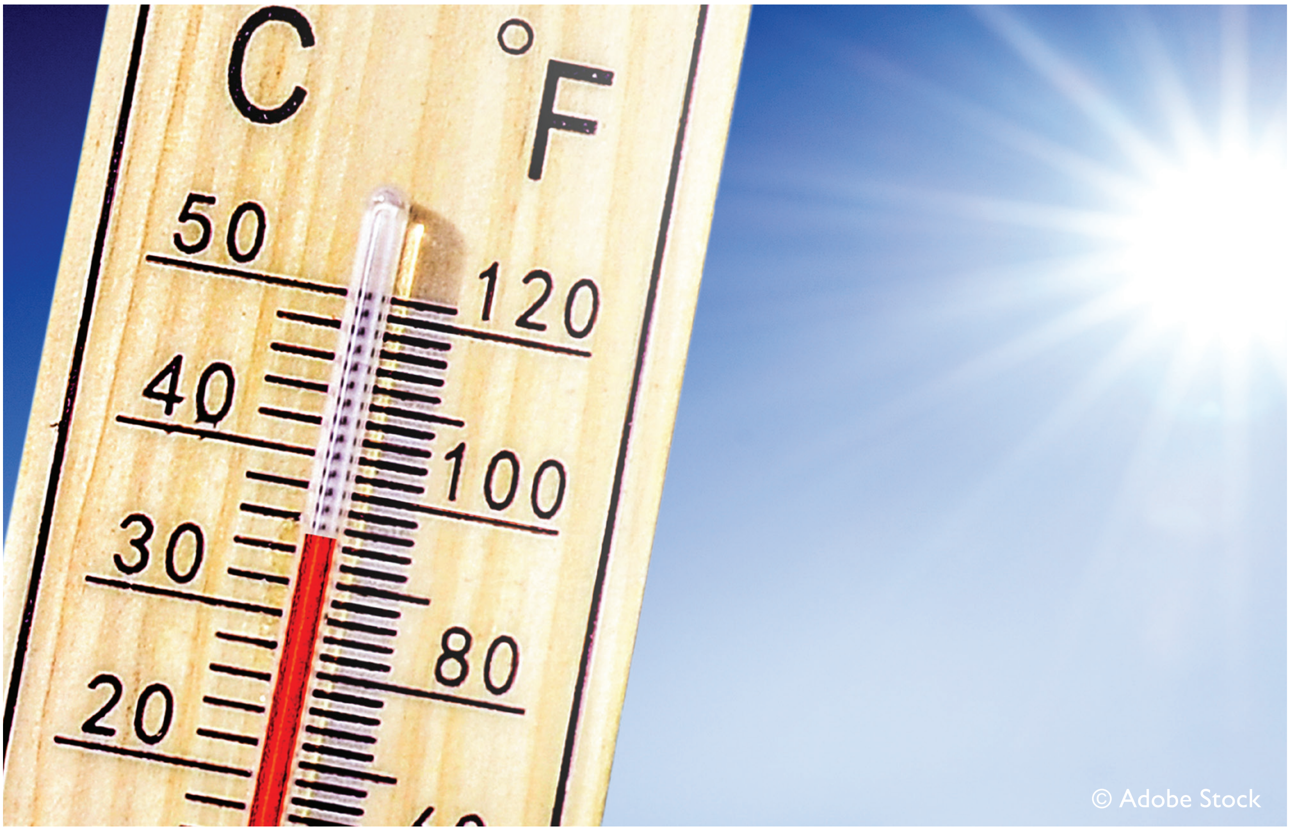
APARC

Atmospheric Processes
And their Role in Climate

Newsletter n°65
July 2025



The run of extremely warm surface temperatures has continued in the first half of 2025, with boreal spring being the second warmest on record behind 2024. These high temperatures provided the backdrop for the recent annual Joint Scientific Committee meeting in Paris - an opportunity to engage across the WCRP family and especially with the two new WCRP co-chairs, Cristiana Stan and Timothy Naish. You find a few more thoughts on this from the APARC co-chairs in their personal reflections.
For those of you celebrating the summer holidays just around the corner, APARC wishes you a restful and enjoyable break with the latest newsletter.

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Personal reflections on the outlook for APARC

We were fortunate to engage with our colleagues from across the WCRP family at the recent Joint Scientific Committee meeting held in May at UNESCO in Paris. This annual event provides a forum for Core Projects, Light House Activities and other relevant bodies to come together to discuss WCRP's work and plan for the coming years. We are pleased to receive very positive feedback on the achievements from within APARC in the past year and thank you all for your continued commitment to supporting the excellent scientific outputs.

A key landmark in the APARC calendar is the quadrennial General Assembly, which brings together the entire APARC community and friends to discuss the latest scientific developments and look ahead to the coming priorities. We are delighted to announce in this Newsletter that the 8th General Assembly will take place from 12-16 October 2026 in Pune, India. We are very grateful to our SSG member Dr Suvarna Fadnavis for leading the local organisation and to the Indian Institute of Tropical Meteorology (IITM) for hosting us. We are currently recruiting members of the Scientific Organizing Committee for this conference. Please make contact if you want to be involved. Also soon there will be a call to suggest and convene sessions. Again, we will welcome ideas. We suggest that if the APARC activity that you are associated with is planning to hold an in-person meeting next year, this meeting should be held at or around the General Assembly. Most of our limited funds expected for 2026 will go towards the General Assembly.

The wider landscape for scientific research remains uncertain, with the potential for significant challenges. WCRP is planning for a significant reduction in its budget next year, which would affect our ability to support workshops, training events and other meetings that we normally co-sponsor. This makes it ever more important to make a success of the General Assembly and we hope you will all mark your calendars to join us in Pune.



APARC co-chairs Olaf Morgenstern, Amanda Maycock and Karen Rosenlof

Next APARC and APARC related meetings

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

15 - 18 July 2025
LEADER/EPESC Meeting
Busan, Republic of Korea

20 - 25 July 2025
IAMAS-IACS-IAPSO Joint Assembly 2025 (BACO-25)
Busan, Republic of Korea

09 - 11 September 2025
APARC SSG Meeting
Leeds, UK

06 - 09 October 2025
Virtual Workshop Series on Strat. Aerosol Injection
https://www.wcrp-climate.org/ci-workshop-series-sai

27 - 30 October 2025
NDACC 35th anniversary symposium
Virginia Beach, VA, USA

09 - 13 March 2026
CMIP Community Workshop
Kyoto, Japan

Report on the Atmospheric Temperature Changes and their Drivers (ATC) Activity 2025 Spring Meeting

Stephen Po-Chedley[1], Andrea K. Steiner[2]

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Dates:
23 – 25 April 2025

Organising Committee:
Andrea K. Steiner
Stephen Po-Chedley

Host Institution:
Wegener Center for Climate and Global Change, University of Graz, Graz, Austria

Number Of Participants:
19 participants

Contact:
pochedley1@llnl.gov

Conference Website:
http://www.aparc-climate.org/activities/temperature-changes/

Sponsors:

Overview

The Atmospheric Temperature Change and their Drivers (ATC) Activity brings together experts interested in improving understanding of atmospheric temperature variability and trends and their representation in climate data records. ATC pursues this goal by fostering intercomparisons of atmospheric temperature datasets, providing and improving uncertainty information for climate data records, comparing observations with model simulations, assessing atmospheric temperature trends and their drivers, and documenting their efforts in review papers and assessment reports.

The ATC activity convened at the Wegener Center for Climate and Global Change at the University of Graz in Graz, Austria over April 23 – 25. The purpose of the meeting was to provide updates on research and datasets related to atmospheric temperature change and variability, to identify areas that need further research, and to coordinate ongoing and future collaborations. Meeting themes included theoretical and simulated controls on atmospheric temperature, the development of new and improved atmospheric temperature datasets, and analysis of atmospheric temperature variability and trends. 18 activity members attended the meeting including 12 in-person attendees and 6 remote attendees. Four new early career activity members attended with support from APARC.

Meeting Presentations in Brief

In setting the stage for the meeting, the organizers discussed ATC's role in monitoring and documenting atmospheric temperature trends and variability (e.g., Steiner et al., 2020; Po-Chedley et al., 2024; Randel et al., 2024a; 2024b; Stocker et al., 2024). These community-driven efforts help to identify new scientific questions and contribute to periodic climate assessment reports (e.g., IPCC 2021; Blunden and Boyer, 2024).

Several ATC researchers contributed to research on theoretical and simulated controls on atmospheric temperature, which is a new area of emphasis with the activity. **Jiawei Bao** discussed the results from radiative convective equilibrium experiments that demonstrate that land-versus-ocean surface properties and the degree of convective organization are important ingredients in controlling the coupling of the surface to tropospheric temperature. **Osamu Miyawaki** identified a unique pattern of atmospheric warming in greenhouse warming simulations that can be explained with variations in the moist adiabat as a function of local surface temperature. **Martin Singh** related metrics for bulk atmospheric stability and humidity to an effective entrainment rate, which has implications for the strength of moist heat waves (Palmer and Singh, 2024).

Several talks during the spring meeting provided analyses of atmospheric trends and variability. **Andrea Steiner** presented an updated comparison of atmospheric temperature trends over 1979 to 2024 from new versions of observational records, which is planned as a community paper. **Florian Ladstädter** shared an analysis of trends and variability in the lapse rate tropopause based on global positioning system (GPS) radio occultation (RO) measurements over the past two decades (Ladstädter et al, 2025; in review). **Cheng-Zhi Zou** presented results based on microwave sounder data since the late 1970s analyzing temperature trends and the potential acceleration of global tropospheric warming. **Alexandra Laeng** derived an inventory of Siberian wildfire events with penetration into the stratosphere. **Pedro DaCosta** isolated variability from the annual cycle, solar cycle, and the quasi-biennial oscillation in LIDAR retrievals of middle atmospheric temperature, allowing him to derive long-term trends. **Aodhan Sweeney** investigated the causes of the observed anomalous warming of the Southern Hemisphere subtropical lower stratosphere over 2002–2022 and found that the warming is linked to a slowdown of the Brewer-Dobson Circulation (Sweeney et al., 2025; in press).

ATC members also shared research on comparisons and analyses across models and observations. **Stephen Po-Chedley** analyzed a large year-over-year increase in global tropospheric temperature beginning in July 2024 and found that similar warming is very rarely reproduced in climate model simulations. On longer timescales, **Matthias Stocker** compared simulated and observed atmospheric temperature trends, contextualizing the results with single-forcing experiments (i.e., greenhouse gas-only, aerosol-only, etc.) from LESFMIP simulations in order to show the unique impact of different atmospheric constituents. This work links to the Large Ensembles for Attribution of Dynamically-driven ExtRemes (LEADER) activity. **Lukas Brunner** presented preliminary results from new high-resolution models at kilometer-scale on the representation of local surface temperature changes and the scaling with global mean temperatures. **Benjamin Santer** shared an analysis demonstrating that human-induced stratospheric cooling would have been identifiable by 1885 had we possessed present-day observational capacity, indicating that anthropogenic influence on climate has existed for over 130 years (Santer et al., 2025).

The ATC group was also active in exploring and advancing new temperature datasets that cover the troposphere up through the mesosphere. **William Randel** shared an update on UCAR/COSMIC's efforts to construct climate data records from RO observations, highlighting challenges in understanding differences across satellite constellations. **Hans Gleisner** illustrated the processing steps of GPS RO data at the Radio Occultation Meteorology Satellite Application Facility (ROMSAF). He presented the data products provided (https://rom-saf.eumetsat.int/), the progress on creating version 2 of climate data records, and comparisons of CMIP6 model temperature trends with GPS RO data. **Sebastian Scher** developed a methodology to quantify and propagate uncertainties from GPS RO profiles to gridded, monthly temperature fields. Although **Leopold Haimberger** could not attend the meeting, it was noted that he is helping to develop a new Comprehensive Upper Air Network dataset comprised of radiosonde measurements. **Philippe Keckhut** provided two updates, sharing progress toward a middle atmosphere temperature dataset derived from satellite-based limb view measurements (Da Costa Louro et al., 2024) and separate work to classify northern hemisphere sudden stratospheric warming events (Mariaccia et al. 2024). **Viktoria Sofieva** presented preliminary results from a new merged stratospheric and mesospheric temperature profile dataset derived from limb and occultation measurements.

Figure 1: *Group photo of the participants of the APARC ATC Activity Spring Meeting 2025.*

Meeting Discussion

Apart from the scientific presentations, the ATC Activity also devoted time to discuss outstanding research needs related to atmospheric temperature change. One discussion thread that emerged was that work should be fostered to scrutinize and intercompare datasets of atmospheric temperature, including those from distinct measurement types (e.g., infrared versus microwave; Zhou et al. 2024) and across research groups. Such comparisons can inform our understanding of the drivers and magnitude of structural uncertainty and will help advance ATC efforts toward a community-driven paper on observed atmospheric temperature change.

The increasing utility of datasets based on GPS RO were also noted: the measurements are stable, high-quality, and the record is now 20+ years long. As the datasets mature, participants noted that gridded data products would be useful and that derived datasets, including cold point or lapse rate tropopause time series, would be helpful for some analyses. Despite the utility of GPS RO data, more work is needed to improve temperature retrievals higher up in the stratosphere, an area of active research. Along the same lines, there is a need for an established, climate quality dataset of mesospheric temperature.

Looking ahead, model-observational comparisons of atmospheric temperature change will be of interest. As simulations from Phase 7 of the Coupled Model Intercomparison Project are finalized, it will be important to determine if most simulations continue to exhibit more warming than is supported in observational datasets (Santer et al. 2017; Po-Chedley et al. 2021; Dunne et al. 2024). It will also be important to analyze high-resolution climate models to determine if their representation of lapse rate changes is distinct from their lower-resolution counterparts (Merlis et al. 2024). Given the important role of internal variability in shaping atmospheric temperature records, assessments of the fidelity of climate model's representation of variability is also critical.

Several ATC members also highlighted the need for theoretical and process level understanding of the controls on atmospheric temperature across timescales. Improved understanding of atmospheric temperature variability and change will need to leverage knowledge of temperature datasets, climate model output, radiative-convective processes, and large-scale climate dynamics.

The ATC Activity discussed several logistical steps designed to build and maintain momentum for improved understanding of atmospheric temperature and for publications contributing to the upcoming IPCC Assessment Report. The group plans to host more frequent (virtual) meetings and some members interested in sub-topics may also meet in smaller groups. ATC will also consider organizing sessions at future geophysical union meetings.

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Acknowledgements

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The Balloon Network for stratospheric aerosol Observation (BalNeO)

Jean-Paul Vernier[1,2,3]

[1]National Institute of Aerospace, Hampton, VA 23666, USA; [2]NASA Langley Research Center, Hampton, VA 23666, USA; [3]GSMA, UMR 7331 CNRS-Université de Reims Champagne-Ardenne, Reims, France

The stratospheric aerosol layer is a key element of the Earth climate system. Largely influenced by major volcanic eruptions, its variability is also affected by smaller volcanic events, extreme wildfires through Pyrocumulonimbus and deep convection especially during the Asian Summer Monsoon. While stratospheric aerosols have been monitored by satellites for more than four decades, in situ measurements are still lacking, especially in the tropical region. Our team at NASA Langley has deployed at multiple locations in India, Brazil, France, Australia and the United States to respond to volcanic eruptions and gather information about aerosol properties. With the increasing influence of wildfires impacting the stratosphere and the proposed geoengineering solutions to artificially inject stratospheric aerosols, there is a growing interest in further assessing the microphysical, optical and chemical properties of these aerosols.

To address these needs, we created the Balloon Network for stratospheric aerosol Observation (BalNeO) project. BalNeo aims to coordinate

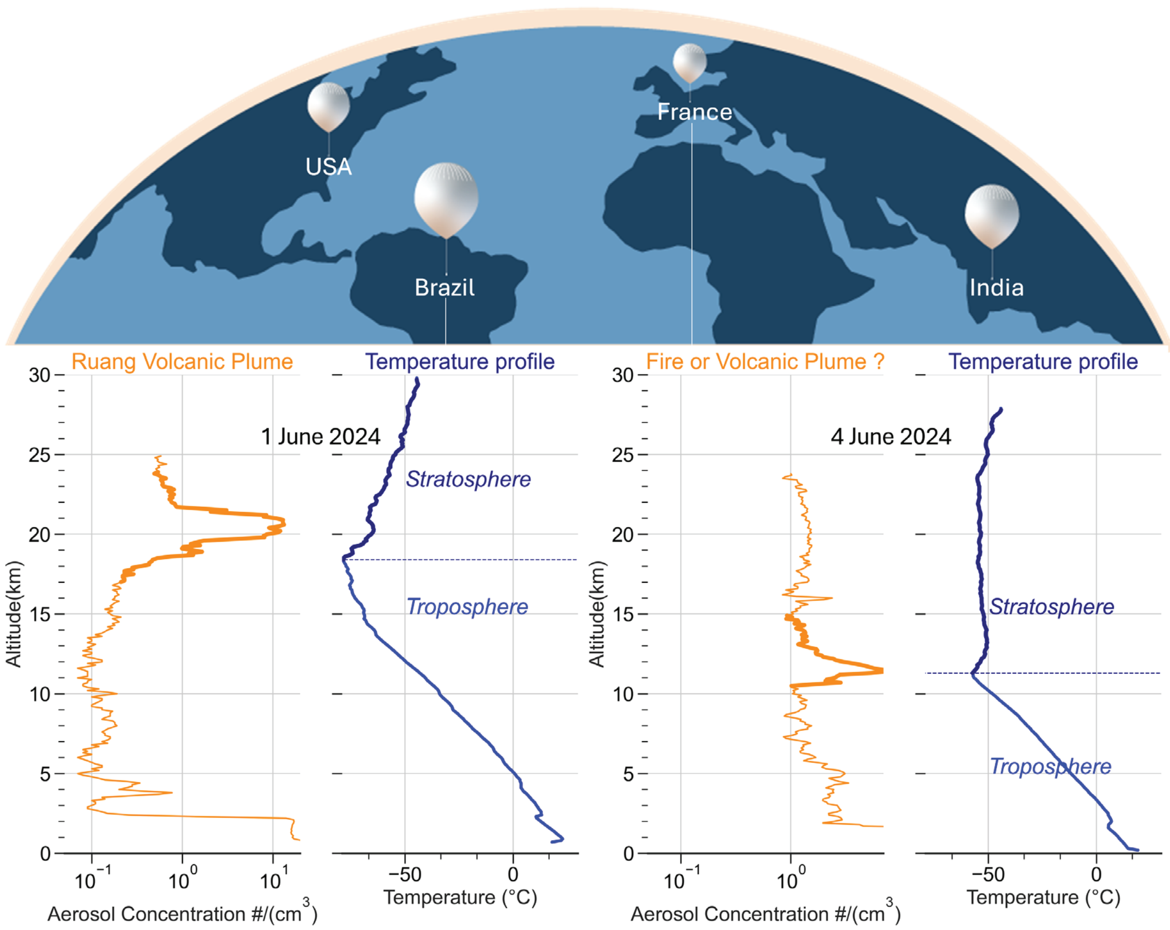

__Figure 2:__ (left) aerosol concentration and temperature profiles obtained during the first BalNeO flight from Bauru/Brazil on 1 June 2024. (right) Another flight took place 3 days after from Reims/France.

balloon-borne aerosol measurements at multiple locations across the world to assess the properties of stratospheric aerosols. The first 2 balloon flights of BalNeO took place in June 2024 from Bauru, Brazil and Reims, France (Figure 2).

16 balloon flights have been conducted within the framework since June 2024 and additional discussions with groups in India and Europe are underway to increase the number of sites.

BalNeO is looking for additional partners, especially in the tropical region. Please contact the PI of the project, Jean-Paul Vernier at Jeanpaul.vernier@nasa.gov if you're interested to take part of this activity.

Information about BalNeO: https://science.larc.nasa.gov/balneo/

QBOi-SNAP-QUOCA Workshop:

Improved simulations of the stratosphere for better predictions of weather, climate and extreme events

Regan Mudhar[1], Anna Hall[2], Jinlong Huang[3], Robert W. Lee[4], Froila M. Palmeiro[5]

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Dates:
24 - 28 March 2025

Scientific Organising Committee:
Alison Ming, Neal Butchart, Scott Osprey, James Anstey, Chaim Garfinkel, Clara Orbe, Amy Butler, Peter Hitchcock, and Yoshio Kawatani

Local Organising Committee:
Alison Ming, Charles Powell, Peter Haynes, Kasturi Shah

Host Institution:
Isaac Newton Institute for Mathematical Sciences, University of Cambridge, UK

Number Of Participants:
105 (from 18 countries)

Contact:
adk33@cam.ac.uk

Activity Website:
https://sites.google.com/view/qsq-workshop-mar-2025/home

Sponsors: Isaac Newton Institute for Mathematical Sciences; University of Cambridge; Institute of Computing for Climate Science; APARC Atmospheric Processes And their Role in Climate; IUGG; Met Office; WCRP World Climate Research Programme

The QBOi, SNAP and QUOCA activities held a joint workshop on 24 - 28 March at the Isaac Newton Institute for Mathematical Sciences. We would like to thank the local organising committee for their coordination of a wonderful week of talks, posters, breakouts and social activities around the historic city of Cambridge.

We gratefully acknowledge the University of Cambridge, the Isaac Newton Institute for Mathematical Sciences, the Institute of Computing for Climate Science, and the Met Office for supporting the workshop. The support of APARC and IUGG in particular enabled travel support for Early Career Scientists to participate, with over half of all attendees being early career.

Figure 3: *The in-person attendees of the QSQ workshop at the University of Cambridge*

Meeting Overview

This was the first joint workshop between the Quasi-Biennial Oscillation initiative (QBOi), Stratospheric Network for the Assessment of Predictability (SNAP) and QUasi-biennial oscillation and Ozone Chemistry interactions in the Atmosphere (QUOCA). All three activities focus on stratospheric dynamics: QBOi on improving climate model representation of the QBO and its teleconnections; SNAP on subseasonal-to-seasonal (S2S) forecast systems' ability to simulate the stratosphere and its tropospheric coupling; QUOCA on ozone feedbacks on the QBO. The workshop aimed to improve understanding of stratospheric processes, variability, uncertainties, and influence on surface climate and predictability.

There was a diversity of scientists participating in the workshop (Figure 3): around a third were women and over half early career. There were 105 people from 74 institutes across 18 countries, with most from the US (26%), UK (19%) and China (14%). Almost 80% attended in person, with a number of colleagues participating online due to travel limitations. There were 54 posters and 55 talks, including 5 invited speakers, on 4 key topics described in the following sections. The programme also included QBOi and SNAP activity reporting, the in-person QUOCA kick-off, breakouts and plenary sessions to facilitate community input into activity planning and potential opportunities for cross-activity collaborations, and various social activities (Figure 4).

Session Overviews

Stratosphere-troposphere coupling in the tropics

This session highlighted challenges in representing stratosphere-troposphere interactions in climate models, focusing on connections between the QBO, Madden-Julian Oscillation (MJO), and El Niño-Southern Oscillation (ENSO).

Several talks addressed the difficulty of modelling the influence of the QBO and extratropical forcings on the tropical stratosphere. For example, there was enhanced tropical convective activity following Sudden Stratospheric Warmings (SSWs) in Stratospheric Nudging And Predictable Surface Impacts (SNAPSI) simulations, but response timing and intensity varied considerably between models (**Shunsuke Noguchi**). The tropical stratosphere also impacts the MJO (**Lon Hood**); despite their QBO-region nudging, QBOi Phase 2 models failed to reproduce a QBO-MJO connection. One study found that MJO-related convection was too shallow, potentially requiring adjusted sea surface temperatures. This raised the question of whether model biases in MJO convection should be corrected first or a better physical understanding of QBO-MJO coupling is needed (**Kai Huang, Chang-Hyun Park**). Correcting ozone profiles in climate models, specifically in the tropical tropopause layer, was also found to significantly reduce temperature and moisture biases. However, the QBO-MJO connec-

Figure 4: *The workshop dinner at Queens' College.*

tion seemed to be particularly sensitive to models' convective parametrisations (**Seok-Woo Son, Jiyoung Oh, Seung-Yoon Back**).

Two other models indicated that the MJO may be more strongly influenced by lower tropospheric processes (i.e. ENSO) than the QBO (**Raina Roy**). QBO period under La Niña lengthened in all models' QBOi-ENSO experiments; the amplitude varied across models, appearing more sensitive to ENSO in those with variable parameterized gravity wave (GW) schemes (**Yoshio Kawatani**). The MJO-ENSO relationship remained evident, with faster MJO propagation, under El Niño, potentially affecting its teleconnections and surface impacts (**Dillon Elsbur**y).

Extratropical stratosphere-troposphere coupling and surface prediction

The SNAPSI project was a focus of this session. It aims to assess the added forecast skill from SSWs in S2S models (**Chaim Garfinkel**). Most models predicted downward impacts but struggled with short lead-time events (**Hera Kim**). They agreed on post-SSW sea-level pressure patterns but varied in magnitude and timing (**Peter Hitchcock**). The 2018 SSW was found to increase the risk of Iberian extreme rains, European cold spells, excess deaths, and high energy demand (**William Seviour, Ying Dai, Regan Mudhar**). Models missed the negative Pacific-North American (PNA) pattern in February 2018, however, due to inaccurate simulation of the East Asian trough (**Jinlong Huang**). While the 2018 and 2019 SSWs both drove negative NAO regimes, their downward propagation differed: the latter showed limited forecast skill (**Robert Lee, Dong-Chan Hong**).

The session also explored coupling mechanisms. Zonally-asymmetric momentum torques in the stratosphere generated zonally-asymmetric tropospheric responses (**Wuhan Ning**), while isentropic mass circulation indicated that stratospheric variability connects to cold air outbreaks across the northern midlatitudes (**Yueyue Yu**). Post-SSW polar-cap pressure changes were also shown to stem from the compression of the polar tropospheric air column (**Mark Baldwin**). S2S models displayed premature "false alarms" and overestimated tropospheric responses for the 2022/23 SSW (**Jian Rao**). Pre-SSW Ural ridge strength was found to shape NAM propagation and Eurasian cooling (**Jiankai Zhang**), while propagating SSWs were accompanied by stronger NAM/NAO impacts (**Rongzhao Lu**). Both CMIP5/6 and C3S models overestimated the NAM's Pacific center due to an exaggerated Aleutian Low (**Simon Lee**), whereas tropical and stratospheric teleconnections enhanced the PNA and NAO forecast skill, respectively (**Alexey Karpechko**).

Overall, this session emphasised how improved stratospheric modeling can enhance weather and climate predictability - though biases remain. Machine learning (ML) was suggested to help, but is limited by sparse stratospheric training data (**Inna Polichtchouk**). There was also description of a new method for identifying atmospheric weather regimes that are particularly useful for impacts (**Marlene Kretschmer**).

Composition/dynamics coupling

This session explored how stratospheric dynamics and composition influence each other. Ozone-climate feedbacks emerged as a crucial driver of stratospheric temperature trends. CMIP6 experiments showed robust upper-stratospheric ozone increases with CO_2 but differing lower-stratosphere responses; interactive chemistry introduced a negative feedback absent in fixed-ozone models (**Gabriel Chiodo**). Alternatively, a conceptual photochemical-transport model to unify many processes was introduced, linking surface warming and QBO phase shifts to ozone distribution variations (**Aaron Match**).

Brewer-Dobson circulation (BDC) responses to QBO phases were found to modulate tropical tropopause temperatures and midlatitude transport, altering water-vapour freeze-drying and ozone distributions (**Veenus Venugopal, Alison Ming**). Velocities derived from space-based observations of tracers also revealed QBO-linked patterns in mean meridional flow, with notable differences from reanalyses, highlighting uncertainties in mixing assumptions (**Tobias Kerzenmacher**). Meanwhile, satellite limb observations and QBO-nudged models revealed persistent biases in age-of-air and semi-annual oscillation representation, highlighting areas for model evaluation and improved GW parametrisations (**Kimberlee Dubé, Aleena Moolakkunnel Jaison**).

Accurate representation of stratospheric polar vortex (SPV)-related mechanisms was deemed essential for predictability and variability. For example, in the Northern Hemisphere, the Barents-Kara Sea ice loss influence on the SPV was strongly modulated by ENSO and QBO (**Xiaocen Shen**), and ozone-circulation interactions reversed intraseasonal temperature trends via enhanced BDC and planetary-wave propagation (**Siyi Zhao**). For the Southern Hemisphere, recent wildfire and volcanic eruption-driven ozone anomalies were shown to influence SPV variability and tropospheric coupling (**Eun-Pa Lim**). This overall highlighted the need for improved QBO and ozone chemistry representation for climate model projections and S2S predictability. Correctly capturing midlatitude wind-QBO interactions was noted to enhance the latter (**Zhe Wang**).

Another interesting theme was geoengineering: injection latitude in stratospheric aerosol injection experiments was found to control lower-stratospheric heating and large-scale circulation changes, underscoring the importance of interactive ozone chemistry (**Ewa Bednarz**). Idealised heating perturbations produced warming and accelerated overturning across models, but differed in terms of magnitude, seasonal timing, and surface response (**Colleen Golja**).

QBO, gravity waves, and their representation in models

There was significant interest in the news that monitoring of the atmosphere with high-vertical resolution sounders may cease by 2027; one suggested solution for combining GNSS-RO/SABER data was vertical smoothing of GNSS-RO (**Corwin Wright**). Observations are necessary for modelling; QBO representation in models remains a challenge and depends on GW parametrisations. A simpler vorticity-based parametrisation in the CAM model reportedly reduced phase speed biases, while a new convection-based GW source parametrisation in the GFDL model improved tropical stratospheric variability. However, it was warned that tuning cannot alleviate all biases (**Martina Bramberger, Pu Lin**). The QBO was also evaluated in the new CESM3-WACCM7 model and a 181-layer version of GEOS; the latter significantly improved the too-weak QBO in the lower stratosphere still present in WACCM7 (**Mijeong Park, Lawrence Coy**).

Models' simulated QBOs are also affected by vertical resolution. Sensitivity experiments with the GISS E2.2 model showed that increasing resolution in the lower-to-mid stratosphere increased wave propagation in the extratropics, reducing SPV biases. However, they advised caution for the upper stratosphere; in the E3SMv2 model, a finer resolution appeared to slow down and weaken a biased QBO through changes in Kelvin and planetary waves (**Natasha Trencham, Wandi Yu**).

Several talks focused on teleconnections; there was found to be strong dependence of these on how models simulate the QBO, including its amplitude and location, and, for Northern Hemisphere winter especially, its interaction with ENSO (**Martin Andrews, Vinay Kumar, Froila Palmeiro**). SNAPSI models unfortunately underestimated QBO amplitude, though reproduced clear signals of Kelvin waves and extratropical teleconnections during easterly QBO. An observed QBO disruption, for example, was not captured in SNAPSI and, in general, models struggle to reproduce it - even in targeted experiments using nudging, as in the CMA model (**Hamid Pahlavan, Yue Wang**). Interestingly, some large volcanic forcing events in Large Ensemble Single Forcing MIP experiments were shown to disrupt the QBO (**Chaim Garfinkel**).

Some modeling centers are using ML to support tuning, with examples shown for E3SM and the intermediate-complexity model MiMA. It is believed that research in this area, including emulators and surrogate accelerated parameter optimisation, will be useful for QBO tuning and understanding parameter sensitivity - though requires significant training data (**Aditi Sheshadri, Walter Hannah**).

Finally, results from CESM2 showed that, under global warming, deep convection in the tropics intensifies, increasing the non-orographic GW drag in the stratosphere. This accelerates the descent of easterly QBO, with a shorter QBO period. Aquaplanet simulations also reproduced the QBO sensitivity to CO2 and ozone increase (**Hyun-Kyu Lee, Christiane Jablonowski**).

Key themes arising and outlook for QSQ

In a post-workshop survey, respondents typically found the workshop highly valuable (~70%); over half found the breakouts and plenary discussions very valuable, with many enjoying this explicit time for discussion. In the breakouts, pre-planned prompts generated engaging discussions on the current and future role of stratospheric research in climate science, identifying gaps in our current knowledge to inform further coordinated model experiments (Figure 5).

There was significant interest in the potential of ML to enhance the representation of stratospheric dynamics, large-scale circulation, and stratosphere-troposphere coupling. Attendees were generally optimistic about the evolution and use of ML in parametrisation and improving model skill. However, there was a shared concern that increased reliance on data-driven methods could come at the cost of physical interpretability; there was support for a hybrid modeling approach that combines ML with physics-based frameworks.

Figure 5: *Word cloud of the most common themes arising across breakout groups. The words are representative of core science objectives, current and future modeling efforts, as well as broader community goals.*

Across most breakout discussions, the need for expanded observational datasets was evident; the current record has limited temporal and spatial coverage, but observations are necessary for constraining models and evaluating ML approaches. Some conversations highlighted shortcomings in model simulations, including increased resolution and interactive chemistry. There was also a general agreement to improve accessibility and awareness of available data; the post-workshop survey revealed that the majority of attendees (~60%) utilised JASMIN/CEDA for downloading, processing and/or analysing data.

We feel this first QSQ workshop was a success: we received positive comments on its size, length, the hybrid experience, networking opportunities, and discussion time. The latter two were particularly celebrated, though some hoped for an improvement in the online experience of the breakouts and posters. Some feedback asked for more introductory talks, whether for those new to the field or for an overview of what we do not know to focus discussions. Nevertheless, this joint meeting successfully enabled the communication of the most up-to-date science across the activities. We especially thank **Peter Haynes** and **Martin Chipperfield** for their summary on the final day, discussing where we've come from, where we're going, and what the important open questions are. Attendee feedback also indicated several science highlights: observations; ozone; GW parametrisations; SNAPSI; stratosphere-troposphere coupling and other teleconnections; ML. Attendees tended to support continued focus on improving the ability to simulate and predict stratospheric variability, which remains essential for advancing model performance, interpreting observational trends, and understanding the long-term behavior of the climate.

Each of the QSQ activities are organised into multiple working groups, each aiming to address key questions around model representation of the stratosphere and broader implications for biases and predictive skill. Many of these groups are actively developing research papers to synthesise progress and identify future directions, including contributions to an upcoming WCD special issue (more info at https://wcd.copernicus.org/articles/special_issue1297.html). For example, SNAPSI phase 2 is under way: it will use multi-model experiments to isolate water vapour and ozone's role in surface predictability. QBO-ozone interactions are also receiving attention through the new QBOi-Chemistry Climate Modelling Initiative activity QUOCA. The workshop demonstrated the community's continued focus on S2S prediction, better simulations of the QBO, the importance of (ozone) chemistry and its interactions, as well as links between meteorological events and stratospheric conditions. Through these activities and projects, we are laying the groundwork for more accurate and comprehensive representations of the stratosphere in climate models, paving the way for improved prediction and understanding of the climate system. You can learn more about and find contact information for each of the activities at https://www.aparc-climate.org/activities/quasi-biennial-oscillation/ (QBOi), https://www.aparc-climate.org/activities/assessing-predictability/ (SNAP) and https://www.aparc-climate.org/activities/working-groups/quoca/ (QUOCA).

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