School of Earth and Environment
INSTITUTE FOR CLIMATE & ATMOSPHERIC SCIENCE

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The 2022 Hunga-Tonga volcanic cloud: Stronger than expected stratospheric aerosol optical depth, alongside also continuing water vapour radiative & chemistry effects

Graham Mann, Sandip Dhomse, Wuhu Feng, Martyn Chipperfield (University of Leeds, U.K.)
Ghassan Taha (NASA Goddard Space Flight Center, USA)

1. **Most explosive eruption in satellite era – injected ~120 Tg H_2O & 0.4Tg SO_2 to stratosphere (Explosive power "likely larger than 1991 Pinatubo & possibly comparable to 1883 Krakatoa", see Wright et al., 2022, Nature, https://doi.org/10.1038/s41586-022-05012-5)."**
2. **Net surface warming eruption (strat water vapour forcing > aerosol forcing, Sellitto et al., 2022)**
3. **Hunga-Tonga caused 2022 highest stratosphere AOD for 30 years (Khaykin et al., 2022) and increased 2022 Antarctic O_3 loss by ~20-30% (Wang et al., in review, 2023)**

Email: G.W.Mann@leeds.ac.uk

"Volcanic eruptions […] are the *dominant* ***natural cause*** of externally forced climate change on the annual and multi-decadal time scales […]"

"The RF [radiative forcing] of volcanic aerosols is well understood"

	Evidence	Agreement	Confidence Level	Basis for Uncertainty Estimates (more certain / less certain)	Change in Under-standing Since AR4
Volcanic aerosol	Robust	Medium	*High*	Observations of recent volcanic eruptions/Reconstructions of past eruptions	Elevated owing to improved understanding

Table 8.5 from Myhre et al., 2013 | **Confidence levels for the forcing estimates**

"The volcanic RF has a **very irregular temporal pattern** and for certain years has a strongly negative RF"

"Although the effects of volcanic eruptions on climate are largest in the 2 years following a large stratospheric injection […] there is **new work indicating extended volcanic impacts** via long-term memory in the ocean heat content and sea level […]"

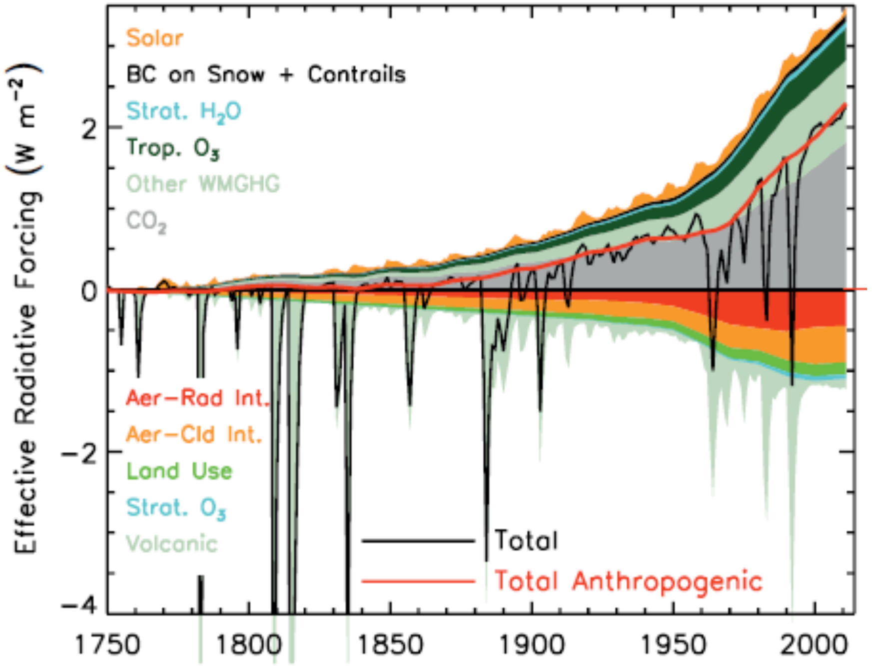


Figure 8.18 from Myhre et al., 2013 **Time evolution for anthropogenic and natural forcing mechanisms**

Volcanoes and climate in a sketch

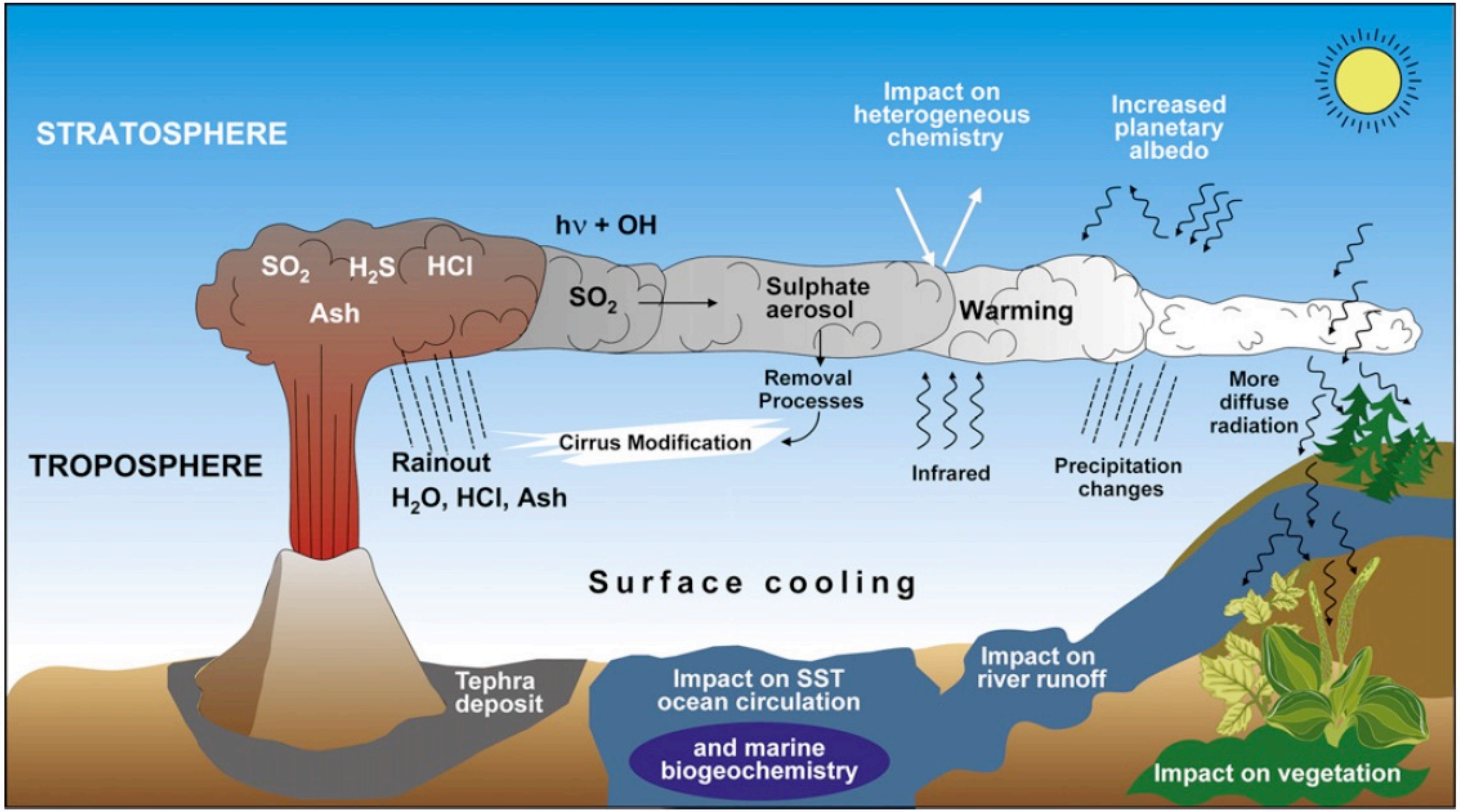


Figure 1 from Timmreck et al., 2011 | **Schematic overview over the climatic effects of very large volcanic eruptions**

Science & Society → Hunga-Tonga net surface warming with tangible impact on near-term climate projections

communications earth & environment

Article | Open Access | Published: 19 November 2022

The unexpected radiative impact of the Hunga Tonga eruption of 15th January 2022

P. Sellitto, A. Podglajen, R. Belhadji, M. Boichu, E. Carboni, J. Cuesta, C. Duchamp, C. Kloss, R. Siddans, N. Bègue, L. Blarel, F. Jegou, S. Khaykin, J. -B. Renard & B. Legras

Communications Earth & Environment **3**, Article number: 288 (2022) | Cite this article

Sellitto et al. (2022)

Abstract

The underwater Hunga Tonga-Hunga Ha-apai volcano erupted in the early hours of 15th January 2022, and injected volcanic gases and aerosols to over 50 km altitude. Here we synthesise satellite, ground-based, in situ and radiosonde observations of the eruption to investigate the strength of the stratospheric aerosol and water vapour perturbations in the

nature climate change

Brief Communication | Published: 12 January 2023

Tonga eruption increases chance of temporary surface temperature anomaly above 1.5 °C

Stuart Jenkins, Chris Smith, Myles Allen & Roy Grainger

Nature Climate Change **13**, 127–129 (2023) | Cite this article

Jenkins et al. (2023)

Abstract

On 15 January 2022, the Hunga Tonga–Hunga Ha'apai (HTHH) eruption injected 146 MtH_2O and 0.42 MtSO_2 into the stratosphere. This large water vapour perturbation means that HTHH will probably increase the net radiative forcing, unusual for a large volcanic eruption, increasing the chance of the global surface temperature anomaly temporarily exceeding 1.5 °C over the coming decade. Here we estimate the radiative response to the HTHH eruption

Emerging policy-relevance of Hunga-Tonga impacts → for both near-term climate projections and impacts on the ozone layer

Submitted case for Hunga-Tonga to be one of World Climate Research Programme annual "10 new insights into climate science" peer-reviewed article in policy-facing journal Global Sustainability, see https://10insightsclimate.science/call-for-inputs-2023/

Projected 5-10 year longevity of the stratospheric water vapour enhancement → a new paradigm in volcano-climate impacts, and the positive radiative forcing from this unique eruption will be a lasting benchmark test for chemistry-climate models.

Wang et al. (submitted Dec 2022) in review in Science → Hunga-Tonga caused ~20-30% more Antarctic ozone loss in 2022
→ due to heterogeneous chemistry on volcanic aerosol https://essopenarchive.org/doi/full/10.1002/essoar.10512922.1

Model predictions show HT increased 60S-82S ozone loss by ~20-30% -- due to chemistry on volcanic aerosol

2022 Antarctic ozone hole was depleted, at similar strong depletion seen in 2021

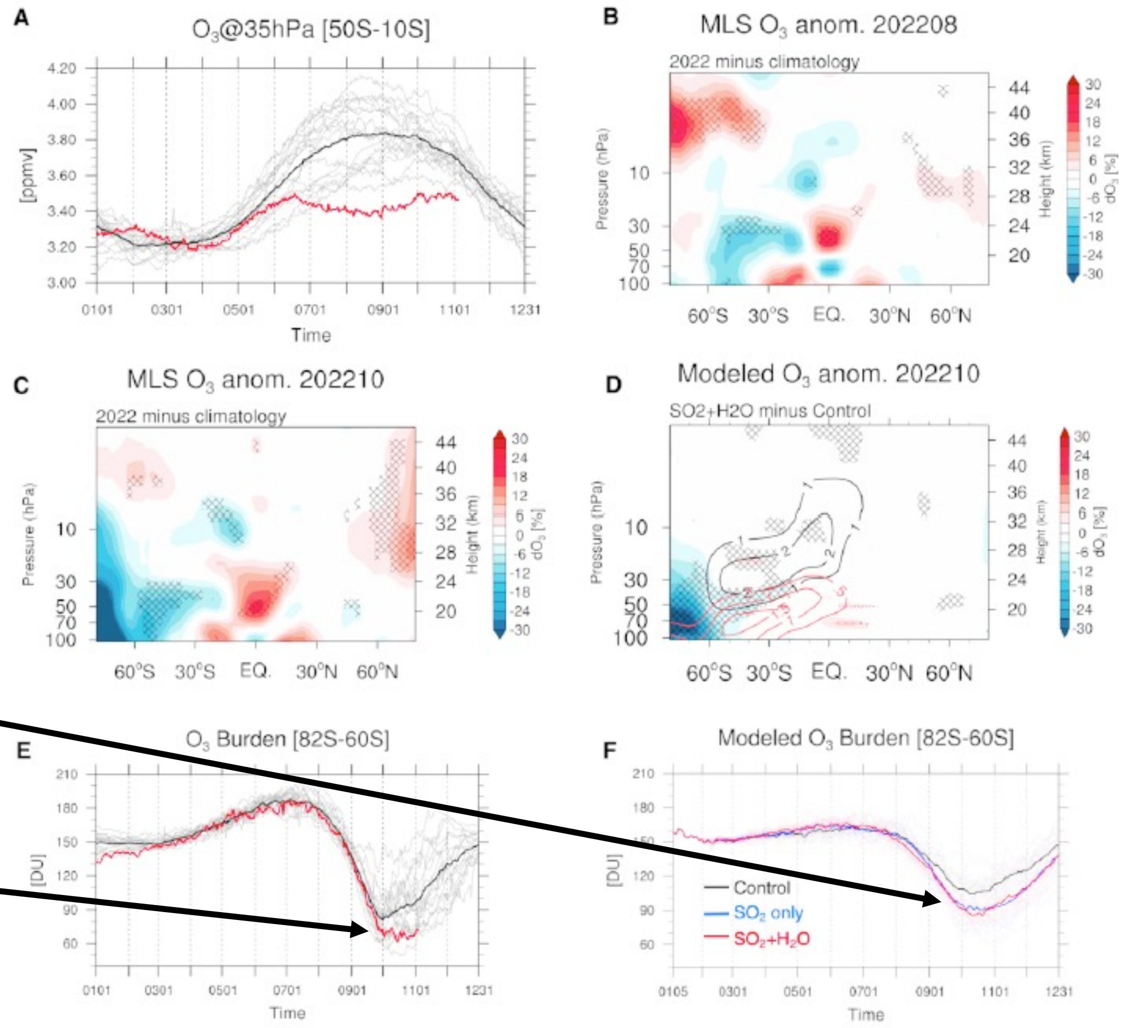


Fig. 4 Evolution of stratospheric ozone after HTHH. (**A**) Time series of MLS observed ozone at 35 hPa, 50°S-10°S, showing large ozone depletion in 2022 (red line). (**B, C**) Fractional ozone anomalies (%) from MLS in August and October 2022, respectively. Hatched regions in (**B, C**) indicate where the 2022 anomalies are outside the range of all variability during 2004-2021. (**D**) Modeled October ozone changes in H_2O+SO_2 minus control simulations. Hatched regions mark the grid points for which the changes exceed the 95% significance level according to Student *t*-test. (**E**) MLS observations of polar cap (82°S-60°S) ozone column over 11-22 km in 2004-2022, and (**F**) corresponding modeled results comparing control, H_2O+SO_2 and SO_2 only simulations.

Wang et al. (in review, MS shared on ESSOAR)

Wang et al. (in review, 2023) submitted MS shared on ESSOAR:
https://essopenarchive.org/doi/full/10.1002/essoar.10512922.1

New project of World Climate Research Program "Stratospheric Processes & Role in Climate" SPARC activity → 2022-2025 SPARC cross-activity focus project "Hunga-Tonga impacts on the stratosphere"

This impressive illustration shows the vulcanic erruption of Hunga Tonga–Hunga Ha'apai of January 2022, and was created by Yungian Zhu. She is one of the co-authors of the new SPARC activity that examines impacts of this erruption. An Introduction to this new activity can be found on page 10.

SPARC Hunga-Tonga impacts activity to co-ordinate for 2025 Honga-Tonga report aligned to 2026 WMO/UNEP "Scientific Assessment of Ozone Depletion" report

Hunga Tonga-Hunga Ha'apai (HTHH) SPARC Report Outline:

This HTHH community assessment spans multiple research topics but is focused on the following three science themes:

A. Plume evolution, dispersion and large-scale transport
B. Impacts on stratospheric aerosols and the ozone layer
C. Radiative forcings from the eruption and surface climate impacts.

1. **Intro to the eruption**
2. **Plume dispersion phase (0-6 days)**
3. **Evolution of the volcanic cloud & its meridional dispersion (shallow BDC branch)**
4. **HTHH effects on stratospheric temperatures, dynamics, and transport.**
5. **HTHH effects on ozone and stratospheric chemistry**
6. **Upper stratosphere to mesosphere and effects & H_2O transport in deep BDC branch**
7. **Radiative and surface/tropospheric climate impacts of the eruption**
8. **Summary**

Upcoming 2-half-day online science meeting on Hunga-Tonga Tue 16th & Wed 17th May

Also EGU session AS3.13 on Mon 24th April "volcanic impacts & strat-aerosol layer" Hunga-Tonga invited Sergey Khaykin (CNRS)
https://meetingorganizer.copernicus.org/EGU23/session/46826#Orals

SPARC
Stratosphere-troposphere Processes And their Role in Climate

See also https://www.sparc-climate.org/activities/hunga-tonga/
and January 2023 SPARC newsletter:
https://www.sparc-climate.org/publications/newsletter/

Proposed Activity Schedule

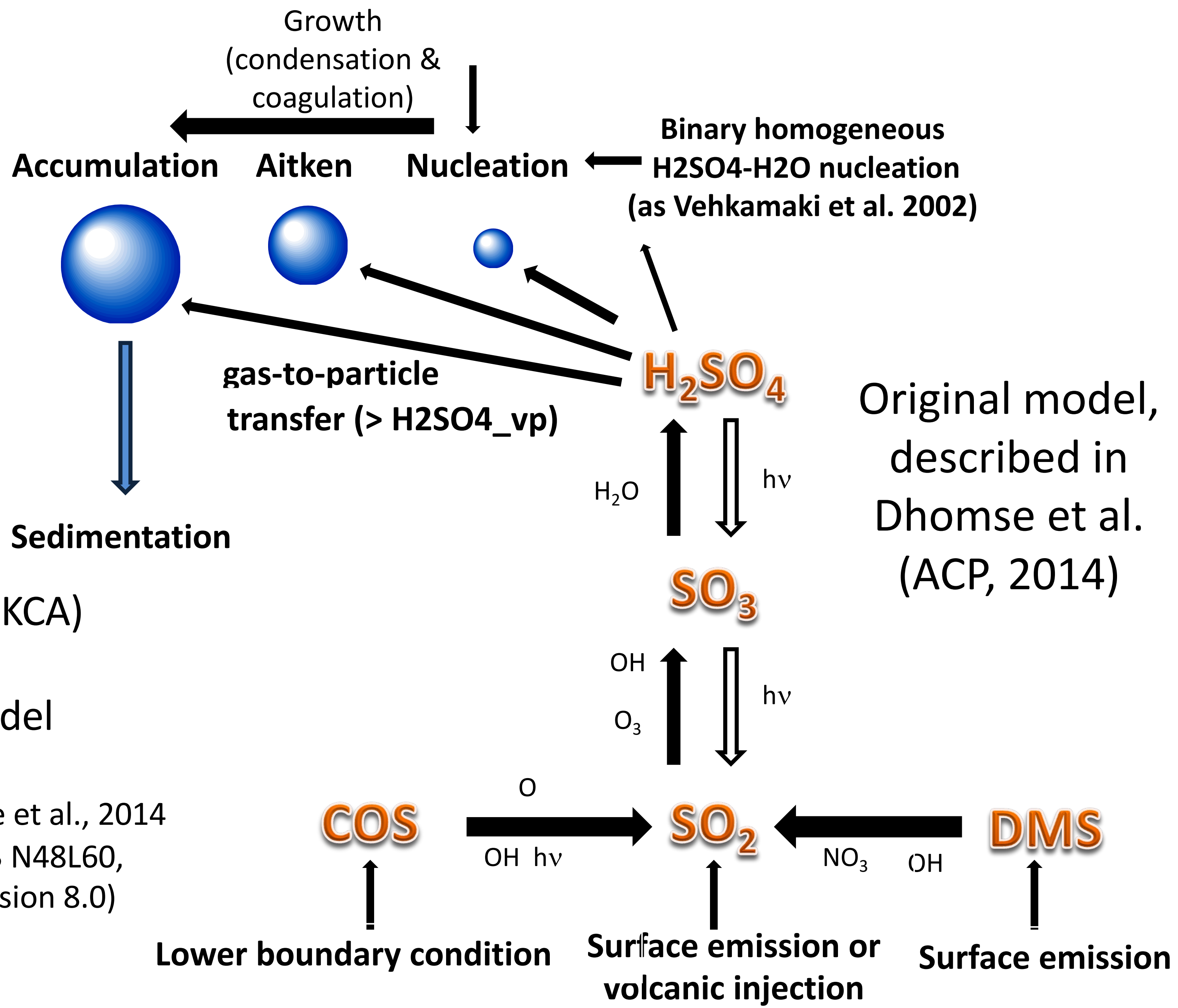
2022
- *Nov*: HTHH activity begun

2023
- *Jan*: Outline 1st circulated for comments
- *May*: 1st On-line open meeting
- *Jun*: Model simulations specified
- *Jun*: Outline 2nd draft completed
- *Aug*: Recruit chapter lead authors
- *Dec*: AGU special session on HTHH (side meeting with chapter leads)

2024
- *Feb*: Model simulations complete, output submitted & begin analysis
- *Feb*: Chapter authors selected by chapter leads finalized
- *May*: Model analysis completed
- *Jun*: In-person open meeting
- *Jul*: Outline 3rd order draft finalized by chapter authors
- *Sep*: 1st draft completed & sent out for external review
- *Nov*: Reviews due, revisions begin

2025
- *Feb*: 2nd draft completed & reviewed by Editors and chapter Leads
- *May*: 3rd draft completed
- *Jul*: Writing of the Executive Summary, revisions added to 3rd draft
- *Sep*. Final chapter submission
- *Dec*. Report Delivered

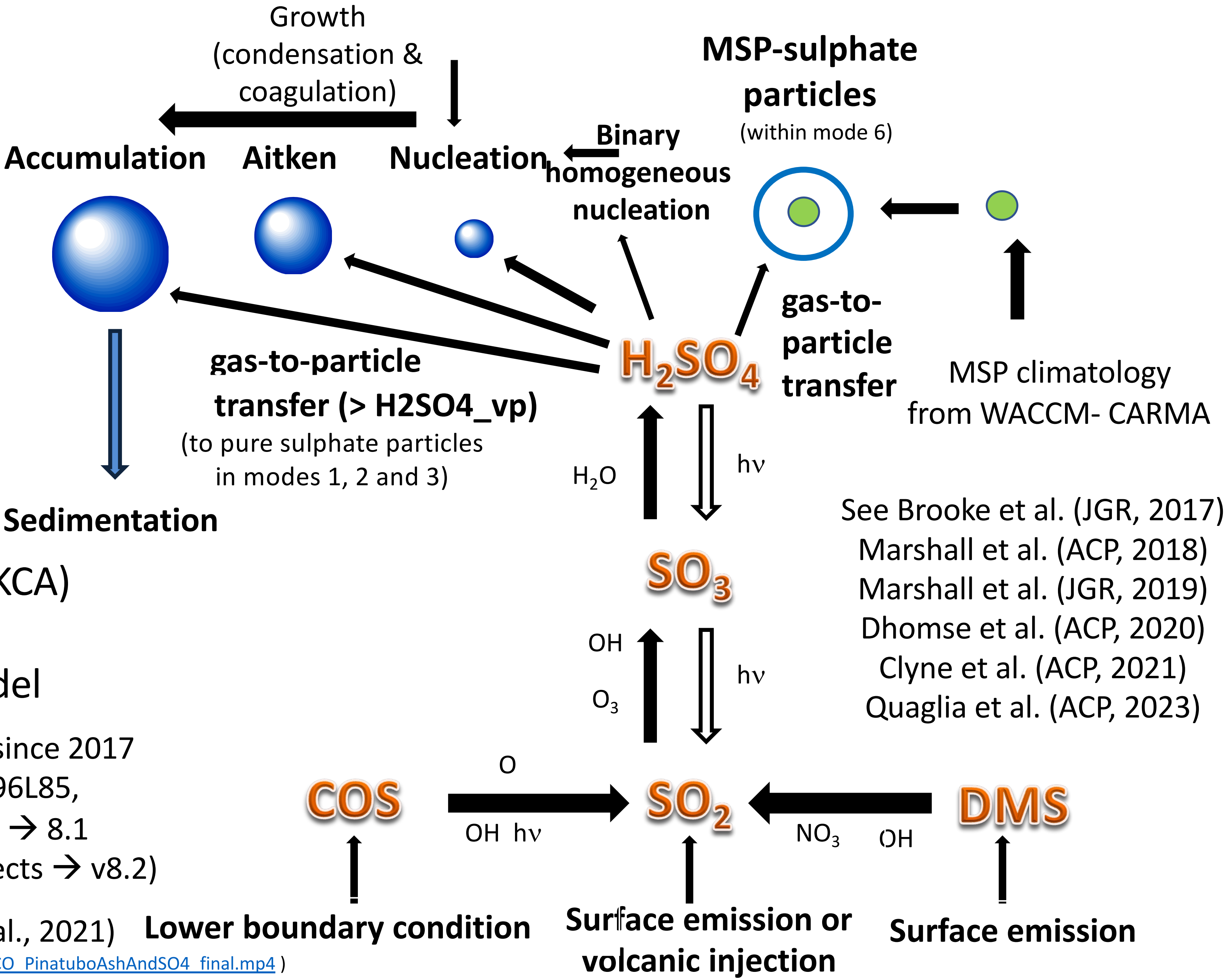
UM-UKCA interactive stratosphere aerosol microphysics model



UK Chemistry & Aerosol (UKCA)
sub-model within
UM Met Office Unified Model

(initial model described in Dhomse et al., 2014
within HadGEM3-A-r2.0, UMv7.3 N48L60,
→ strat-updated GLOMAP – version 8.0)

Updated GA4 UM-UKCA stratospheric aerosol model (GLOMAP v8.2)

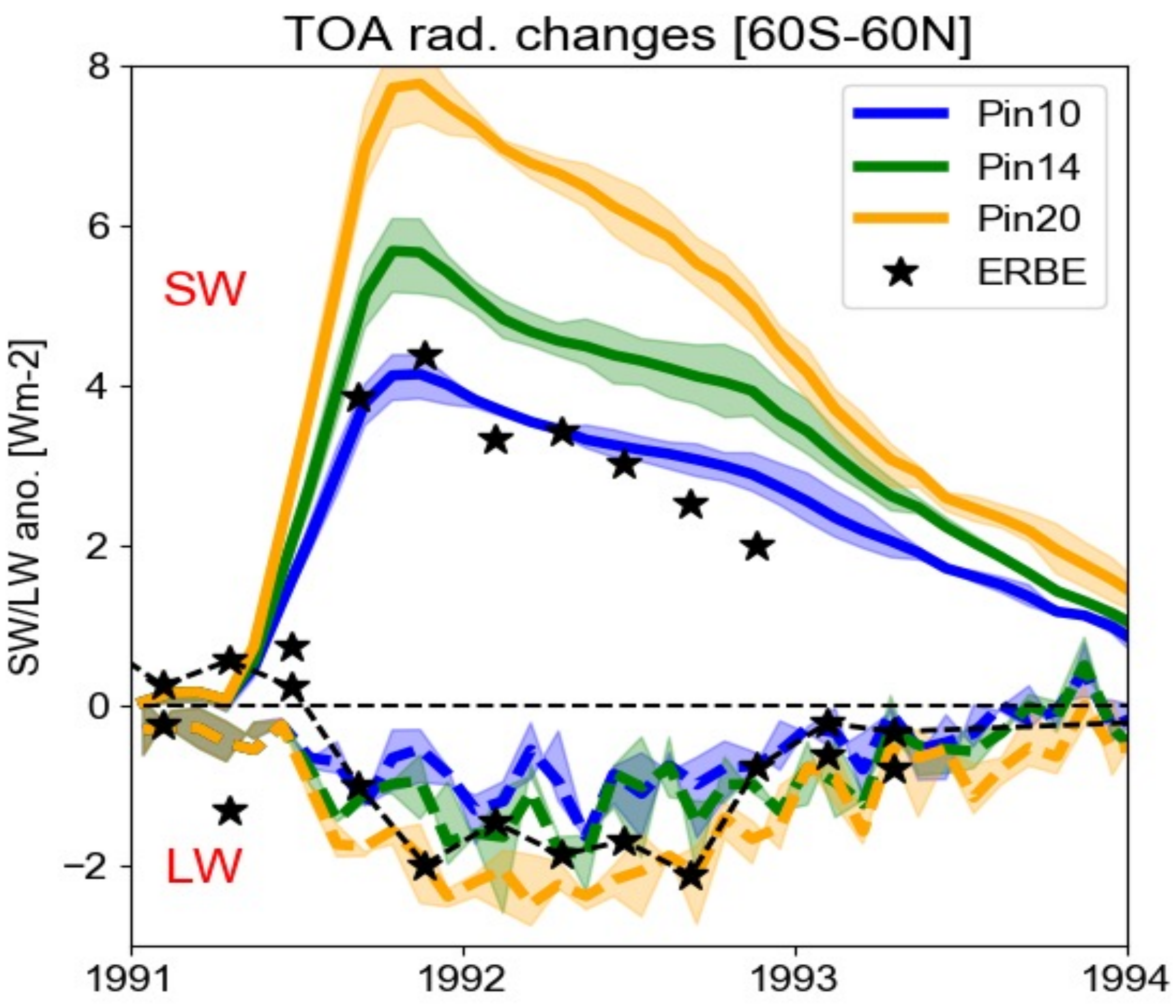


UK Chemistry & Aerosol (UKCA)
sub-model within
UM Met Office Unified Model

(updated model in all publications since 2017
within GA4 UM-UKCA, UMv8.4 N96L85,
-- trop-aerosol updates to GLOMAP → 8.1
-- strat-aerosol meteoric smoke effects → v8.2)

Adapted for ash-SO_4 (Shallcross et al., 2021)
(https://homepages.see.leeds.ac.uk/~amtgwm/vEGU_vPICO_PinatuboAshAndSO4_final.mp4)

UM-UKCA interactive stratospheric aerosol Pinatubo radiative forcings



In UM-UKCA GCM simulations, emit an assumed SO_2 to form volcanic sulphate aerosol interactively, within well-resolved stratosphere (85 vertical levels)

SW surface-cooling effect and LW surface-warming effect (both stem from emitted SO_2)

Compare 10Tg, 14Tg and 20Tg SO_2 emission model runs (emitted at 21-23km altitude)

ERBE satellite-observed SW and LW TOA (36-day & 72-day data) (Wielicki et al., 2002)

Dhomse et al. (2020, ACP)

Simulated volcanic aerosol Surface Area Density (SAD) → key metric for stratospheric ozone layer impacts

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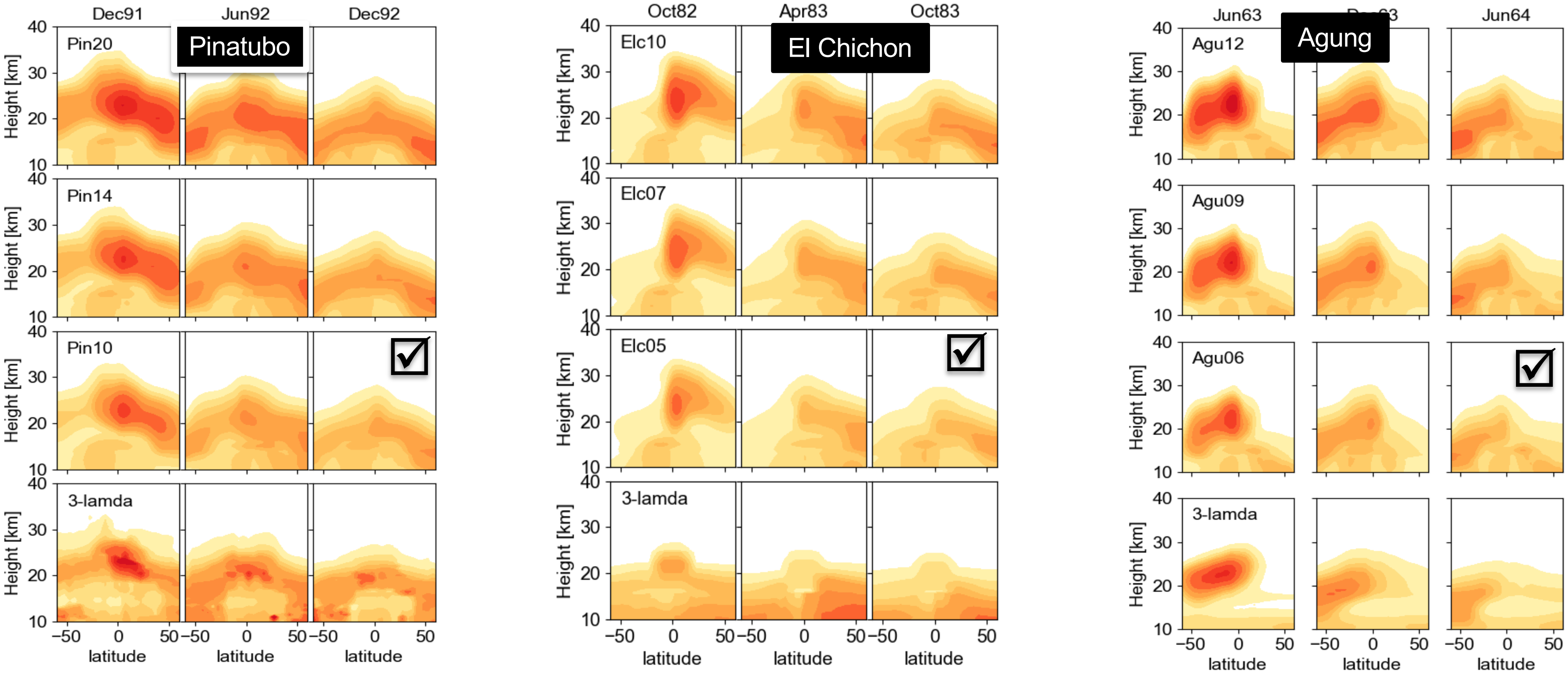
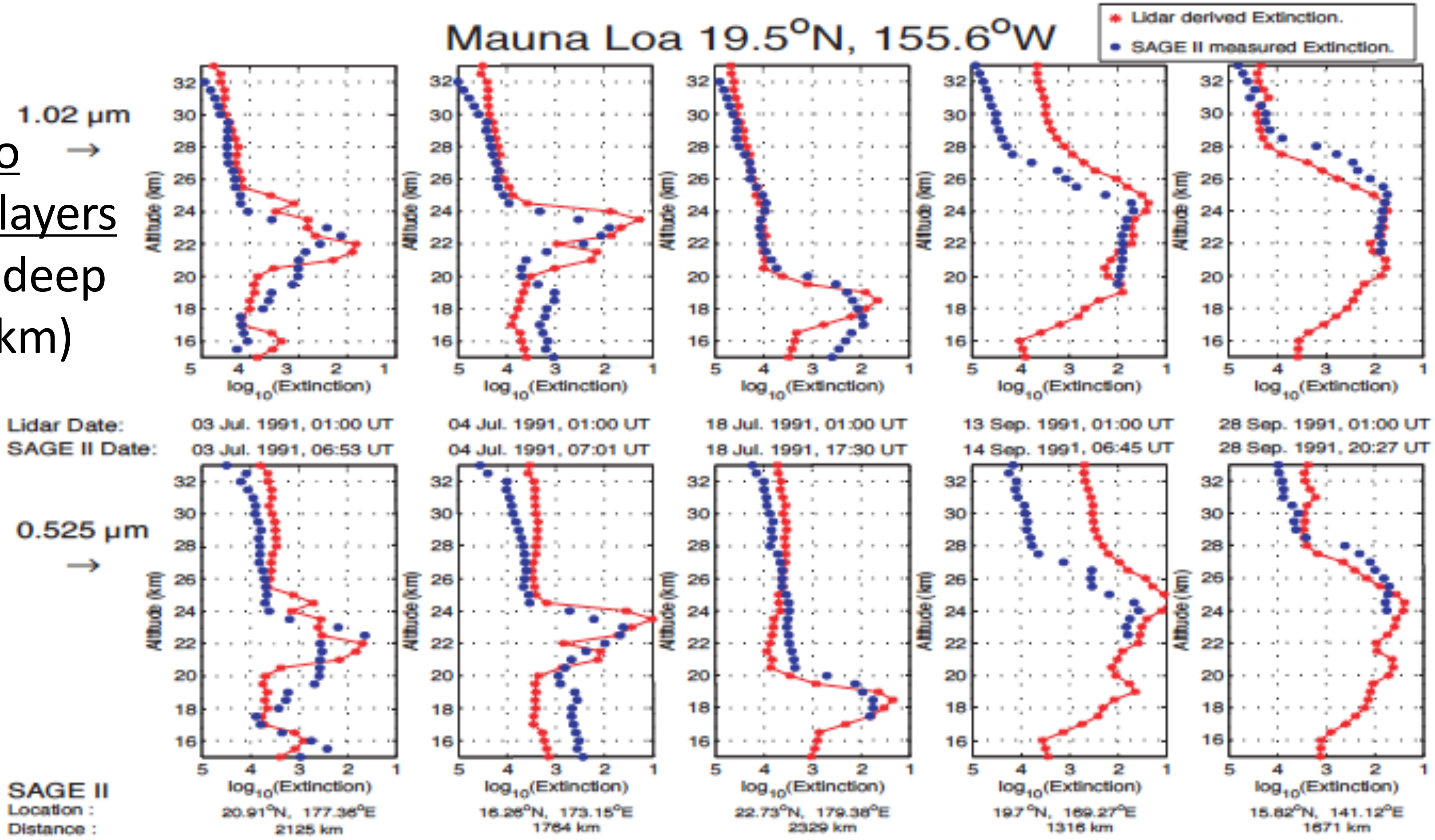


Dhomse et al. (2020, ACP)

Lower panels show "3-lamda" SAD dataset for 1960-2010 CCMI integrations (SAGE-II for Pinatubo)
Good agreement for UM-UKCA simulated Pinatubo, El Chichon & Agung (Dhomse et al., 2020)
→ validates predictive capability → heterogeneous chlorine activation on volcanic aerosol

Pinatubo aerosol cloud in tropics self-lofted & became deeper

Initial Pinatubo aerosol layers ~1-2km deep (~21-23km)



Then aerosol progresses to higher altitude & ~6km deep (20-26km)

Figure 4.55: SAGE II (blue filled circles) and lidar (red stars) coincident profiles for Mauna Loa during the first seven months after the Pinatubo eruption. Upper panel: 1.020 µm wavelength. Lower panel: 0.525 µm. Coefficients used for converting lidar backscatter profiles at 0.532 and 0.694 µm to SAGE II extinction profiles at 0.525 and 1.020 µm are from Thomason and Osborn [1992].

SPARC 2006 Assessment of Stratospheric Aerosol Properties report (“ASAP report”)

UM-UKCA tropical lower stratospheric aerosol-absorptive heating

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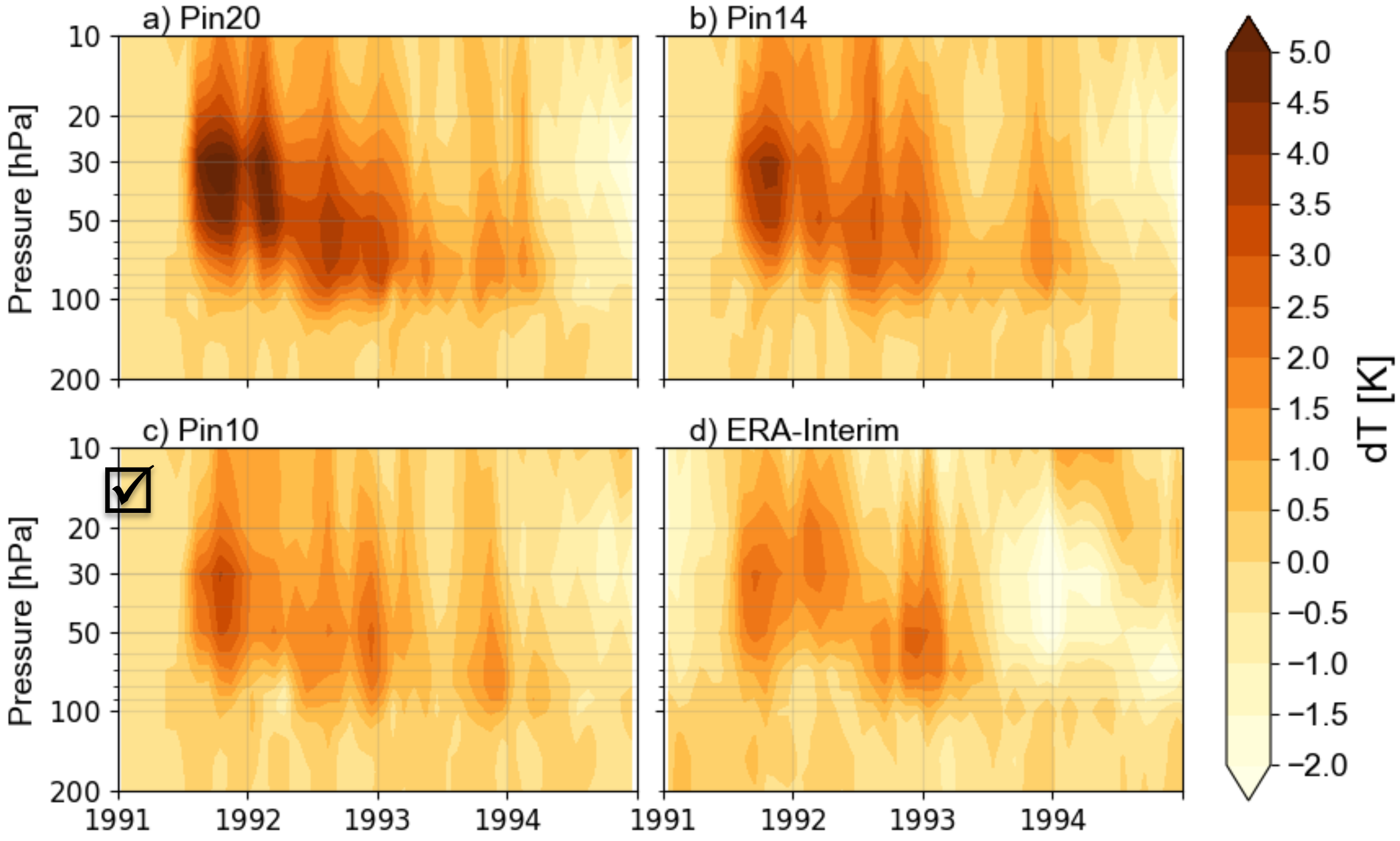
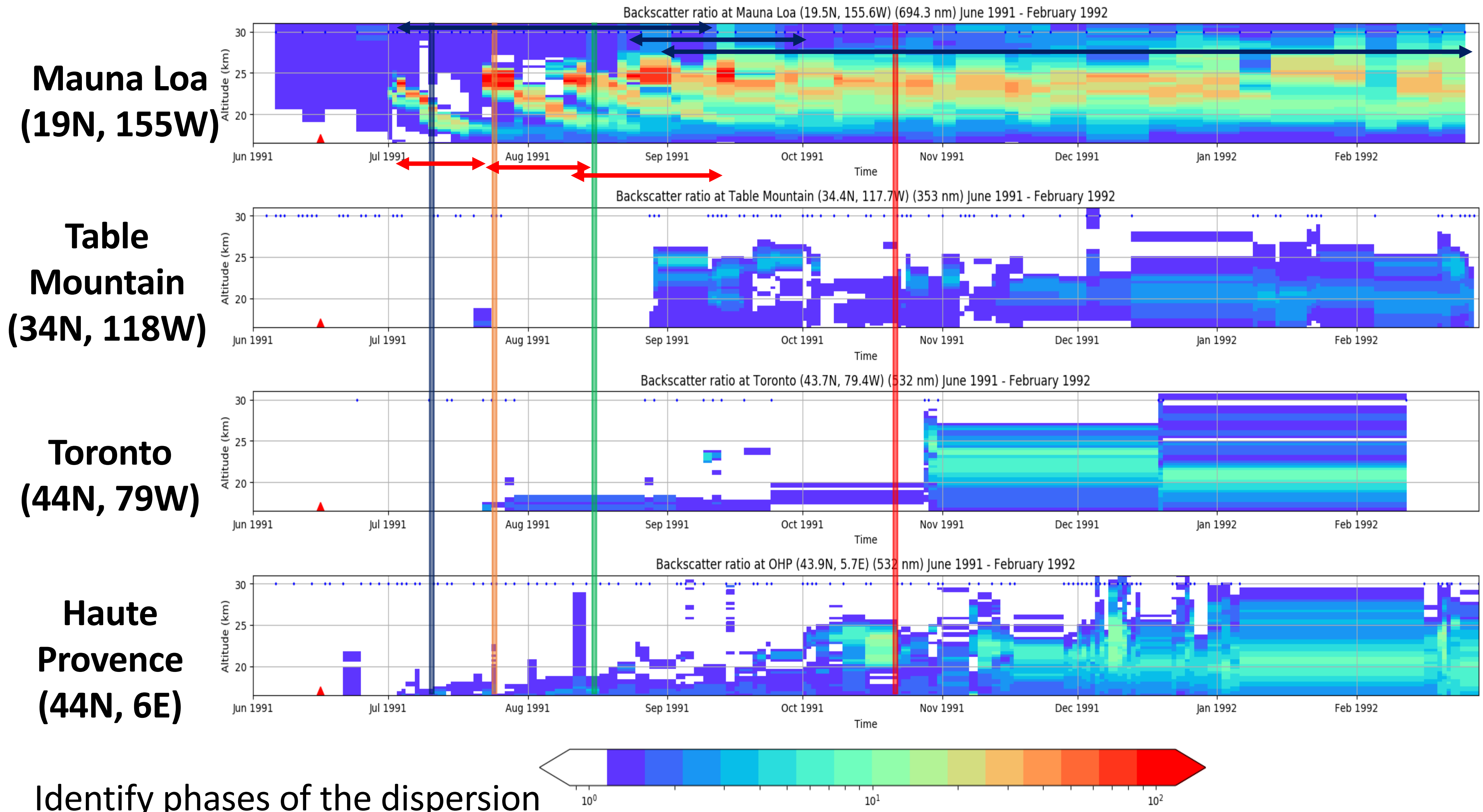


UM-UKCA Pinatubo warming of stratosphere (monthly model delta-T) compared to ERA-interim temperature-anomaly from 5-year mean (1991-95)

Dhomse et al. (2020, ACP)

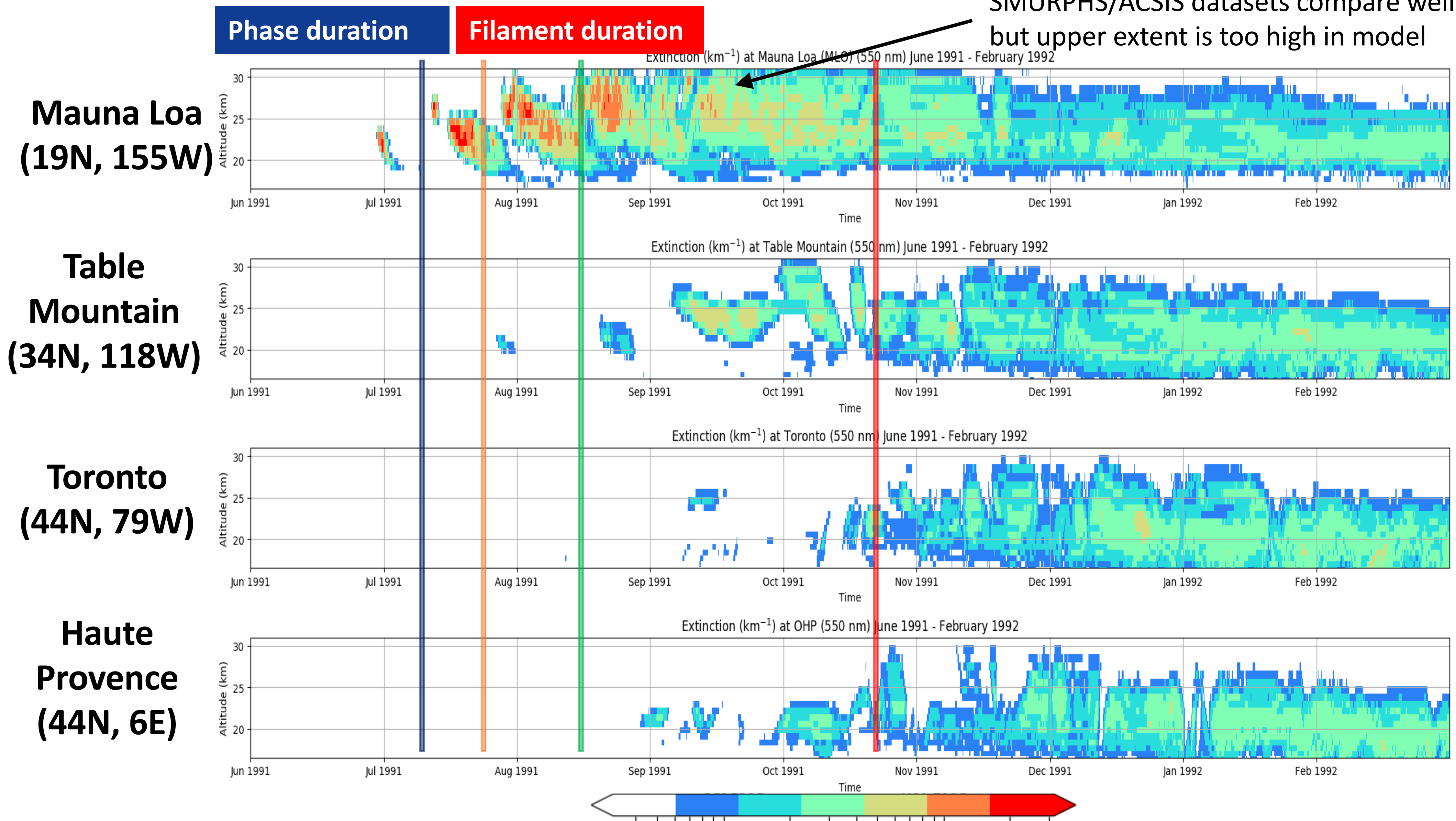
Within the ERA-interim T-anomaly have both volcanic aerosol heating, but also warming-driven circulation-responses (e.g. changes in strat O_3 and H_2O) & effect of prevailing QBO (n.b. easterly phase of QBO after Pinatubo → cold-anomaly, offsetting part of aerosol heating signal)

Ground-based lidar measurements at Mauna Loa (19N), and 3 NH-mid-latitude sites



Identify phases of the dispersion
And detections of the plume/filaments at MLO and at NH mid-lat sites.

Sarah Shallcross (PhD thesis, 2020)



Identify phases of the dispersion
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OMPS-LP observations show that the Hunga-Tonga aerosol penetrated into the vortex during August 2022 (in the lower-most stratosphere)

But water vapour remained outside the vortex (transported to high latitudes only after vortex breakup).

2022 SH stratosphere coldest for entire MLS-Aura record

Stratospheric water vapour strongly cooled the lower stratosphere through 2022

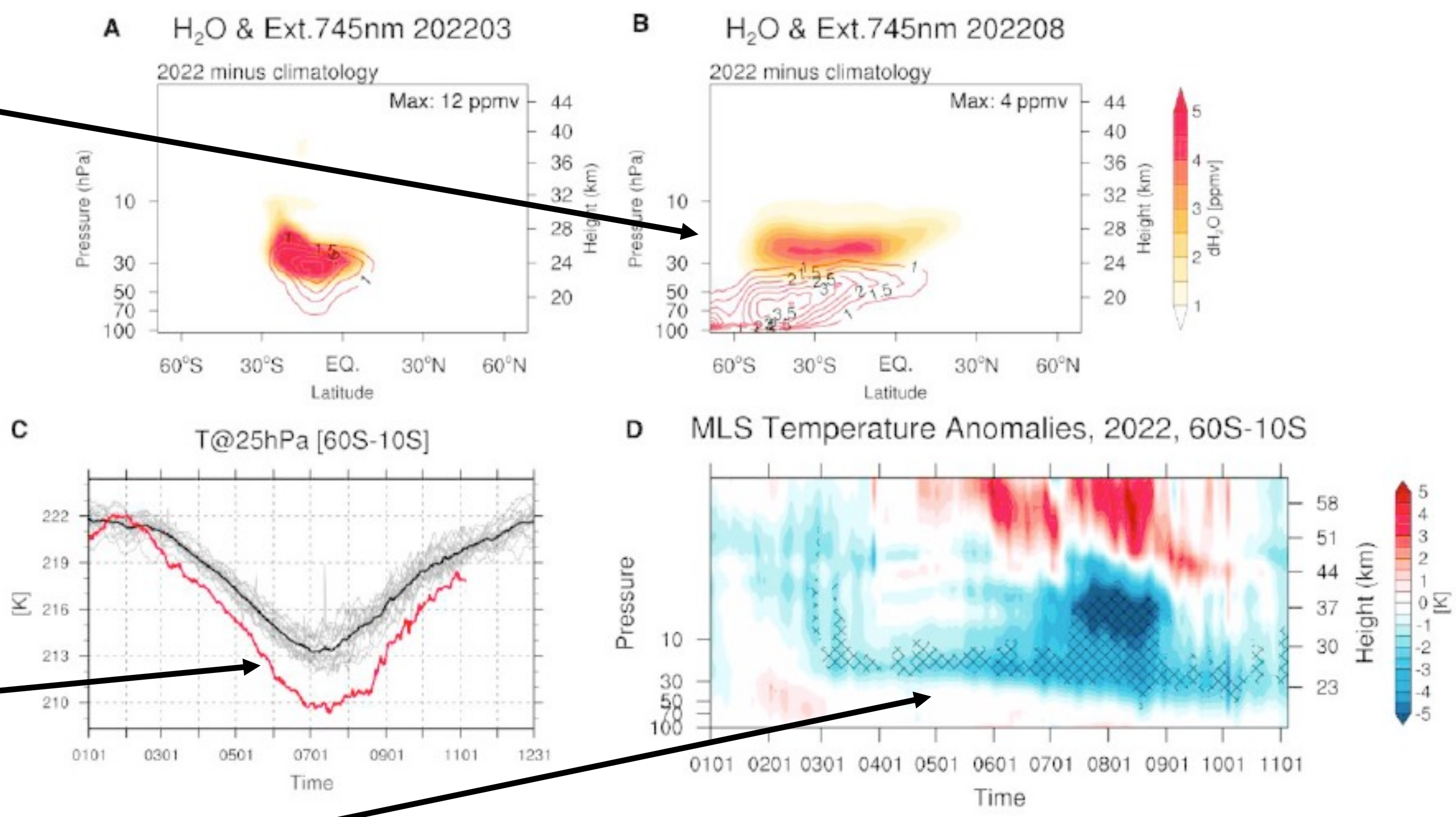

Fig. 1. Observed perturbations after the HTHH eruption. (**A** and **B**) Dispersion of the HTHH H_2O and aerosol plumes between March and August 2022. H_2O anomalies (colors, ppmv) are derived from the Aura Microwave Limb Sounder (MLS) data and calculated as deviations from the 2004-2021 background. The maximum increase is indicated by the number on the top right corner. Aerosol is quantified by the Ozone Mapping and Profiler Suite Limb Profiler (OMPS-LP) aerosol extinction at 745 nm (red contours, 10^{-3} km^{-1}). (**C** and **D**) Anomalous stratospheric temperature changes in the SH during 2022. (**C**) Temperatures at 25 hPa over 60°S-10°S from MLS observations showing persistent anomalous cooling in 2022 (red line). (**D**) Temperature anomalies

Wang et al. (in review, 2023)
submitted MS shared on ESSOAR:
https://essopenarchive.org/doi/full/10.1002/essoar.10512922.1

UM-UKCA interactive strat-aerosol Hunga-Tonga simulations using “free-running approximate QBO” future projection approach

Same model setup as for HErSEA UM-UKCA runs (Agung, El Chichon & Pinatubo) -- see Dhomse et al. (2020)

- (a) GA4 UM-UKCA v8.4 (L96L85), with GLOMAP-v8.2
- (b) interactive strat-aerosol coupled with radiation scheme (RADAER) → so then aerosol-absorptive heating influences volcanic aerosol dispersion
- (c) includes Meteoric Smoke Particle (MSP) interactions with sulphate (2 types)
  → “pure sulphuric” particles & “meteroric-sulphuric” particles (as in Murphy et al., 2014, QJRMS)

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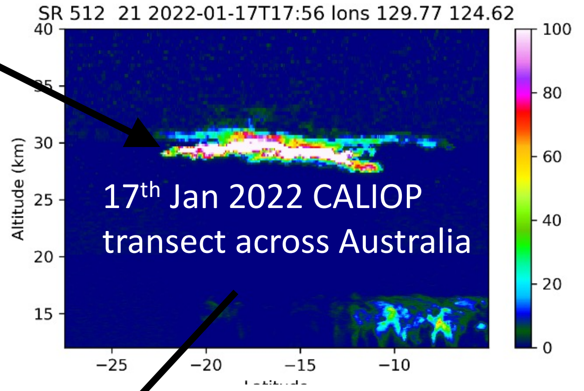
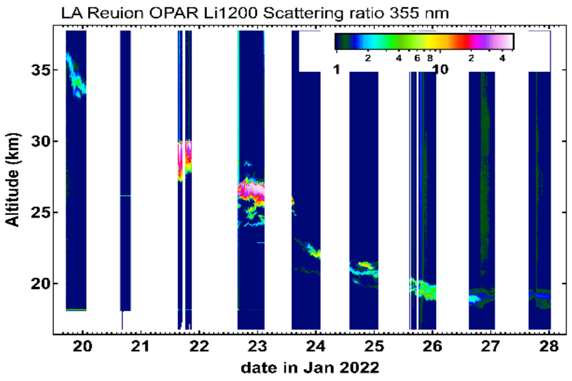
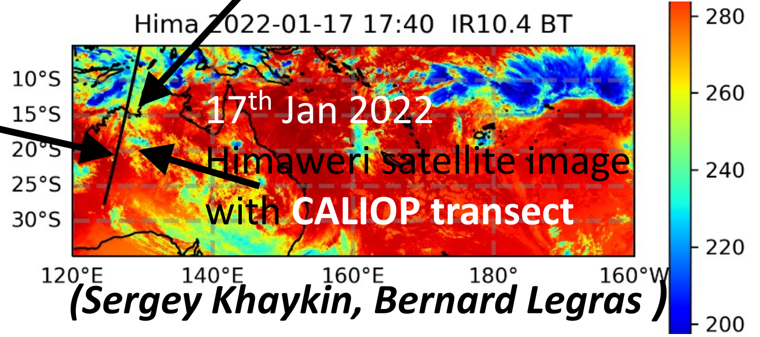
- (c) includes Meteoric Smoke Particle (MSP) interactions with sulphate (2 types)
  → "pure sulphuric" particles & "meteroric-sulphuric" particles (as in Murphy et al., 2014, QJRMS)
- Four simulations each injecting SO2@29-31km
  - 0.4 Tg (best-estimate for the 15/01 explosions)
  - 0.8 Tg (x 2)
  - 1.2 Tg (x3)
  - 1.6 Tg (x4)

29-31km altitude-range chosen as indicative of the "main detrainment" of the Hunga-Tonga SO2

e.g. 17th Jan 2022 CALIOP transect across Australia







Reunion Island lidar 1st detections of sheared aerosol cloud confirm detrainment ~26-30km, (with only weak layer below 25km)

CALIOP & Reunion Island Figures (Sergey Khaykin, Bernard Legras)

Evaluation of the initial 29-31km SO2-only UM-UKCA Hunga-Tonga model projections (first 4 months after)

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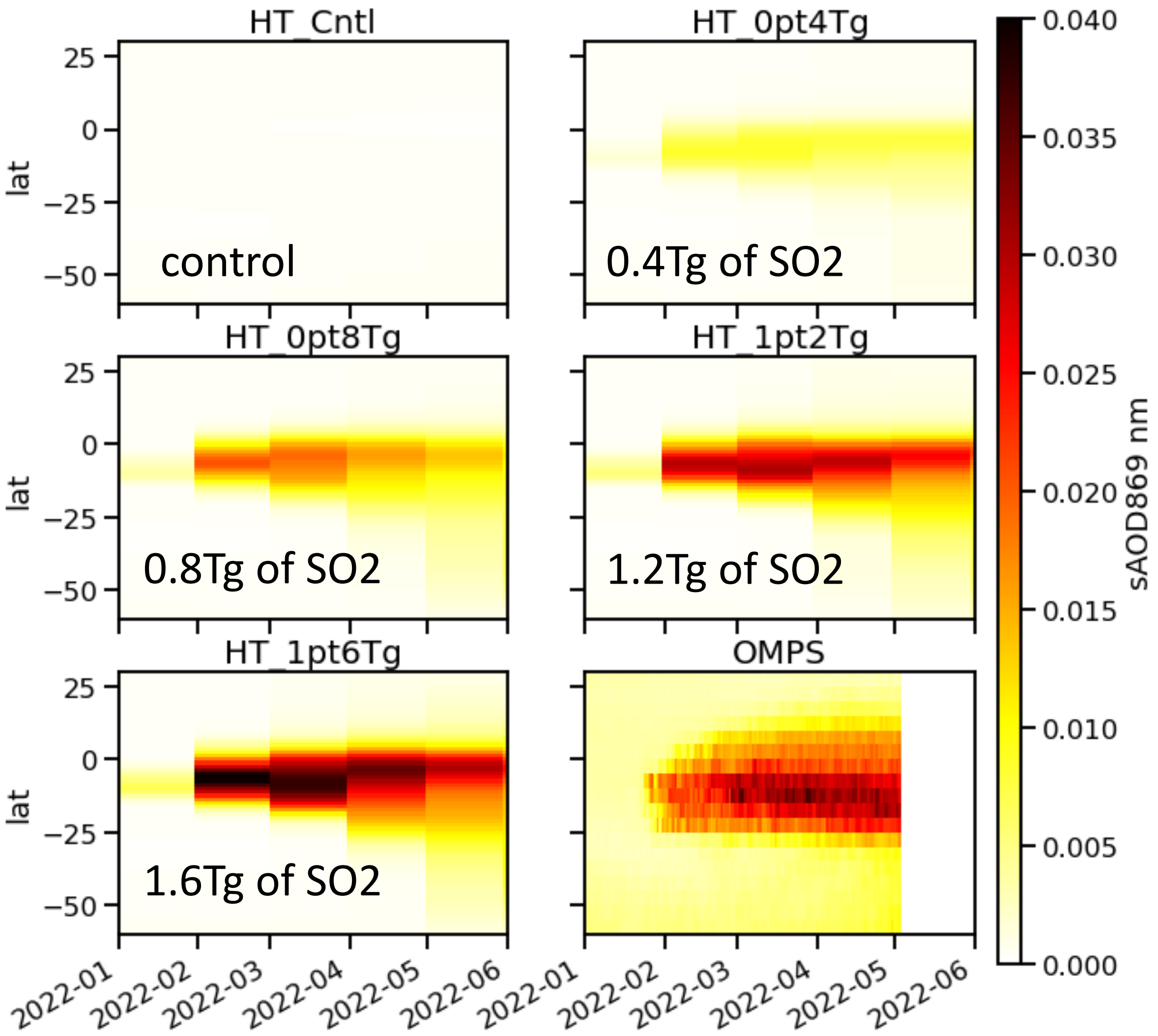
- Best-estimate SO2 emission of 0.4Tg generated only ~ 0.01 sAOD at 870nm
- The ~0.03 $sAOD_{869nm}$ observed by OMPS corresponds to ~1.2-1.6 Tg of SO2 (according to UM-UKCA simulations)
- Temporal progression with 1.2 - 1.6 Tg SO2 matches relatively well to OMPS but the model band is too narrow → OMPS has 25°S-10°N

n.b. UM-UKCA strat-AOD@ 870nm shown to compare with "cleanest" OMPS aerosol retrieval (869nm channel)



All simulations here emitted SO_2 at 29-31km

Approximate-QBO free-running approach enables simulations to project forward how sAOD will evolve (869nm/870nm)

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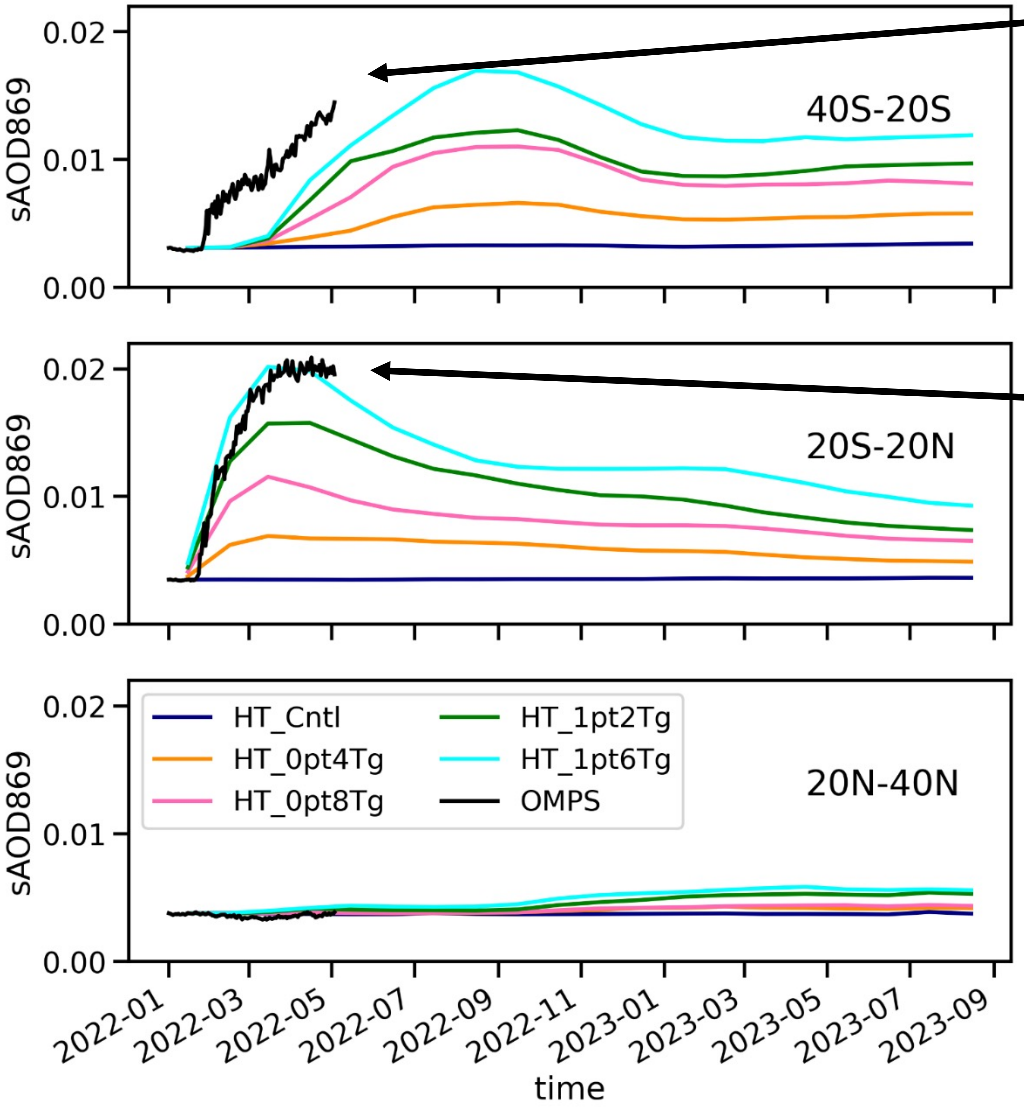
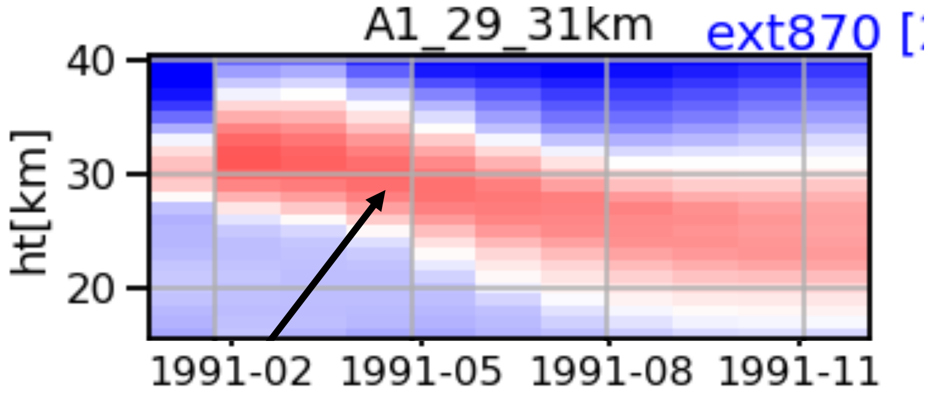
1. Retrospective of initial model projections and Initial evaluation vs OMPS obs (May '22)



3. OMPS observed sAOD shows H-T cloud spreads southward from late-February, but modelled cloud remains confined between 20S-20N until mid-March

2. In the tropical reservoir, the 4 x SO2 (1.6 Tg) model projections match observed strat-AOD

4. H-T cloud remained confined to SH through to May 22



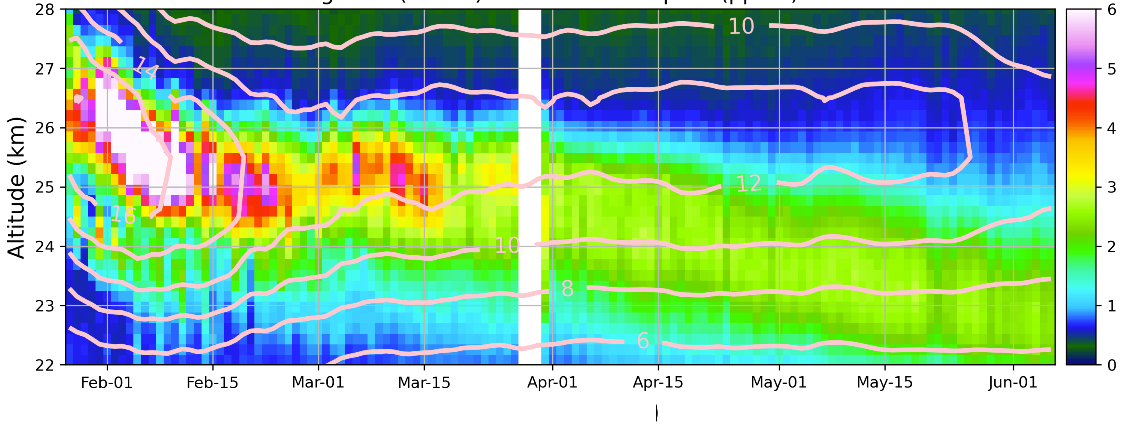
5. Microphysical UKCA model projections generate modest initial uplift of cloud then steady ~1km/mo descent (sedimentation proceeds at size predicted)

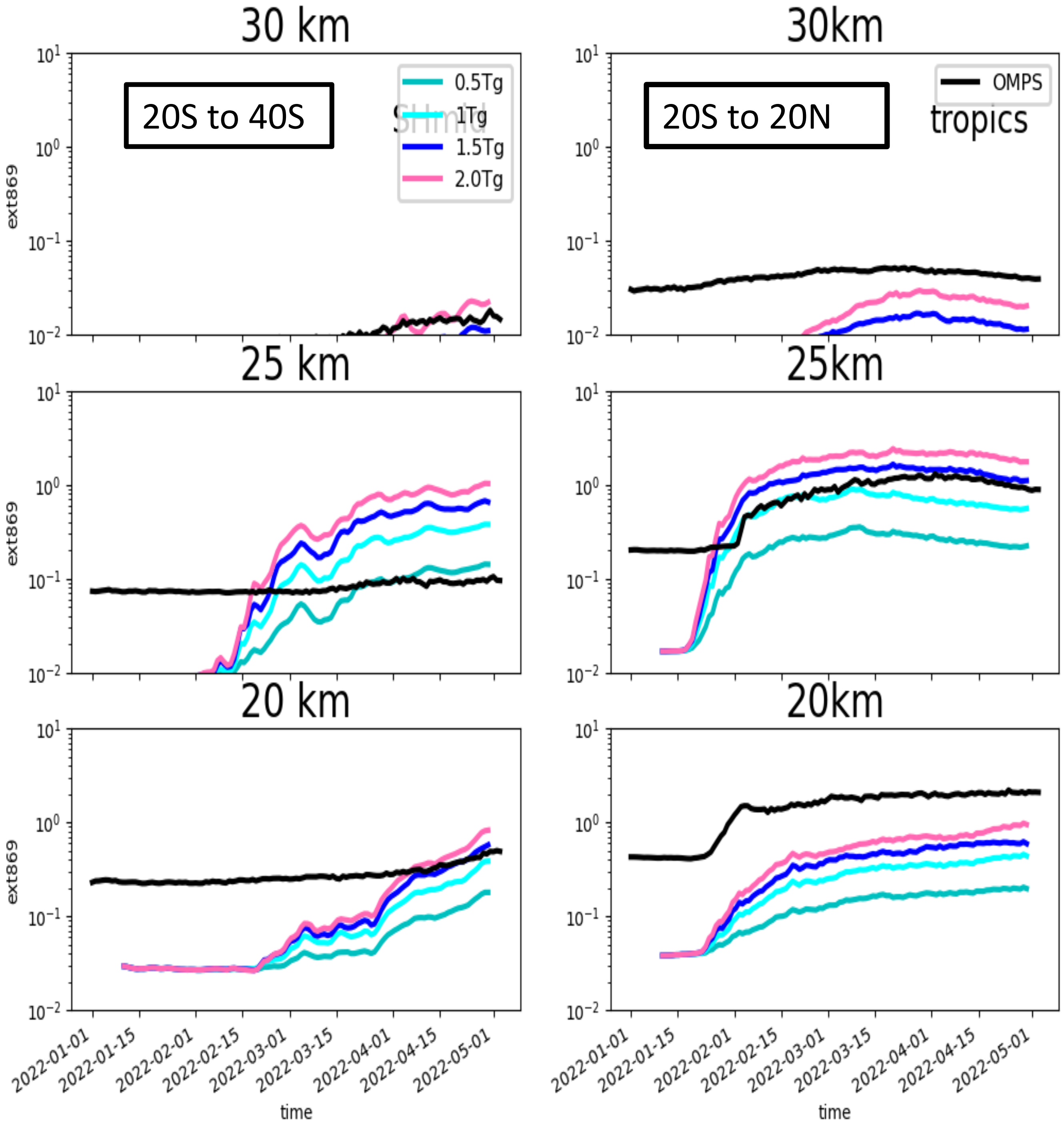
Extinction@879nm

When emitting only SO2, exploring the extent to which can adjust to emit at 23-25km .

These simulations then do not attempt to capture the steep-descent phase, but where the aerosol emerges in mid-February 2022

Satellite obs indicate that, in contrast to Pinatubo's absorptive-heating self-lofting, HT-aerosol descended rapidly due to water vapour LW radiative cooling





ERA5-nudged "Hunga-Tonga re-analysis" GA4 UM-UKCA runs

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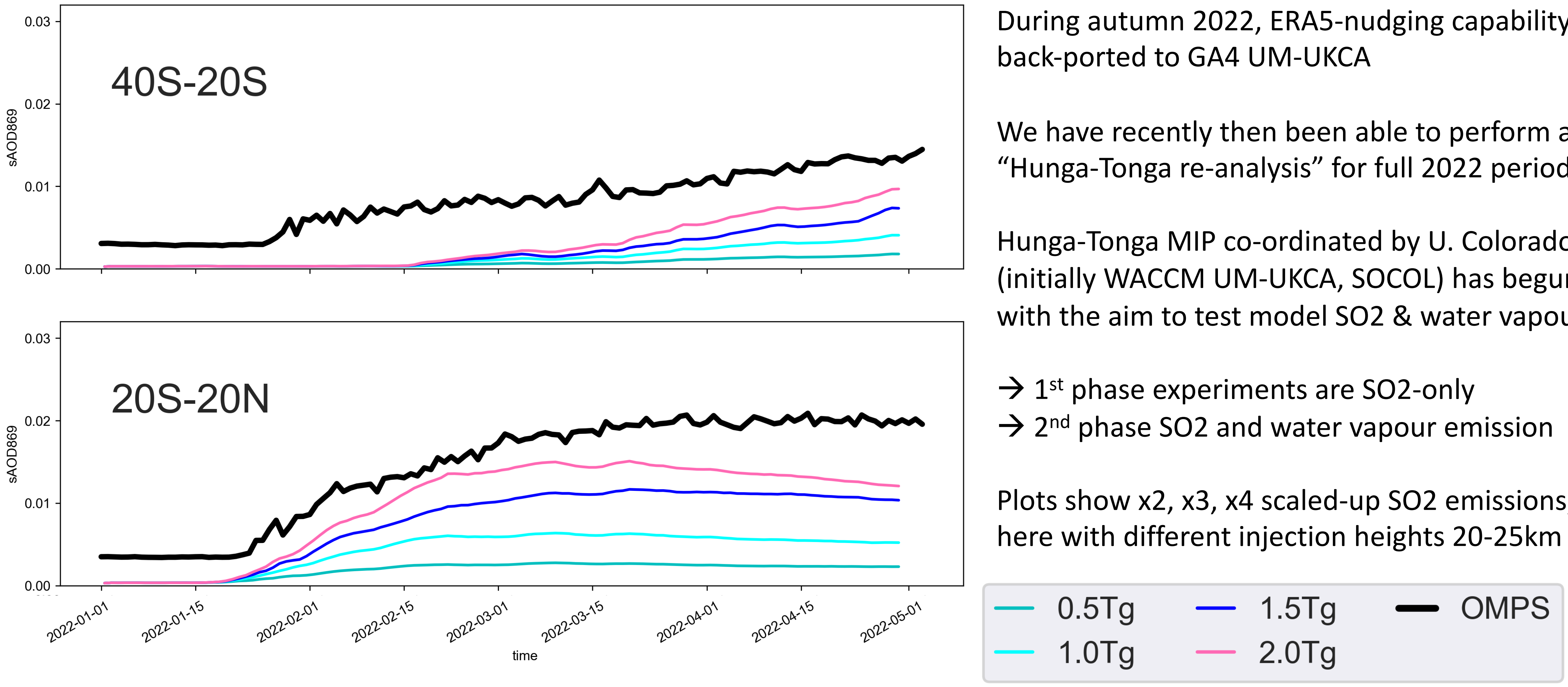

During autumn 2022, ERA5-nudging capability back-ported to GA4 UM-UKCA

We have recently then been able to perform a "Hunga-Tonga re-analysis" for full 2022 period.

Hunga-Tonga MIP co-ordinated by U. Colorado (initially WACCM UM-UKCA, SOCOL) has begun, with the aim to test model SO2 & water vapour

→ 1st phase experiments are SO2-only
→ 2nd phase SO2 and water vapour emission

Plots show x2, x3, x4 scaled-up SO2 emissions, here with different injection heights 20-25km

Conclusions

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- 2022 Hunga-Tonga eruption unprecedented in satellite era, explosivity similar to Krakatau
  → emitted 150 Tg of water vapour but only ~0.4 Tg of sulphur dioxide into stratosphere
- Volcanic aerosol initially at higher altitude than Pinatubo (~30km), descended to ~23-25km
- Much stronger than expected stratospheric aerosol enhancement from Hunga-Tonga
  → stratospheric aerosol optical depth consistent with ~3-4 times emitted SO2.
- Water-vapour dominated cloud caused highly unusual strong cooling of the stratosphere, causing a steep descent of volcanic plume in initial weeks after (aerosol & water vapour)
- Challenging for global models to represent two-phase progression of the volcanic cloud
- Heterogeneous chemistry on Hunga-Tonga aerosol caused substantial O_3 depletion in 2022 S. Hemisphere stratosphere → ~20-30% more O_3 loss at high-latitudes (Wang et al., 2023)
- HT strat H_2O remained outside 2022 Antarctic vortex → but likely to enhance PSCs in 2023

Free-running UM-UKCA, initialised for "approximate QBO transition" → capability to project volcanic aerosol dispersion for T+1yr

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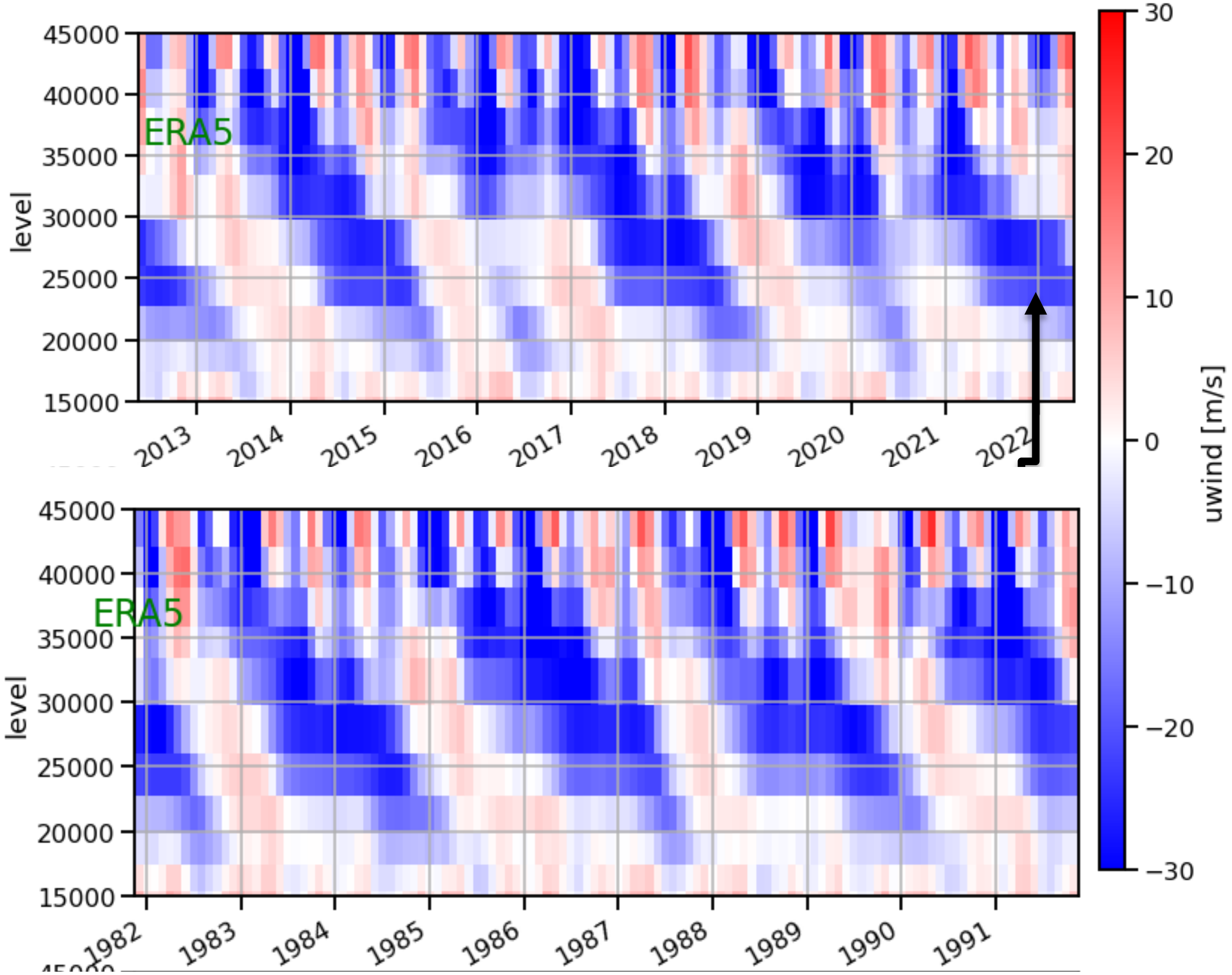
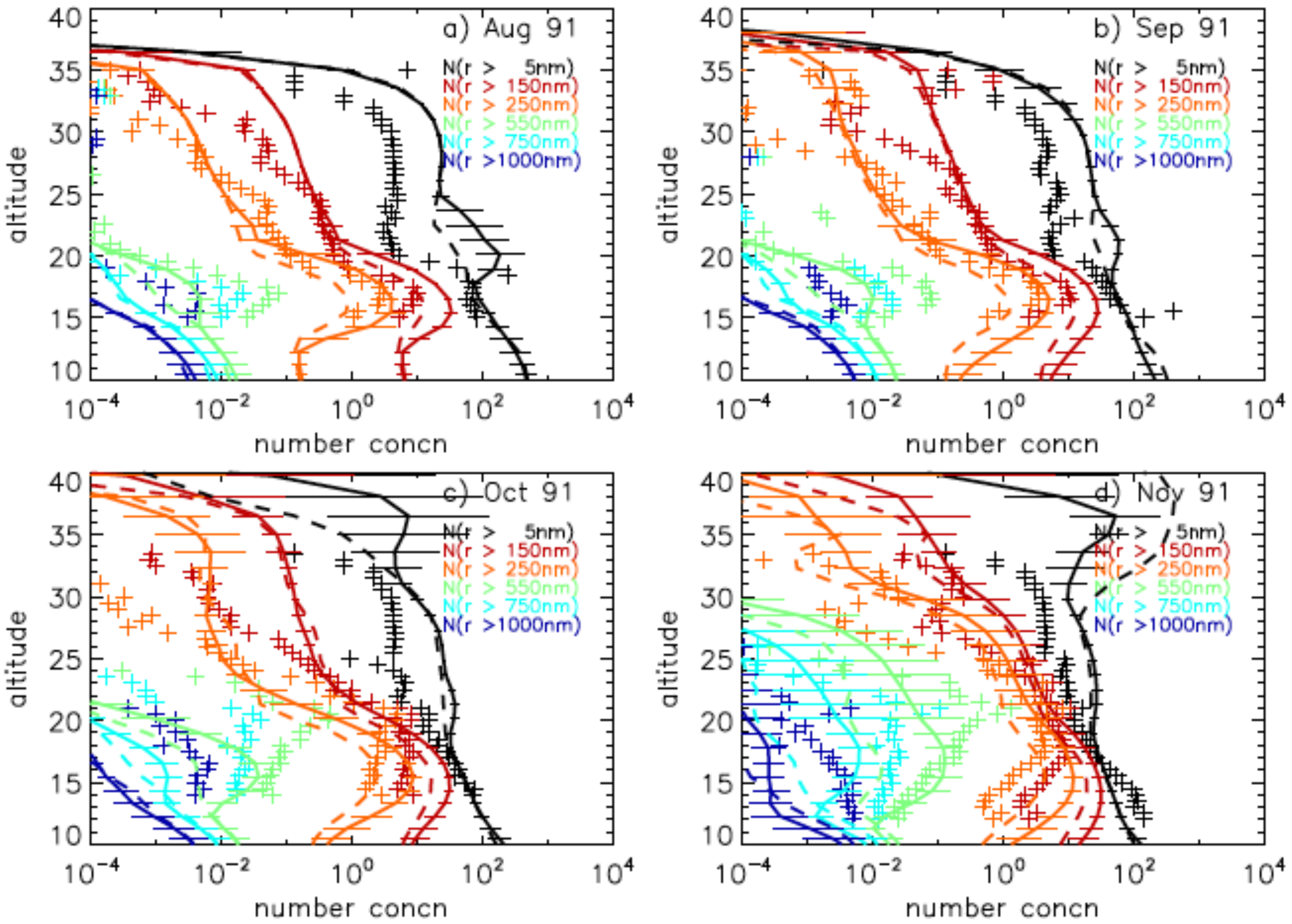


When Hunga-Tonga (19S) erupted Jan 2022, the QBO easterly phase similar to that seen at the time of Pinatubo.

In the model --> we run projections for the volcanic aerosol dispersion forward in time

"Mirror-image" of Pinatubo (19N, Jun 1991)

- Westerly to easterly transition
- Summer-time str. circulation
- Edge of the tropical lats



High-altitude balloon measurements at Laramie in Aug, Sep and Oct 1991 (Deshler et al., 2003)

→ validate UM-UKCA simulated particle size variations (Dhomse et al., 2014)

Impacts on climate from large-magnitude explosive eruptions arise primarily from emitted SO_2
→ but growing understanding of influences from co-emitted species (e.g. halogens, ash & water vapour)

Staunton-Sykes et al. (2021)

Atmospheric Chemistry and Physics · Open Access · EGU

Co-emission of volcanic sulfur and halogens amplifies volcanic effective radiative forcing

John Staunton-Sykes[1], Thomas J. Aubry[2,4], Youngsub M. Shin[1], James Weber[1], Lauren R. Marshall[1], Nathan Luke Abraham[1,3], Alex Archibald[1,3], and Anja Schmidt[1,2]

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[2]Department of Geography, University of Cambridge, Cambridge, UK
[3]National Centre for Atmospheric Science, Leeds, UK
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Abstract. The evolution of volcanic sulfur and the resulting radiative forcing following explosive volcanic eruptions is well understood. Petrological evidence suggests that significant amounts of halogens may be co-emitted alongside sulfur in some explosive volcanic eruptions, and satellite evidence indicates that detectable amounts of these halogens may reach the stratosphere. In this study, we utilise an aerosol–chemistry–climate model to simulate stratospheric volcanic eruption emission scenarios of two sizes, both with and without co-emission of volcanic halogens, in order to understand how co-emitted halogens may alter the life cycle of volcanic sulfur, stratospheric chemistry, and the resulting radiative forcing. We simulate a large (10 Tg of SO_2) and very large (56 Tg of SO_2) sulfur-only eruption scenario and a corresponding large (10 Tg SO_2, 1.5 Tg HCl, 0.0086 Tg HBr) and very large (56 Tg SO_2, 15 Tg HCl, 0.086 Tg HBr) co-emission eruption scenario. The eruption scenarios simulated in this work are hypothetical, but they are comparable to Volcanic Explosivity Index (VEI) 6 (e.g. 1991 Mt Pinatubo) and VEI 7 (e.g. 1257 Mt Samalas) eruptions, rep-

Zhu et al. (2020)

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Persisting volcanic ash particles impact stratospheric SO_2 lifetime and aerosol optical properties

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Abstract

Volcanic ash is often neglected in climate simulations because ash particles are assumed to have a short atmospheric lifetime, and to not participate in sulfur chemistry. After the Mt. Kelut eruption in 2014, stratospheric ash-rich aerosols were observed for months. Here we show that the persistence of super-micron ash is consistent with a density near 0.5 g cm^{-3}, close to pumice. Ash-rich particles dominate the volcanic cloud optical properties for the first 60 days. We also find that the initial SO_2 lifetime is determined by SO_2 uptake on ash, rather than by reaction with OH as commonly assumed. About 43% more volcanic sulfur is removed from the stratosphere in 2 months with the SO_2 heterogeneous chemistry on ash particles

Satellite-observed progression of Pinatubo aerosol cloud

June 14 to July 26 1991 (sunset)
1 μm extinction (at theta = 425K)

June 23 to Aug 8 1991 (sunrise)
1 μm extinction (at theta = 425K)

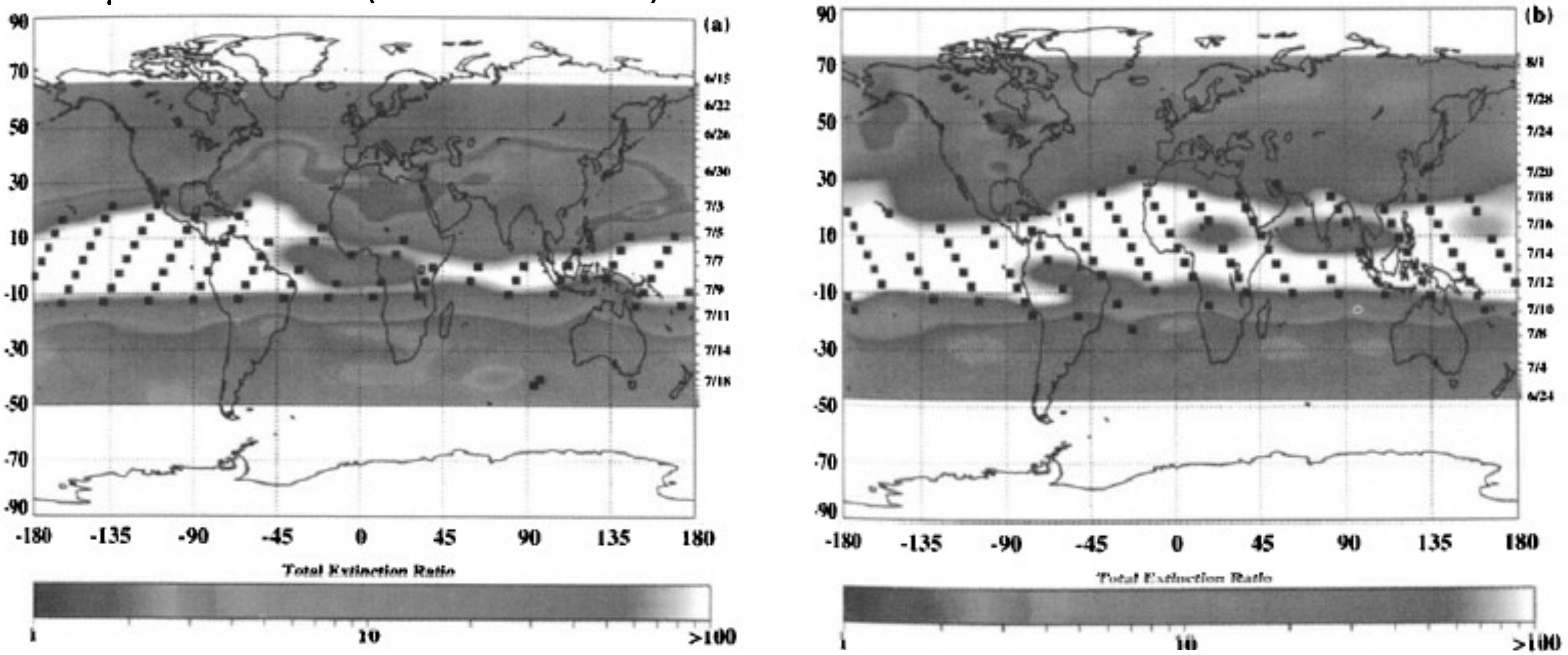


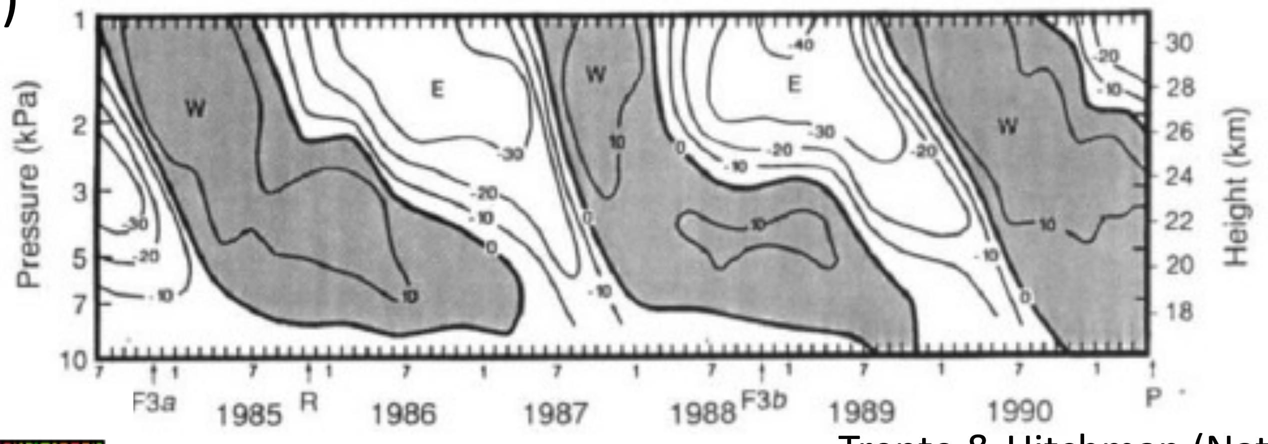
Plate 2. SAGE II 1-μm extinction ratio on a 425 K surface. Dates of the daily averaged latitude of the SAGE II measurements are indicated along the right axis. Squares denote SAGE II profiles which had no data at the altitude of 425 K. The zonal mean β_r was used for these missing values. (*a*) June 14 to July 26, 1991, sunset. (*b*) June 23 to August 8, 1991, sunrise.

Trepte et al. (1993)

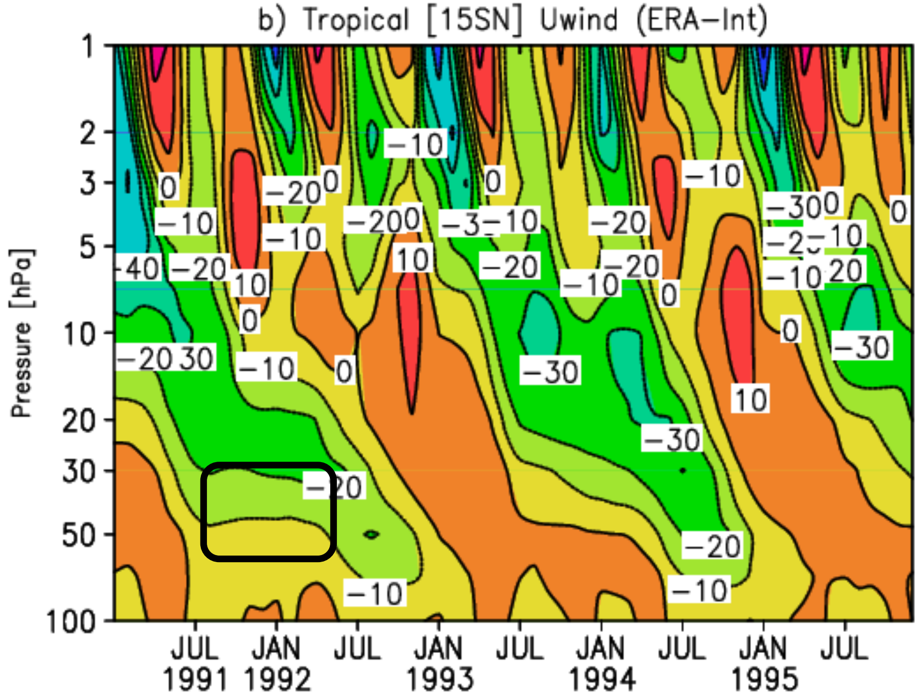
UM-UKCA has well-resolved stratospheric dynamics for internally-generated QBO

(e.g. for Pinatubo, June 1991)

FIG. 1 Time-altitude section of monthly mean zonal wind component at Singapore (1° N, 104° E) for July 1984 to May 1991, adapted from ref. 24, showing the quasibiennial oscillation in the equatorial lower stratosphere, contour interval 10 m s^{-1}. Marked times R, P, F3*a* and F3*b* are the eruptions of Mounts Ruiz and Pinatubo and the aerosol cross-sections in Fig. 3*a*, *b*.



Trepte & Hitchman (Nature, 1992)



Dhomse et al. (2014, ACP)

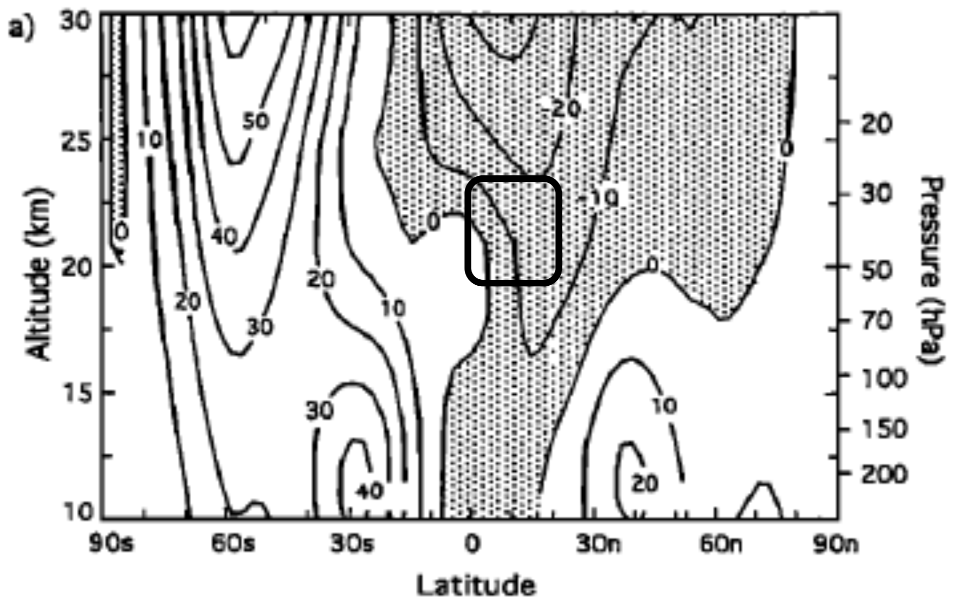
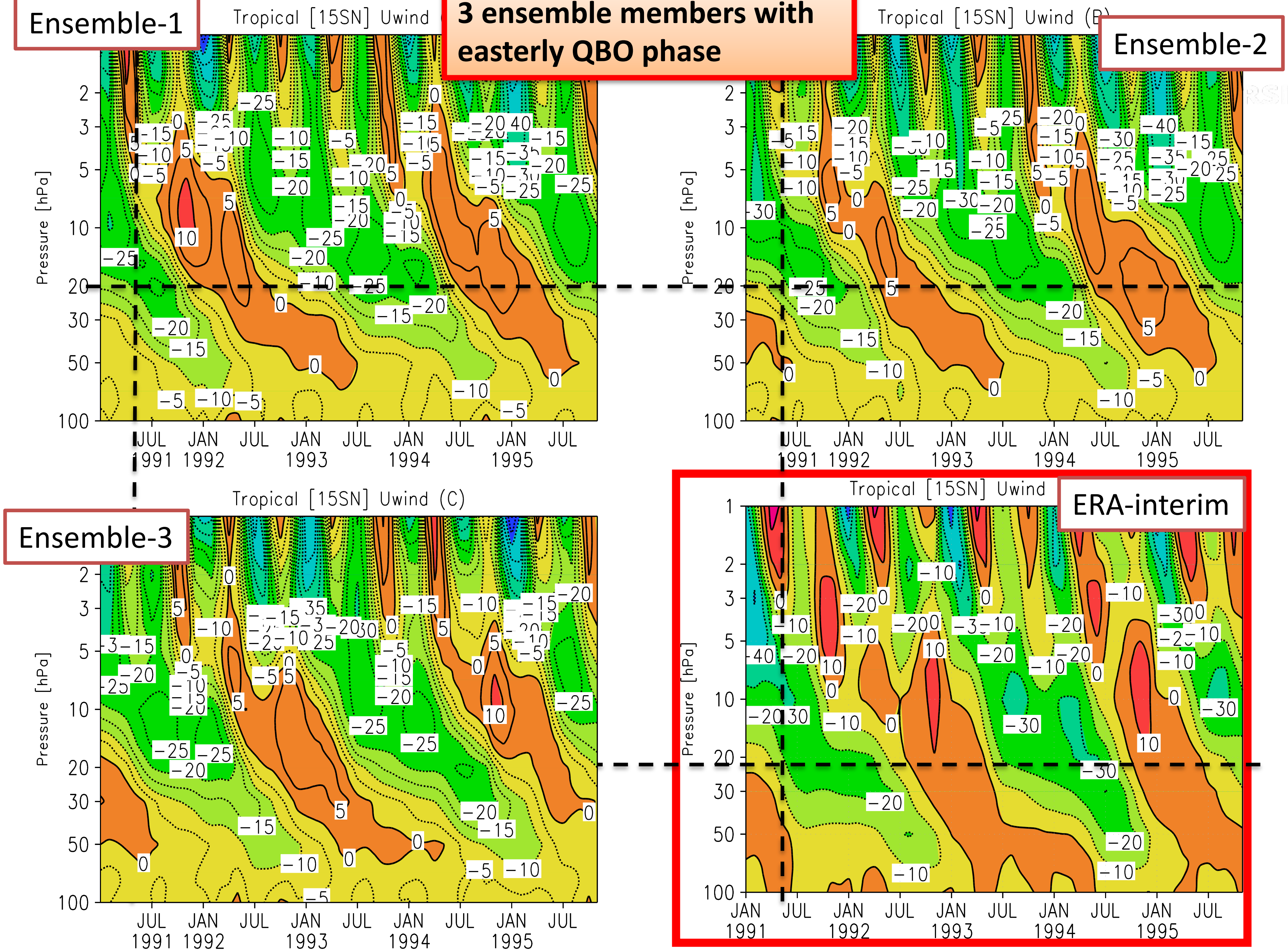


Fig. 2. Latitude-altitude cross sections averaged over the period June 16–30, 1991, for (*a*) $\bar{u}$ (m s^{-1}) and (*b*) $\overline{v'^2}$ (m^2 s^{-2}). Shaded regions indicate easterly winds.

Trepte et al. (JGR, 1993)



Dhomse et al. (ACP, 2020)