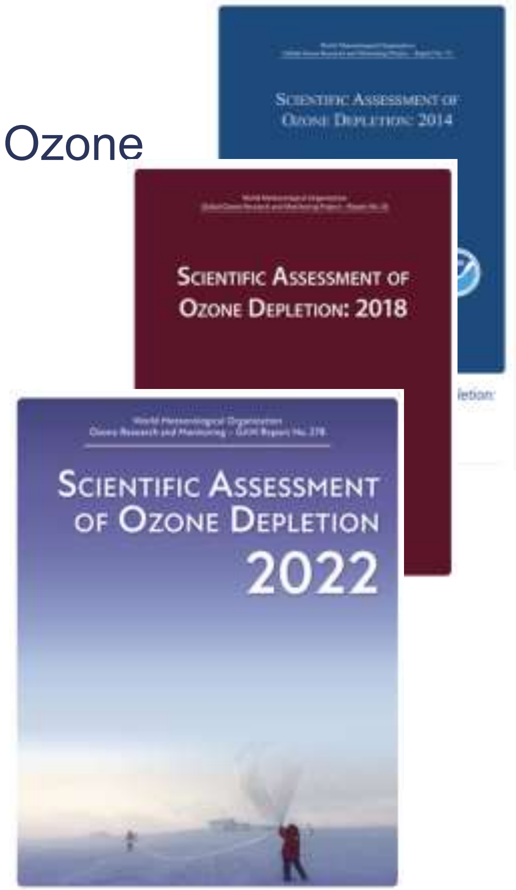


Other recent science enabled by TOMCAT modelling on ARCHER2

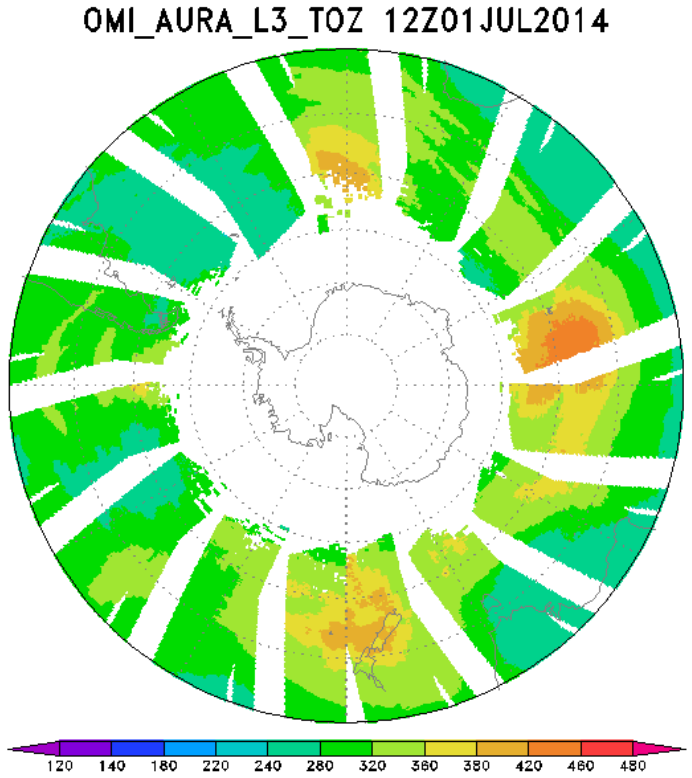


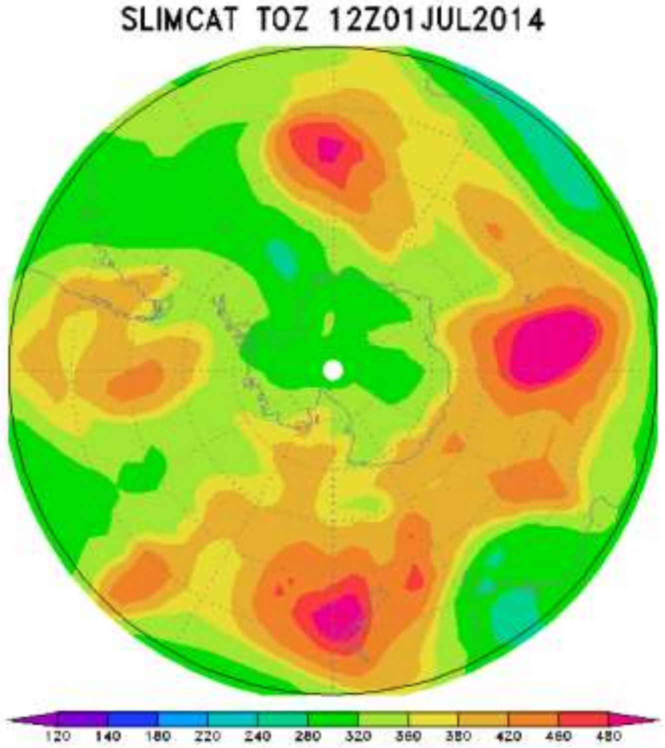
https://tomcat.leeds.ac.uk/

- TOMCAT Simulations performed on successive generations of UK national HPC systems (e.g. HECToR → ARCHER → ARCHER2)
- Study stratospheric transport, ozone depletion, and trace gas evolution
- Supported international assessments, including the World Meteorological Organization Ozone Assessments.



Satellite v TOMCAT 3-D Model – Ozone Hole





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LETTER

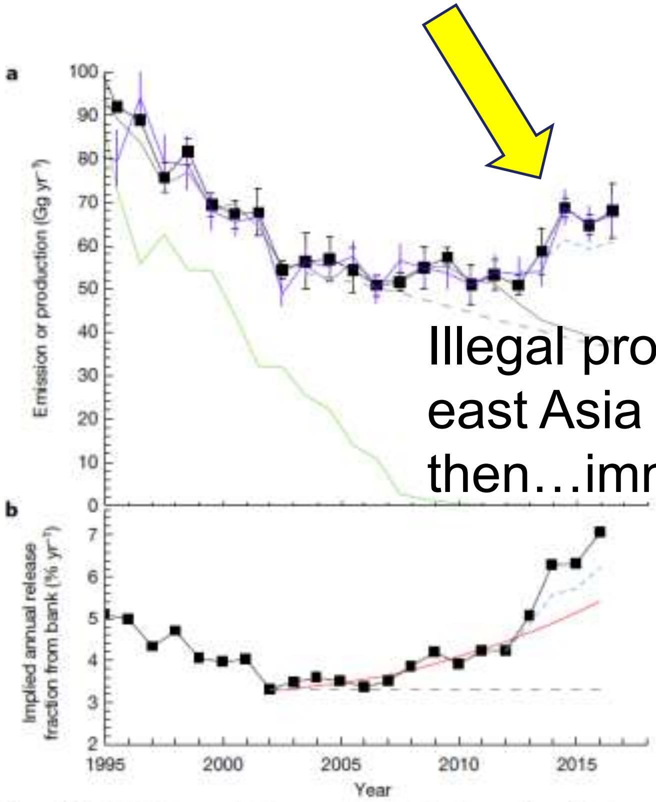
https://doi.org/10.1038/s41586-018-0106-2

An unexpected and persistent increase in global emissions of ozone-depleting CFC-11

Montzka et al (Nature 2018)

CFC-11 emissions increasing over 2008-2017, contrary to expectations under Montreal Protocol

CFCs (e.g., CFC-11 CFC-12)



Illegal production from east Asia including China then…immediate action

Fig. 2 | Global CFC-11 emission, reported production and implied release rate from CFC-11 banks. a, Production magnitudes reported

Article

A decline in global CFC-11 emissions during 2018–2019

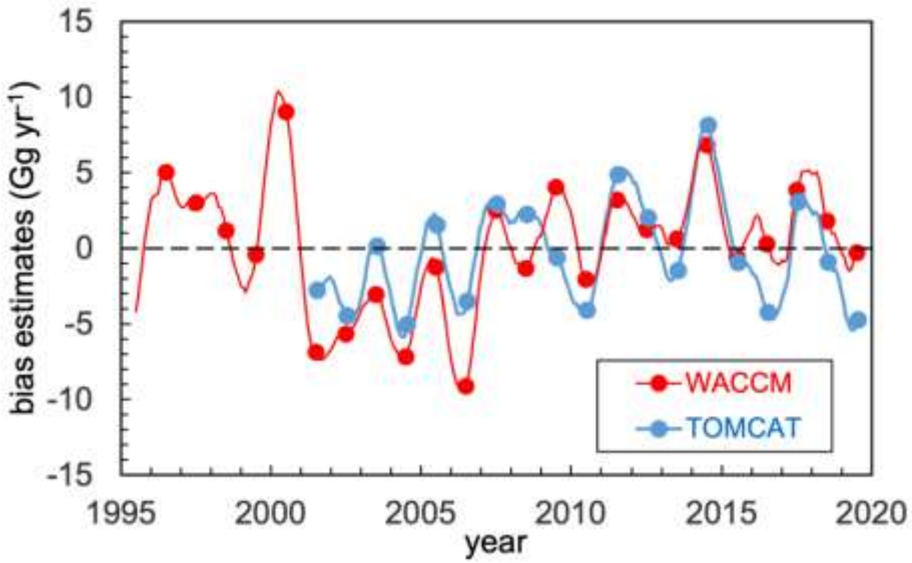
nature

Montzka et al (Nature 2021)

It actually worked.

“Probably the single most successful international agreement to date” Kofi Annan (2004)

TOMCAT used to quantify impact of meteorology on derived emissions, to confirm that CFC11 is back on track



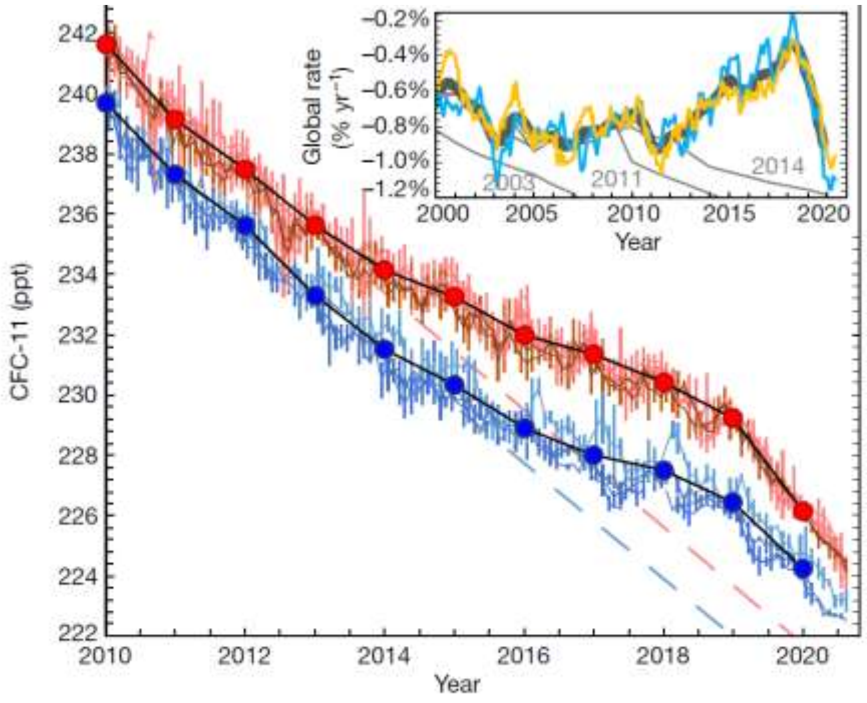


Fig. 1 | Measured atmospheric mole fractions of CFC-11 and global mean rate of change. Monthly mean mole fractions and standard deviations (s.d.) measured at 12 remote sites from NOAA flasks by gas chromatography with

Article

nature

Methane emissions from the Nord Stream subsea pipeline leaks

Harris et al (Nature 2025)

UN environment programme

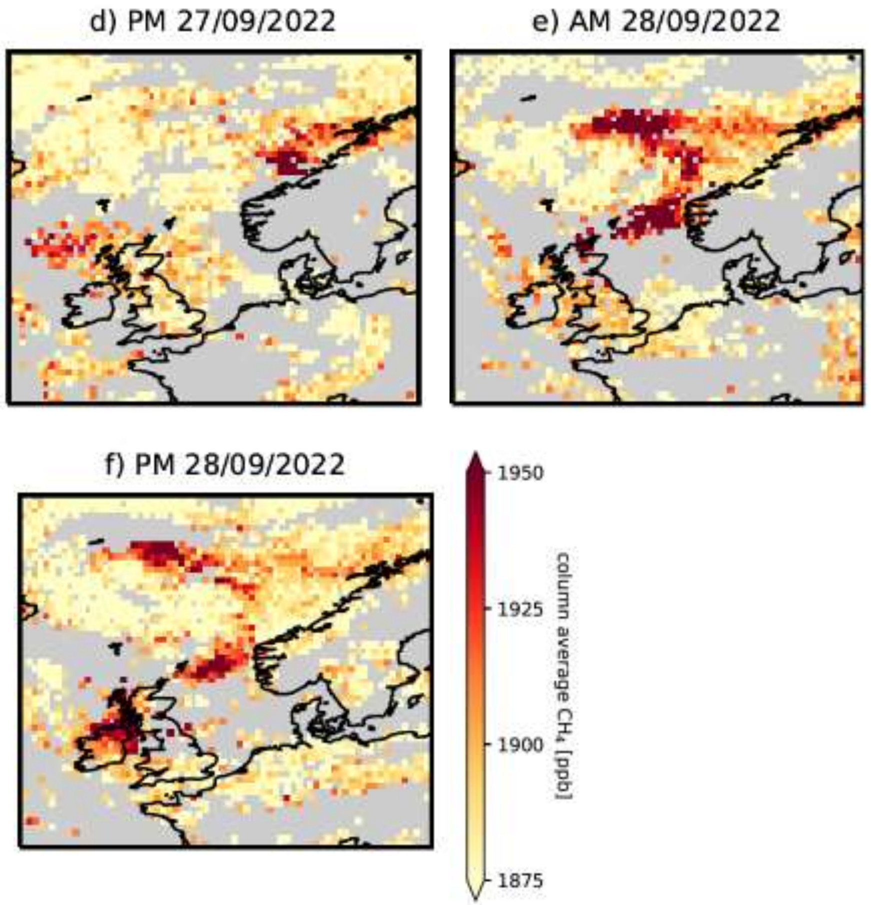
Bubbles of natural gas emerging from the sea the day after the explosions – September 27th 2022

Nord Stream pipeline explosions in 2022 released 100,000s of tonnes of methane (CH_4) into the atmosphere – **but how much exactly?**

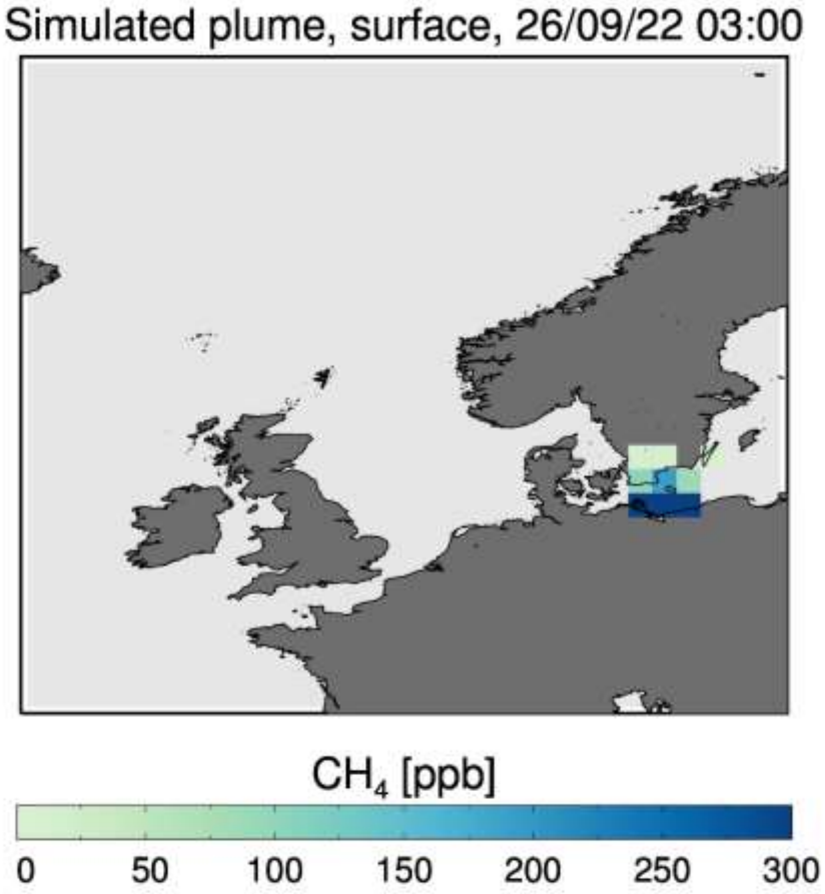
UNEP-led study (Harris et al., Nature, 2025) combined model simulations, atmospheric monitoring and satellite data to estimate the total CH_4 release.

Modelling Nord Stream CH_4 with TOMCAT

The IASI satellite instrument saw the plume of elevated CH_4 as it passed over the North Sea on September 28th



TOMCAT simulations matched the dispersion seen by the satellite and could be used to estimate the total CH_4 release – **485,000 tonnes!**



Nord Stream was the largest human-caused CH_4 leak on record – our findings showed that it was **twice as large as initial estimates**

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Where do we go next?

Closing thoughts

- ARCHER2 (and predecessors) has played a critical role in advancing global chemistry modelling that is essential for understanding atmospheric composition changes and their impacts.
- It has underpinned a wide range of studies in our group using the TOMCAT 3-D chemical transport model (tomcat.leeds.ac.uk/tomcat), including quantification of greenhouse gases emissions, the impact of ozone-depleting substances and recent work on the global impacts of the 2022 Hunga volcanic eruption.
- These are critical functions. We need continuing national HPC machines like ARCHER2.

Additional Slides

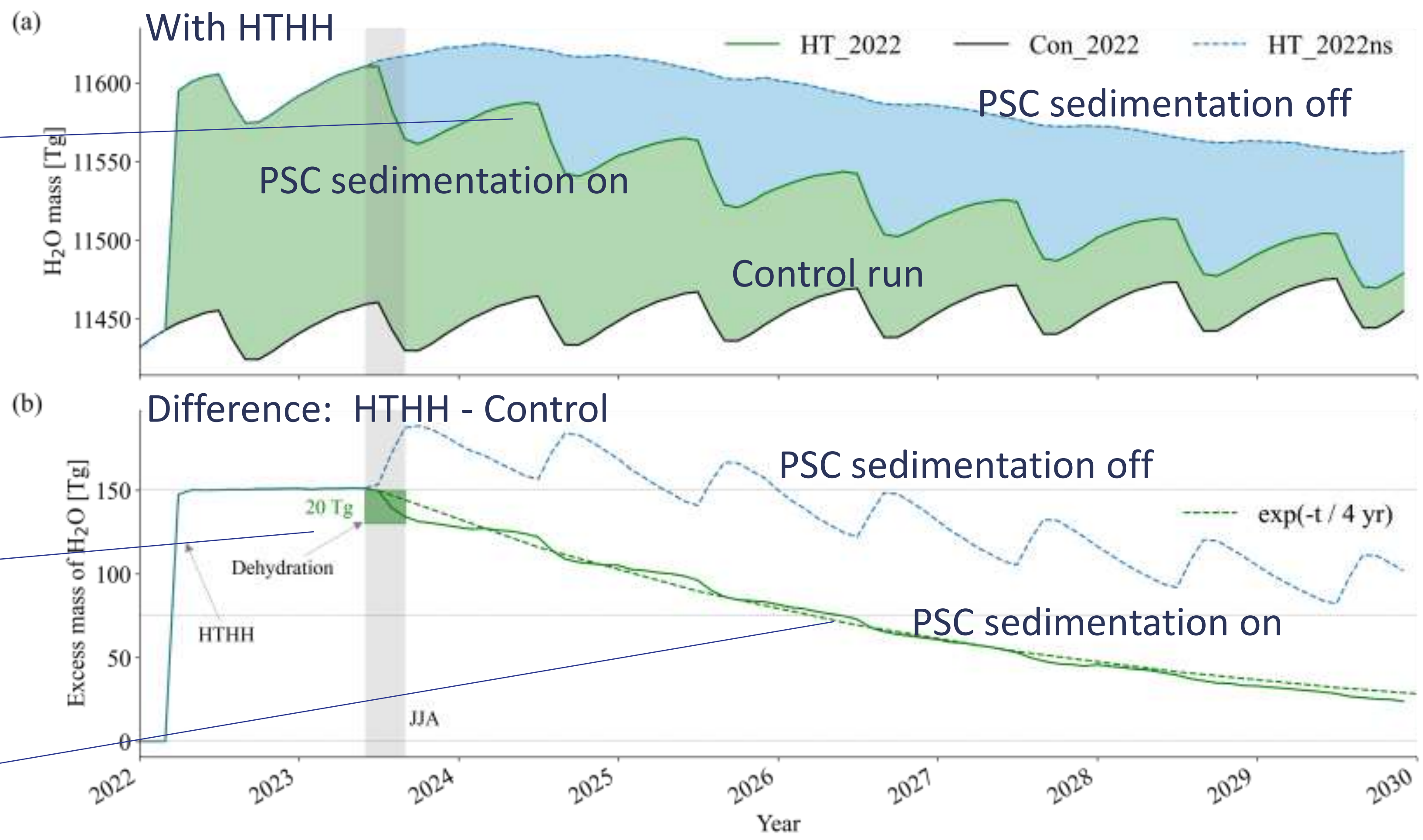
We compare the runs with & without PSC dehydration to quantify the loss due to freezing.

Total water vapour above ~100 hPa

Perpetual ERA5 2022 dynamics

Removal in SH winter from 2023 onwards

Half-life of additional H_2O is ~3 yrs



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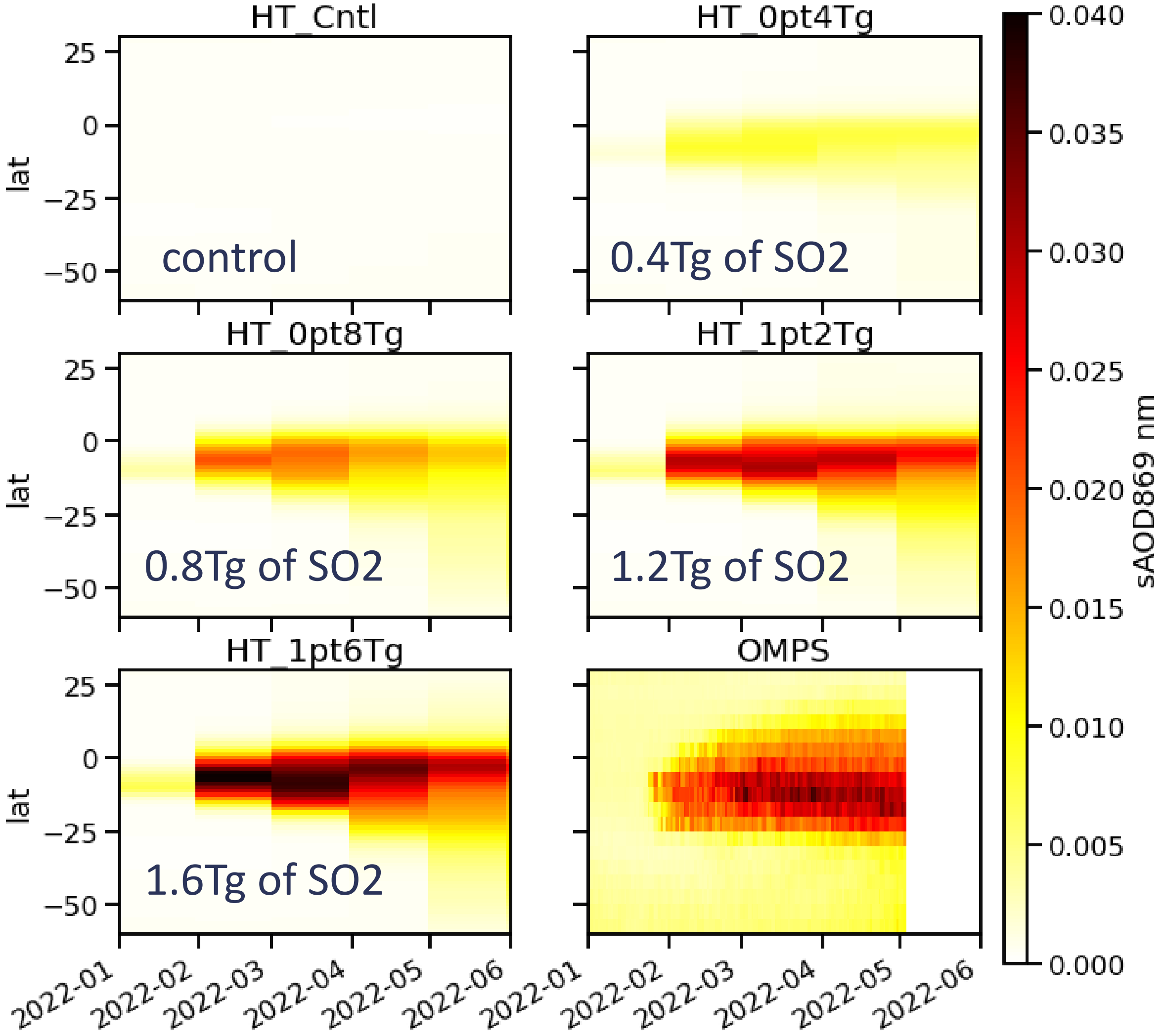
Stratospheric AOD (sAOD) from increased-sulfur Hunga runs (SO2-only UM-UKCA, first 4 months after)

UM-UKCA strat-AOD@ 870nm
(to compare to "best" OMPS@869nm)

- Best estimate SO_2 emission of 0.4Tg generated only ~ 0.01 sAOD (at 870nm)
- The ~0.03 $sAOD_{869nm}$ observed by OMPS requires ~1.2-1.6 Tg of SO_2 in SO2-only (according to UM-UKCA simulations)
- 1.6Tg agrees quite well to satellite obs but model remains south of equator → OMPS has increased-sAOD 25°S-10°N



Here same GA4 UM-UKCA model applied for Pinatubo, El Chichon & Agung in Dhomse et al. (2020)

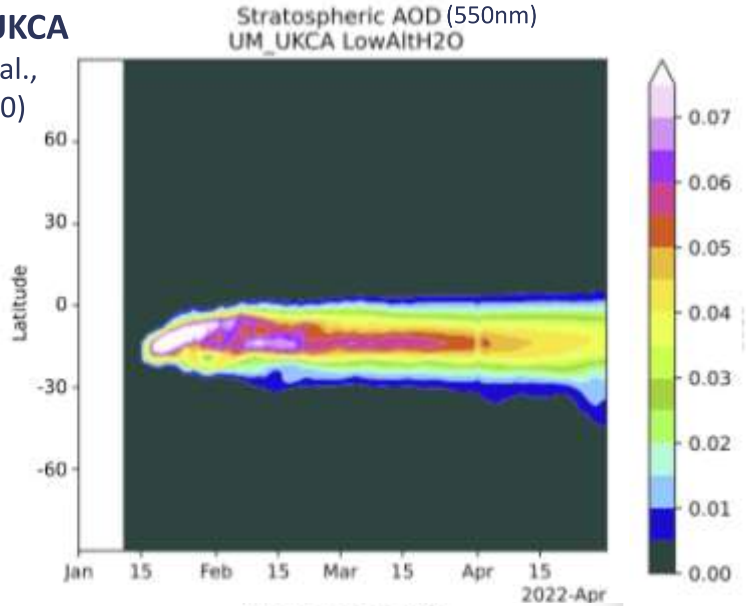
All model runs here emit SO_2 at 29-31km (free-run forward-projection runs, spring 2022)

Hunga water-vapour can explain observed strat-AOD, and exploring that H_2O-cooling causes "plume turning effect"

UNIVERSITY OF LEEDS

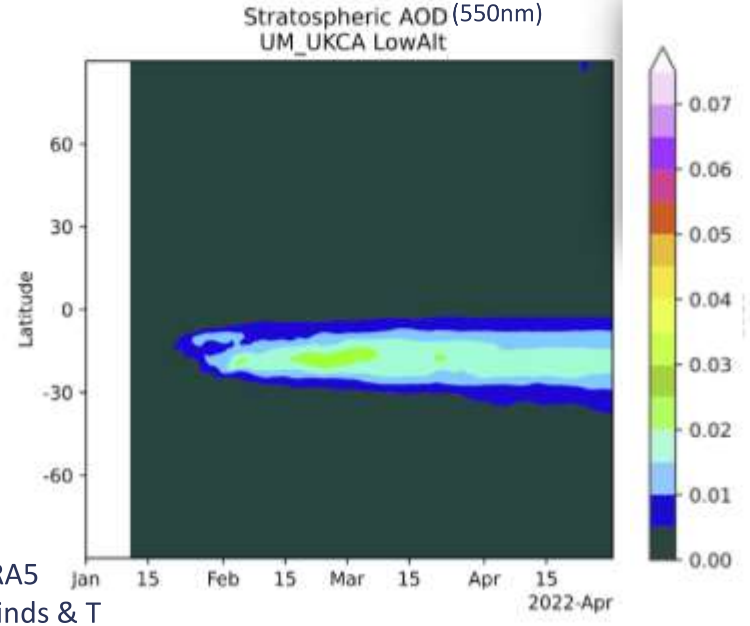
GA4 UM-UKCA (Dhomse et al., 2014; 2020)

0.4 Tg SO_2 & 150 Tg H_2O vapour emission (25-30km)



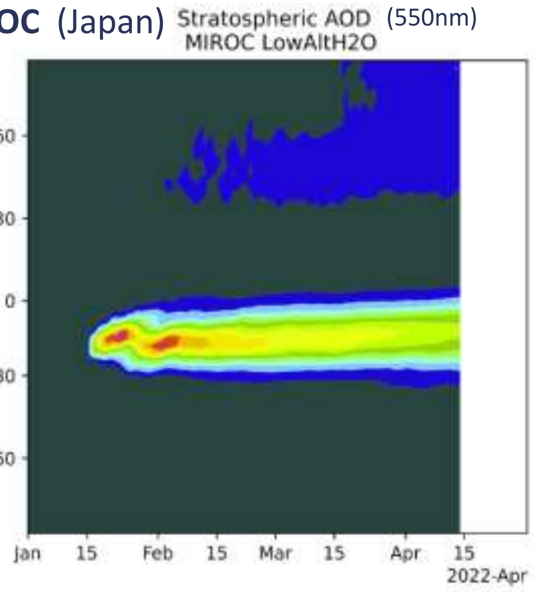
0.4 Tg SO_2 only emission (25-30km)

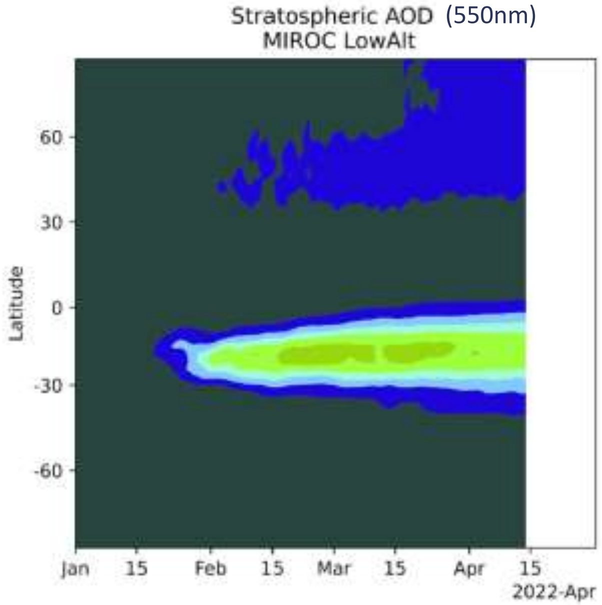
(no H2O emission)



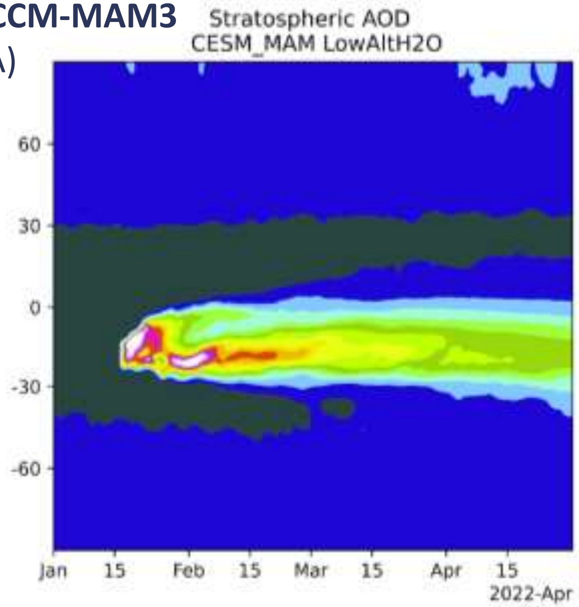
Nudged to ERA5 re-analysis winds & T

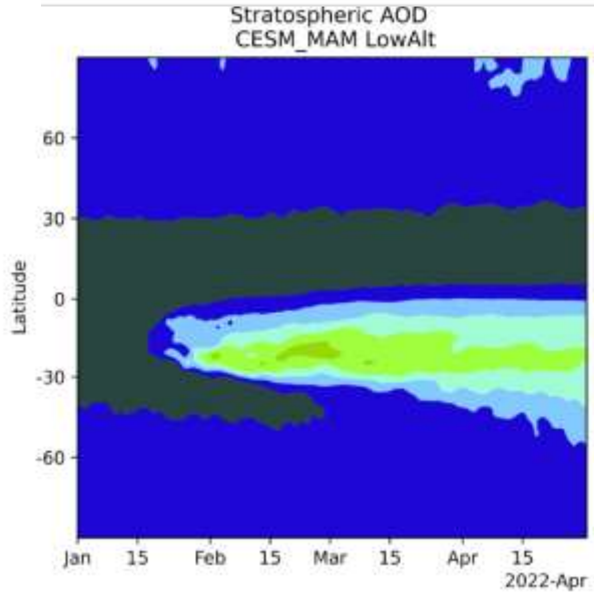
MIROC (Japan)





WACCM-MAM3 (USA)





Clyne et al. (2026, in prep.)

(first 100 days post-eruption)