APARC

Atmospheric Processes And their Role in Climate

Newsletter n°66
January 2026

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The year 2025 concluded with a highlight for APARC. Just before the end of the year, the Hunga activity presented its newly published report at the AGU Fall Meeting in New Orleans. In this issue, you will find a brief summary along with a link to the full report. This newsletter also features key outcomes from the EPESC/LEADER Meeting in Busan, as well as insights from the Virtual Workshop Series on Stratospheric Aerosol Injection. Looking ahead, we are excited to turn our attention to 2026, with the APARC General Assembly scheduled for October in India. Abstract submission is already open, and we warmly invite your contributions.

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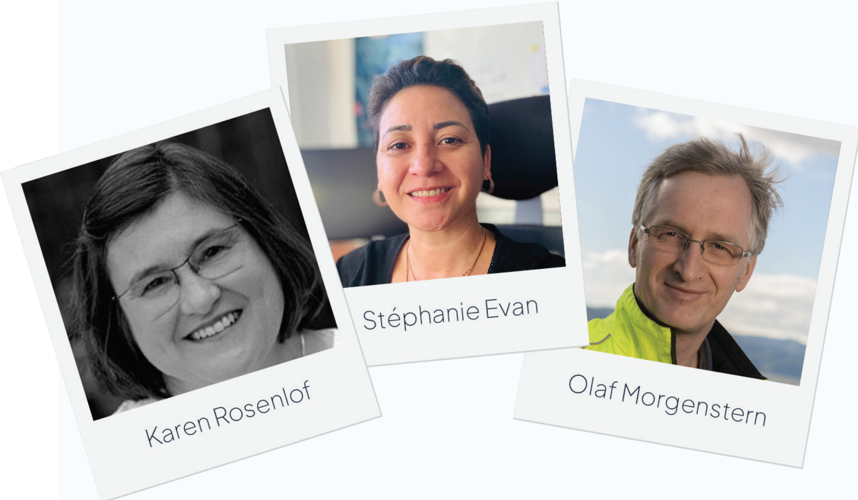
Personal reflections on the outlook for APARC



In spite of the uncertainty in regards to funding this past year, APARC activities still achieved a lot. In September we had our Scientific Steering Group meeting in Leeds, hosted by our outgoing co-chair Amanda Maycock. One recent highlight was the completion of the Hunga Assessment report that will inform the 2026 WMO/UNEP Scientific Assessment of Ozone Depletion. It was finalized in December, and you can find a video on the report on the WCRP YouTube page (https://www.youtube.com/@WCRP1980/videos). There were several activity meetings held during the year, the ACAM training school in Bali during June 2025, and a Joint APARC/WCRP Workshop and Training School on AI for Climate and Weather Forecast held in Dakar in November 2025. There were also multiple papers published by APARC activities during the year. Overall, 2025 proved to be a successful year for APARC science.

We offer congratulations to our now former co-chair Amanda Maycock, who was selected to be a member of the WCRP Joint Scientific Committee (see https://www.wcrp-climate.org/news/wcrp-news/2362-new-jsc-new-members) and thus could not continue as APARC co-chair. We are happy to see someone with strong APARC credentials serve on the JSC, and thank her for her strong leadership provided to APARC during her tenure as co-chair. A note from Amanda reflecting on her time co-chairing APARC is included below.

With Amanda's departure (after completing her 4-year term) we now welcome Stephanie Evan, who is affiliated with the Observatoire des Sciences de l'Univers de La Réunion (OSU-Réunion), UAR3365, an atmospheric observatory and research facility on La Réunion jointly operated by CNRS (French National Centre for Scientific Research), Météo-France, the University of La Réunion, and IRD. Stephanie has worked extensively on APARC related topics and brings expertise in both modeling and in situ observations.

We extend our gratitude to our outgoing IPO director, Rolf Müller, and wish him all the best for his retirement. Apart from serving as APARC Director, he has been a stalwart of APARC/SPARC science for his whole career. Ines Tritscher, who has been serving as assistant director, has succeeded him as IPO director, so we expect a seamless transition. Rolf will continue to help out, in particular with the upcoming General Assembly to be held later this year. We are also grateful to Ines for her readiness to take on this additional role.

In further IPO related news, the APARC web page has been updated thanks to hard work by Olaf Stein. We ask that everyone take a look at it, and if you find any issues to let the IPO know.

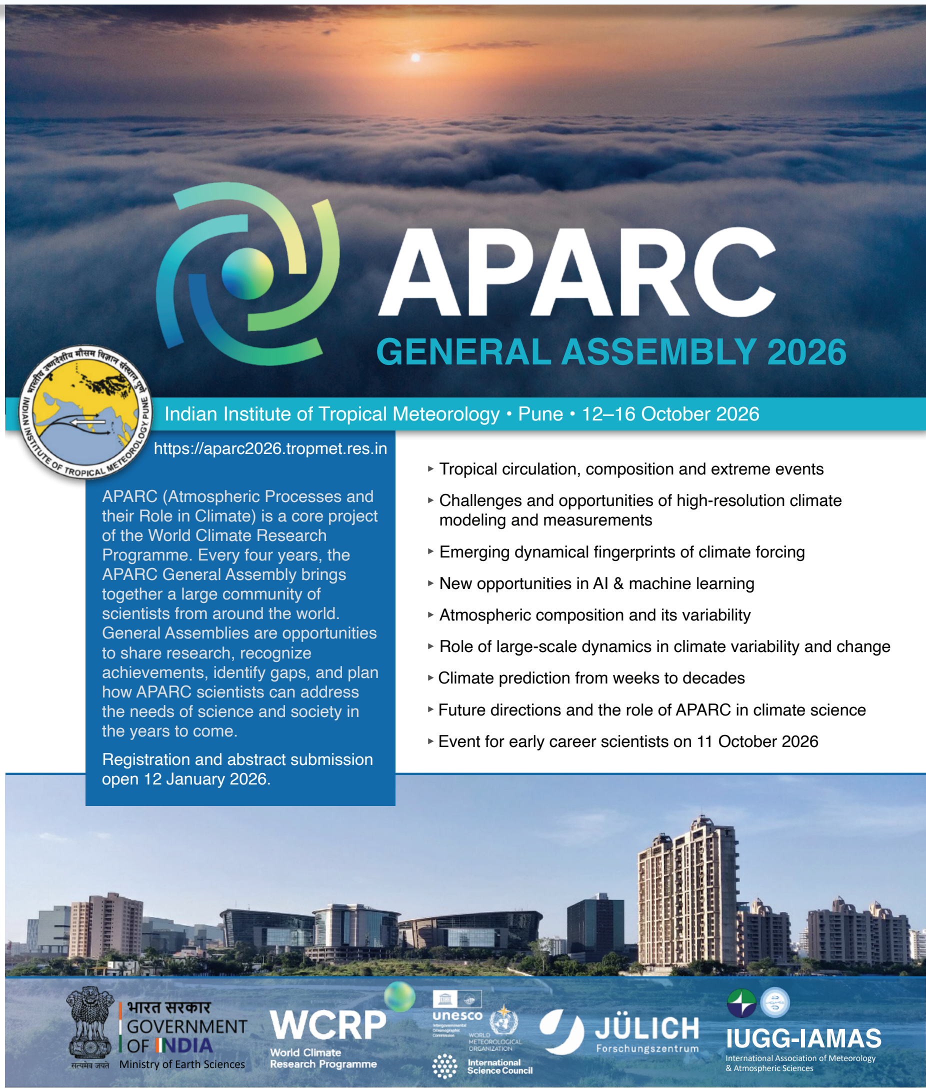
As noted, the General Assembly will be held at the Indian Institute of Tropical Meteorology in Pune from 12–16 October 2026. Check the web page for registration and abstract submission. We look forward to seeing all of our activities represented at the GA.

Personal note from Amanda Maycock

I'm sorry to be stepping down as APARC co-chair at the end of my 4-year term, but excited to continue to support our community through my new role on the Joint Scientific Committee of WCRP. It's been a pleasure to work with my co-chairs Seok-Woo Son, Karen Rosenlof and Olaf Morgenstern, and am very grateful to the support we've received from the International Project Offices at DLR and most recently FZJ. The IPO team in particular do an enormous amount to support our community and to coordinate our work with that of the wider WCRP. It's been personally satisfying to have helped deliver the launch of our new project name APARC, play a small role in the pioneering multi-hub General Assembly in 2022, and to have seen much great community research continuing to emerge from our vibrant Activities. We face significant challenges as a community from the rising public distrust in science and the increasingly divided international governance of climate change policy. To ride the storm, it is vital our work is addressing pressing societal needs and that we communicate the importance of science research to a broad audience of stakeholders. I look forward to remaining a close member of the APARC community and wish the new co-chair Stéphanie Evan all the best with her role.

Amanda Maycock

Registration is now open:
https://aparc2026.tropmet.res.in



Busan EPESC/LEADER Meeting Summary

Chaim Garfinkel[1], Scott Osprey[2], Kirsten Findell[3], June-Yi Lee[4], James Risbey[5], Doug Smith[6], Stephanie Fiedler[7], Jonathon S. Wright[8]

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Dates:
15 - 18 July 2025

Scientific Organising Committee:
Kirsten Findell, Erich Fischer, June-Yi Lee, Scott Osprey, James Risbey, Chaim Garfinkel, Andrea Dittus, and Maureen Wanzala

Local Organising Committee:
June-Yi Lee, Seok-Woo Son, Alexia Karwat, Jin-Ho Yoo, Suyeon Moon, Seung-Ki Min, Yeongeun Yun

Host Institution:
Asia-Pacific Economic Cooperation Climate Center in Busan, South Korea

Number Of Participants:
92 participants (from 20 countries)

Contact:
chaim.garfinkel@mail.huji.ac.il

Conference Website:
https://www.wcrp-climate.org/epesc-leader-meeting2025

Sponsors:

In July 2025, the Asia-Pacific Economic Cooperation Climate Center in Busan, South Korea hosted the joint science meeting of two ongoing initiatives of the World Climate Research Programme (WCRP): the Lighthouse Activity on Explaining and Predicting Earth System Change (EPESC) and Large Ensembles for Attribution of Dynamically-driven ExtRemes (LEADER), an activity of the Core Project Atmospheric Processes And their Role in Climate (APARC). The meeting was attended by 78 in-person and 28 virtual participants representing 20 different nations. Among the in-person participants were 29 early-career scientists. We would like to thank the local organising committee for their coordination of a wonderful week of talks, posters, breakouts and social activities.

The workshop took place the week before the much larger BACO-25 conference, and approximately half of the in-person participants stayed for BACO. This resulted in a significant savings in CO_2 emissions as compared to a baseline scenario in which the meetings were not back-to-back.

We gratefully acknowledge the Asia-Pacific Economic Cooperation Climate Centre (APCC), G-Impact in Pusan National University (PNU), Institute for Basic Science Center for Climate Physics (ICCP), World Climate Research Program (WCRP), and International Association of Meteorology and Atmospheric Sciences (IAMAS) within the International Union of Geodesy and Geophysics (IUGG). The support of APARC and IUGG in particular enabled travel support for Early Career Scientists to participate.

Meeting Overview

The EPESC and LEADER communities are working together to improve understanding and attribution of dynamical drivers of extreme Earth system events, how those drivers are changing in a warming climate, and how we might leverage this understanding to improve seasonal-to-decadal predictions, particularly of hazards and extremes.

The meeting centered around critical advancements and ongoing challenges in climate modeling, observation-model discrepancies, predictability, and the role of external forcings. Key themes included the assessment of model performance, understanding the physical mechanisms behind climate variability, and improving prediction accuracy on seasonal, decadal, and multi-decadal scales.

At the heart of the meeting, much attention was given to circulation variability and trends in the Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP; Smith et al., 2022) simulations, covering topics including predictions and predictability of large-scale modes, responses to solar and volcanic forcing, and regional foci on the tropics, Northern Hemisphere summer, the Southern Hemisphere, and the North Atlantic. The workshop allowed for substantive discussions on the strengths and weaknesses of different methodological approaches used to explore data from this new model intercomparison project. This work is especially timely as the IPCC AR7 report will emphasize the circulation response to global warming.

Session Overviews

Model/Observation Discrepancies and Their Implications

[Tiffany Shaw, Kirsten Findell, Yang Chen, Andrea Steiner, Lijing Cheng, Stephanie Fiedler]

As climate change signals begin to emerge, so too are discrepancies between models and observations across various climate variables. A recent US CLIVAR workshop identified approximately twenty discrepancies between models and observations (Simpson et al., 2025). Discrepancies in one region can influence others due to teleconnections; for example, east-west Pacific SST discrepancies relate to storm track trends in the Southern Ocean.

There was much discussion about best practices in evaluating discrepancies. Any comparison between models and observations must be rooted in an understanding of observational uncertainty; substantial progress on the quantification of uncertainties in multiple data products was shared, including ocean heat content, tropospheric and stratospheric temperature trends, atmospheric reanalyses, relative humidity, and the suite of exogenous climate forcing factors tackled by the Climate Forcings Task Team of the Coupled Model Intercomparison Project (CMIP). These uncertainties can be due to measurement biases, vertical interpolation errors, and sparse sampling, among others.

Although gaps and discontinuities in the observational system are unavoidable, they remain a significant challenge in evaluating models against observations. These challenges are especially steep in regions where observational coverage has historically been poor, including much of the Global South. Although reanalysis products may be used to fill these gaps, reanalyses are also sensitive to sparseness and discontinuities in assimilated data, and are therefore often unreliable for evaluating trends and low-frequency variability. The LEADER and EPESC activities are working with the APARC Reanalysis Intercomparison Project (A-RIP) to develop and implement better practices and guidance on the use of reanalysis products for model evaluation.

Overall, the comparison of model trends with observations requires careful practices: matching spatial grids, temporal frequency, subsampling models to observational coverage, and analyzing individual model runs rather than ensemble means, to better evaluate internal variability. Using a suite of models at different resolutions can help clarify whether discrepancies are due to insufficient model resolution, with preliminary work indicating that east-west Pacific SST discrepancies may become smaller when ocean mesoscale eddies are explicitly resolved.

Predictability at Annual to Decadal Timescales

[June-Yi Lee, Doug Smith, Jeong-Eun Yun, Leonard Borchert, Dim Coumou, Rashed Mahmood, Markus Donat]

Operational prediction systems show that much of the predictability on annual to decadal timescales in tropical Pacific and Atlantic trans-basin variability stems from ENSO and Atlantic Multidecadal Variability (AMV). Other sources of predictability on these timescales include the stratospheric polar vortex, the Quasi-Biennial Oscillation, volcanic eruptions (for

Figure 1: *Group photo of the in-person attendees of the EPESC/LEADER workshop.*

the ensuing several years), solar variability, land-use, and changing patterns of aerosol emissions. These forcing agents and modes of variability affect not only the mean climate, but also extremes including heatwaves.

A common problem in using models for prediction (and also attribution) is how to account for model errors, noting that models sometimes produce divergent responses to the same forcing (e.g., NAO trends; Smith et al., 2025). One promising technique to improve seasonal or decadal forecasts of heat hazards is to subselect ensemble members based on known teleconnection patterns—e.g., the PDO phase or Pacific SSTs (Donat et al., 2024). Other techniques include utilizing emergent constraints to select models that are more consistent with observations, or using machine learning techniques to either correct physics-based models or as a replacement for physics-based models. Machine learning methods are demonstrating particular promise for predictions on weather to subseasonal timescales.

Tropical circulation variability and trends

[Andrea Dittus, Jonathon Wright, Suyeon Moon, Seok-Woo Son, Chaim Garfinkel, Rei Chemke, Shubham Waje, Annalisa Cherchi]

One of the most well-known model vs. observations discrepancies relates to the East-West Pacific SST gradient (Seager et al., 2022). While models do a reasonable job if the start-date of the trend calculation is in the 1950s, trend calculations starting in 1979 fail to capture a warming plateau in the Niño3.4 region since 1990. Preliminary work using LESFMIP models shows that some models perform relatively better, and in these models aerosols seem to play a large role. Another previously reported discrepancy between models and observations is whether the Hadley Cell has intensified or not, however this discrepancy largely goes away when observationally-constrained metrics of Hadley Cell intensification (and not reanalysis-based metrics) are used instead (Chemke and Yuval, 2023). Ongoing work is clarifying the forcings responsible for this intensification using LESFMIP experiments.

There is substantial interannual and decadal variability in monsoons that differs across regions, and the LESFMIP output are being used to unravel the contribution from external forcings. The mechanisms underlying these forced changes in the monsoons, and also the processes underlying interannual and intraseasonal variability, can be clarified by analyzing moisture fluxes across the different LESFMIP experiments. Monsoons are also affected by the stratospheric QBO, and more generally the QBO can allow for surface predictability through a variety of mechanisms that are captured by some of the LESFMIP models.

Solar and Volcanic Influences

[Scott Osprey, Basudev Swain, Wenjuan Huo, Davide Zanchettin, Indrani Roy, Melissa Seabrook]

Volcanic eruptions and solar variability can influence climate on annual to decadal timescales. These impacts are evident both in decadal predictions and in LESFMIP simulations, and influence a range of processes in the troposphere from Arctic amplification, to globally averaged surface temperature, to multidecadal Pacific atmospheric and oceanic circulation, in addition to their well-known influence in the stratosphere. These surface impacts are often state dependent, possibly due to sea-ice and ocean feedbacks, and can be hard to discern in the short observational record. Some of these impacts arise due to the ability of both solar and volcanic eruptions to influence the phase and evolution of El Nino, though others can be obscured by ENSO and hence are easiest to extract if ENSO effects are removed statistically. Ongoing work with the LESFMIP solar-only and volcano-only simulations is clarifying these issues.

Southern hemisphere circulation trends and extremes

[Leandro B. Díaz, William Dow, Kewei Lyu, Bianca Mezzina, Sabine Bischof, Ghyslaine Boschat, Rei Chemke]

The Southern Hemisphere atmospheric and oceanic circulations, including the jet stream and Hadley Cell, are changing in response to external forcings. Forced changes in the stratospheric polar vortex and subsequent stratosphere-troposphere coupling can be isolated using LESFMIP output, and these stratospheric changes are important for regional changes throughout the SH. Ozone plays as important a role as greenhouse gases (GHGs) in austral summer over the ozone depletion era (McLandress et al., 2011), and preliminary results with the LESFMIP data has helped reveal a notable role in austral fall and spring as well. Perhaps surprisingly, preliminary work with the aerosol-only LESFMIP run shows a notable influence on jet shifts in both the troposphere and stratosphere and on regional precipitation patterns, in many cases counteracting GHG effects. External forcings can influence temperature extremes, and while LESFMIP models were shown to capture large-scale atmospheric circulation patterns such as the SAM, regional warming trends often differ from observed data in e.g., the Antarctic Peninsula.

Southern Ocean warming is affected by both external forcings and teleconnections from the tropical Pacific; these teleconnections from the tropical Pacific also appear to be partially responsible for a discrepancy between models and observations in SH storm track trends (Kang et al., 2024). There is a notable improvement in ocean heat content in CMIP6 models, but there are persistent, large biases in sea surface temperature in models in the Southern Ocean. Finally, ongoing LESFMIP analysis suggests that sea ice is strongly affected by a range of external forcings, and the rapid decline in Antarctic sea ice after 2014 is affected by GHGs and aerosols but with large intermodel variability.

North Atlantic atmosphere and ocean circulation

[Chaim Garfinkel, Shoshiro Minobe, Ales Kuchar, David Avisar, Rachel Wu, Sara Bennie, Rei Chemke]

External forcings (primarily GHGs, ozone, and aerosols) influence large-scale circulation patterns in the Northern Hemisphere, however there is also significant unforced variability driven by natural factors. There are substantial differences across LESFMIP models in the magnitude and pattern of forced changes. Externally forced changes in many LESFMIP models project strongly onto the North Atlantic Oscillation, with much of the residual on the East Atlantic Pattern (the second leading mode), however in others the forced response does not closely resemble naturally occurring modes. Some of this intermodel spread can be partially accounted for by considering intermodel differences in, e.g., changes in the Arctic or in the stratosphere, but a large component remains unexplained. The LESFMIP models also disagree as to forced changes in the stratosphere. These changes in the large-scale circulation have implications for heatwaves, storms, and precipitation in, e.g., the Mediterranean sector.

There are notable discrepancies between models and observations over the historical record in the strength of the North Atlantic jet: a long-term strengthening of the jet speed in winter is far too weak in all LESFMIP models, similar to the discrepancy in CMIP6 models (Blackport and Fyfe 2022). This might be related to state-dependent feedbacks from volcanoes and sea-ice, it could reflect deeper problems also evident in seasonal to decadal prediction models in the signal to noise ratio, or it could be due to missed multi-decadal variability in the ocean or stratosphere (or all three).

Summer northern hemisphere atmospheric circulation trends

[Alexia Karwat, Tiffany Shaw, Tilda Huntingford, Jitendra Singh, Gerard Marcet-Carbonell]

Ongoing LESFMIP analysis indicates that trends in the boreal summer atmospheric circulation are driven in large part by aerosol emissions, and specifically decreasing emissions in North America and Europe have had a significant effect on regional energy fluxes and storm track weakening, particularly in Eurasia. Recent observed wave-5 trends in the boreal summer circulation also are mostly associated with aerosol forcings, and not with sea surface temperature patterns. Finally, regional contrasts in this wave-5 trend were shown to be due to forced changes in the atmospheric circulation rather than due to thermodynamic factors.

A previously reported discrepancy in summer storm track strength over the North Atlantic in CMIP5 models goes away with the CMIP6 models, likely due to differences in the aerosol forcing (Chemke and Coumou 2024). This highlights the importance of accurate forcings for reliable projections.

The role of external forcings and internal variability on atmospheric temperature trends

[Benjamin Santer, Matthias Stocker, Sebastian Sippel, Erich Fischer, Satyajit Singh Saini]

It has been known for more than 50 years that rising atmospheric CO_2 concentrations would cause stratospheric cooling and tropospheric warming. This fingerprint of anthropogenic climate change could have been detected as early as 1885 had observations been available as compared to a 1860 baseline (Santer et al., 2023). Natural forcings, including volcanic and solar forcing, have distinctly different fingerprints on temperature trends. The LESFMIP models can capture the observed fingerprint patterns from these various forcings, however, there are some discrepancies across models, especially in their response to volcanic forcing. Likewise, there are differences in the response to anthropogenic GHG and aerosol emissions. Some models overestimate tropical upper tropospheric warming trends in response to anthropogenic forcing while others are more consistent with observed trends. However, there is still substantial observational uncertainty due to disagreement between different satellite and radiosonde products, affecting the intensity of the trends even over the past 20 years.

Observational uncertainties are typically larger during the early observational record, particularly in regions with sparse observational coverage. A newly identified correction to early SST records due to a previously unrecognized change in the timing of new measurement techniques results in changes in SST time series in the early 20th century (Sippel et al., 2024; Chan et al., 2024). Correcting these biases suggests that high climate sensitivity CMIP6 models may not overestimate warming as much as previously thought, while low climate sensitivity CMIP6 models likely underestimate warming.

These changes in mean temperature have substantial impacts on extremes, including an increased likelihood of heat extremes including record-shattering events (Fischer et al., 2021). Heatwaves in polar regions (among other regions) are affected by not just increasing GHG concentrations, but also by aerosols and albedo processes.

Regional Climate Extremes, Compound Events, and Event Attribution

[Zhuo Wang, Hamish Ramsay, Marlene Kretschmer, Yukiko Imada, Wenxia Zhang, James Risbey, Nick Leach, Seung-Ki Min,Yang Chen, Christian Franzke]

These sessions addressed how large-scale atmospheric patterns influence extreme weather, assessed changes in regional extremes, and provided a survey of the multiple different approaches used in extreme event attribution. Presentations on individual phenomena such as precipitation extremes, drought, and tropical cyclones discussed mechanisms that underlie trends towards stronger events. These mechanisms included increasing atmospheric moisture content for extreme precipitation, and warmer SSTs for tropical cyclones. Atmospheric humidity can drive other types of extreme events as well as compound events, and it was noted that models with stronger drying trends align better with observed data. However, there remains significant uncertainty in predicting future humidity-related extremes, especially in models that underestimate drying responses. Finally, connections between the large-scale circulation and extremes were illustrated using both physics-based and advanced ML techniques. In view of the multiple different approaches used in extreme event attribution, there is a need for intercomparison studies to evaluate the strengths and weaknesses of different attribution methods, and to improve the speed and accuracy of post-event analysis.

The event attribution approaches discussed included climate model studies with counterfactual simulations of the selected events in cooler and warmer climates, as well as those based on numerical weather prediction systems. Key issues include the impact of model errors on simulation of extreme events, and also how various methodologies for bias correction and for isolating the role of dynamical processes, can influence the uncertainty in attribution of extreme events. While the thermodynamic effects of GHGs have a large impact on extreme events, dynamical effects and other climate forcings (such as aerosols) are also important in many cases; there is comparatively less confidence in these (Bellouin et al., 2020).

Outlook on single forcing decadal forecasts

[Anca Brookshaw, OkYeoin Kim, Doug Smith, Erich Fischer]

The final session of the week highlighted the challenges in reconciling research needs and operational needs for annual to decadal predictions. The lack of annual updates to the CMIP climate forcings dataset is a major obstacle in the planned transition to LESFMIP phase 2. Furthermore, the need for modeling centers to produce CMIP7 runs to meet AR7 deadlines will also delay the planned transition to LESFMIP phase 2. Due to this delay, the sunsetting of the LEADER activity (originally scheduled for the end of 2026) has been delayed by at least a year.

More generally, speakers emphasized the need to manage expectations about model capabilities and skills. Targeted communication is needed to help users understand where models can and cannot predict with confidence, and to help with capacity-building and sector-specific applications. Ongoing efforts through the World Meteorological Organization (WMO) to synthesize operational annual-to-decadal forecasts include skill metrics and probabilities of exceeding key temperature thresholds like 1.5°C, but underlying model uncertainties must be addressed to improve forecast confidence.

Opportunities, challenges, and the way forward

Presentations and discussion during the meeting highlighted several significant challenges and opportunities in the path ahead, which will guide ongoing efforts and future initiatives within EPESC and LEADER:

1. While observationally-based data products will always be imperfect, progress on quantification of uncertainties is encouraging.

2. The signal-to-noise paradox, whereby model responses to forcing factors are more muted relative to internal variability than they are in the real world, highlights the need for mechanistic understanding of the climate system and the need to fully evaluate model responses rather than taking them at face value. Users of LESFMIP data should test for signal-to-noise errors by, e.g., computing the ratio of predictable components (Eade et al., 2014).

3. Inter-model differences in response to forcing factors highlight the importance of new techniques that go beyond simple multi-model-mean assessments, instead leaning more heavily on simulations by "skillful" models by using, e.g., emergent constraints, and clearer understanding of the sources of model differences. Extensive discussion at the EPESC-LEADER meeting was centered on how to best use the LESFMIP data given these challenges.

4. Earth system-relevant applications of machine learning methods are advancing rapidly, underscoring the need for identification of aspects of model development and forecasts that are likely to benefit most from adoption of these novel techniques.

5. Non-linearities in dynamical systems often mean that single-forcing experiments do not produce linearly additive responses (particularly related to the atmospheric circulation response to external forcings in winter), highlighting the need for additional experimental methodologies (e.g., all-but-one forcing experiments).

6. Numerous approaches to extreme event attribution exist, but models and their responses are often insufficiently evaluated, highlighting an opportunity for a methodological intercomparison applied to case studies with a common definition of the extreme events and counterfactuals scenarios.

7. Annual updates to the CMIP forcing datasets (as opposed to updates every ~7 years) are crucial if we are to develop an operational ability to

attribute and predict upcoming extreme events. Operationalizing efforts to produce these forcing datasets is a priority for WCRP.

8. The UK's JASMIN system for environmental data analysis was widely used to produce results presented at the workshop. JASMIN is a tremendous resource for the community, not only in providing facilities for coordinated analysis, but also in facilitating direct connections with other APARC activities. Continued access to this system is essential to the long-term success of the LEADER and EPESC activities.

Several of these challenges are discussed in greater detail in Findell et al. (in press). Overall, uncertainty will always be part of the equation, but the goal is to provide as much confidence as possible in predictions and in attribution statements. The challenge is to identify areas where we can be certain and where we need to highlight uncertainties. These near-term challenges and opportunities are followed by the longer-term challenge of EPESC and LEADER: taking these research-focused initiatives into the operational realm of decadal attribution, prediction, and projection. While that goal remains far down the road, our EPESC- LEADER meeting in Busan gave us the opportunity to share significant progress and define our next steps and goals. We look forward to the road ahead.

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A new community assessment of the stratosphere in seasonal prediction systems

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Variability in the stratosphere spans from slow radiative processes to some of the most explosive atmospheric dynamics on Earth. The heartbeat of the Quasi-Biennial Oscillation is extremely predictable yet remains a challenge to model accurately. Sudden stratospheric warmings influence the subsequent evolution of the stratosphere and troposphere for several months, but their onset occurs on synoptic timescales which limits longer-term predictability.

Over the past decade, the SNAP community has led extensive analysis of the stratosphere in subseasonal prediction systems, spurred by the WWRP/WCRP S2S Prediction Project (2013–2023). Thus far, SNAP-led S2S papers have examined the subseasonal predictability of the stratosphere (Domeisen et al., 2020a), tropospheric predictability arising from the stratosphere (Domeisen et al., 2020b), model biases in the stratosphere (Lawrence et al., 2022) and biases in stratosphere-troposphere coupling processes (Garfinkel et al., 2025). The related Stratospheric Nudging And Predictable Surface Impacts (SNAPSI) project (Hitchcock et al., 2022) has begun to isolate the contribution of the stratosphere to subseasonal skill with a set of targeted nudging experiments.

The success of multi-model S2S analyses depended on being able to easily access data in a consistent format from the S2S database. To conduct similar analyses on seasonal timescales – which are not covered by the typical ~6-week lead-times of S2S forecasts – requires a similar database, which had been a limiting factor until recently. However, since 2017, the Copernicus Climate Change Service (C3S), implemented by ECMWF, has been developing a growing multi-model seasonal forecast database. C3S produce operational forecast graphics, including stratospheric polar vortex indices (https://climate.copernicus.eu/charts/packages/c3s_seasonal) and public/forecaster-facing discussions (https://climate.copernicus.eu/seasonal-forecasts). The model data are freely available via the Climate Data Store (CDS) (https://cds.climate.copernicus.eu/) on a common 1° resolution at sub-daily and monthly temporal resolution. Currently, nine centres contribute seasonal forecast data to the CDS: ECMWF, the UK Met Office, Météo France, DWD, CMCC, NCEP, JMA, ECCC and BoM. Of these, all but the NCEP contribution include stratospheric level data (10, 30, 50 and 100 hPa). Hindcasts cover a common period of 1993–2016, but individual model hindcast sets include additional years (e.g., ECMWF's SEAS5 hindcasts cover 1981–2016). Previous model versions are also available for some models.

This dataset provides a new opportunity to assess the representation of the stratosphere, its coupling with the troposphere and its contribution to surface skill within a large number of present-generation seasonal prediction systems, building on existing studies (e.g., Portal et al., 2022; Baker et al., 2024). Seasonal prediction models also enable us to ask a range of interesting questions unique to this timescale. These include the role of the initialisation/ensemble spread generation strategy: some prediction systems use a "burst" approach where all ensemble members are initialised on the same day, while some prediction systems use a "lagged" approach where different ensemble members are initialised on different days. Given the synoptic-scale onset but seasonal-scale persistence of stratospheric circulation anomalies, these can yield vastly different outcomes. For example, Figure 2 shows the Météo-France forecast for 10 hPa 60°N zonal-mean zonal winds from the start of February 2023. The ensemble spread is bifurcated, with half of the ensemble showing a strong vortex through February before an increased risk of an SSW during March, while half the ensemble shows an SSW already occurring with the vortex recovering during March. This is due to the initialisation strategy: Météo-France initialise 25 of 51 members on the penultimate

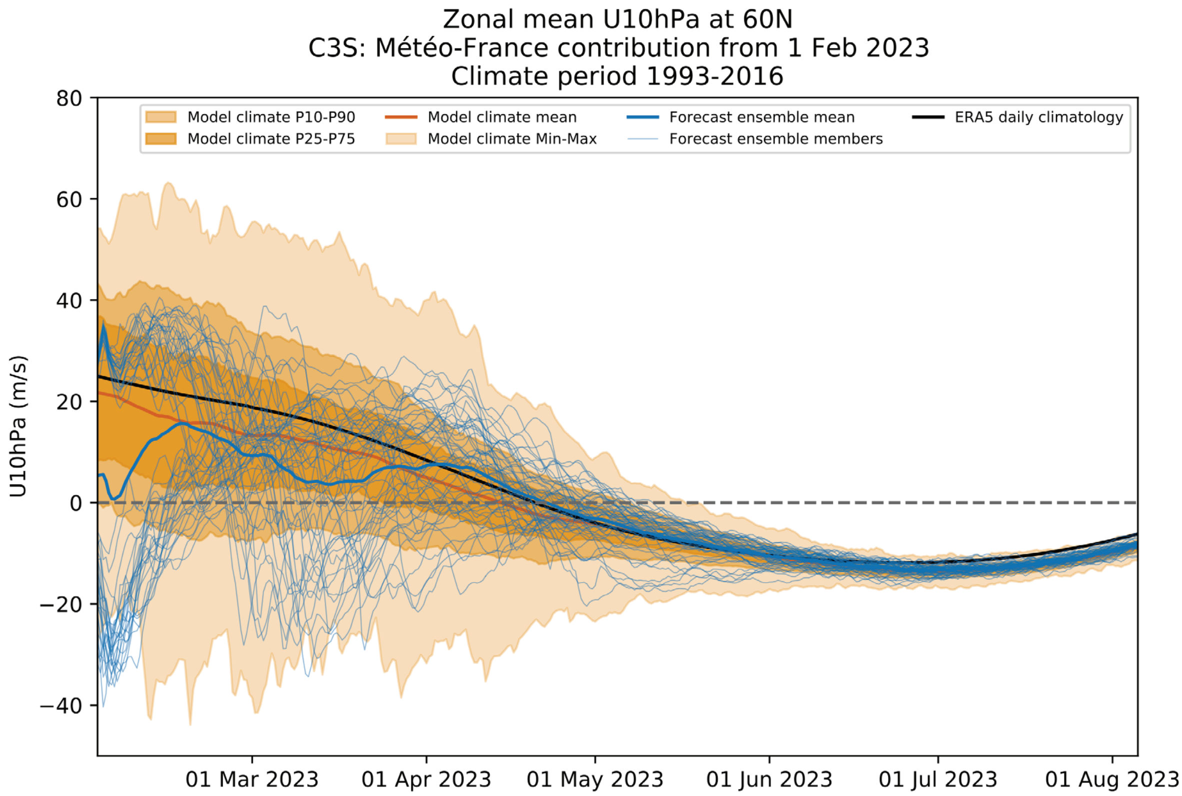

Figure 2: *10 hPa 60°N zonal-mean zonal wind forecast from the Météo-France contribution to the C3S database on 1 February 2023. Of the 51 ensemble members, 25 were initialised on the penultimate Thursday of January, 25 on the final Thursday, and 1 on 1 February, leading to a bifurcated ensemble with seasonal-scale consequences. Source: https://climate.copernicus.eu/charts/packages/c3s_seasonal/.*

Thursday of the previous month, 25 members on the final Thursday, and 1 member on the first day of the nominal forecast month. The gap between the two halves of the ensemble approximately corresponds to the deterministic predictability window for SSWs.

Furthermore, several recent studies have noted that biases present in CMIP-class/uninitialized climate models are present in seasonal models (e.g., Beverley et al., 2024), and that process-based analyses of their development may help rectify persistent problems in climate models.

Hence, we here introduce a new SNAP-led, multi-year community project examining the stratosphere and stratosphere-troposphere coupling in seasonal models which contribute to the C3S database. Our overall goal is to quantify the state of the art in modelling on this timescale, and to assess progress in stratospheric-related seasonal prediction skill since Butler et al. (2016), which examined some of these aspects using an older generation of seasonal forecast models.

Initial subtopics/working groups include, but are not limited to:

- Quantifying biases in stratospheric mean state and variability (including boreal and austral polar vortices and the QBO)
- Stratospheric seasonal forecast skill
- Contribution of polar vortex variability to surface skill, including the effect of SSWs, strong vortex events and final warmings
- Response of the stratosphere to the El Niño–Southern Oscillation and other slowly varying modes of tropospheric variability
- Unprecedented/'unseen' stratospheric events

Anyone interested in participating in the analysis of these data, or who is working on similar topics, is encouraged to contact Simon Lee (shl21@st-andrews.ac.uk) for further information. More information on the C3S seasonal forecast database can be found here: https://confluence.ecmwf.int/display/CKB/Seasonal+forecasts+and+the+Copernicus+Climate+Change+Service

A virtual kick-off meeting is planned for February 2026. Details to follow via a dedicated mailing list.

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Progress on the Stratospheric Nudging And Predictable Surface Impacts (SNAPSI) project: early results and data publicly available

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Sudden Stratospheric Warmings (SSWs) are the most dramatic example of wintertime polar stratospheric variability. They involve a rapid increase in polar stratosphere temperatures and an abrupt deceleration of the polar vortex (Baldwin et al., 2021). In the Northern Hemisphere (NH), SSWs occur around six times a decade and are primarily driven by the sustained dissipation of planetary-scale Rossby waves travelling upward from the troposphere. These stratospheric anomalies can then persist for a month or longer, with impacts that extend well into the troposphere. For instance, SSWs affect tropospheric large-scale weather regimes (Lee et al., 2025) and enhance the likelihood of extreme precipitation and surface temperature events (Domeisen and Butler, 2020; Dai et al., 2025; Feng et al., 2025) up to two months following their onset. Although rare, similar sudden warmings also occur during mid-winter or spring in the Southern Hemisphere (SH).

Given their long-lasting influence on the troposphere, SSWs have the potential to increase tropospheric predictive skill on subseasonal to seasonal (S2S) timescales. Assessing this stratospheric contribution to tropospheric predictability is the main goal of SNAP (Stratospheric Network for the Assessment of Predictability), one of the WCRP APARC (Atmospheric Processes And their Role in Climate) activities. Through coordinated analyses, SNAP has characterized biases in the representation of stratospheric processes (Lawrence et al., 2022) and explored links between stratospheric variability and surface predictive skill in S2S forecast systems (Domeisen et al., 2020a,b; Garfinkel et al., 2025). One of the current goals of SNAP is to isolate the role of the stratosphere in surface predictability. To this end, SNAP has coordinated a model intercomparison project for S2S forecast systems called Stratospheric Nudging And Predictable Surface Impacts (SNAPSI) (Hitchcock et al., 2022).

The SNAPSI protocol defines a set of experiments designed to quantitatively evaluate both internal stratospheric processes and stratosphere-troposphere coupling processes around three recent stratospheric events: the boreal major warmings of February 2018 and January 2019, and the austral minor warming of September 2019. These events differ in terms of predictability, but all three were followed by surface extremes such as the extreme precipitation over Iberia in March 2018 (Dai et al., 2025) or exceptionally dry and warm conditions in Australia during late spring 2019 (Feng et al., 2025). SNAPSI was highlighted in an APARC newsletter article in July of 2021 and an S2S newsletter in March of 2023. The present article provides an overview of the dataset and advertises the data to the broader community now that the data embargo has ended. We also highlight some early published results.

The SNAPSI experimental design consists of a set of 50-member ensemble hindcasts initialized around the start dates of the three aforementioned stratospheric events. The experiments include three core types: FREE runs where the model evolves without stratospheric constraints; NUDGED runs where the zonal-mean stratospheric state is nudged globally toward observations (simulating a “perfect stratosphere”); and CONTROL

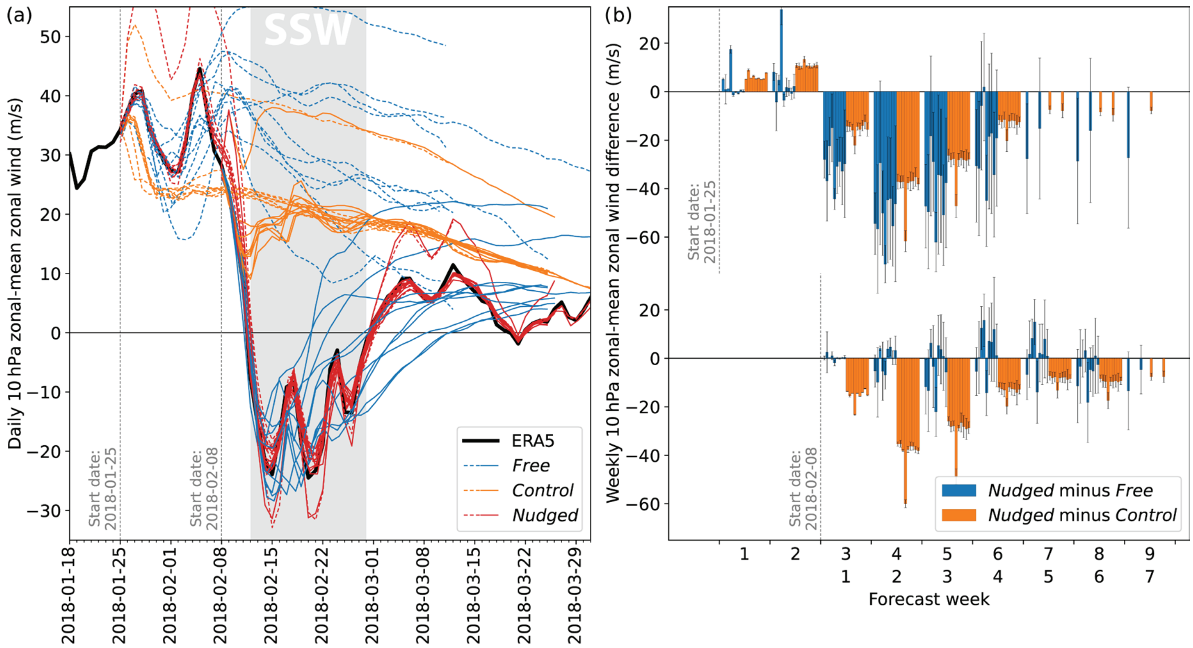

Figure 3: *(a) Ensemble means of zonal-mean zonal wind at 60°N, 10 hPa (u60_10) and (b) weekly nudged difference of u60_10. Right panel's colored bars represent individual models; error bars show twice the ensemble standard error. Vertical gray dashed lines (all panels) denote the two initialization start dates; right panel data for these dates are separated vertically and correspondingly shown on different x-axis levels. Left panel lines are dashed for the first and solid for the second start date. Adapted from Lee et al. (2025).*

runs where the stratosphere is nudged toward climatology, effectively removing the influence of the observed stratospheric perturbation during the specific events. ERA5 reanalysis provides the reference observational and climatological states. Each experiment is run for two initialization dates per event, one several weeks before and another near the SSW onset. Comparing the NUDGED and FREE forecasts helps quantify the benefit of a perfect stratospheric forecast, while comparing the CONTROL and FREE cases quantifies the effect of removing the zonal mean stratospheric information. Eight modeling centers have contributed data for this basic set of ensembles to the Centre for Environmental Data Analysis (CEDA), and three additional modeling centers have performed a subset of the requested runs. In addition to the core NUDGED, FREE, and CONTROL experiments, the SNAPSI protocol specifies two additional experiments, NUDGED-FULL and CONTROL-FULL, where the zonally asymmetric components of the stratosphere are also nudged to observations and climatological state, respectively. This enables us to explore the full contribution of the stratospheric state to the occurrence of surface extremes and disentangle the effects of zonal structure for the surface response to these events. Three modeling centers have performed NUDGED-FULL and CONTROL-FULL.

As a clarification of the SNAPSI set up, Figure 3a displays the time evolution of the zonal mean zonal wind at 10 hPa and 60°N (u60_10) surrounding the 2018 SSW for ERA5 (black line) and for the ensemble means of three experiments and two initializations. In the NUDGED runs (red lines), u60_10 reproduces the SSW-related deceleration of the vortex in ERA5 for both initialization dates. In the CONTROL runs, u60_10 follows the seasonal cycle of the vortex, with similar values across both initializations for the last weeks of the common period of both simulations. In both experiments, the intermodel spread is small. In contrast, FREE runs exhibit larger intermodel spread due to unconstrained stratospheric evolution. FREE results depend strongly on the initialization as the models only predict the occurrence of the SSW in the later one (~4 days before the SSW date). This is also reflected in the large NUDGED-minus-FREE differences in u60_10 for the early initialization (Figure 3b).

A major strength of the SNAPSI data archive is the number and resolution of variables output, which is higher than what is typically available in the S2S archive, to support a more comprehensive analysis of the relevant processes. The data include full three-dimensional fields of vector winds, humidity, temperature, and geopotential height on a 34-level vertical grid, along with a variety of surface variables and fluxes (Hitchcock et al., 2022). Additionally, the SNAPSI data has 50 members for each model except for NAVGEM that has 80, whereas each model has a different number of ensemble members in the S2S archive, being much lower than 50 in most of the cases.

The SNAPSI dataset has already been used in several studies, four of which are currently published (Lee et al., 2025; Feng et al., 2025; Dai et al., 2025; Ayarzagüena et al., 2026) and several more currently in review. Early results confirm the key contribution of the stratospheric events on the predictability of surface extremes. For instance, an accurate stratospheric representation during the 2018 SSW improved forecasts of the persistent negative North Atlantic Oscillation phase (Lee et al., 2025) and the associated extreme precipitation over the Iberian Peninsula observed following this SSW (Dai et al., 2025). As an example, the composite maps of precipitation for the 25 days after the 2018 SSW (Figure 4) suggests that for the early initialization, only the experiment capturing an SSW (NUDGED, Figure 4b) reproduced the observed "Dry Scandinavian, wet Iberian" pattern in ERA5 (Figure 4a). In contrast, during the 2019 SSW, improved stratospheric forecasts degraded mid-latitude skill, as the models overrepresented stratospheric impacts while likely missing tropical teleconnections that contributed to the observed ridge-like patterns (Lee et al., 2025).

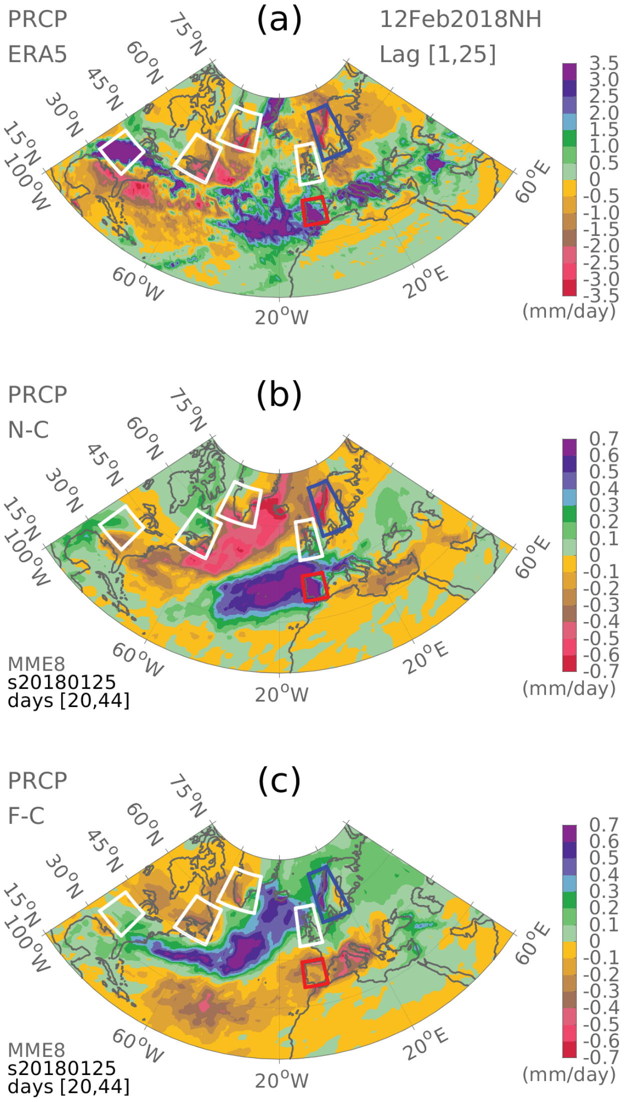

Figure 4: (a) Precipitation anomalies from ERA5, averaged over lag days [1, 25] relative to the 2018 SSW onset date. Multi-model-ensemble mean precipitation anomalies averaged over the same period from the (b) nudged ensemble and (c) free ensemble with respect to the control ensemble of the first initialization. From Dai et al. (2025).

In the SH, SSWs lead to dry and warm conditions over Australia; the minor SSW in 2019 likely contributed significantly to the dry and warm conditions that followed, resulting in widespread damaging bushfires. However the SNAPSI models show that this effect depends on whether the stratospheric nudging includes the zonally asymmetric component (Feng et al., 2025). Specifically, nudging only the zonal-mean stratospheric state leads to 2m temperature forecast anomalies that are too zonal and mostly restricted to Antarctica (Figure 5b). However, when adding the zonally asymmetric stratospheric variations, there is an amplification of warm anomalies over Australia (Figure 5c).

Beyond these individual analyses, the official SNAPSI working groups (WGs) are in the process of finalizing or have recently finalized (as it is the case of WG4, Ayarzagüena et al., 2026) their respective community papers. The data embargo has now been lifted, allowing individual researchers to use the dataset, which is being archived at CEDA (https://data.ceda.ac.uk/badc/snap/data/post-cmip6/SNAPSI). The data adheres to CMIP6-like meta-data standards, facilitating analysis with common diagnostic tools. A README with issues in the data can be found here SNAPSI_data_issues (https://docs.google.com/document/d/1v9k57bkziyBSLR3NYvy4EYL4FhVcUUVrwisB9mz54mE/edit?tab=t.0).

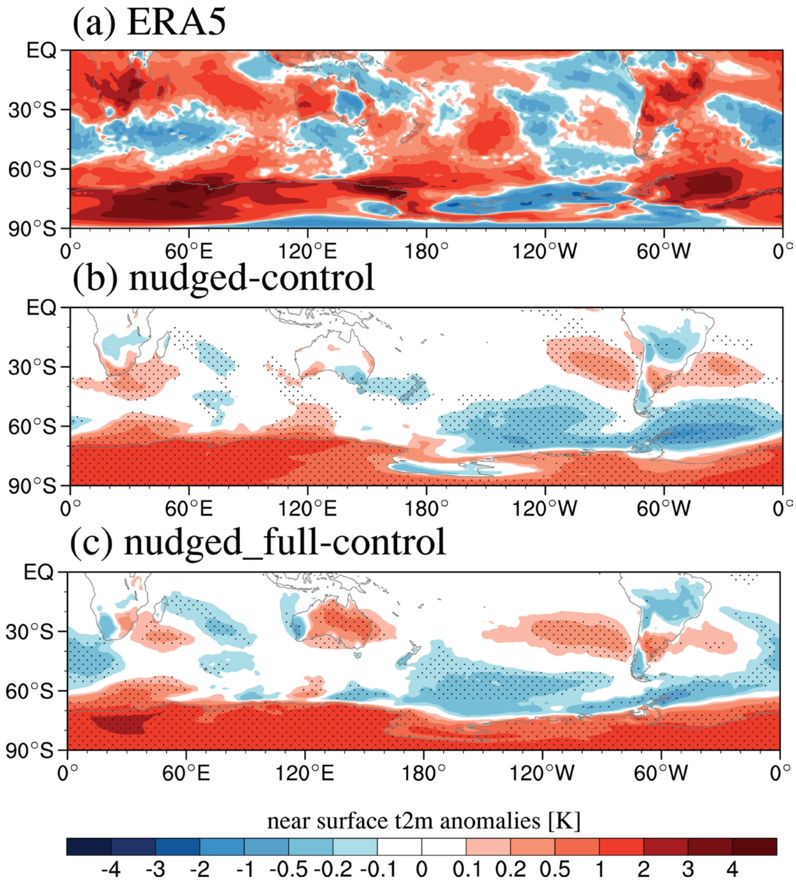

Figure 5: *(a) 2m temperature anomalies from ERA5 averaged from 18 October to 14 November 2019. (b) Multi-model-ensemble mean of 2m temperature differences between the nudged and control run averaged over the same time period. (c) Same as b but for the differences between nudged-full and control run. Adapted from Feng et al. (2025).*

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Virtual Workshop Series on SAI Research

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Figure 6: *Cover of the recordings on the WCRP YouTube channel (e.g.* https://www.youtube.com/watch?v=2hQo3Jk4IaU*)*

Dates:
06 - 09 October 2025

Scientific Organising Committee:
Daniele Visioni, Marc von Hobe, Karen Rosenlof, Jean-Paul Vernier, Simone Tilmes

Meeting Venue:
Online, hosted as a Zoom meeting by WMO Conference Services

Number Of Participants:
258 (registered participants)

Contact:
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Conference Website:
https://www.wcrp-climate.org/ci-workshop-series-sai

The consequences of global climate change are becoming increasingly visible, and the risk of reaching critical threshold levels or tipping points is rising rapidly. With the necessary Greenhouse Gas (GHG) emission reductions not being pursued at the necessary rate, Climate Intervention (CI) methods, i.e. technical solutions to remove GHGs from the atmosphere or to change the Earth's energy balance, are starting to gain more attention. To provide an objective perspective on proposed climate interventions and to foster rigorous, transparent, and globally inclusive research to further our understanding of CI and its implications, WCRP launched in 2023 the Lighthouse Activity "Research on Climate Intervention" (https://www.wcrp-climate.org/ci-overview). One proposed climate intervention that falls under Solar Radiation Management (SRM) is Stratospheric Aerosol Injection (SAI), which aims to reduce global warming through the injection of reflective particles or particle precursors in the stratosphere. After fostering collaboration across observational and modelling groups to better understand radiative and chemical impacts of stratospheric aerosol and drivers for its variability for more than a decade, the Stratospheric Aerosol Activity (https://www.aparc-climate.org/activities/stratospheric-aerosol/) of APARC has recently added SAI-related research to its portfolio and will collaborate with the WCRP lighthouse activity.

The two activities jointly organized a virtual workshop series on SAI in early October 2025, aiming to summarize the current state of research on SAI and to stimulate an inclusive, interdisciplinary, and international dialogue within the scientific community. Spread over four 3-hour sessions on consecutive days, accommodating different time zones, the online event attracted 258 participants from around the globe.

In 53 short presentations and five extensive discussion blocks, different aspects of SAI were addressed under five themes. For each theme, presentations and discussions are summarized below. The full program with presentation abstracts as well as session recordings (see Figure 6) are available on the conference website.

Capacities and Strategies for SAI Detection, Monitoring and Attribution

Kicking off the workshop on Monday, **Landon Rieger** provided an overview of past, current, and future stratospheric aerosol observations from ground-based, airborne, and satellite platforms. This work is part of a white paper describing challenges and recommendations for stratospheric aerosol observations. Talking about the space-based GloSSAC database used in the climate modelling activities of CMIP7, **Mahesh Kovilakam** emphasized the challenge of including multiple datasets into GloSSAC and the diversity in the optical properties of recent volcanic plume properties. A new SO_2 database developed by Oxford University and crucial to studying natural analogues of SAI was presented by **Antonin Knizek**. Two talks on balloon-borne in-situ observations by **Alexandre Baron** and **Jean-Paul Vernier** showed plans led by NOAA and NASA for future in-situ stratospheric aerosol monitoring using balloon-borne instruments such as optical particle counters and backscatter sondes. They explained the crucial role of in-situ measurements for detecting SAI attempts in the future and pointed out the need for coordinated activities worldwide. **Anna Lange** showed through theoretical considerations that SAGE-like solar occultation observations would detect SAI injections of at least 1 Tg S per year after at least one month from initial injection. Her efforts to simulate satellite observations using aerosol transport models and radiative codes help to better understand the detectability of SAI. **John Dykema's** presentation proposed that a constellation of small "cubeSAT" type solar occultation instruments would be an ideal platform for monitoring future SAI activities. He is looking for partnerships that would make such an activity feasible, given the history of solar occultation measurements from SAGE. Continuing with satellite observations but focusing on infrared limb emission measurements, **Michael Höpfner** discussed simulated space-based observations using the ECHAM model. He demonstrated the ability of the ESA Earth Explorer 11 candidate mission CAIRT (Changing-Atmosphere Infra-Red Tomography Explorer) to detect 0.5-1 t of SO_2 in the lower stratosphere. However, this mission was recently not selected by ESA. **Frank Keutsch** provided an overview of current observation and modelling limitations to fully represent plume evolution injected from an airplane compared to natural analogues, emphasizing the imperfection of natural analogues to study SAI. The last talk on detection and attribution was given on Thursday by **Kai Qie**, who discussed the use of numerical simulation of SAI constrained by balloon measurements to diagnose the detectability of SAI-induced changes in the stratospheric aerosol properties against natural variability.

Following a brief summary of all session talks, the open discussion on Thursday was organized around a series of questions.

Are we equipped with enough measurements to detect and monitor artificial SAI?

Marc von Hobe argued that we would probably have sufficient capabilities for monitoring coordinated SAI efforts but might not be able to detect unsolicited unilateral deployment. He also emphasized the need to consider additional aspects such as monitoring stratospheric chemistry. Karen Rosenlof commented that SAI deployments that were not detectable by the currently available aerosol measurements would probably have no significant radiative impact. And when SO_2 was injected as a precursor, even small amounts could be detected by instruments like TROPOMI.

Do we need a coordinated effort to summarize existing measurements of stratospheric aerosols and their applicability to study potential SAI?

Jean-Paul pointed out the existing efforts by the APARC Stratospheric Aerosol Activity to coordinate stratospheric aerosol observations, but that they are not specifically related to SAI. Karen highlighted the relation of this question to governance and that any coordinated SAI effort would likely require a standardized measurement strategy, like the Montreal protocol for ozone depleting species.

Are SAI outdoor experiments needed or is monitoring natural analogues like volcanic eruptions and pyroCbs sufficient to improve our current understanding?

Karen mentioned that we still don't understand natural analogues well with limited measurements inside volcanic plumes. We can also learn about small scale SAI by measuring exhaust from aircraft or rockets. Jean-Paul agreed with her and added that there are still many things to be learnt from natural analogues.

How can we differentiate between aerosols from natural events and potential SAI deployments?

Penfei Yu responded that a key element to detecting SAI is continuous monitoring of natural variability in the stratosphere. His work with Kai Qie to assess SAI detectability is based on this concept. Karen raised the question of what levels of SAI would be detectable especially after a volcanic eruption or a pyroCb. Jean-Paul argued that the complexity of stratospheric aerosols through new sources was greater than people thought 10 years ago. Karen said that the B2SAP network was created to monitor background stratospheric aerosols and to detect SAI or volcanic activities. Pengfei argued that monitoring SAI can be done in different ways using microphysical variables.

SAI Projections using Earth System Models

Presentations on SAI modelling took up much of the Tuesday session, with one block dedicated to capabilities, uncertainties, and processes parameterizations, and another one to simulation strategies and scenario exploration, followed by two talks on Thursday on specific SAI simulations. Presentations were mainly based on results from few Earth System Models that include complex processes of aerosol microphysics, chemistry, transport and radiative forcing and can comprehensively simulate the impacts of SAI injections.

In the session that was focused on process parameterizations and uncertainties, **Sebastian Eastham** provided a community-based overview of missing and uncertain physical processes in SAI modeling and their implications for impact assessment, highlighting key gaps in current model representations (see Figure 7). Main uncertainties included the representation of aerosols, stratospheric transport, and coupling between the atmosphere and the land/ocean surface. **Simone Tilmes** compared models with modal and sectional representations of aerosol size distributions in the same model framework and found significant differences in their predictions of the aerosol burden and radiative efficiency for equivalent injections. **Christian von Savigny** explained uncertainties in aerosol size retrievals from remote sensing measurements in the visible/NIR spectral range and proposed forward modeling approaches that compare simulated satellite measurements to actual observations as a promising remedy. He illustrated the effects of particle size distribution on observable phenomena like sky color changes and Bishop's ring formation. Using the 1991 Mount Pinatubo and the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruptions as natural analogues for validating SAI models, **Ilaria Quaglia** found that inter-model disagreements persist and stem from differences in how models handle transport and microphysical processes. She proposed a set of metrics based on weighted root mean square error metrics to evaluate model performance across multiple variables simultaneously. **Johan Friberg** presented a method constrained by the CALIPSO spaceborne lidar to produce profiles of volcanic SO_2 layers at significantly higher vertical resolution than used in today's climate models. Simulations using these SO_2 profiles align well with the observed stratospheric aerosol load after the June 2009 Sarychev eruptions. It was also shown that the clear-sky volcanic forcing was twice as high over one-year timescales, demonstrating that injection height precision substantially affects model predictions. **Ayse Koyun** investigated physicochemical properties of alternative SAI materials including diamond, alumina, calcite, magnetite, zinc carbonate, and dolomite. The findings provide critical data for CCM and inform selection criteria for viable SAI materials. Using a variable-resolution climate model (CESM2) in a study focused on Africa, **Kwesi Quagraine** showed that resolution particularly influences rainfall extremes, with a general better representation of extreme precipitation in high-resolution runs.

The following session provided a glimpse into the complexity of understanding various options for SAI strategies and scenarios. **Wake Smith** outlined the practical engineering boundaries for SAI deployment, reminding everyone that the technical means to deploy a required 1 million tons of SO_2 per 0.1°C cooling above the tropopause is currently lacking. He identified polar deployment as offering practical advantages since lower polar tropopause heights allow existing aircraft to operate, and polar injection preferentially cools regions warming at three times the global average, potentially stabilizing tipping elements like the Atlantic Meridional Overturning Circulation (AMOC). Investigating modified climate scenarios using a simple emulator with post-2100 net-negative GHG emissions, **Pete Irvine** found that SAI deployment reduced overshoot duration by approximately

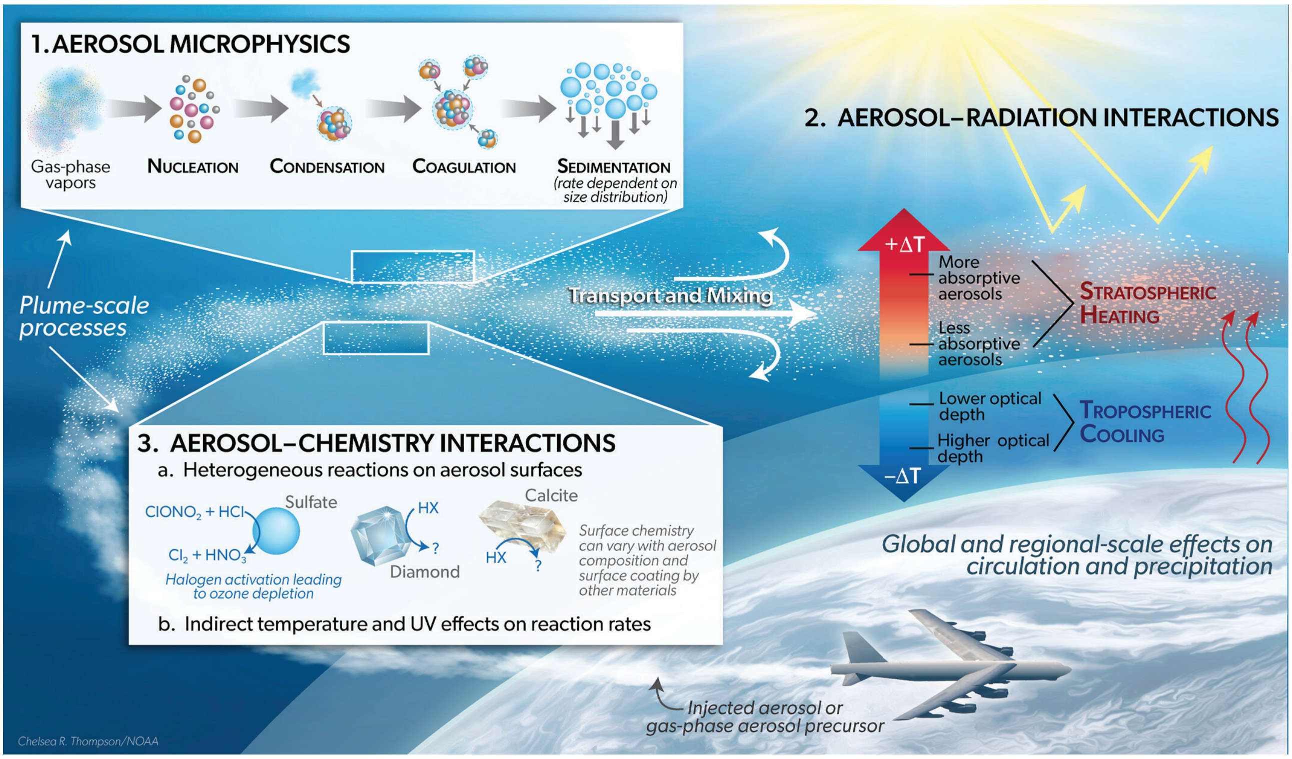

Figure 7: *Modeling gaps in the representation of stratospheric aerosol under SRM scenarios. Taken from Eastham, S. D., Butler, A. H., Doherty, S.J., Gasparini, B., Tilmes, S., Bednarz, E.M., et al. (2025). Key gaps in models'physical representation of climateintervention and its impacts. Journal ofAdvances in Modeling Earth Systems, 17,e2024MS004872.* https://doi.org/10.1029/2024MS004872

20 percent. The mechanism proved primarily related to ocean heat content. Larger overshoots showed greater proportional reductions, with significant implications for century-long CO_2 removal scenarios. **Patrick Keys** emphasized that society experiences natural climate variability rather than smooth model ensemble means. Ten-year temperature trends can show warming or cooling regardless of SAI deployment, and 40 percent of global areas could experience temperature increases even after SAI begins in some realizations. He identified critical gaps in current scenario development, including better understanding of temperature attribution, tools for detecting policy surprises, and how bounded rationality affects policy continuity. Challenging the "jumping from an airplane" analogy, **Douglas MacMartin** argued that SAI is fundamentally reversible because stratospheric aerosols have roughly one-year lifetime. He proposed a scaled experimental approach: small experiments of 10 to 100 tons to validate aerosol microphysics, subscale deployment of around 50 kilotons to validate transport and lifetime, and full deployment informed by resolved uncertainties. Major stratospheric uncertainties could be resolved before climate-scale deployment, with peak shaving scenarios allowing a decade or more of learning. **Jared Farley** presented the Climate Intervention Dynamical Emulator (CIDER), which emulates Earth system model responses for rapid scenario exploration. Designed for uncoordinated deployment scenarios with multiple actors pursuing different objectives, CIDER combines semi-infinite diffusion modeling to assess CO_2 warming with pattern scaling for regional climate change and SAI projections. Validation showed good agreement with full climate models at much reduced computational efficiency. **Melinda Berman** presented a worldwide inventory of pyroCb events from 2013 to 2023. These events generate anti-cyclonic circulation, displace ozone through heterogeneous chemistry, and create dynamic perturbations, providing natural analogues for understanding stratospheric interventions. **Walker Lee** explored whether the ARISE-SAI-1.5 modeling exercise could have produced different outcomes using alternative strategies. His G2-SAI experiments revealed two distinct stable climate states achieving identical temperature targets: one with mostly 15°S injection producing a weaker AMOC and cooler North Atlantic, another with more balanced 30°N/30°S injection producing a stronger AMOC and warmer North Atlantic. Statistically significant differences emerged after just 35 years between strategies, suggesting identical temperature objectives may not uniquely determine climate outcomes.

On Thursday, **Hongwei Sun** presented a multiscale Plume-in-Grid (PiG) model, in which a Lagrangian plume model is embedded into a global Eulerian model to overcome difficulties to accurately represent stratospheric plumes and to simulate chemical and aerosol processes within. The new approach represents a computationally efficient way to improve the representation of subgrid-scale mixing and nonlinear plume-scale processes in the stratosphere and will hopefully enable more accurate simulations of stratospheric aerosol perturbations including SAI scenarios. In the final talk on SAI simulations, **Pengfei Yu** showed that injection at 50 km, near the stratopause, could minimize stratospheric side effects of sulfur-based climate intervention. In such a scenario, the mean meridional overturning circulation near the stratopause rapidly transports aerosols to mid-high latitudes, preventing their accumulation in the tropical lower stratosphere. The approach reduces tropical stratospheric warming to 3 K and shortens the Antarctic ozone recovery delay to 5 years compared to a reference scenario with injection at 25 km. Furthermore, the high-altitude injection scenario demonstrates greater cooling efficiency, enhancing global and polar surface cooling by 22% and 40% respectively.

To start the open discussion, Karen briefly summarized all presentations of the session and highlighted the overarching observation that, besides the remaining imperfections in all models and process parameterizations, simulations tend to be highly sensitive to the SAI deployment strategies considered. Many different ones were presented in terms of where, when, how much and what kind of aerosol or precursor was injected, resulting in rather different cooling patterns, dynamic responses, etc. For improving process understanding and validating models, comparison to observations was identified as a key factor, and the discussion turned to promising data that already exist as well as needs for additional measurements. Jean-Paul suggested studies using Hongwei's PiG model together with observations of volcanic and pyroCb events, and Marc mentioned that interesting lessons might be found in the APARC report on the Hunga eruption (https://aparc-climate.org/publications/aparc-report-no-11/) that has been extensively studied using the full range of observational and modeling tools. Highlighting the advantage of models to explore the full strategy space of potential SAI deployment, Jean-Paul wondered whether the available evidence from simulations could already be used to make recommendations with respect to "realistic scenarios" in terms of both, desired outcome and technical feasibility. On the question of what can still be learned from simulations and studying natural analogues and whether small scale experiments were needed to go forward, Marc pointed out that global models will always be needed as they are the only means to identify and study impacts and risks on larger scales. Two final points in the discussion were made by Hongwei Sun, who asked whether it is worth further investigating alternative materials other than sulfate aerosol and stressed the need to consider potential tipping points not only in the discussion of climate change but also in the context of SAI strategies and risk assessments.

SAI Risks and Impacts across different Scenarios

Global and regional climate impacts and risks were covered in two presentation blocks on Monday and Wednesday. **Andrin Jörimann** compared the effects of SAI in the middle atmosphere in five climate models with uniformly prescribed aerosol optical and physical properties. Compared to reference simulations following a moderate climate change scenario, key changes in the middle atmosphere related to both dynamical and chemical processes were identified. Comparing CESM2 and UKESM1 simulations, **Ivy Glade** showed that future increases in warm-spell frequency, intensity and duration are reduced when SAI is deployed. However, distinct differences in the two models' projections were found that may be related to differences in the spatial pattern and magnitude of warming and in the expected response of plant physiology to increasing CO_2 over tropical rain-forests. **Jim Hurrell** presented a framework for assessing the impact of climate intervention on mesoscale convective weather systems over the United States and showed that increased storm frequencies and intensities under global warming scenarios were reduced in solar climate intervention scenarios. **Mari Tye** explored the probability of widespread regional hydrometeorological extremes in the recent past and under different SAI scenarios and pointed out that regional impacts of SAI could vary considerably depending on which extremes change and where, as well as on local practices. **Cameron Dong** presented an analysis of the short-term response to unilateral injections, within two years of deployment, using an explainable artificial intelligence (XAI) framework. Given seasonal 2m-temperature or precipitation, neural networks skillfully determine the latitude of SAI within two years of deployment, indicating that there would be distinguishable differences in impacts depending on SAI injection latitude. **Taveen Singh Kapoor** reported non-negligible alumina absorption from new experiments using photoacoustic spectroscopy and electron energy loss spectroscopy. The findings call for revisiting SAI efficacy calculations with alumina and reassessing the optical properties reported for other candidate materials. Concluding the presentation block on Monday, **Ewa Bednarz** provided a comprehensive overview of SAI impacts on stratospheric ozone, large scale circulation, stratosphere-troposphere coupling and links with surface climate. She pointed out that model response often depends on the specifics of SAI realization and reminded the audience that to narrow down uncertainties in SAI impacts, work is still needed to better understand the processes driving those impacts and uncertainties.

On Wednesday, **Alistair Duffey** presented simulations showing that high-latitude low-altitude SAI could achieve meaningful global cooling at feasible injection magnitudes and heights. Compared to a conventional high-altitude subtropical SAI strategy, cooling would be strongly polar focused and weaker in the tropics, particularly for a low injection altitude of 13 km. Using idealized simulations from six climate models participating in GeoMIP6 to investigate the response of Asian Summer Monsoon (ASM) rainfall to SAI, **Chao He** showed that equatorial SAI would not reduce ASM rainfall more than achieving the equivalent surface cooling by GHG reduction. **Shrabani Tripathy** identified and explained various mechanisms by which climate change and potential SAI strategies affect polar regions and proposed a "Risk-Risk Analysis Framework" allowing for direct comparison of the likelihood and magnitude of negative impacts of SRM vs non-SRM scenarios. Using the 1991 Pinatubo eruption as a natural analogue, **Mohamadou Diallo** studied the stratospheric circulation response to SAI, which impacts ozone recovery, tropospheric circulation, and surface climate and weather through two-way stratosphere-troposphere coupling. Overall, circulation response is complex and remains highly uncertain, and there is an urgent need for further study of the mechanisms related to gravity/planetary waves as interest in SAI continues to grow. Presenting results from simulations of an explosive tropical volcanic eruption, **Xin Zhou** showed that aerosol heating significantly enhances the entry of water vapor into the stratosphere. Such moistening would be expected to also operate under SAI and could partially offset the intended cooling effects. **Manouk Geurts** explained that for SAI effects on the hydrological cycle, stratospheric heating caused by the absorption of terrestrial longwave radiation plays a key role. Such undesirable side-effects of SAI could be reduced by using alternative materials with less long wave absorptivity.

A presentation block on Tuesday focused on how SAI would potentially affect atmospheric composition and chemistry as well as health and economy. **Etienne Gilgien** pointed out that including the interactions of SAI and potential future halogen sources such as rocket launches could substantially alter effects on stratospheric ozone, potentially making things worse. Such effects are usually not considered in SAI studies. **Sandro Vattioni** discussed uncertainties in the effects of calcite SAI on ozone and how they strongly depend on the knowledge of kinetic parameters. He also showed recent lab experiments to constrain these. **Cindy Wang** showed that for a medium forcing scenario, the effects of SAI on air quality are minor compared to the effects of future changes without SAI, because changes in air quality are mostly driven by anthropogenic emissions and changes in climate. **Alice Wells** presented an open-access workflow to assess the health impacts of air quality under climate interventions. She pointed out that health effects strongly depend on the models used. **Olivier Boucher** discussed the impact of SAI on solar photovoltaic (PV) energy production. Small reductions caused by the shading would potentially be compensated because the efficiency of solar panels is usually higher at lower temperatures.

The open discussion on Wednesday was started by Simone with the question, whether and how an "impact matrix" could be designed that would balance the likelihood vs. the magnitude of impacts, ideally capturing SAI strategy dependence and inter-model differences. It was noted that Alistair would present a related idea in his later talk (see below). With reference to the Monday session on ethical aspects (also see below), Marc endorsed the idea and stressed that precise information, and ideally robust numbers, on SAI impacts, risks and uncertainties would give policy makers the means to make informed decisions. Daniele commented that providing a comprehensive and meaningful assessment of all global and regional impacts for all possible SAI scenarios could be challenging and suggested focusing on a few agreed scenarios. Gabriel Chiodo added that uncertainties related to intermittency should also be considered.

Shifting the discussion to identifying the largest and most critical uncertainties, Simone stressed the role of simplified experiments and model intercomparisons to identify model differences and process uncertainties. Mohamadou suggested taking a closer look at recent smaller volcanic eruptions to investigate model responses and uncertainties, esp. with respect to transport processes, and Jean-Paul framed the more general question of how to tie studies on natural analogues to processes that need to be better understood. Using arguments that would be discussed in detail in the context of ethical aspects (see below), Greg Slater advocated for small scale tests, which would avoid detrimental effects by studying impacts incrementally. In response, Daniele stressed the importance of targeting uncertainties in the design of such outdoor experiments, and Jean-Paul raised concerns that their full scientific exploitation would currently suffer from the scarcity of available measurements, especially in-situ, that has also been an issue when studying natural analogues. Agreeing that small scale SAI experiments could provide useful information, Simone concluded the discussion by stating that such experiments would need to be done in a responsible way, requiring governance that people would trust.

Ethical Aspects of Studying and Testing SAI

Controversial viewpoints on SAI research were expressed in four presentations on Monday. **James Fleming** provided historical context on SAI governance, drawing parallels to the Asilomar conferences and examining the tension between self-regulation and external oversight. He emphasized critical governance gaps that require international, interdisciplinary, and intergenerational collaboration to address. Taking a critical stance, **Jenny Stephens** argued that SAI inherently concentrates wealth and power with no pathway to equitable deployment and raised concerns about threats to human rights, disruptions to hydrological cycles and food systems, advocating for systemic transformation focused on fossil fuel phase-out rather than technological interventions. Taking the opposite view, **Ron Baiman** framed SAI deployment as increasingly inevitable, advocating for near-term cooling measures to complement emission reductions and carbon removal, and proposed gradual polar deployment combined with evolving governance frameworks. Focusing on research ethics, **Ryan O'Loughlin** suggested four criteria for evaluating small-scale field experiments: scientific rigor, safety, utility, and transparency. He emphasized risk-register prioritization, cautioned against relaxing standards under climate urgency, and stressed the need for broader stakeholder representation in decision-making. The presentations and the discussion that followed revealed fundamental disagreements about whether SAI should be pursued at all, ranging from outright opposition based on justice concerns to pragmatic acceptance with calls for careful governance and experimental protocols.

Three more presentations and an open discussion on ethics and governance that concluded the Thursday session were not quite as controversial. **Xavier Landes** introduced the question whether mission-driven SAI research, i.e. research addressing questions, issues and uncertainties of direct relevance to policy making and initiated and coordinated under a clear mandate, should be subject to the same ethical norms and practices as traditional curiosity-driven approaches or whether specific norms are needed. **Timothy Daly** explained how the discussion on ethics and governance of SAI research is made difficult by inaccuracies in language and wording. He stressed how important it is to rectify terms and definitions to avoid injustice and confusion and illustrated this by a historical reference to the 1979 Belmont report on the ethics of research on human subjects. **Yvette Ramos** identified a lack of clear and transparent categorization of SAI in international patent systems that complicates scientific modelling of SAI. She identified a need for governance structures that ensure open-access SRM research registries and public reporting of SRM-related funding and experiments and stressed the importance of including the Global South to avoid asymmetries in decision-making and climate risk exposure. Directly following the three talks, a question was raised concerning the "Slippery Slope Argument", i.e. the concern that simply conducting research and showing that SRM might work could increase the likelihood of deployment and reduce momentum for decarbonization. Timothy explained that the latter represents a possible use of research by certain actors, and that the argument really is less about the ethics and governance of the research itself but about what society does. Xavier added that the Slippery Slope Argument is a fallacy when it is raised without clearly demonstrating the sliding steps towards deployment.

In the open discussion that followed, Gregory Slater raised the question whether the ongoing climate catastrophe calls for an urgency that must be acknowledged in the science. Xavier commented that it is indeed an important question whether the urgency justifies compromising certain moral considerations and the full inclusion of all stakeholders and interest groups (like the Global South). But without a clearly defined "emergency threshold" and as long as it is not clear who makes that call, there is no good basis for decision-making. Timothy expressed agreement with Greg to the extent that there is a "duty to do research", so that when the catastrophe becomes so big that we must do something, we have the knowledge to make educated decisions and can avoid emergency deployment scenarios. Referring back to the Slippery Slope Argument, Jean-Paul made a strong point, met with widespread approval, that there needs to be a clear and unambiguous prioritization, and that the first priority must be fixing the root cause of climate change by cutting GHG emissions, and that the next step could be capture to reduce GHG levels in the atmosphere. SRM, including SAI, should only be the third priority, considered for peak shaving if the other measures come too late and don't go far enough to keep temperatures below certain thresholds.

Another point made by Greg was that the complexity of the system would make it impossible to accurately know all the effects on the climate system and side effects based on simulations and studies of natural analogues alone, and that "we would always be in beta" when injecting aerosols into the stratosphere. He stressed the importance of having adequate instruments and measurement systems in place and acknowledged critical gaps especially with respect to satellite observations but suggested relying on in-situ measurements for small scale experiments. In line with the presentations by Ryan O'Loughlin in the earlier ethics session on Monday and by Doug MacMartin in the Strategies and Scenario Session on Tuesday, such experiments should start on small scales and have a clear research focus on understanding SAI effects. Nevertheless, the balance between making scientific progress as quickly as possible while maintaining a "social license" remains a critical issue, and a "psychological strategy" is needed to not alienate important groups or society as a whole.

SAI Assessments and Evaluation

Gabirel Chiodo gave an overview of the work being done in the Environmental Effects Assessment Panel (EEAP) that reviewed expected changes in stratospheric ozone and UV radiation, potential climate effects caused by changes of stratospheric temperature and dynamics, possible impacts of changes in the ratio of direct to diffuse radiation, and other consequences on ecosystems and air quality. The EEAP report is expected to be released early in 2026. **Alistair Duffey** introduced the concept of a "living uncertainty database" for research prioritization and decision-making related to SAI. Prioritized according to consequence level and degree of uncertainty, an initial matrix of uncertainties across four categories – engineering, aerosol evolution, climate response, earth system response – was prepared by the organization Reflective with input from selected experts (see https://airtable.com/appSo5NCXrD6KkhxD/shr6DuL372CiQHt7P/tblolAiBBRWEu8y5a). Further input is sought from experts across relevant physical sciences and engineering disciplines to refine and further develop the list into the envisaged comprehensive database. The initiative to start the database as a long-term community effort was appreciated in the discussion. It was noted that political uncertainties are currently not addressed but may represent some of the largest SAI related uncertainties or even obstacles.

Turning to the question what further assessments and recommendations are needed and the role the WCRP lighthouse activity should play, Simone proposed a continuous assessment process as a "living document", an idea that Daniele endorsed and that could be followed parallel to "fixed deadline" assessments like the EEAP report or the SRM chapter for the next IPCC assessment report. Several participants commented positively on the fact that the APARC Stratospheric Aerosol Activity now explicitly includes SAI related science questions and research in its implementation plan, which is expected to strengthen the engagement of the wider stratospheric aerosol research community. Jean-Paul said that a living assessment could also cover stratospheric aerosol observations, which may help to acquire support for the much-needed capacities. Daniele suggested that it should also cover SAI relevant research on natural analogues like volcanic eruptions. Simone and Jean-Paul pointed to the advantages and disadvantages of studying natural analogues versus carrying out small scale SAI experiments, and Jean-Paul made a point that the social sciences should probably be engaged in the discussion as well, because societal perception and support is important.

The Assessment Report on Hunga Volcano Atmospheric Impacts Produced by the Hunga Science Team and the APARC Hunga Impact Activity (2022-2025)

Yunqian Zhu[1], Graham Mann[2,3], Paul A. Newman[4], and William Randel[5]

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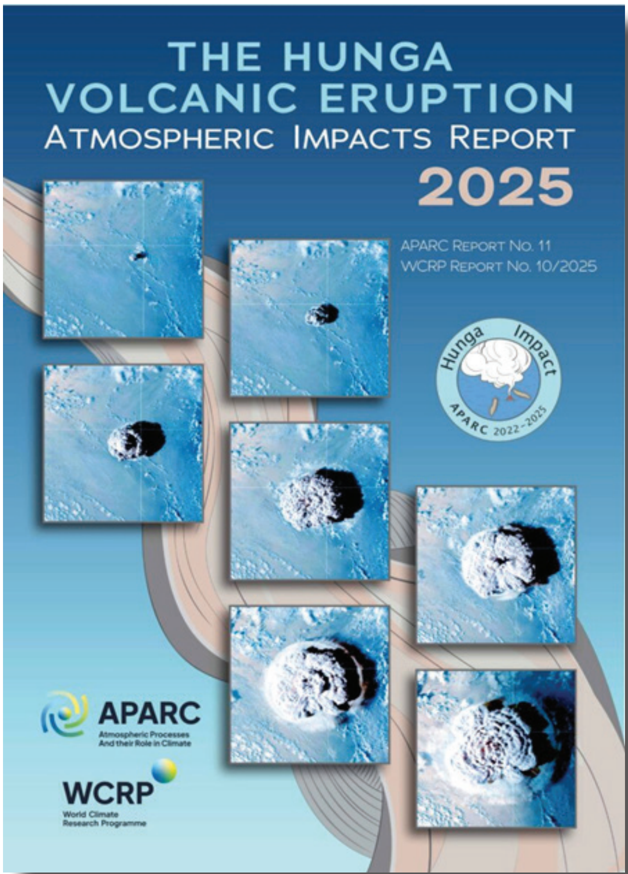

The eruption of the Hunga volcano on January 15, 2022, was the most explosive event of the satellite era. Within hours, the unprecedented altitude of its initial plume drew immediate attention from the scientific community and public via social media. Scientists immediately mobilized to organize observational campaigns, analyze satellite data, and interpret ground observations to fully understand the deep and far-reaching impacts of the eruption. Numerous papers and presentations were produced in the following months, which prompted an effort to scope a potential community assessment of the eruption and its impacts.

A three-year APARC "limited-term cross-activity focus" project for the Hunga Assessment was established, running from February 2023 to January 2026. This activity was coordinated by Drs. Yunqian Zhu (CIRES/NOAA CSL), William Randel (NSF NCAR), Graham Mann (U. Leeds), and Paul A. Newman (NASA, U. Maryland). This new APARC activity created a platform to coordinate the cross-cutting nature of the eruption's impacts. Its primary goal was to serve as a definitive source ahead of the 2026 UNEP/WMO Scientific Assessment of Ozone Depletion. Beyond synthesizing observational studies on the volcanic cloud's evolution and impacts, the project was also tasked with coordinating Hunga chemistry-climate model simulations from different groups in the community, expanding on initial studies that had forecast significant impacts on climate and the ozone layer.

The Hunga assessment report brought together 159 scientists from 21 countries, including many contributors from other APARC activities such as SSiRC, S-RIP, CCMI, ACAM, ATC, OCTAV-UTLS, and Gravity Waves. To foster the report's production, the Hunga Impact Activity organized focused meetings over three years, which included: open science workshops in 2022 (online) and 2024 (Ecole Normale Supérieure, Paris); the Hunga assessment meeting in 2025 (NCAR, Boulder); a monthly online HTHH-MOC meeting; co-chair weekly meetings; monthly lead-author meetings; Hunga sessions at the 2023 and 2025 AGU fall meetings; lead-author meetings at the 2023 AGU fall meetings; and a press release at the 2025 AGU fall meeting.

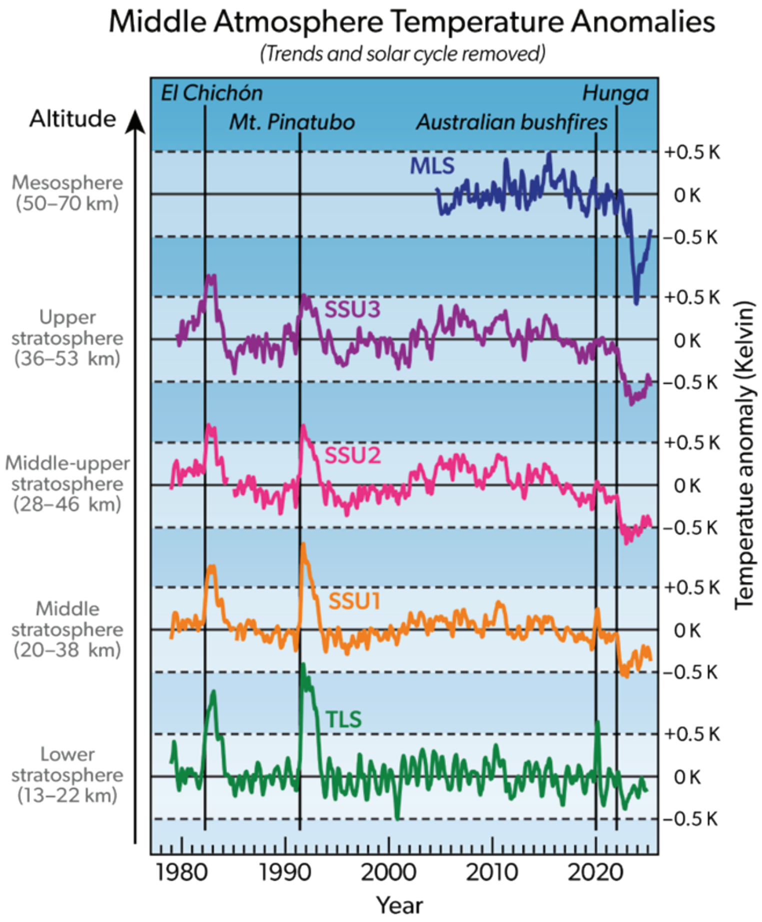

Figure 8: Long-term records of global temperature anomalies from the lower stratosphere to mesosphere (bottom to top), derived from data with trends and solar cycle effects removed. Results highlight anomalous cooling of the middle atmosphere after 2022 due to Hunga, contrasting stratospheric warming from El Chichon and Pinatubo. (from the APARC Hunga report, Ch4, Figure 4.2).

The report is organized into seven chapters that synthesize findings from observations, data analyses, and climate model simulations. This includes contributions from the Hunga Tonga–Hunga Ha'apai Impact Model Observation Comparison (HTHH-MOC) project, an international modeling effort with over ten global chemistry-climate models. The chapters cover: basic eruption information, the Hunga cloud evolution across short (less than one month) and multi-year time scales, impacts on atmospheric chemistry and dynamics, the stratospheric ozone layer, upper atmosphere effects, and surface radiative and temperature effects.

The report delivered the key finding as follows:

- The 2022 Hunga eruption was a high-magnitude underwater explosion with a volcanic explosivity index of 6. The eruption was unique because it increased global stratospheric water vapor by ~10%, much of which remains in the atmosphere through 2025.
- In contrast to previous eruptions that produced stratospheric warming from enhanced aerosols, the water vapor injected by Hunga resulted in a cooling of 0.5–1 K in the mid-to-upper stratosphere and a cooling exceeding 1 K in the mesosphere (Figure 8, from the APARC Hunga report, Ch4, Figure 4.2).
- The eruption perturbed stratospheric ozone in the Southern Hemisphere for several months, but its total impact on column ozone and the Arctic and Antarctic ozone hole, as well as on surface climate, was minor.
- The report emphasizes that record global temperatures in 2023 and 2024 were not caused by the eruption. Model simulations indicate that surface cooling influence from Hunga, which was about 0.05 K, was indistinguishable from natural climate variability.

The final report is available through the APARC and WCRP websites: https://aparc-climate.org/publications/aparc-report-no-11/

Next APARC and APARC related meetings

Find more meetings at: www.aparc-climate.org/meeting

23 - 26 February 2026
QUOCA virtual Workshop
https://docs.google.com/forms/d/e/1FAIpQLSc64rrPkDIZBy17-GcSsS-B9NxtF1NHzJ43Q25xL8dROrRQJ9Q/viewform

09 - 13 March 2026
CMIP Community Workshop
Kyoto, Japan
https://cmip2026.org/

03 – 08 May 2026
EGU General Assembly
Vienna, Austria
https://www.egu26.eu/

27 May 2026
JpGU-AGU meeting
Chiba, Japan
https://www.jpgu.org/meeting_e2026/

01 - 09 August 2026
COSPAR Scientific Assembly
Florence, Italy
https://cospar2026.org/

07 - 11 September 2026
Third International Conference on Subseasonal to Seasonal to Decadal Prediction (S2S2D)
Reading, UK
https://www.wcrp-esmo.org/activities/s2s2d-conference-2026

12 - 16 October 2026
APARC General Assembly
Pune, India
https://aparc2026.tropmet.res.in/

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