DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

LMU Ludwig-Maximilians-Universität München

BGS British Geological Survey

Early Warnings for All

Volcanoes: a multi-hazard and multi-scale challenge (including climate forcing and impact)

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Advancing Volcanic Hazards in Early Warnings for All, July 7-9, Geneva, 2025.

Volcanoes and EW4all – why do volcanoes matter?

- 1250 active volcanoes in 79 countries, 65 volcanoes erupted in 2024[1]
- over 30 million people live within 10 km of an active volcano and over 800 million people live within 100 km[2,3]
- volcanic eruptions last from minutes to years[1], and are variable in terms of intensity, frequency, hazards, impacts[5]
- long-lived or frequent volcanic activity has complex and chronic social, economic, political and climate impacts.

- volcanic activity likely to occur with other hazards: (e.g. intense rainfall, drought, cyclones, diseases, conflict)
- annualised fatality rate has declined in recent decades[3]
- Volcano Observatories, civil protection authorities, their partners and communities at risk have saved lives and have much experience of anticipatory action[5]

[1]Global Volcanism Program, Smithsonian Institution, [2]Brown et al. 2015a,b, [3]Auker et al 2013, [4]Brown et al. 2017, [5]Loughlin et al. 2015

Multiple interacting, compounding, cascading hazards and impacts

Pyroclastic density currents, Indonesia

Pyroclastic density currents Guatemala


AFP PHOTO / Johan ORDONEZ

Lava flows, volcanic air pollution La Palma, Spain


Borja Suarez/Reuters

Lahars (mudflows) Philippines


Reuters

Ash/tephra fall Sicily, Italy

- Before, during and after eruptions there are multiple hazards
- PDCs are most dangerous hazard – fast-moving, hot, destructive
- Lahars triggered by rainfall, may travel far from source, may be hot

Local to global impacts over years to decades

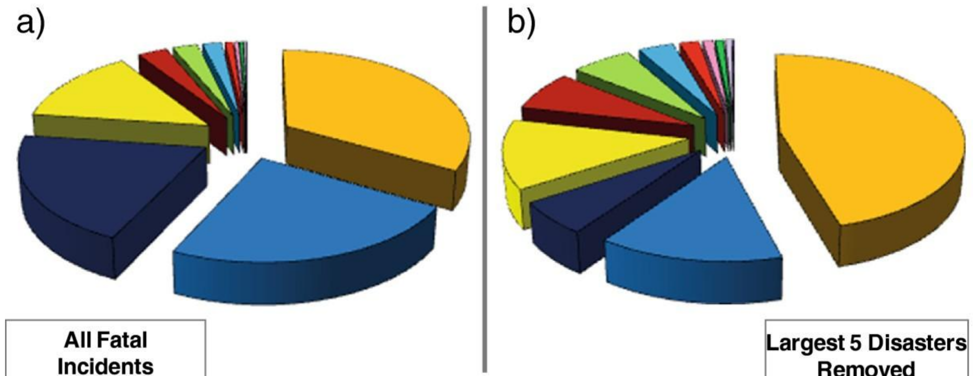
- Volcanic eruptions may generate transboundary hazards (tsunami, pdcs, lahars, plumes of ash, gas and aerosol)

- Volcanic eruptions may affect climate, and be affected by, climate change

- Impacts of volcanic eruptions can be widespread and long-lived (e.g. evacuated or permanently displaced populations, aviation disruption, damage to critical infrastructure, economic losses, environment)

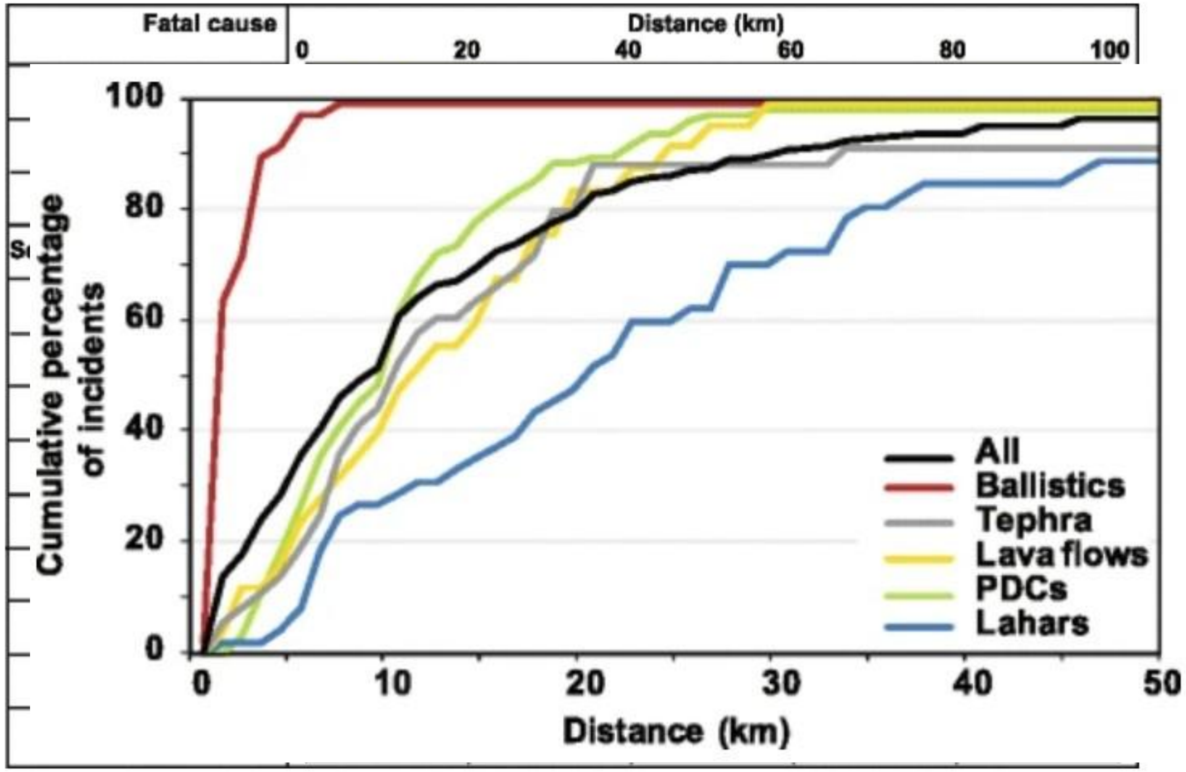
Volcanic hazards, fatalities, distance

Causes of fatalities associated with volcanoes[1]



All Fatal Incidents			Largest 5 Disasters Removed	
Fatalities	%	Hazard	Fatalities	%
91,484	33	Pyroclastic Density Currents	50,994	46
65,024	24	Indirect	15,724	14
55,277	20	Waves (Tsunami)	6,813	6
37,451	14	Lahars (Primary)	14,054	13
8,126	3	Tephra	8,126	7
6,801	3	Lahars (Secondary)	6,801	6
5,230	2	Avalanches	3,953	3
2,151	0.78	Gas	2,151	2
1,163	0.42	Floods (Jökulhlaups)	1,163	1
887	0.32	Lava Flows	887	0.79
765	0.28	Seismicity	765	0.69
142	0.05	Lightning	142	0.13

0-5 km ballistics (tourists, scientists, media, miners, emergency response)
5-15 km pyroclastic density currents
15 km+ lahars, tsunami, tephra



[1]Auker et al. 2013, [2]Brown et al. 2017

Challenges and knowledge gaps

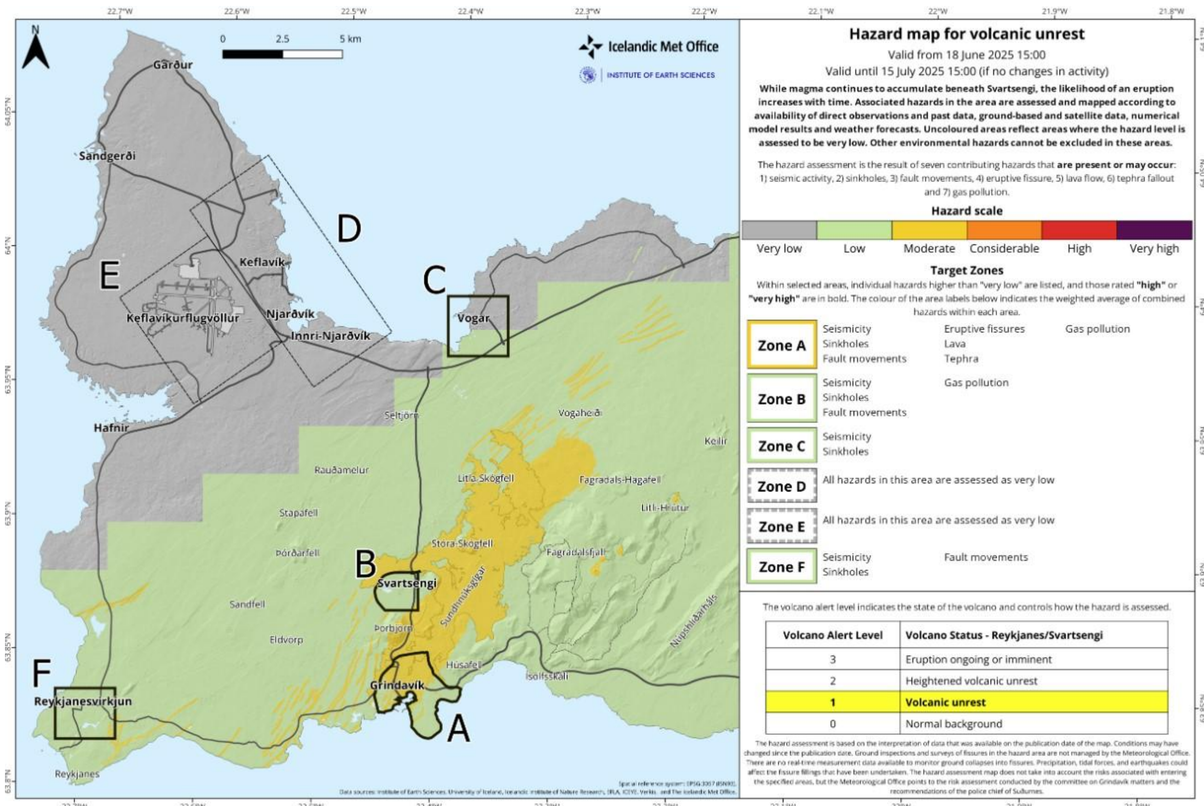
Volcano Observatories: multi-hazard approaches and forecasts for anticipatory action

- **Volcano Observatories are authoritative sources** of local-national monitoring, alert level information, forecasts, hazards assessments and maps, communication, and many are national institutions – sharing opportunities

- VOs combine multiparametric monitoring data, observations, past data, numerical model outputs, weather forecasts, satellite data to advise – data harmonization and innovation.

- Challenge to make multi-hazard assessments and forecast information available, accessible and actionable in near-real-time, local to global.

- VOs work with civil protection and communities under conditions of uncertainty – tools and approaches for dealing with uncertainty



60 hazard assessment maps have been published by Icelandic Met Office between November 2023-June 2024

1 IAVCEI (Commission on Volcanic Hazard and Risk) Volcanic Hazard Maps database: 2089 hazard maps, 612 volcanoes, 54 countries, 15 languages

Evacuation and the physical and social drivers of risk

- more than 3 million people evacuated since 1985[1,2] , includes self-evacuation and phased evacuation
- volcanic evacuations can be prolonged, causing people to return to support livelihoods, escape shelters, support livestock etc
- evacuation duration - Hurricanes: 1-3 days, floods: days to weeks, volcanoes: days to years
- fatalities amounted to 0.01% of the evacuated populations who suffered severe disruption and possible impacts to livelihood and wellbeing[2]
- need to better understand the physical and social drivers of risk in different contexts

a) Shared knowledge of the push and pull factors that impact on decision-making;

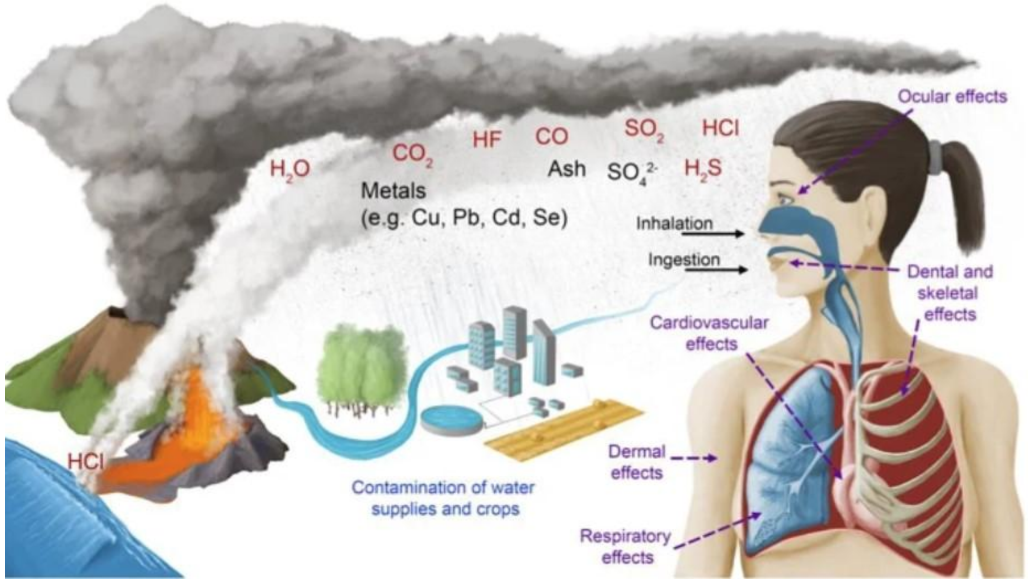
(b) Improved understanding of evacuation time-scales that are robust to variations of eruptive activity, and their associated warning signals and uncertainties;

(c) Robust development of a 'risk culture' that includes scientific and community experience of creating the best possible life outcomes in the face of volcanic activity.

Barclay et al. 2019

[1]Loughlin et al. 2002, [2]Barclay et al. 2019

Potential impacts and risk knowledge at local to global scales



All islands with volcanoes, including Small Island Developing States are particularly vulnerable due to size and proportion of population exposed[3]

Significant opportunities in regional approaches: coordination, collaboration, harmonisation
MYRIAD - https://www.myriadproject.eu/
EUROVOLC - https://project.eurovolc.eu/

Global data, databases, harmonisation, tools, platforms of hazards and risk - sustainability

Development of evidence-based, locally specific measures for health protection[1]. Knowledge gaps on chronic health impacts of volcanic air pollution[2], scarcity of epidemiological studies.

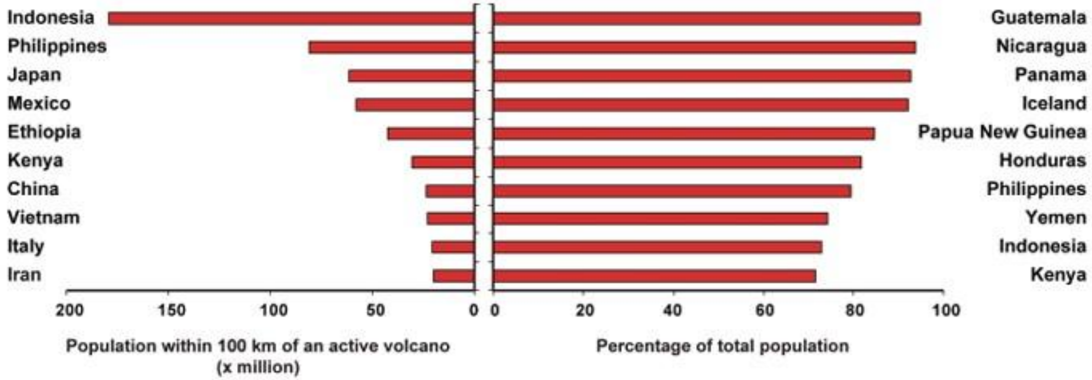


Figure 4.1 The top 10 countries for population within 100 km of a volcano (left) and the top 10 countries (area over 31,415 km²) for percentage of the total population (right).

[1]Horwell et al. 2023, [2]Stewart et al., 2022, Brown et al. 2015

People-centred EWS

- Many different experiences worldwide. Need to continue documenting good practice and lessons learnt – share across hazards communities
- May be supported by informal networks (e.g. the *Vigía* network at Tungurahua, Ecuador[3], *Beidar* at Sinabung[4]) – explore good practice
- EWS require risk understanding, establishment of thresholds/triggers, testing, training, preparedness plans, scenario planning and exercises – sharing good practice
- Diverse EWS are needed for different purposes including high-risk activities (e.g. official workers in exclusion zone, high risk land use, emergency responders) - guidelines

Tristan da Cunha, Hicks et al. 2014

Island-wide evacuation exercise

- Need to enhance interdisciplinary research and approaches worldwide.

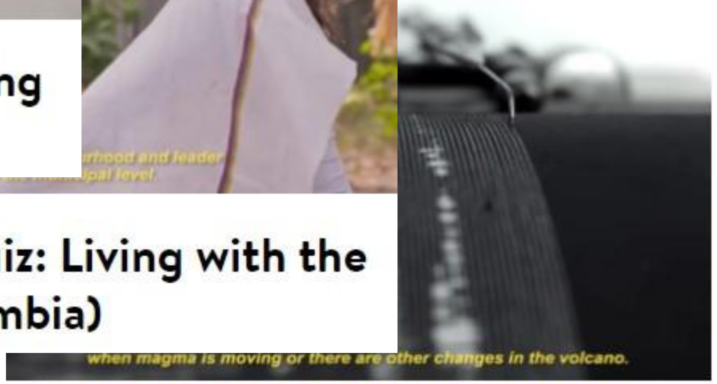
[1]Twigg and Lavall 2006, [2]Leonard et al. 2008, [3]Stone et al. 2014, [4]Wulandari et al. 2018.

Progressing anticipatory action

- Planning and preparing for future multi-hazard scenarios (reasonable worst case)
- Understanding and managing risk for evacuation and displacement, under conditions of uncertainty
- Resilience building across scales and sectors
- Better anticipating potential impacts and needs across sectors and disciplines in the context of climate change and the climate effect of volcanoes

Nevado del Ruiz: Remembering 1985 (Colombia)

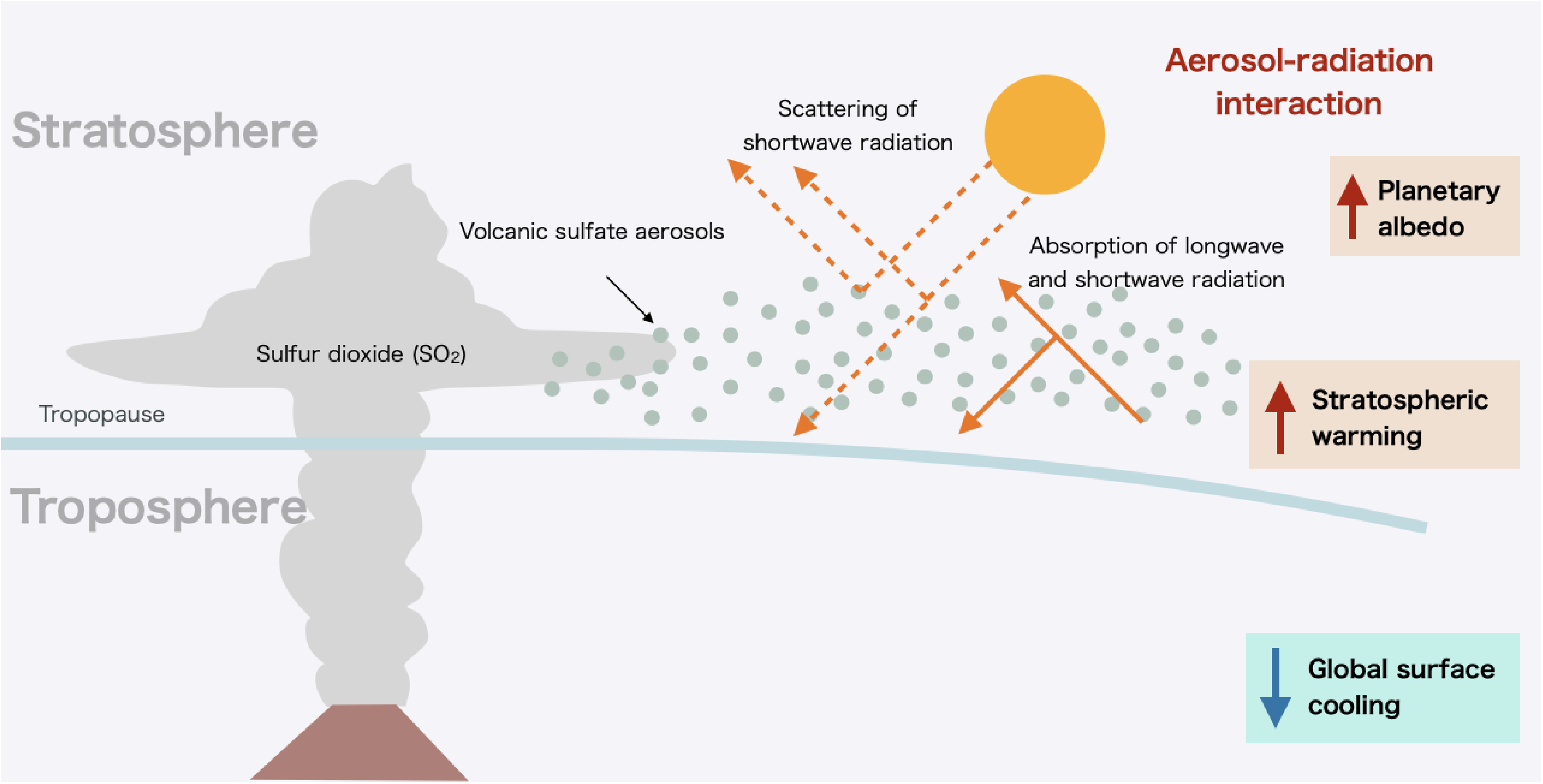
Nevado del Ruiz: Living with the volcano (Colombia)



Nevado del Ruiz: Knowing the volcano (Colombia)

Volcanic forcing of climate

Volcanic sulfate aerosol particles cause short-term surface cooling



- Sulfate aerosol particles are primary driver of climate effects
- Climate effect modifiers:
  - eruption style
  - location
  - injection height
  - co-emissions
  - background atmospheric climate state
  - non-linear chemistry and particle microphysics, …

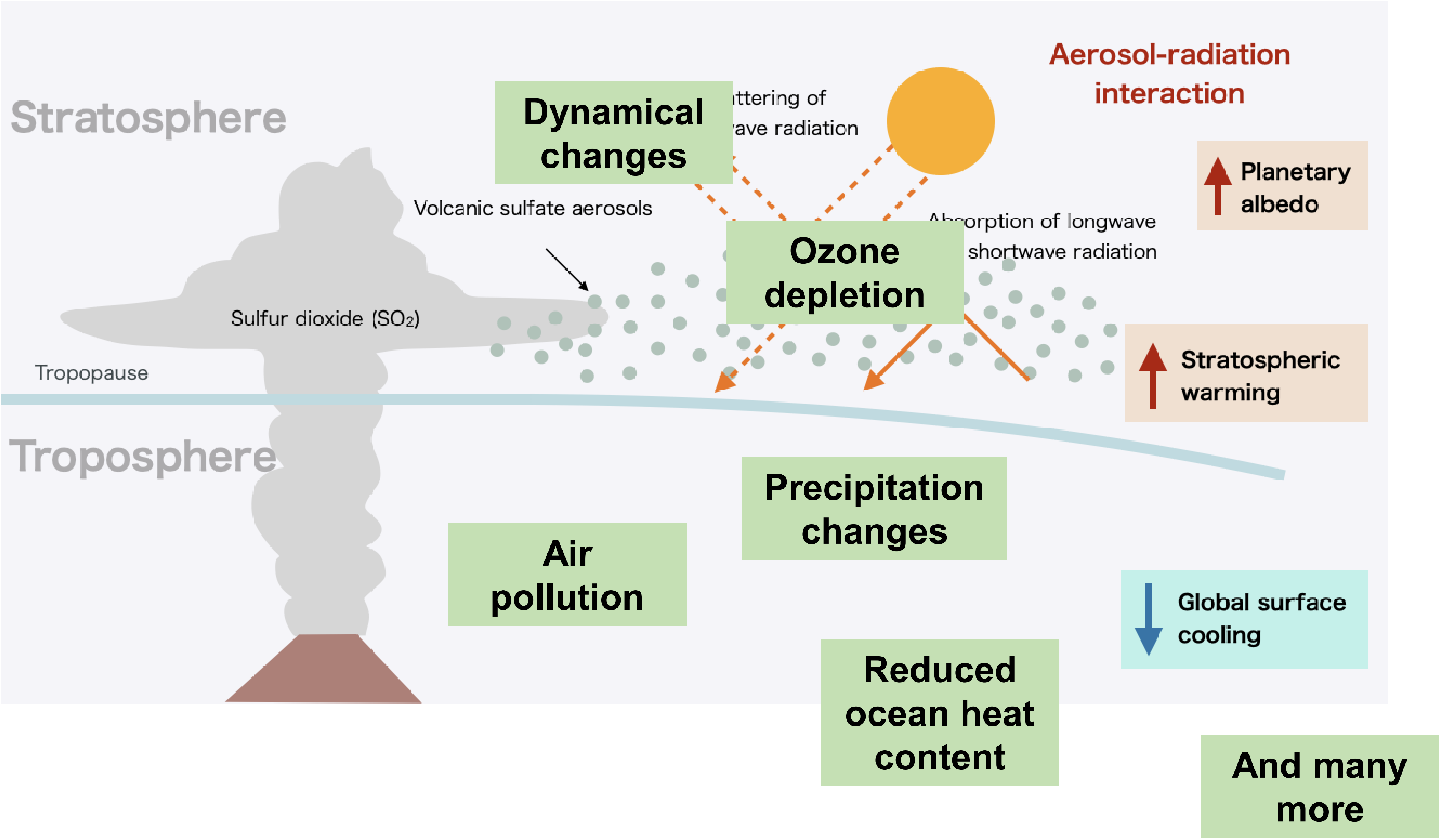
Mechanistic understanding highest for surface cooling; less certainty for other climate effects (e.g. rainfall)

Timescales: days to years in atmosphere; decades to millenia for ice-sheets, ocean

For reviews see Timmreck (2012); Marshall et al. (2022); Schmidt & Black (2022)

Figure from May Chim

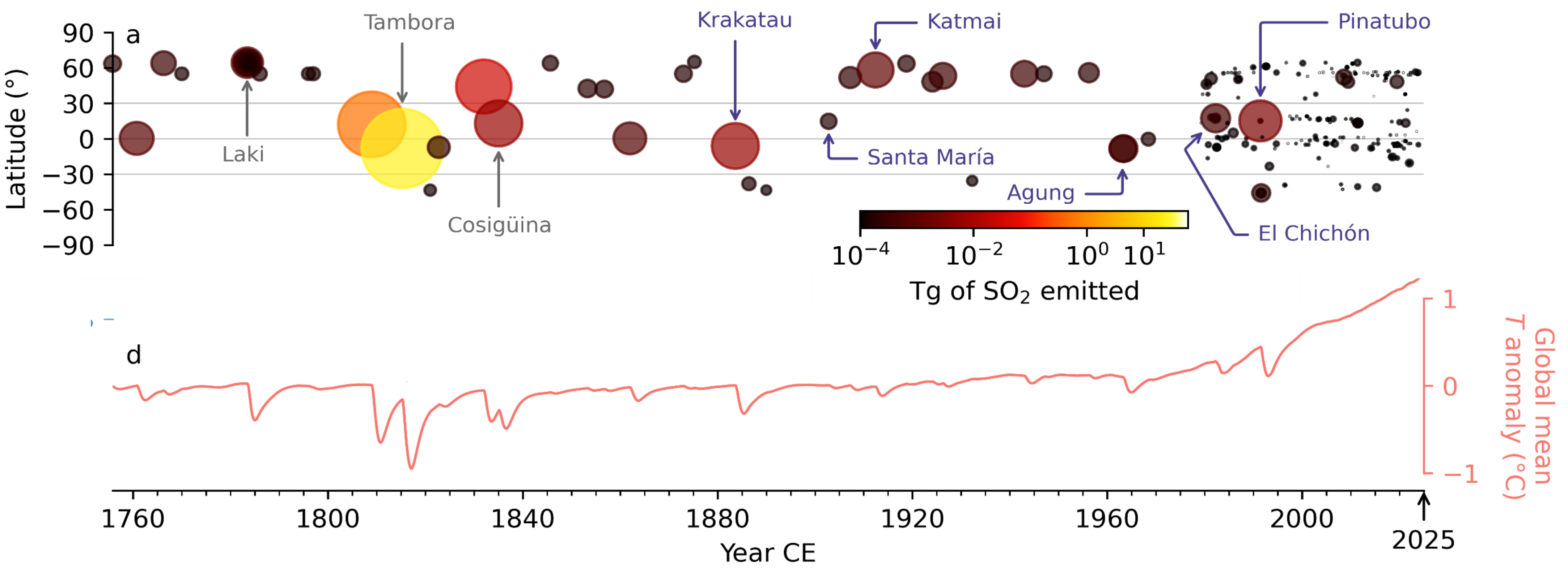
Volcanic eruptions cause multiple hazards on multiple scales



- Surface cooling is first-order effect, but cascades into many other effects
- Changes in ozone, precipitation, and large-scale dynamics are subject to more uncertainty than temperature response

For reviews see Marshall et al. (2022) and Schmidt et al. (EOV Chapter)

Average global surface cooling of around 0.15°C



- On average, peak global surface cooling is around 0.15°C with a range of negligible to 0.6°C cooling since year 1750 (IPCC AR6)
- Regional temperature changes are highly variable (incl. warming) and more uncertain yet key for mitigation and adaptation

Improve understanding of regional-scale climate effects incl. cascading hazards

Figure from Schmidt et al. (EOV Chapter, in prep.)

Data and tools available to assess probability of exceeding cooling thresholds

- Peak global surface cooling of 1991 Mt. Pinatubo eruption was about 0.29°C (uncertainty range: 0.21–0.37°C)
- 70% chance of a 1991 Mt. Pinatubo-magnitude surface cooling before year 2100
- Awareness of risks and cascading hazards in scientific literature (*)
- Tools to assess probability of surface cooling readily available (e.g. Volc2Clim)

Assess the probability of all climate-related effects incl. cascading hazards → integrate into early-warning systems

Develop tools to assess socio-economic consequences

*e.g. Loughlin et al. (2015); Bethke et al. (2017); Newhall et al. (2018), Mani et al. (2021); Cassidy & Mani (2022), Mani (2025), Chim et al. (2025)

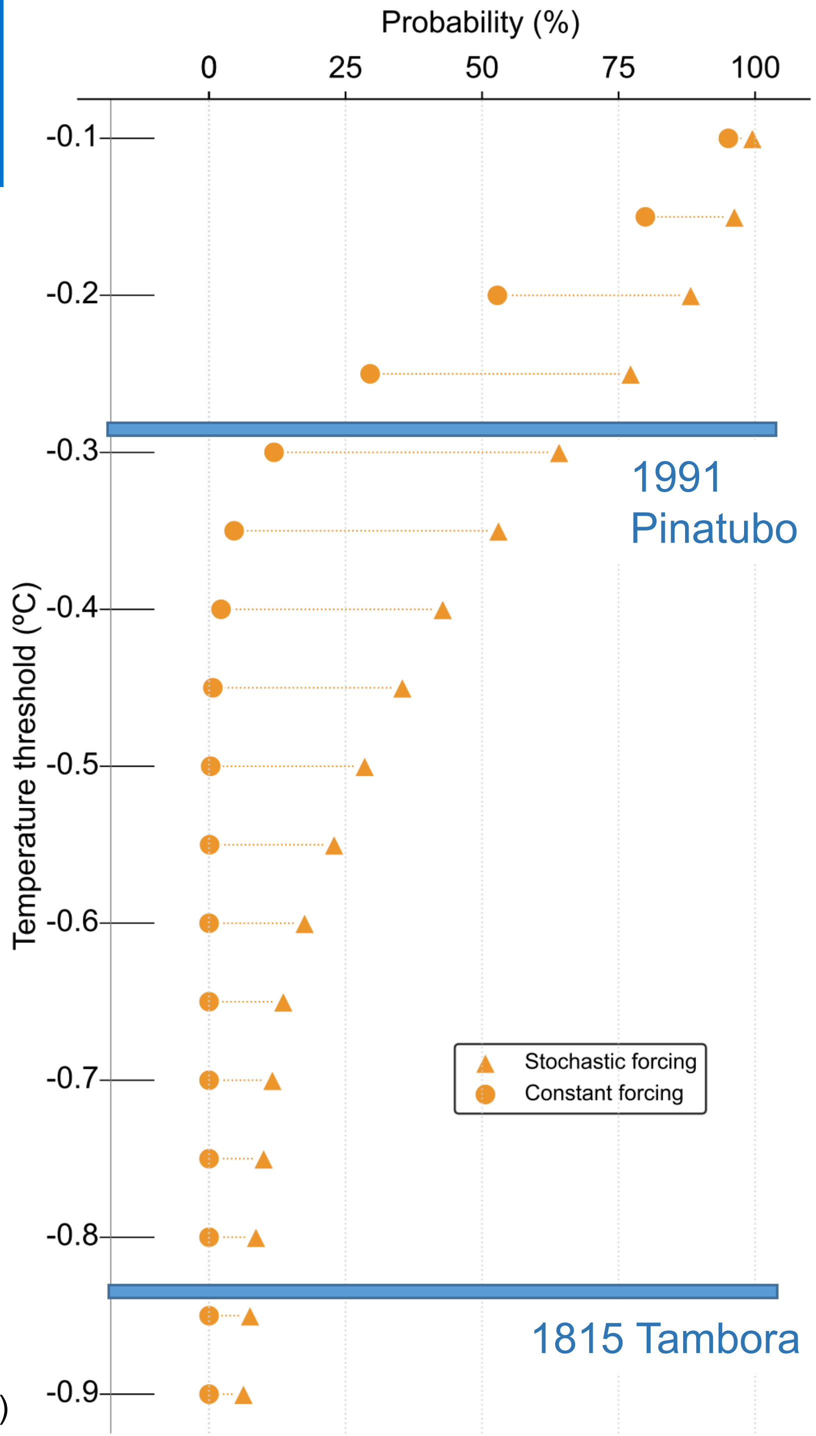
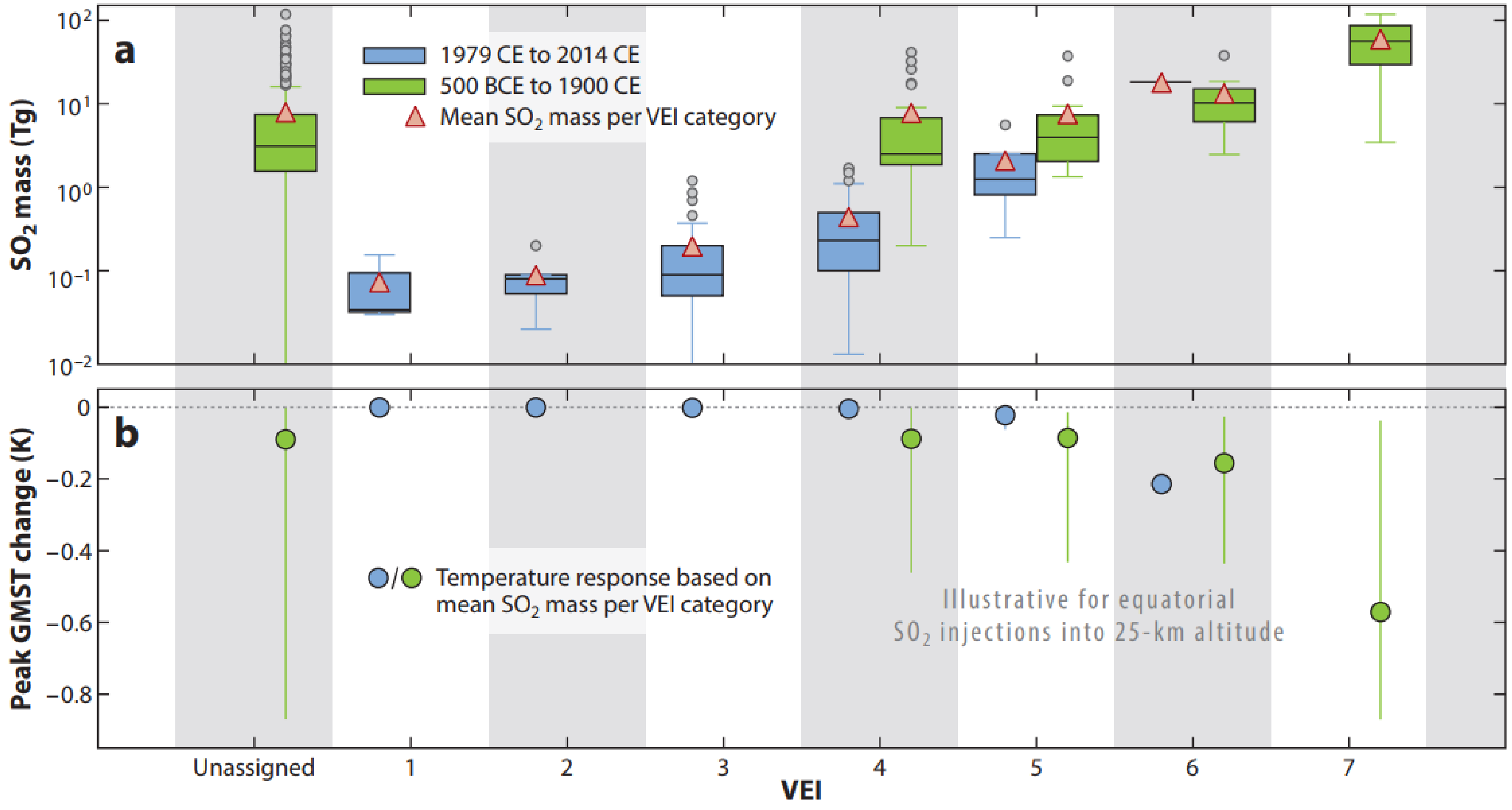


Figure from Chim et al. (2025)

Challenges and knowledge gaps

VEI does not necessarily correlate with SO_2 emissions thus climate effect



- VEI is not a climate effect scale, so VEI of X not equal to a cooling of Y

  → risk of under- or overestimating effects and thus misleading early warning

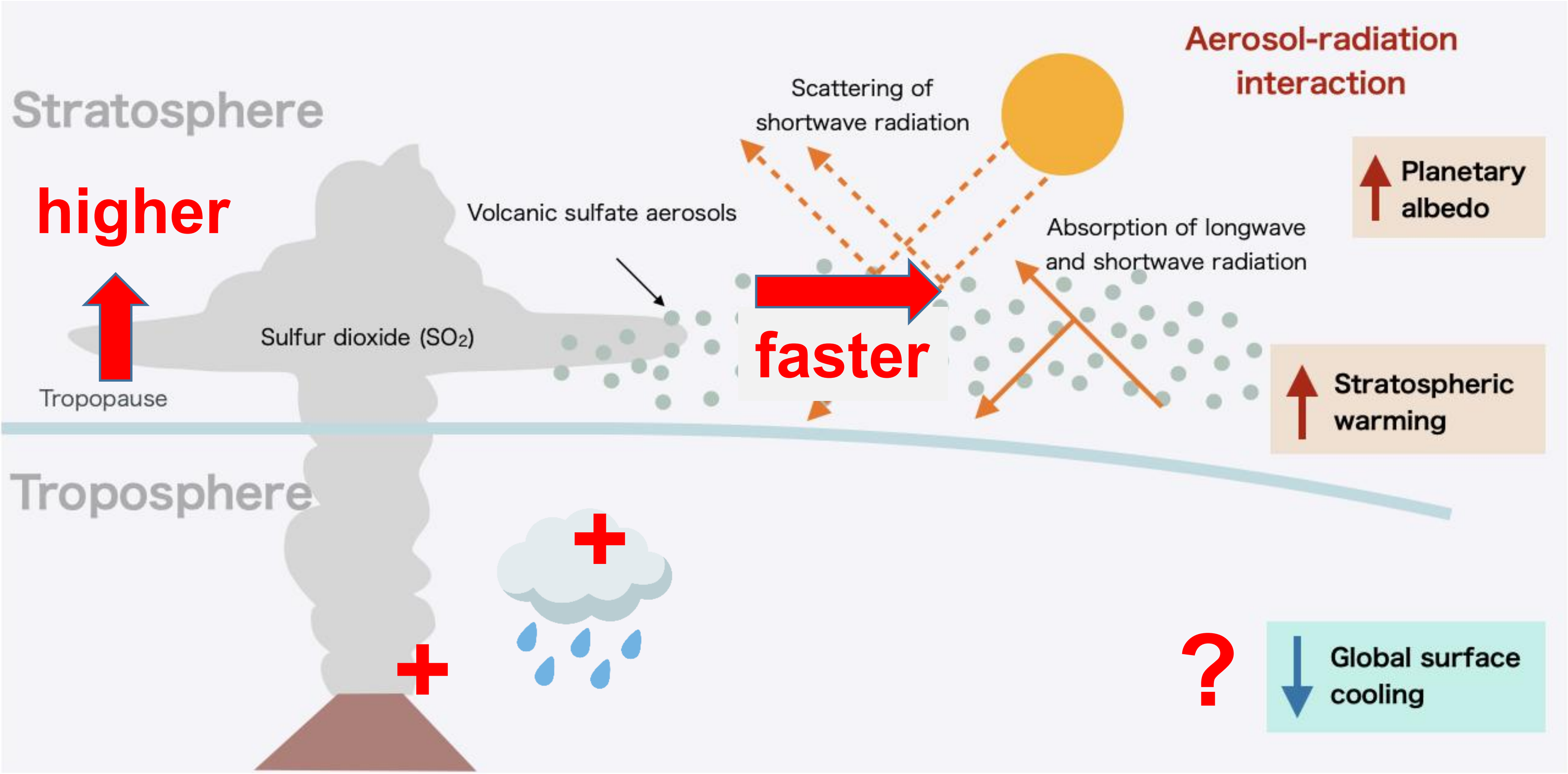
- Hunga Tonga 2022: VEI 5 but only 0.4 Tg of SO_2 and >100 Tg of H_2O → initially proposed to cause a net warming

Avoid using VEI as climate effect proxy

Bridge knowledge, tools, institution, e.g. atmospheric science, climate modelling, earth observations, volcanology, disaster management and planning, ….

Figure from Schmidt and Black (2022)

Climate change affects syn- and post-eruptive processes



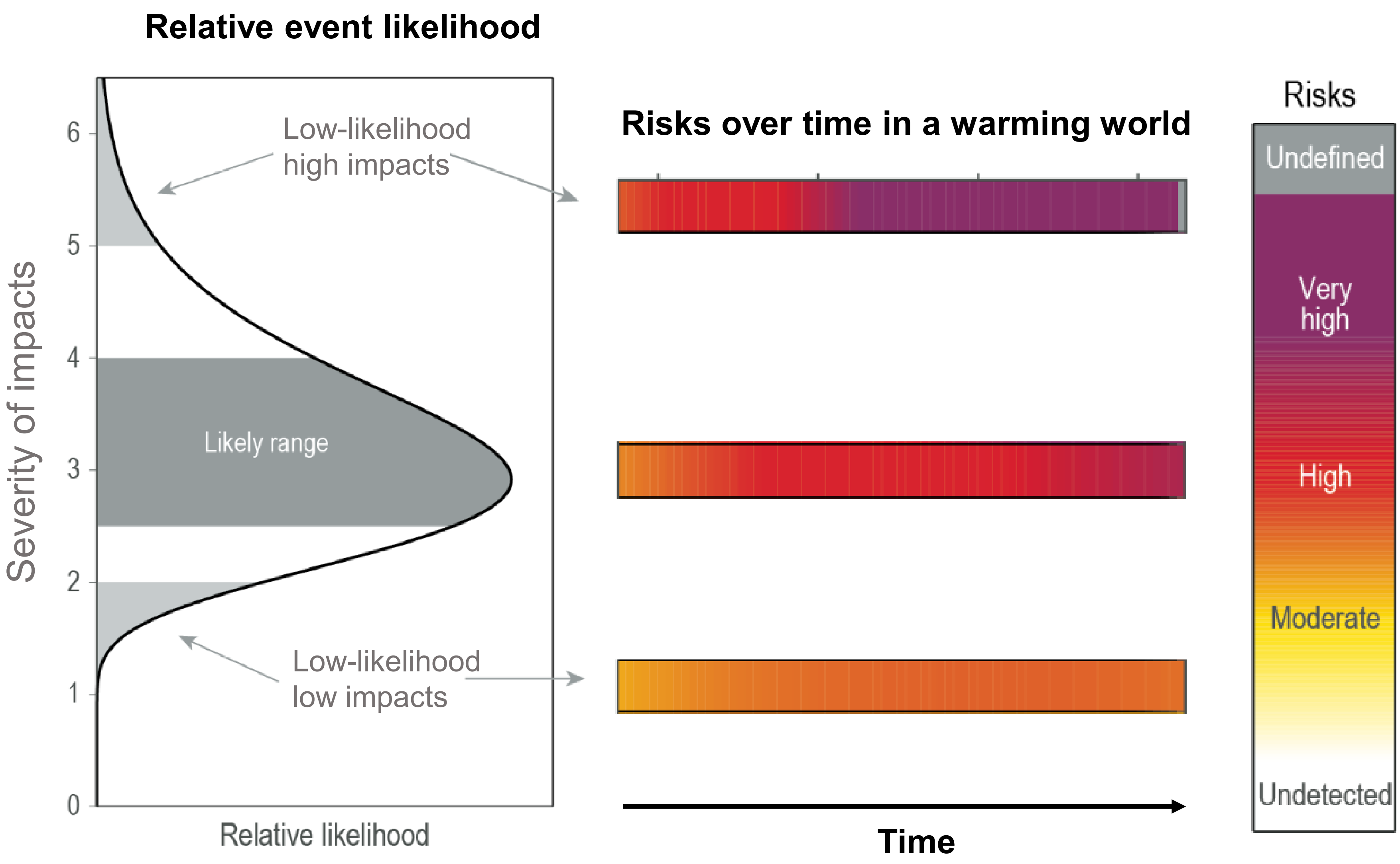
Early warning systems need to consider how rapid climate change reshapes volcanic risk knowledge as a cross-scale hazard modifier

Rapid climate change:

- affects syn- & post-eruptive processes (sea-level, precipitation erosion, plume height, magnitude of forcing, …)
- raises odds of eruptions coinciding with other extreme events (rainfall, heatwaves)

For a review see Aubry et al., 2022

Preparedness for tail risk is preparedness for resilience



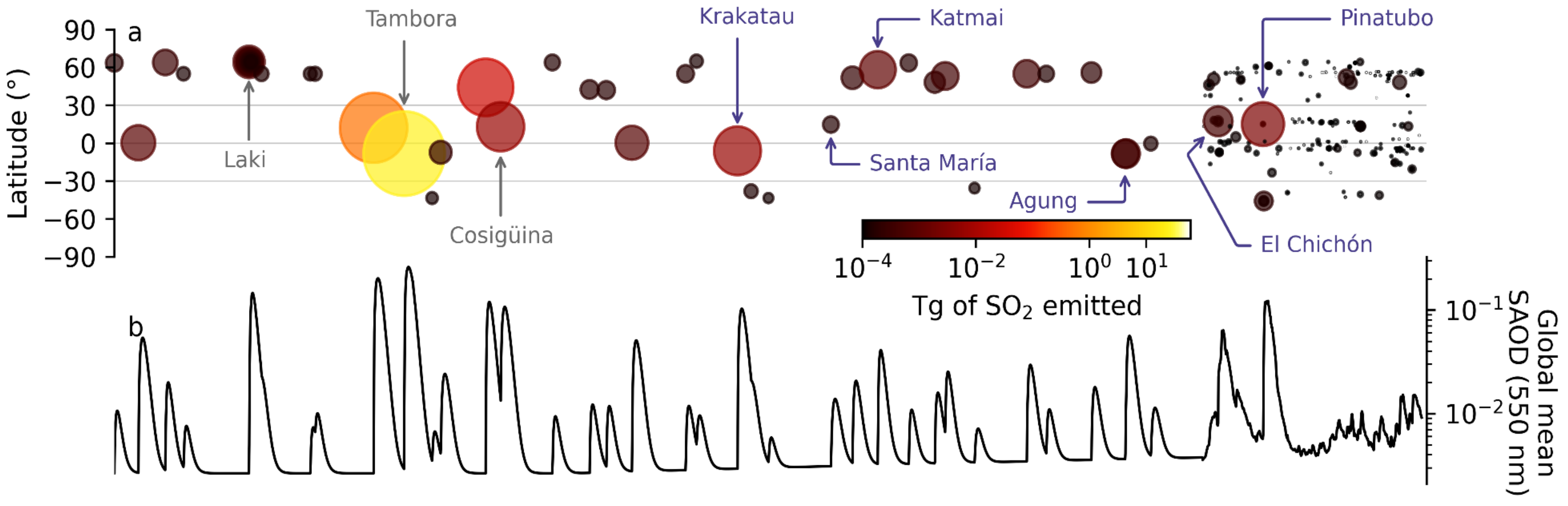
- Closest analogues Samalas 1257 and Tambora 1815 did not occur in an 8 billion-person, hyper-connected, and much warmer world

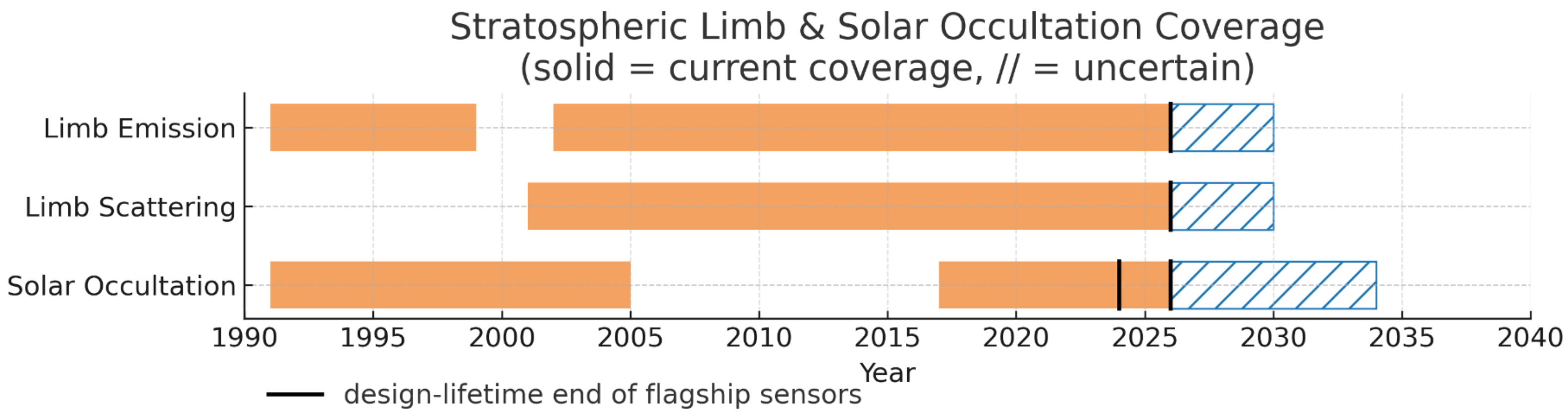
Prepare for rising risks and modified hazards in a warming world

Consider black-swan event including coinciding extreme events

Figure for illustrative purposes only, modified from IPCC AR5

Risk of an imminent data desert in the stratosphere





- Combination of ground-based and space-based measurements
- Key measurements for forcing and evaluating climate models → IPCC, WMO ozone assessment
- Models and measurements have high relevance for solar radiation modification proposals, wildfire events, …

Urgently sustain space-based satellite measurements, otherwise threat to early warning systems

Top figure from Schmidt et al. (EOV Chapter, in prep.) Bottom figure modified from Salawitch et al. (2025)

Summary

Understand impacts

- Integrated networks, across scales, sectors, harmonized – regional very effective for coordinated action, funding etc
- Planning for dynamic management of risk during evacuation, anticipating impacts on livelihoods, assets.
- Support observatories to document experiences and eruption case studies with climate and hydromet relevance
- Link volcanic emissions to multi-hazard climate effects (cooling, rainfall shifts, ozone loss) incl. socio-economic assessments
- Understand effects of climate change as "modifier"

Identify actions

- Ensure continuity of stratospheric monitoring (satellite, ground-based)
- Develop scenarios for rare, high-impact events incl. overlap with other extremes
- Embed volcanic forcing into seasonal forecast and humanitarian planning tools
- Sustainable observatories with effective DRM governance and EWS for all active volcanoes
- Update and sustain existing global risk data, databases, indices etc.

Assess information needs

- Future multi-hazard risk scenarios including tail-end risks
- Understand who 'stakeholders' in multi-hazard risk are, understand their needs, embrace interdisciplinary methods and research.
- Data collection after events, monitoring data, hazard, exposure, vulnerability, impacts, experience.

Clarify actors

- Everyone
- Aligned and coordinated proposals?
- IAVCEI working groups
- VOBP, CoV
- Funders