



Scientific investigations in atmospheric processes have continued during the ongoing COVID-19 pandemic, that has prevented most SPARC workshops from taking place. Among other articles, this issue of the SPARC Newsletter contains an overview of a recently published review paper on sudden stratospheric warmings (page 8), and some updates from our activities, including the report from the SPARC SSG meetings held in February 2021 (page 2), as well as some new modelling initiatives.

Image credit: Katja Riedel Photography.

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The 28th SPARC Scientific Steering Group Meeting

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The 28th SPARC Scientific Steering Group (SSG) meeting was split in two parts. In the first part, in December the Strategy Task Team presented its views and ideas, (see [previous Newsletter](#)), to the SPARC SSG and activity leads. The second part took place online on 2 and 9 February, and was reserved for the usual reporting by the activities and further discussions among the SPARC leaders on the strategy, and possibilities for collaborations and development. During the meeting, activities had the opportunity to report on recent achievements, emerging issues, and new ideas. Further, the community discussed some short-term issues, including a new agreement with CEDA, the upcoming SPARC General Assembly, and other upcoming SPARC meetings. There was also a more general discussion on possible meeting formats.

Activity highlights

Despite the pandemic, which has caused most SPARC workshops to be postponed to 2022, many science highlights and good progress could be reported by our activities. A selection of those highlights is presented below.

ACAM (Atmospheric Composition and the Asian Summer Monsoon; **Hans Schlager**), reported successful community building and capacity building in the Asian Monsoon region. They are holding an online Training school in June/July 2022, and are preparing their regular workshop and training school for next year, while continuing support for research campaigns in the Asian Monsoon region. Closer connections to the Monsoon Panel would be welcome.

The publication of their community paper on observed atmospheric temperature trends [1], as well as on consistency and structural uncertainty of GPS RO records [2] are major achievements of ATC (Atmospheric Temperature Changes and their Drivers; **Amanda Maycock/Andrea Steiner**), along with their fruitful collaboration with other WCRP projects in the joint publication on the Earth's heat inventory [3].

CCMI (Chemistry-Climate Model Initiative; **Tatsuya Nagashima/David Plummer**) have been asked to prepare model runs for the 2022 Ozone Assessment. One requested topic includes solar radiation manage-

ment. The model definitions are now finished (see report on page 22).

DAWG (Data Assimilation Working Group; **Quentin Errera/John McCormack**), has been working on their implementation plan, and are planning further collaborations with the S-RIP (SPARC Reanalysis Intercomparison Project) activity. DAWG participated in the proposal of the Changing-Atmosphere Infra-Red Tomography Explorer (CAIRT) for an ESA Earth Explorer II, which has been selected as one of four projects. They emphasised their predestined role for satellite data advocacy.

Close collaborations have continued between the DynVar (Dynamical Variability; **Daniela Domeisen/Alexey Karpechko**) and SNAP (Stratospheric Network for the Assessment of Predictability). DynVar reported a leadership change and the publication of two community papers on predictability of the stratosphere [4], and on the predictability arising from stratosphere-troposphere coupling [5], see also [SPARC newsletter No. 54](#). They have a new focus on tropospheric dynamics, and plan to connect to the storm tracks community.

FISAPS (Fine Scale Atmospheric Processes and Structures; **Marv Geller**), was involved in a review paper on Tropical temperature variability in the UTLS: New insights from GPS radio occultation observations [6] and is planning a workshop to stimulate availability of high-resolution radio sounding data.

The Gravity Wave Symposium, organised by GW (Gravity waves; **Riwal Plougonven/Laura Holt**) was postponed to 2022. The activity has started collaborations with QBOi (Towards Improving the Quasi-Biennial Oscillation in Global Climate Models), establishing an online seminar series in early 2021. They also keep working within their ISSI Team on "New Quantitative Constraints on Orographic Gravity Wave Stress and Drag".

A number of workshops, training sessions and data set evaluations were organised by LOTUS (Long-term Ozone Trends and Uncertainties in the Stratosphere; **Daan Hubert/Sophie Godin-Beekmann**). They are preparing contributions to chapter 3 of the 2022 Ozone Assessment.

They noted the challenge of managing various different timelines of assessments they are working towards.

Another ISSI group was proposed by the OCTAV-UTLS activity (Observed Composition Trends And Variability in the Upper Troposphere and Lower Stratosphere, **Peter Hoor/Luis Millán**). It focusses on understanding Satellite, Aircraft, Balloon, and Ground-Based Composition Trends: Using Dynamical Coordinates for Consistent Analysis of UTLS Composition.

QBOi (**Scott Osprey/James Anestey**) has finished their first phase and are currently planning their phase 2. The event to celebrate 60 years of the discovery of the QBO has been further postponed to 2022.

The final report by S-RIP (**Masatomo Fujiwara/Gloria Manney**) was in review in 2020, and the final manuscript was submitted to the IPO in the end of 2020. An early-online release of the report is planned for July 2021. Definition of phase II of the project will start this year.

Two community papers were published by SATIO-TCS (Stratospheric And Tropospheric Influences On Tropical Convective Systems; **Shigeo Yoden/Peter Haynes**) on the influence of the QBO on the tropical and subtropical UTLS [7], and the other on the QBO downward coupling [8]. They are looking for guidance on further topics to work on and to connect to communities within as well as outside of WCRP/SPARC.

SNAP (**Chaim Garfinkel/Amy Butler**) has made significant progress on its two current community projects, the Stratospheric biases in S2S forecast systems and the Damping experiments. They are looking to widen their view beyond the stratosphere, and have defined a new project, Stratospheric Nudging And Predictable Surface Impacts (SNAPSI); see description on page 21 of this newsletter issue, while keeping up their work on stratospheric biases in S2S forecast systems.

The solar forcing recommendations for the planned CCMI experiments in support of the 2022 Scientific Assessment of Ozone Depletion (CCMI-2020) has been generated and made available by SOALRIS HEPPA (Solar Influences on Climate; **Bernd Funke**). The solar forcing data is an extension of the historical CMIP6 forcing dataset (extended until end of 2019), and the activity is looking for feedback from the community on the solar CMIP6 forcing data set as input/guidance for the planned solar forcing revision (in preparation for CMIP7). Assessments of model runs have been continued.

A new version of the Global Space-based Stratospheric Aerosol Climatology has been archived at NASA's Atmospheric Sciences Data Center (see <https://doi.org/10.5067/GloSSAC-L3-V2.0>) and a supporting paper has been published [9] with participation of SSiRC (Stratospheric Sulfur and its Role in Climate; **Stefanie Kremser/Marc von Hobe**). A workshop is planned for 2022.

An overview paper was published by TUNER (**Thomas von Clarmann/Nathaniel Livesey**), which lays down a terminology and a common methodological understanding of error reporting, hoped to be applicable to all instruments under assessment has been published [10]. This paper is intended to provide a set of guidelines to data providers. There are further plans to write a use tutorial paper and a tutorial workshop for data users.

Two activities are terminating. PSC (Polar Stratospheric Clouds) has published a review paper [11], which will be presented in the next issue of the SPARC Newsletter. WAWAS II (Water Vapour Phase II) suggests that trend analysis and merging of water vapour data sets from satellites could be done in an activity with experience, e.g., LOTUS. In-situ water vapour measurements, which are of interest to the cirrus cloud community, may be a topic to be picked up by SPARC in the future.

General discussions

In the general discussion part, the activity leads and SPARC leadership agreed to strengthen the connection to the GEWEX/CLIVAR Monsoon panel, which can tie to a number of SPARC activities, such as ACAM or SATIO-TCS and others.

Further, it was brought to attention, that data from commercial satellites are not freely available and communities are looking for support from programs, as commercialization is a growing trend, with detrimental effects for research (difficult access to "proprietary" data, and even to amount and locations of profiles...). This was seen as probably better placed with WMO.

Many SPARC activities are closely related to ongoing preparations of the 2022 Ozone Assessment. Those activities could be clustered to facilitate and strengthen collaborations with GAW (Global Atmosphere Watch). Communication has already been established through **Neil Harris, Greg Carmichael** and **Matt Tully**.

News from the SPARC IPO

In the discussion around the data needs of the SPARC activities it was decided, that an agreement with CEDA (Centre for Environmental Data Analysis; **Charlotte Pascoe, Martin Juckes**) is to be written to meet data storage and documentation needs within SPARC. A data panel was formed, led by **Nili Harnik**, and joined by representatives from those activities that have indicated interest and need. This group will also maintain the connection to the new WCRP Model & Data core project (led by Susann Tegtmeier) that is currently being established.

A larger discussion on SPARC meetings, possible collaborations and meeting formats evolved during the second session. The usefulness of in-person meetings for training schools and ECS events, especially in the context of networking, is clear to many activities. In the organisation of online or hybrid meetings, a number of issues were identified, such as consideration of time zones or additional features (e.g. subtitles for hearing impaired). It was suggested, that in the future, SPARC travel support rules could be changed to encourage airfare with less CO₂ footprint rather than cheapest ticket (a decision was not made).

Concerning the future structure of SPARC, a large majority was in favour of keeping the bottom-up activity structure that is typical for SPARC. However, there was an overall agreement, that clustering activities will facilitate collaborations, as it may give an easier-to-understand look to the outside. At the same time, it is important to leave room for smaller activities working on important, but not-as-popular topics.

More ideas for the future of SPARC include organising a SPARC summer school at some point in the near future, and working on new forms of media outreach. Scientifically, embracing the topic of radiation management was seen as essential in the context of the expected demands from politics in the future. A task team could help establish links to the existing geoengineering community.

In the closed session, nominations to the Steering Group for the term starting in January 2022 were discussed. Three current members are finishing their last terms: co-chair **Neil Harris**, and members **Hauke Schmidt** and **Tianjun Zhou**. The SSG decided to not only fill the newly vacant co-chair seat for the European/African time zones, but also the still-vacant co-chair spot for the Americas. In their 42nd session, the WCRP Joint Scientific Committee (JSC) has approved the nominations of **Amanda Maycock** (UK) and **Karen Rosenlof** (USA) as new co-chairs, as well as the appointment of members **Wenshou Tian** (China) and **Sophie Szopa** (France).

The agreement between WCRP and DLR to host the SPARC IPO is in the process of being signed. It will be valid until December 2023. **Hans Volkert** has retired as office director in July 2020, and **Mareike Heckl** has taken over this position. **Sabrina Zechlau** is joining the Office as the new project scientist in part-time. Further, **Stefanie Kremser** will join the SPARC Office team as a stand-in (in part-time) while Mareike Heckl is on parental leave (until summer 2022).

A focus of the upcoming IPO work will be the finalisation of the new SPARC strategy, and the organisation of the next SPARC General Assembly. The organisation committee is led by **Andrew Charlton-Perez**, who was able to secure three hubs (ECMWF, UK; FIO, China; and NCAR-NOAA-NASA, USA) to host the in-person meetings, which are now scheduled for the week of 24 October 2022. The preparation work is further aided by support from the CLIVAR International Office, and first organisation telecons have started in June.

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Personal reflections on the outlook for SPARC

The WCRP is now moving forward at full speed, having put its review and reorganisation behind it. The new structure is centred around 6 core projects and 5 lighthouse activities with cross-WCRP working becoming more important to meet the climate challenge.

In early July 2021, the WCRP Joint Steering Committee approved its new strategy and implementation plan. The four existing core projects covering ocean, atmosphere, cryosphere and water/energy cycles will remain, as will the activity on producing regional climate information through downscaling. Two new core projects, i.e., Earth System Modelling and Observations and Regional Climate Information for Society, are being formed, with the core projects acting as homes for the climate science research communities and disciplines. Five Lighthouse Activities (WCRP Academy, Safe Landing Climates, Explaining and Predicting Earth System Change, and Digital Earths) will act as the main route to work with broader society on important societal challenges. This is inevitably complex (like the climate challenge!), but we need to make it work.

What is important is that the proposed lighthouse themes are directly relevant to SPARC, offering excellent opportunities for SPARC scientists to contribute to or lead lighthouse activities, to join in pan-WCRP initiatives as well as to develop and carry out SPARC activities. More active and flexible involvements from SPARC scientists at all career stages are critical for the success of these plans. We strongly encourage everyone to help address these fascinating challenges in the coming years.

Over the past 2 years, the preparation of the new SPARC Implementation Plan was deliberately delayed while the WCRP structure was unclear. Now that is clearer, we are going to further develop the implementation plan. The detailed plan fleshed out by the Task Team, will be reported in the next newsletter. About 10 years ago after much soul-searching, SPARC changed the name from “Stratosphere” to “Stratosphere-troposphere” by adding the troposphere. However, this transition has only been partly successful, and SPARC is still too focused on the stratosphere. More emphasis on tropospheric composition and dynamics is desired by SPARC and requested by WCRP. The SPARC Task Team has recommended that more tropospheric topics need to be addressed in two-way interactions with other core projects and lighthouse activities. The proposed topics include Rossby wave dynamics and teleconnections, dynamical attribution, extreme and com-

pound events, local impacts of climate change, and cloud processes. Additional inputs are welcome.

Naturally we need to carefully consider future members of the community when designing the Implementation Plan. Several years ago, SPARC developed its own capacity development plan. It has only been partly successful because capacity building is often pan-WCRP issue and financial support was limited. However there has been progress notably in the Asian monsoon region through the Atmospheric Chemistry and Asian Monsoon activity. Such efforts need to continue by increasing regional contacts in cooperation with the WCRP Academy, Regional Climate Information for Society, and Regional Climate Forums. Beyond training schools, other activities especially for postdocs should be developed.

In the short term, one way to attract more Early Career Researchers into the SPARC community is the General Assembly, which will be held on 24-28 October, 2022. The General Assembly is traditionally valued as much for its networking as for its science. We are trying to maintain and enhance that aspect in person and online. As announced previously, the upcoming Assembly will have an unconventional format designed to allow the SPARC community to meet together while minimizing carbon footprint. In particular, there will be three hubs (the First Institute of Oceanography in China, NASA/NOAA/NCAR in US, and ECMWF in Europe) instead of a single big meeting. The Chinese hub will be supported by the CLIVAR office, exemplifying inter-office work and the importance of collaborating across WCRP. The three hubs will also allow more ECRs to join the meeting by reducing travel expenses. Any suggestions for the sessions and hub activities to be included in the programme are more than welcome.

Leadership will be critical for the new SPARC and next year, Amanda Maycock and Karen Rosenlof will join Seok-Woo Son as co-chairs when Neil Harris steps down. Amanda and Karen have an excellent overview of SPARC through their roles as activity leaders and authors of SPARC reports. They will provide a new team to help SPARC through this transition.

Finally, we would like to draw your attention to the SPARC office change. The director, Mareike Heckl, will be on parental leave at the end of July. Her role will be taken over by Stefanie Kremser until summer 2022.

Prof. Dr. Veronika Eyring receives the 2021 Leibniz Prize

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Veronika Eyring, DLR, and University of Bremen, Germany.

Veronika Eyring is one of the 2021 winners of the German Research Council's Leibniz Prize, the most important research award in Germany, for making "a significant contribution to improving the understanding and accuracy of climate predictions through process-oriented modeling and model evaluation".

I think it's fair to say that the origins of this prestigious prize began with Veronika's role in SPARC, and I would like to take the occasion to reflect back on that time for the benefit of the SPARC readership.

After stratospheric halogen loading peaked in the late 1990s, the scientific questions concerning stratospheric ozone changed from understanding ozone depletion to understanding the coupling between ozone recovery and climate change. This required the use of three-dimensional chemistry-climate models (CCMs), but at that time such models were in their infancy. The conclusions of the 2002 WMO/UNEP Ozone Assessment were seriously limited by the available model simulations, which used different methodologies and forcing scenarios (Figure 1), and often didn't save critical model fields for validation. For example, no conclusions whatever could be drawn concerning midlatitude ozone. Many CCM modellers felt embarrassed by this state of affairs. Veronika Eyring was certainly one of them, and shortly afterwards she took the initiative for organizing a coordinated approach to CCM validation to provide a more rigorous

input into the 2006 Assessment. She began by organizing a workshop in Grainau, Germany in November 2003 (a report from this workshop can be found in [SPARC Newsletter No. 22](#)), which developed a novel concept of process-oriented model validation (Eyring et al., 2005). That workshop was a landmark event, and the evaluation tables in Eyring et al. (2005) (Figure 3) were a huge step forward for the CCM community to become more coordinated and rigorous in its self-evaluation. Subsequently the CCM Validation (CCMVal) activity was formally launched as a SPARC initiative in August 2004 - with, naturally, Veronika as its leader. Her first priority was to make sure that the next round of CCM simulations was performed with the same methodologies and forcing scenarios, to ensure consistency between the results. She then, as part of the 2006 Ozone Assessment, ensured that the process-oriented diagnostics defined in Eyring et al. (2005) were applied to the CCMs. This turned out to be critical, as on this basis, half of the models were deemed unreliable in terms of their ability to project Antarctic ozone recovery, which considerably narrowed the range of uncertainty of the projections in the Assessment. (This was an early example of what is now called an 'emergent constraint'.) The core of the CCM analysis for the Ozone Assessment was published in Eyring et al. (2006, 2007), which took the Ozone Assessment to a new level, effectively responding to the scientific challenges that lay before it.

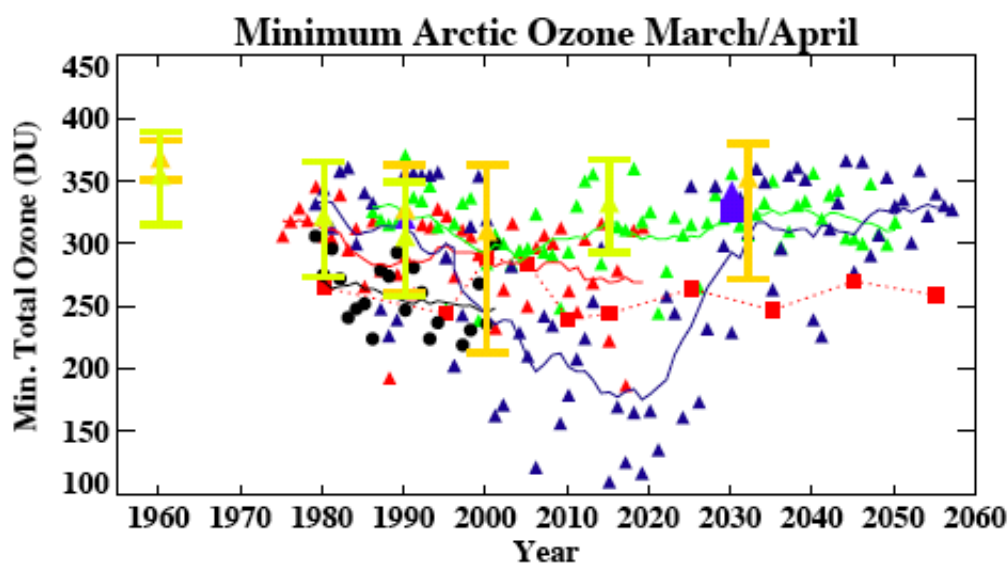


Figure 1: Minimum Arctic total column ozone in March/April as calculated by various CCMs. Black dots show the observations, the other symbols show the models (transient or timeslice). From WMO, 2003.

TABLE 2. List of core processes to validate CCMs with a focus on their ability to model future stratospheric ozone.				
Process	Diagnostic ^a	Variables	Data	References ^b
Stratospheric transport				
Subtropical and polar mixing barriers	PDFs of long-lived tracers	N ₂ O, CH ₄ , CFC-II, etc.; potential vorticity (PV)	Satellite and in situ (aircraft, balloons) chemical measurements and meteorological analyses ^c	Strahan and Douglass (2004)
	Latitudinal gradients of long-lived tracers			Sankey and Shepherd (2003)
	Correlations of long-lived tracers			Sankey and Shepherd (2003)
	Phase and amplitude of tropical CO ₂ or H ₂ O annual cycle in lower stratosphere (tape recorder)	CO ₂ , H ₂ O or idealized annually repeating tracer	Satellite and in situ measurements	Hall et al. (1999), Mote et al. (1996)
	Annual cycle of streamer frequency	Daily PV (maybe long-lived tracers)	Meteorological analyses ^c satellite measurements	Eyring et al. (2003), Waugh (1996), Waugh et al. (1997)
Meridional circulation	Mean age	Conserved tracer with linearly increasing concentration, SF ₆ or CO ₂	In situ measurements	Hall et al. (1999), Waugh and Hall (2002)
	Correlation of interannual anomalies of total ozone and Planetary wave flux	Total ozone and heat flux at 100 hPa, zonal and monthly means	Satellite measurements, meteorological analyses ^c	Randel et al. (2002), Weber et al. (2003)

Figure 2: Subset of the original core processes used in CCMVal to validate CCMs with respect to their ability to model future stratospheric ozone, showing the direct traceability from data to process-based metrics. From Eyring et al. (2005) © American Meteorological Society. Used with permission.

Veronika then led the CCMVal community in a comprehensive assessment of the models, published as a major SPARC Report (2010), and leading to many highly-cited community papers in a special issue of JGR. This massive effort underpinned the extensive CCM contribution to the 2010 Ozone Assessment (Figure 3). Although CCMVal was a community effort, it would never have happened without Veronika. It was her drive for excellence in modelling that brought everybody together and kept us all focused on the key scientific questions, and it absolutely transformed the role of CCM modelling within the Ozone Assessment.

Veronika subsequently became chair of CMIP and for the last decade has been fully focused on Earth System Modelling, where she continues to advance the cause of process-oriented model evaluation, supported by the ESMValTool (Eyring et al., 2016, 2020) which also had its origins in SPARC CCMVal. On behalf of SPARC I would like to congratulate her for this honour and thank her for her profound contributions to SPARC over the first decade of this century.

Ted Shepherd

CCMVal-2

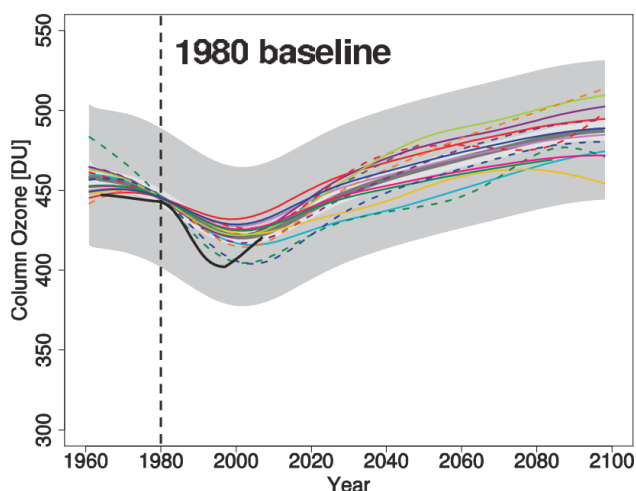


Figure 3: CCM projections of Arctic March total column ozone, statistically adjusted to a 1980 baseline, for individual models (coloured lines), the multi-model ensemble with 95% prediction interval (gray shading), and an unadjusted lowess fit to the observations (black line). (From Fig. 9.11 in SPARC, 2010).

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Sudden stratospheric warmings: a phenomenon with global effects

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Introduction

Sudden stratospheric warmings (SSWs) are the most dramatic phenomena of the wintertime polar stratospheric variability. Their effects are not limited to the polar stratosphere, but extend beyond the stratosphere to the troposphere, mesosphere, and even space weather. Thus, SSWs have become a hot research topic for the scientific climate community. Very recently, a review of the current knowledge on SSWs has been published in *Reviews of Geophysics* (Baldwin *et al.*, 2021). Here we summarize the most important aspects of this publication.

Current general knowledge about SSWs

The polar winter stratosphere is dominated by a strong cyclonic circulation, also called the stratospheric polar vortex, which forms primarily through radiative cooling. However, at times, this cyclonic circulation can be disrupted and the polar stratosphere experiences a rapid warming and an abrupt deceleration of the climatologically westerly winds, which can lead to the reversal of this circulation. All these changes happen within a few days, which explains the name “sudden stratospheric warming” (as shown in Figure 4 for the SSW of 2019). SSWs happen preferentially in the Northern Hemisphere. Since the wave activity is greater in the Northern Hemisphere, the polar vortex is also weaker than in its southern counterpart and it is hence easier to perturb by waves.

Since the discovery of SSWs in 1952 by Richard Scherhag in radiosonde tem-

perature measurements above Berlin (Germany; Scherhag 1952), the scientific community has shown strong interest in understanding these events. As such, it is accepted that SSWs are driven by sustained dissipation of atmospheric waves in the stratosphere, which rapidly slows down the polar vortex winds. When the vortex slows down, air is moved poleward to conserve angular momentum, with descent over the polar cap.

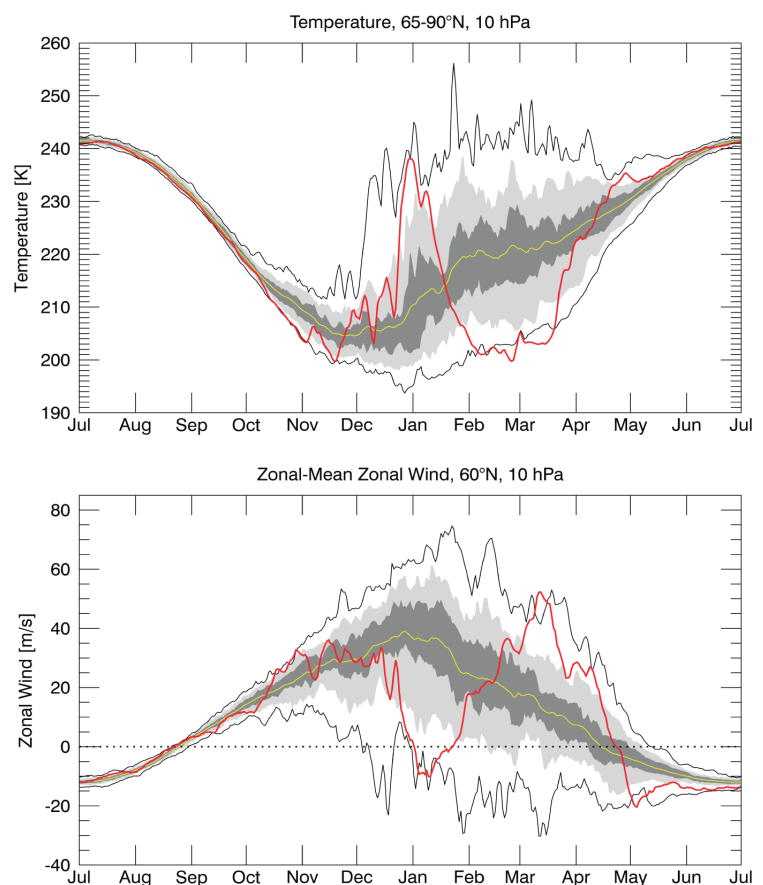


Figure 4: 10-hPa 65–90°N ERA-Interim reanalysis zonal-mean temperatures (top) and zonal-mean zonal wind at 60°N (bottom) for July 2018 to June 2019 (red lines). An SSW event is seen as the upward spike in temperature and the reduction to less than 0 m s⁻¹ in zonal wind (easterlies). The yellow lines signify the daily average conditions in the stratosphere for that time of year, while the gray shading shows 30th/70th (dark) and 10th/90th (light) percentiles. Solid black lines show the daily max/min for prior winters 1979–2018. The month ticks indicate the first day of the month. Figure from Baldwin *et al.* (2021), ©AGU. Used with permission.

The descending air leads to compression and adiabatic heating, resulting in the rapid increase in polar temperatures. After the vortex breakup, strong radiative cooling helps to recover the vortex, if there is sufficient time before the end of the winter.

While the relevance of the wave activity in the occurrence of SSWs is clear, it is not sufficiently resolved where these waves originate: One theory suggests that SSWs are preceded by anomalous bursts of planetary wave activity from the troposphere (Matsuno 1971), while the second theory indicates that there is no need of an anomalous injection of tropospheric wave activity beyond a climatological upward flux, but that the stratosphere itself regulates the upward-propagating wave activity and the polar vortex may feed back onto the wave field so that both are amplified (e.g. Plumb 1981). Case studies of SSWs in observations and model simulations support both possibilities.

Apart from internal variability, some external factors have been shown to modulate the occurrence of SSWs by modulating the stratospheric state, the propagation and breaking of waves in the stratosphere or the generation of planetary Rossby waves in the troposphere. Some of these precursors correspond to stratospheric phenomena outside the polar region (e.g., the Quasi-Biennial Oscillation; Holton and Tan, 1980), others refer to atmosphere-ocean variability (the El Niño Southern Oscillation (Domeisen *et al.* 2019) and the Madden Julian Oscillation (Schwartz and Garfinkel, 2017a) or land surface properties such as snow cover, in addition to factors outside the Earth such as the 11-year solar cycle.

Effects of SSWs on chemistry

The disruption of the stratospheric circulation associated with SSWs is also linked to changes in ozone and other trace gases in the stratosphere. Together with the poleward and downward movement of air during SSWs, the transport of trace gases such as carbon monoxide (CO) and nitrogen oxides (NO_x) towards the pole is enhanced (Manney *et al.*, 2019). In addition, the breakdown of the polar vortex enhances mixing between middle and high latitudes (Manney *et al.*, 2019). Total column ozone is also strongly affected dur-

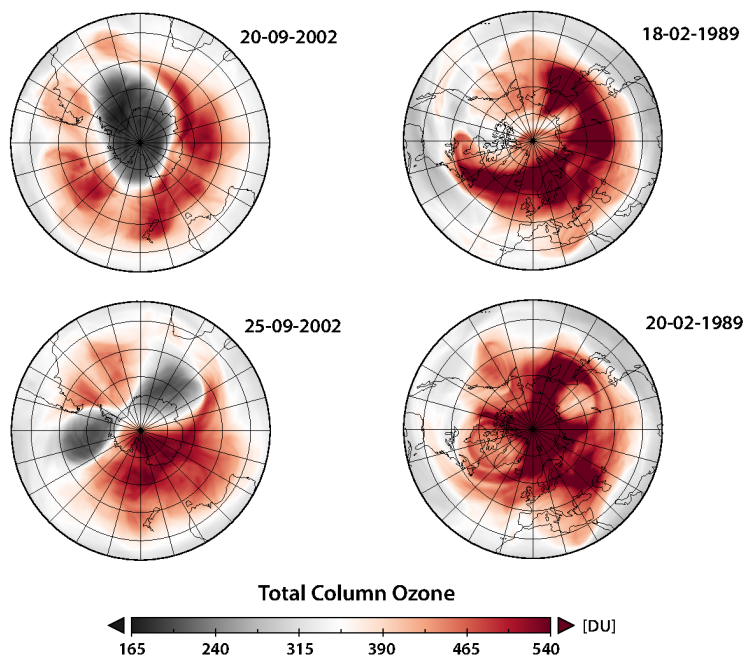


Figure 5: Total column ozone distributions in [DU] as obtained from ECMWF ERA5 before (upper panels) and after (lower panels) SSW events, for the Antarctic polar region in 2002 (left column) and the Arctic polar region in 1989 (right column), respectively. Figure from Baldwin *et al.* (2021), ©AGU. Used with permission.

ing SSWs (as shown in Figure 5). The vertical structure of ozone also changes: Ozone concentrations increase above about 24 km and decrease below that level. The region of increased ozone then slowly descends, and the region of the initial ozone increase relaxes back to normal (Kiesewetter *et al.*, 2010).

Effects of SSWs on other atmospheric layers

The occurrence of SSWs also affects other atmospheric layers. In the last two decades, much work has been done to study the tropospheric effects of these phenomena. On average, SSWs induce a negative phase of the North Atlantic Oscillation that may persist for up to two months after the central date of the event (Figure 6a) (Butler *et al.*, 2017). As a result, low temperatures are found in Northern Eurasia and the eastern United States as well as the Barents and Norwegian Seas, whereas positive temperature anomalies are detected over Greenland and eastern Canada (Figure 6b) (Butler *et al.*, 2017). Wet anomalies over the Iberian Peninsula have also been identified in association with SSWs (Figure 6c) (Butler *et al.*, 2017). Considering stratospheric information in seasonal forecast models could therefore be useful. However, not all SSW events are followed by tropospheric circulation anomalies, and despite efforts to understand the reasons for this case-by-case variability, it is not yet understood.

The lack of a detailed mechanism explaining the downward impact of stratospheric anomalies might be one of the reasons for this uncertainty.

The effects of SSWs are not only restricted to the troposphere, but they also extend above the stratosphere, modifying the upper atmosphere (mesosphere, thermosphere and ionosphere). In the polar mesosphere, SSWs have an opposite effect to that observed in the stratosphere, i.e. a rapid cooling and a wind reversal from easterly to westerly (Körnich and Becker, 2010). These changes are primarily due to changes in gravity wave drag. The changes in the stratospheric winds during an SSW result in a modification in the filtering of gravity waves that reach the mesosphere. Consequently, the meridional circulation in the mesosphere also changes, as does chemical transport.

In the ionosphere, strong changes occur in the low latitude ionosphere electron density. These changes are on par with what occurs during moderate strong geomagnetic storms. SSWs may further influence the generation of small-scale, turbulence-like, structures in the ionosphere (Goncharenko *et al.* 2010). These structures negatively impact satellite-based navigation and communication signals. The drag experienced by low-Earth orbiting satellites is also decreased during SSWs.

Challenges

Although significant advances have been made to improve our knowledge of SSWs, there are still many issues that remain unclear.

There is still debate about the relative importance of the two forcing mechanisms: should SSWs primarily be viewed as a forced phenomenon, driven by tropospheric wave forcing, or as a manifestation of internal stratospheric variability, the product of resonant behaviour within the stratosphere itself? We do not yet have relatively simple models that are fully able to capture both of these mechanisms. Such models would aid in connecting our mechanistic understanding to comprehensive model simulations and could shed more light on the predictability of events. It is also conceivable that not all SSWs fall exclusively into one of these categories, and each paradigm may explain some events. Relatedly, some events have been shown to be more predictable than others, and the factors that determine how far in advance SSWs can be predicted are still not known.

Not only simpler models have problems simulating all SSWs, but also state-of-the-art numerical models are known to have persistent biases in the stratosphere, particularly in the lowermost polar stratosphere. How these cold biases affect the ability of models to predict when SSW events occur and their connection to the surface is currently not known. A first step in this direction is the Stratospheric Network for the Assessment of Predictability ([SNAP](#)) biases project which is seeking to comprehensively characterize and compare stratospheric biases in sub-seasonal prediction models.

Despite significant effort and the engagement of many leading atmospheric dynamicists over many years a precise mechanism or set of mechanisms that enable quantitative prediction of the link between SSW events and surface weather remain elusive.

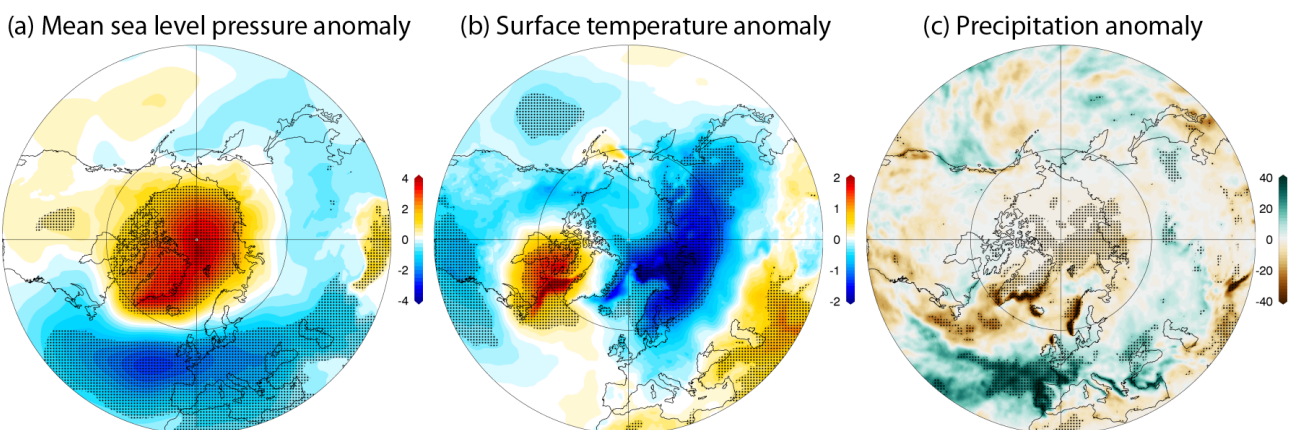


Figure 6: Composites of the 60 days following historical SSWs in the JRA-55 reanalysis for (a) mean sea-level pressure anomalies (hPa), (b) surface temperature anomalies (K), and (c) precipitation anomalies (mm). Stippling indicates regions significantly different from climatology at the 95 % level. Figure from Butler *et al.* (2017), ©Copernicus. Used with permission.

One significant step in this direction is another SNAP project (SNAPSI, the Stratospheric Nudging And Predictable Surface Impacts project, see announcement on page 21), which will conduct a series of experiments in which the same stratospheric state is imposed in a series of operational forecast models for two NH SSWs and one SH SSW so that their tropospheric dynamical response and its predictability can be examined and compared.

Also, recent work has emphasized that the troposphere is not always strongly influenced by the stratosphere. In some cases, SSWs appear to have small impacts on surface weather and in these cases, this might be strongly related to the pre-existing tropospheric conditions at the time of the SSW occurrence. More work in understanding the transitions between different tropospheric weather regimes and how they are influenced by the stratosphere may help to advance our understanding of the mechanisms by which the stratosphere and troposphere are coupled during SSW events.

Apart from the tropospheric effects, the full extent to which SSWs impact near-Earth space remains unknown. There is some evidence that SSWs can impact the generation of small-scale ionospheric disturbances. The evidence is, however, far from conclusive, and it thus remains largely unknown how SSWs influence the formation of small-scale structures in the ionosphere. Understanding these effects is of particular importance owing to their influence on communication and navigation systems. We further have little understanding of how the predictability of SSWs can be used to improve current capabilities to forecast day-to-day space weather.

Acknowledgements

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Improving the QBO in climate models

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Climatic impacts of stratospheric variability and long-term change are routinely evaluated in coordinated community efforts such as the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) supporting Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, and the World Meteorological Organization (WMO) Ozone Assessments. The large observed interannual variability of the tropical stratosphere affects distributions of con-

stituents such as water vapour and ozone and impacts regional surface climate via teleconnections. Ten years ago most of the models being used to support the IPCC and WMO assessments could not properly represent such impacts due to the absence or poor representation of the quasi-biennial oscillation (QBO; see Figure 7). To address this the Quasi-Biennial Oscillation initiative (QBOi) was conceived in 2012 to advance understanding of the QBO and the accuracy of its representation in models.

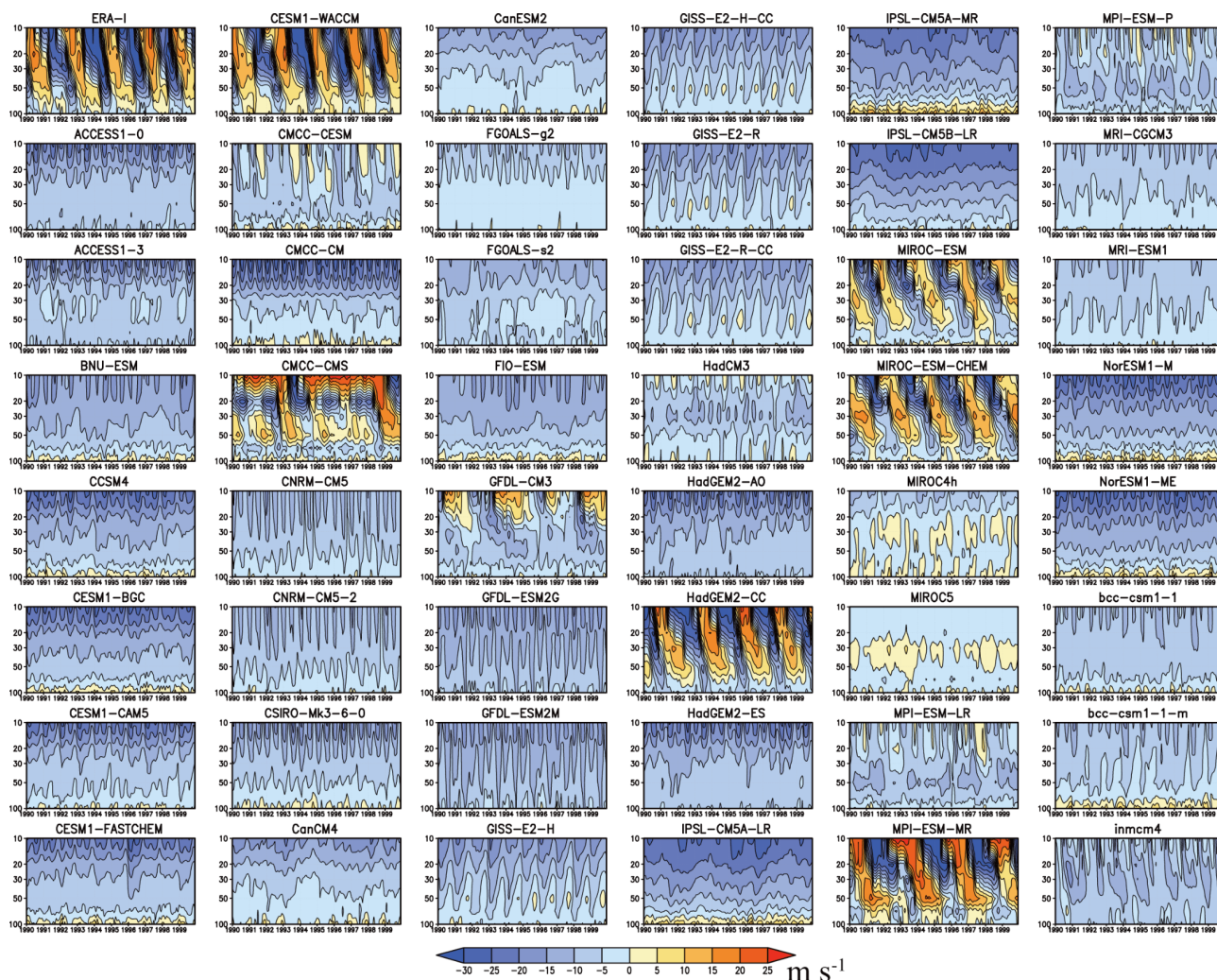


Figure 7: Tropical stratospheric winds in climate models at the time QBOi was conceived. Ten years (1990–1999) of equatorial vertical profiles (10–100hPa) of zonal-mean zonal wind in 47 CMIP5 models, and ERA-Interim reanalysis at top right. CESM1-WACCM is nudged to observations. From Butchart et al. 2018.

QBO & QBOi Milestones

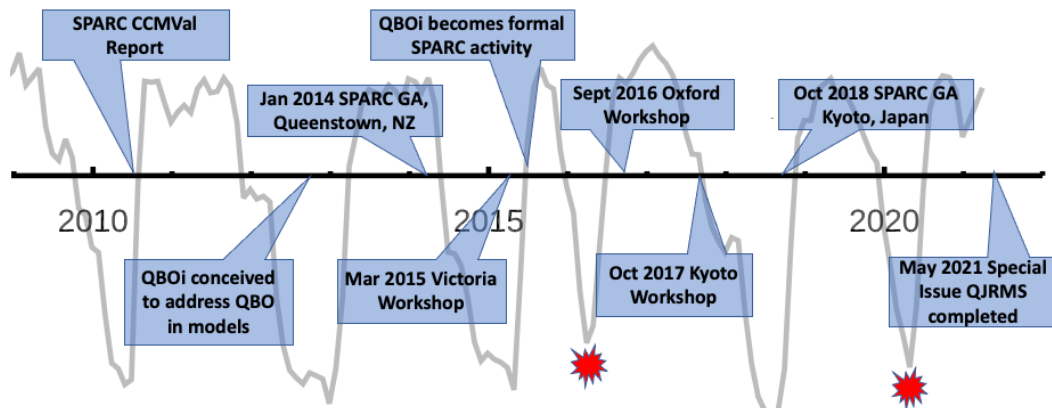


Figure 8: Time series of the 40 hPa equatorial wind with the key developments in the life of the QBOi activity marked on the same timeline. The two QBO disruption events during the Northern Hemisphere winters of 2015/16 and 2019/20 are marked with red stars.

In 2015 QBOi became a SPARC activity and the first phase began in March 2015 with a kick-off workshop in Victoria, Canada. Phase I has now concluded with a set of multi-model studies published in a Special Section of the Quarterly Journal (QJ) of the Royal Meteorological Society. In this article we give a brief overview of phase-I scientific findings, focusing on those aspects that motivate the sec-

ond QBOi phase. This new phase has just started and will examine the causes of the biases identified in phase I and the effects of these biases on QBO impacts.

From the outset QBOi has been community-driven, with coordinated experiments and analyses developed over a series of workshops (Figure 8). Experiments for phase-I were agreed at the Victoria workshop and the lead authors for the core multi-model analyses were identified at a September 2016 workshop in Oxford, UK. Phase I was extended to include investigations of El Niño-Southern Oscillation (ENSO) impacts in October 2017 at the FISAPS/QBOi/SATIO-TCS joint SPARC workshop in Kyoto, Japan. Finalization of phase-I core analyses and preparatory discussions for phase-2 took place at the QBOi side meeting of the 2018 SPARC General Assembly, also in Kyoto.

Breakout group discussions at the workshops proved essential to moving the activity forward and helped prioritise scientific questions that could be usefully addressed using the multi-model ensemble such as:

- Are modelled QBOs realistic? Are there common biases?
- How might the QBO change under increased greenhouse gas concentrations?
- Is the QBO accurately predicted by initialized models?
- How well do models represent the equatorial waves that drive the QBO?
- Do models capture the observed linkages between the QBO and other regions (teleconnections)?

Model	Institutes	Investigators
60LCAM5	NCAR	J. Chen, J. Richter
AGCM3-CMAM	CCCma U. Toronto	J. Anstey, J. Scinocca C. McLandress
CESM1- (WACCM5-110L)	NCAR	R. Garcia, J. Richter
EC-EARTH3.1	BSC	J. Garcia-Serrano
ECHAM5sh	ISAC-CNR	F. Serva, C. Cagnazzo
EMAC	KIT	P. Braesicke, T. Kerzenmacher, S. Versick
HadGEM2-A	Ewha W. U. Yonsei U.	Y.-H. Kim H.-Y. Chun
HadGEM2-AC	Ewha W. U. Yonsei U.	Y.-H. Kim H.-Y. Chun
IFS43r1	ECMWF	T. Stockdale
LMDz6	IPSL-LMD	F. Lott
MIROC-AGCM-LL	MIROC	Y. Kawatani
MIROC-ESM	MIROC	S. Watanabe
MPI-ESM-MR	MPI U. Hamburg	H. Pohlmann M. Dobrynin
MRI-ESM2	MRI-JMA	K. Yoshida, H. Naoe, S. Yukimoto
UMGA7	Met Office MOHC U. Oxford	A. Bushell N. Butchart S. Osprey
UMGA7gws	Met Office MOHC U. Oxford	A. Bushell N. Butchart S. Osprey
UMGC2	MOHC	A. Scaife, M. Andrews

Table 1: Models, institutes and investigators participating in QBOi phase-I by running and providing output from the coordinated experiments. Adapted from Table 5 of Butchart et al. 2018.

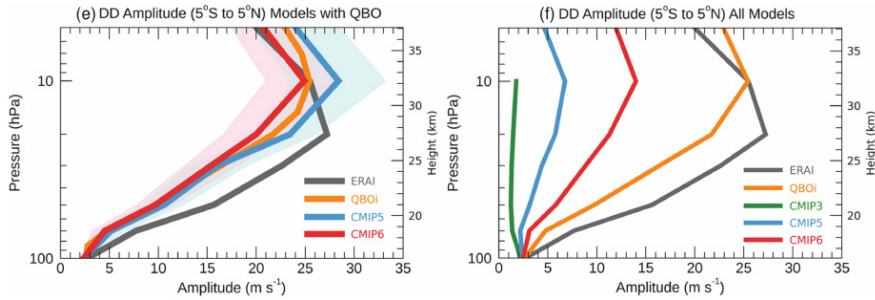


Figure 9: Root-mean square amplitude of tropical wind variability in the ERA-Interim reanalysis and QBOi and CMIP multi-model ensembles. Averaged over the full ensemble, simulated tropical stratospheric variability has improved over time (right panel), but when the average includes only those models with QBOs, there is no discernible improvement (left panel). From Richter et al. 2020b.

By the time of the Victoria workshop the number of global models exhibiting spontaneous QBO-like oscillations had increased sufficiently to allow a meaningful model intercomparison to address the above questions. Models that took part in this intercomparison (QBOi phase I) are listed in Table I. For the latest CMIP phase (CMIP6) there was a further increase in the number of models featuring QBO-like oscillations. Yet although QBOs are now more common in climate models, their overall quality has not improved (Figure 9), indicating a need to understand and address the common biases identified in the QBOi phase-I model intercomparison.

Present-day simulations

Perhaps the most distinctive feature of the QBO is its long period of ~ 28 months. The period is

often well represented in models, but this can usually be accomplished by tuning the parametrized non-orographic gravity wave drag (GWD) that represents QBO forcing due to small-scale waves generated by tropical convection. Such tuning is justified by the large observational uncertainty in the forcing contribution from these waves. Capturing the vertical structure of the QBO appears to be more difficult. In the 10 km above the tropical tropopause the QBO amplitude is, on average, unrealistically weak in successive generations of models (Figure 9). Underestimates of around 50% near 50 hPa are common. Potentially this limits the accuracy of teleconnections that are sensitive to the QBO winds at these altitudes. These include the QBO teleconnections to the Northern Hemisphere polar vortex in the winter stratosphere, the subtropical jet, and the Madden-Julian Oscillation. The ubiquitous amplitude bias in the lowermost stratosphere suggests a pervasive problem in tuning wave parameterizations to allow the models to simulate both adequate amplitudes and the correct QBO mean period.

Another pervasive error is that the simulated QBOs are too narrow in latitude at lower altitudes (Figure 10).

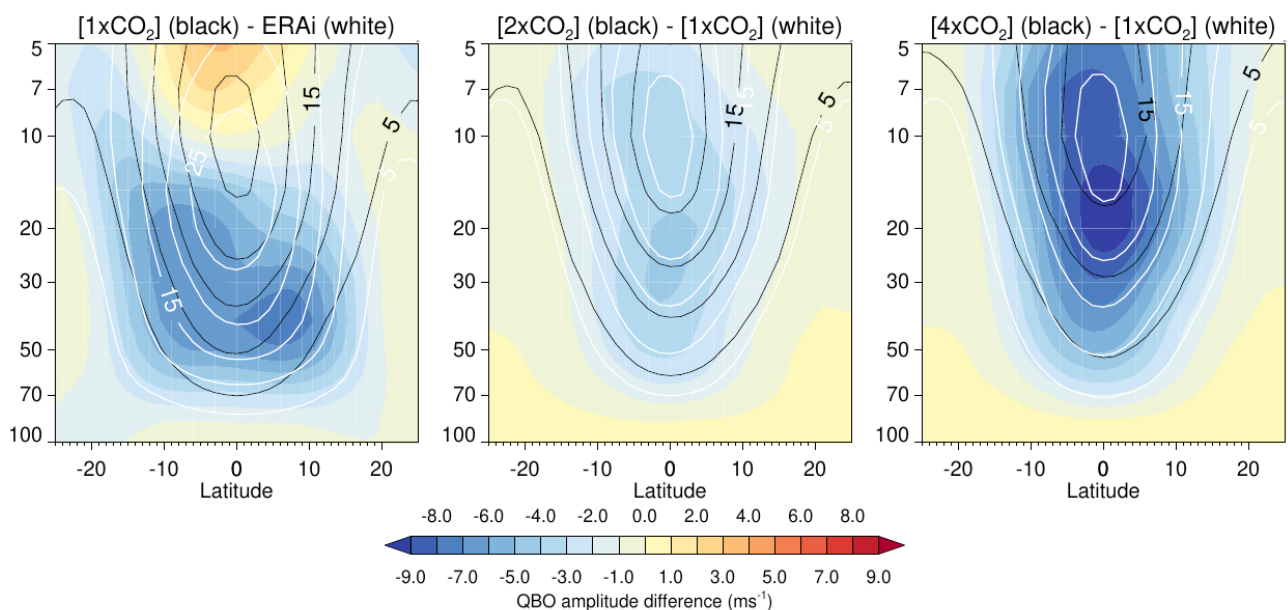


Figure 10: QBO zonal-mean zonal wind amplitude as a function of latitude and altitude for the QBOi multi-model ensemble (MME). Left panel: MME-mean present-day experiment (black lines), ERA-Interim reanalysis (white lines), and their difference (filled contours). Centre and right panels: as left panel, but white lines are present-day and black lines are 2xCO₂ and 4xCO₂ experiments, respectively. Amplitudes are calculated as in Figure 9.

Since the westward phase is observed to be meridionally broader than the eastward phase this suggests that the low altitude amplitude biases may be linked more to that phase. The models have particular difficulty maintaining the strength of the westward QBO phase at these altitudes, as evidenced by its rapid decay in simulations initialized from reanalysis (Figure 11). Forcing of westward QBO winds is believed to come mainly from small-scale gravity waves. At resolutions typical of current climate models, the bulk of this forcing must be parametrized, although resolved waves also contribute. Dissipation of resolved waves is known to be sensitive to vertical resolution, and this is evident across the QBOi ensemble for both eastward and westward waves (Figure 12). Hence the resolved wave forcing is likely too weak in at least some of the models. However, given the amplitude biases this shortfall is clearly not being compensated by the parametrized waves. Understanding why is an important objective for QBOi phase 2.

Projecting the future

Future changes to the QBO are relevant for surface climate because of its teleconnections, for instance to the North Atlantic Oscillation. Also, because of its regularity and prominent signal, any changes in the QBO are potentially a powerful indicator (fingerprint) of a changing climate, provided that the response is

independent of the tuning. It has become evident that a robust prediction by climate models is a slowing down of QBO wind speeds. The response of QBO wind amplitude to doubled and quadrupled CO₂ concentrations is seen in Figure 10. Weakening amplitude is not only predicted by the QBOi models, but also by CMIP5 and CMIP6 models. Arguably this, and a speeding up of the Brewer-Dobson circulation, are among the few robust changes to the general circulation that have been obtained to date from model climate projections.

Consensus suggests confidence, but caution is warranted: according to these same models, other aspects of the QBO's future behaviour are highly uncertain. Increased CO₂ concentration causes a longer QBO period in some models, but a shorter period in others. In some models the oscillation becomes erratic, or retreats to higher altitudes, or even ceases. Why such varied projections? Possibly the tuning of the GWD parametrizations is only valid for a narrow range of climates and therefore there is work to be done on improving the parametrizations or reducing the dependency on them. Consequently, the models almost certainly lack predictive power when applied outside of the present-day climate forcing conditions under which models are developed and tuned. In this respect the diverging future projections have provided a useful test of modelling assumptions (i.e., tuning).

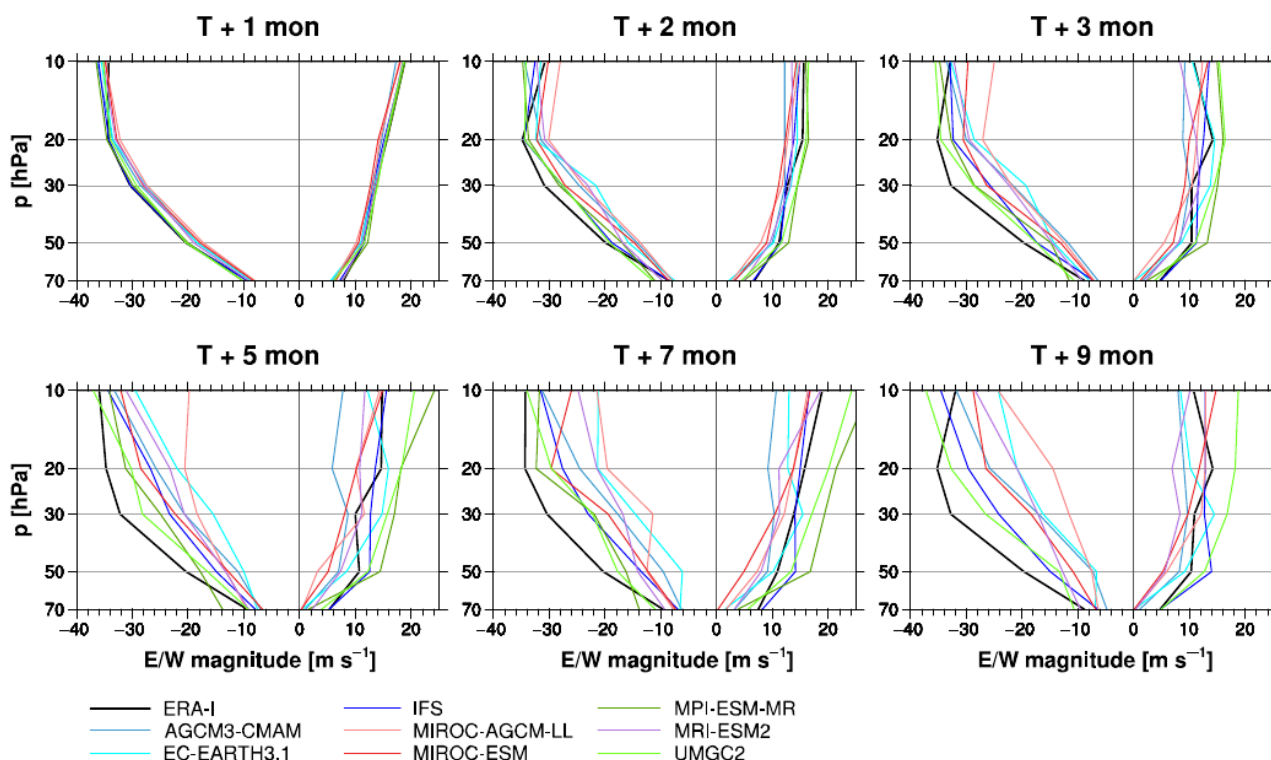


Figure 11: Eastward and westward equatorial zonal-mean zonal wind in QBOi models, composited at each altitude for the 10 cases of strongest eastward and westward reanalysis wind at the hindcast verification time. From Stockdale et al. 2020.

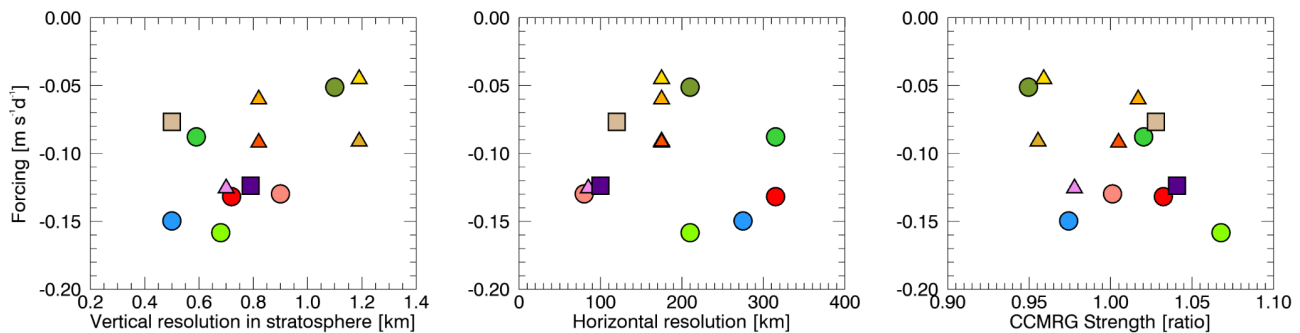


Figure 12: Resolved westward wave forcing at 26-10hPa (26-32 km), 10S-10N in QBOi models vs. (a) vertical resolution at 20-25 km, (b) horizontal resolution, (c) convectively coupled mixed Rossby-gravity wave strength. Figure 18 of Holt et al. 2020 shows the corresponding plots for eastward waves.

Verification of future QBO projections could take some time (i.e., many cycles of ~ 28 months), so any confidence in them will have to rely more on the knowledge that the models can accurately represent the QBO mechanisms in the present.

Predicting the present

Understanding the dependency on choice of model parameters and configuration is complicated by the strong coupling between zonal-mean flow and waves that characterizes the QBO: the waves induce the mean flow to change direction, while the mean flow controls wave propagation and dissipation. Faced with a chicken-egg problem, predictions initialized from reanalysis data are a valuable tool because they allow processes influencing the QBO to be examined under realistic mean-flow conditions before biases develop. Because of the QBO's slow timescale, biases take a few months to reassert themselves - as the hindcasts by QBOi models in Figure 11 showed - and before they do, the resolved and parametrized waves respond to realistic QBO shear zones. In the first month of the QBOi model hindcasts, the strength of westward GWD forcing near 50 hPa is roughly half of that inferred from reanalysis, consistent with the models' inability to maintain westward QBO phases (Figure 11).

An important question is to what extent do mean-flow biases limit the skill of QBO predictions on seasonal-to-decadal timescales? All of the QBOi hindcasts show high skill at predicting the 20-30 hPa QBO winds, but no single model performs well at all altitudes - reinforcing the contention that models have difficulty in accurately capturing the QBO's vertical structure. Possibly greater skill could be achieved by reducing the common systematic errors shared by the models, though further investigation will be required in phase 2 to confirm this.

Disruptions

The forecasting potential implied by the QBO's exceptionally long (28 month) timescale mainly comes about through its regional impacts. However, the occurrence of two recent disruptions to the QBO - during the NH winters of 2015/16 and 2019/20 (Figure 8) - suggests the QBO could be less predictable than previously thought. Hence it is important to understand the conditions under which the QBO's usual cycling breaks down. Based on the two observed disruptions, these conditions include strong forcing by equatorward-propagating Rossby waves. In the extratropics, from where these waves originate, the predictability timescales are much shorter (typically < 1 month) than in the tropics. Therefore, a strong extratropical influence on the QBO could limit its predictability, if disruptions become more common.

With only two observed events it is hard to draw definitive conclusions about their causes or rarity, though their appearance in the last 5 years following 60 years of QBO observations without disruption raises the question of whether they are becoming more likely. These questions could be difficult to answer using the current models, as a significant finding of QBOi phase-I was that most models were unable to capture the observed variability of the QBO in the 60 years prior to disruptions. One reason for this could be that the parametrized GWD is not directly linked to deep convection in most of the models. The models also show significant amplitude errors near 40 hPa, the altitude at which shallow westward jets emerged during both of the observed disruptions.

Moving forward

QBOi was conceived as a community effort to improve the representation of the QBO in climate models. We expect this to enable better representa-

tion of QBO impacts (teleconnections) and more skilful QBO predictions. Phase 1 revealed model biases that could degrade QBO teleconnections, potentially explaining why they are usually weak or absent in models. Phase 2 will test this with nudging experiments that bias-correct the tropical stratospheric winds. This will provide insight into what aspects of the QBO are important for its teleconnections. Using the same experiments, the behaviour of resolved and parametrized waves in the presence of realistic QBO winds will be examined. This will help identify the causes of QBO biases, and determine where further model development is needed to reduce the biases. Disruptions were not anticipated when the phase-I experiments were designed, but reducing QBO biases would likely benefit modelling studies of these events. Improving the models is expected to improve confidence in future projections of QBO behaviour.

Compared to previous generations of climate models, simulated QBOs are now relatively common, but have not substantially improved in accuracy. The QBO results from a sensitive balance of many atmospheric processes including tropical deep convection, a broad spectrum of tropical waves, vertical advection by the Brewer-Dobson circulation, radiative feedbacks (e.g., from ozone heating), and in light of the recent disruptions, large-scale waves from the extratropics. Incorporating all this complexity is a reason why comprehensive climate models are valuable for understanding the QBO and its interactions with other parts of the climate system. The complexity also means that simulating the QBO is a sensitive test of models, as many different processes must be represented accurately in order to realistically simulate the QBO. In the context of Earth System Model development, particularly as increasing horizontal resolution reduces models' dependence on parametrized tropical convection, this makes simulating the QBO a useful test case for stratosphere-resolving climate models. The two recent disruptions are a reminder that nature can be surprising. But better predictions could be on the cards with the expected improvements such as increased resolution with the next generation of models.

Participation

Interested scientists are welcome to participate in QBOi. For more information please contact the QBOi coordinators:

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Workshop reports

March 2015, Victoria, Canada: SPARC Newsletter no. 45 (July 2015)

September 2016, Oxford, UK: SPARC Newsletter no. 48 (January 2017)

October 2017, Kyoto, Japan (joint with the FISAPS and SATIO-TCS activities): SPARC Newsletter no. 50 (February 2018)

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The Dynamics and Variability Model Intercomparison Project (DynVarMIP) is an endorsed participant in the Coupled Model Intercomparison Project Phase 6 (CMIP6). DynVarMIP does not call for additional model experiments but instead asks its participating model centres to provide additional model output from existing CMIP6 experiments. This additional output is critical for understanding the role of the atmospheric circulation in the past, present and future climate, and includes various terms of momentum or thermal budgets as well as upper level atmospheric variables at increased vertical resolution and at daily resolution.

Gerber and Manzini (2016) describe the objectives and scientific questions pursued by DynVarMIP, and they provide detailed information about the variables requested. The following key scientific questions are addressed:

1. How do dynamical processes contribute to persistent model biases in the mean state and variability of the atmosphere, including biases in the position, strength, and statistics of the storm tracks, blocking events and the stratospheric polar vortex?
2. What is the role of atmospheric momentum and heat transport in shaping the climate response to anthropogenic forcings (e.g., global warming, ozone depletion), and how do dynamical processes contribute to uncertainty in future climate projections and prediction?
3. How does the stratosphere affect variability on intra-seasonal, inter-annual, decadal, and climate timescales?

Model name	utendnogw		utendogw		vtendnogw		vtendogw		utendvtem		utendwtem	
	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ	EmonZ
CESM2			X						X		X	
CESM2-FV2			X									
CESM2-WACCM	X	X	X						X		X	
CESM2-WACCM-FV2	X	X	X									
CanESM5			X				X		X		X	
GFDL-CM4	X		X				X		X		X	
GFDL-ESM4	X		X				X		X		X	
HadGEM3-GC31-LL	X	X	X									
HadGEM3-GC31-MM	X	X	X									
INM-CM4-8	X	X	X									
INM-CM5-0	X	X	X									
IPSL-CM5A2-INCA			X				X					
IPSL-CM6A-LR	X	X	X		X		X		X		X	
MIROC6	X		X						X		X	
MRI-ESM2-0	X		X						X		X	
UKESM1-0-LL	X	X	X									
UKESM1-0-LL	X	X	X		X		X		X			

Table 3: Zonal mean eastward and northward wind tendencies. These are zonal mean variables on the plev39 grid.

Model name	epfy & epfz		vtem & wtem		utendepfd		psitem
	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ	EmonZ	EdayZ
CESM2	X	X	X	X	X	X	X
CESM2-WACCM	X	X	X	X	X	X	X
CanESM5	X	X	X	X	X	X	X
CanESM5-CanOE		X		X		X	
GFDL-CM4	X	X	X	X	X	X	X
GFDL-ESM4	X	X	X	X	X	X	X
GISS-E2-1-G		X		X		X	
GISS-E2-1-H		X		X*		X	
GISS-E2-2-G		X		X*			
HadGEM3-GC31-LL	X	X	X	X	X	X	
HadGEM3-GC31-MM	X	X	X	X	X	X	
INM-CM4-8	X	X					
INM-CM5-0	X	X					
IPSL-CM6A-LR					X		X
MIROC6	X	X	X	X	X	X	X
MRI-ESM2-0	X	X	X	X	X	X	X
UKESM1-0-LL	X	X	X	X	X	X	

* only vtem (EmonZ)

Table 2: EP-flux and residual circulation diagnostics. These are zonal mean variables on the plev39 grid.

The purpose of this article is to provide an account of DynVarMIP data availability. DynVarMIP data are available as part of the CMIP6 dataset via the Earth System Grid Federation (ESGF) data portals (<https://esgf-node.llnl.gov/search/cmip6/>). The information provided below is based on the analysis of ESGF made in May 2021. Further updates on data availability and DynVarMIP related papers, are provided on the DynVarMIP website, <https://dynvarmip.github.io/>.

DynVarMIP requested output from the four DECK experiments (AMIP, piControl, abrupt4xCO₂, pctCO₂), historical, the high emission scenario (ssp585) as well as three Cloud Feedback Model Intercomparison Project (CFMIP) experiments (amip-4xCO₂, amip-future4K, amip-p4K). While some of the models provided DynVarMIP diagnostics also for other experiments, this analysis is focused on the above-mentioned experiments only.

Model name	utendnogw Emon	utendogw Emon	vtendnogw Emon	vtendogw Emon
CESM2		X		
CESM2-FV2		X		
CESM2-WACCM	X	X		
CESM2-WACCM-FV2	X	X		
CNRM-CM6-1	X	X		
CNRM-ESM2-1	X	X		
CanESM5		X		X
CanESM5-CanOE		X		X
GFDL-CM4	X	X	X	X
GFDL-ESM4	X	X	X	X
HadGEM3-GC31-LL		X		
HadGEM3-GC31-MM		X		
IPSL-CM5A2-INCA		X		X
IPSL-CM6A-LR	X	X	X	X
MIROC-ES2L		X		
MRI-ESM2-0	X	X		
UKESM1-0-LL		X		

Table 4: 3-D monthly mean wind tendencies due to orographic and non-orographic gravity waves on the plev19 grid.

EP-flux and residual circulation diagnostics

EP-flux diagnostics include three variables: meridional (epfy) and vertical (epfz) components of the EP-flux as well as the zonal mean zonal wind tendency due to the EP-flux divergence (utendepfd). Residual meridional circulation diagnostics include Transformed Eulerian Mean (TEM) meridional (vtem) and vertical (wtem) wind components as well as the TEM mass streamfunction (psitem). The data are provided as daily mean (EdayZ) and monthly mean (EmonZ) zonal mean values at an increased number of vertical levels (39 levels). Models that provided these data are listed in Table 2. Note that most models provided data only for several of the requested experiments. Data for the historical experiment is provided by most of the listed models, while data for the CFMIP experiment is only provided by few models.

Model name	histori- cal	piCon- trol	lpct- CO2	abrupt- 4xCO2	ssp- 585	amip
CNRM-ESM2-1	X	X	X	X	X	X
GFDL-ESM4	X	X	X	X	X	X
MPI-ESM-1-2-HAM		X	X			
MRI-ESM2-0	X				X	
UKESM1-0-LL	X	X	X	X	X	X

Table 5: Age of air.

Model name	tauu Amon	tauv Amon	tauupbl Eday	tauvpbl Eday
ACCESS-CM2	X	X		
ACCESS-ESM1-5	X	X		
AWI-CM-1-1-MR	X	X		
AWI-ESM-1-1-LR	X	X		
BCC-CSM2-MR	X	X		
BCC-ESM1	X	X		
CAMS-CSM1-0	X	X		
CAS-ESM2-0	X	X		
CESM2	X	X	X	X
CESM2-FV2	X	X	X	X
CESM2-WACCM	X	X	X	X
CESM2-WACCM-FV2	X	X	X	X
CIESM	X	X		
CMCC-CM2-HR4	X	X		
CMCC-CM2-SR5	X	X		
CMCC-ESM2	X	X		
CNRM-CM6-1	X	X		
CNRM-CM6-1-HR	X	X		
CNRM-ESM2-1	X	X		
CanESM5	X	X		
CanESM5-CanOE	X	X		
E3SM-1-0	X	X		
E3SM-1-1	X	X		
E3SM-1-1-ECA	X	X		
EC-Earth3	X	X		
EC-Earth3-AerChem	X	X		
EC-Earth3-CC	X	X		
EC-Earth3-LR	X	X		
EC-Earth3-Veg	X	X		
EC-Earth3-Veg-LR	X	X		
FGOALS-f3-L	X	X		
FGOALS-g3	X	X		
FIO-ESM-2-0	X	X		
GFDL-AM4	X	X		
GFDL-CM4	X	X		
GFDL-ESM4	X	X		
GISS-E2-1-G	X	X		
GISS-E2-1-G-CC	X	X		
GISS-E2-1-H	X	X		
GISS-E2-2-G	X	X		
HadGEM3-GC31-LL	X	X	X	X
HadGEM3-GC31-MM	X	X	X	X
IITM-ESM	X	X		
INM-CM4-8	X	X		
INM-CM5-0	X	X		
IPSL-CM5A2-INCA	X	X		
IPSL-CM6A-LR	X	X		
IPSL-CM6A-LR-INCA	X	X		
KACE-1-0-G	X	X		
KIOST-ESM	X	X		
MCM-UA-1-0	X	X		
MIROC6	X	X		
MIROC-ES2H	X	X		
MIROC-ES2L	X	X		
MPI-ESM-1-2-HAM	X	X		
MPI-ESM1-2-HR	X	X		
MPI-ESM1-2-LR	X	X		
MRI-ESM2-0	X	X		
NESM3	X	X		
NorCPM1	X	X		
NorESM1-F	X	X		
NorESM2-LM	X	X		
NorESM2-MM	X	X		
SAM0-UNICON	X	X		
TaiESM1	X	X		
UKESM1-0-LL	X	X	X	X

Table 6: Surface stresses.

Note that a number of other models, or model versions, (GISS-E2-I-G-CC, HadGEM3-GC31-HH, HadGEM3-GC31-LM, HadGEM3-GC31-MH, INM-CM5-H, MRI-AGCM3-2-H, MRI-AGCM3-2-S, NorESM2-LM, TaiESM1) provided these diagnostics for several other experiments, but these are not included in the table.

Wind tendencies

In addition to the zonal mean wind tendency due to EP-flux divergence (see Table 2), other terms of the momentum budget are requested.

These include the tendency of eastward winds due to orographic (utendogw) and non-orographic gravity waves (utendnogw), the tendency of northward wind due to orographic (vtendogw) and non-orographic gravity waves (vtendnogw), as well as the tendency of eastward wind due to TEM northward (utendvtem) and vertical (utendvtem) wind advection and the Coriolis term. The availability of these data for the DynVarMIP requested experiments is listed in Table 3.

In addition to the zonal mean wind tendencies, 3-D monthly mean zonal mean tendencies were requested. Due to the large data volumes, these data are requested on the standard pressure levels (19 levels).

Age of air

Age of air (meanage) is a diagnostic crucial for the analysis of stratospheric transport and the Brewer-Dobson circulation. The diagnostic (Table 5) is provided as monthly mean zonal mean values (AERmonZ) on 39 pressure levels.

Some of these models plus CESM2-WACCM also provide data for other experiments, not requested by DynVarMIP.

Surface momentum budget

DynVarMIP requested to archive parameterized zonal (tauu) and meridional (tauv) surface stresses as well as the components of the total stress due to mixing within the boundary layer (taupbl and tauvpbl) (Table 6). These diagnostics were requested as monthly mean values; however only a few models provided tauupbl and tauvpbl diagnostics, and these are only available as daily values.

Model name	tntmp EmonZ	tntrl&tntrs EmonZ	tntrlcs&tntrscs EmonZ	tntc EmonZ	tntscp EmonZ	tnnogw EmonZ	tnogw EmonZ
AWI-ESM-1-1-LR	X	X		X	X		
CESM2	X	X	X				X
CESM2-FV2	X	X	X				X
CESM2-WACCM	X	X	X			X	X
CESM2-WACCM-FV2	X	X	X			X	X
GFDL-CM4	X	X	X	X	X	X	X
GFDL-ESM4	X	X	X	X	X	X	X
INM-CM4-8	X	X		X	X	X	X
INM-CM5-0	X	X		X	X	X	X
IPSL-CM5A2-INCA	X	X	X	X	X		X
IPSL-CM6A-LR	X		X	X	X		X
IPSL-CM6A-LR-INCA	X			X			
MIROC6	X		X	X	X		
MIROC-ES2L	X		X	X			
MPI-ESM-1-2-HAM	X	X		X	X		
MPI-ESM1-2-LR	X	X		X	X		

Table 7: Temperature tendencies due to parameterized processes

Thermal budget

DynVarMIP also requested parameterized temperature tendencies due to various physical processes. These include: tendency of air temperature due to model physics (tntmp), tendency of air temperature due to all-sky longwave (tntrl) and shortwave (tntrs) heating, tendency of air temperature due to clear-sky longwave (tntrlcs) and shortwave (tntrscs) heating, tendency of air temperature due to convection (tntc), tendency of air temperature due to stratiform clouds and precipitation (tntscp), and tendency of air temperature due to orographic (tnnogw) and non-orographic (tnogw) gravity wave dissipation. The variables are requested as zonal mean monthly mean values on a higher number of vertical levels (plev 39 levels). Models that archived the requested temperature tendencies are listed in Table 7.

We encourage researchers interested in the atmospheric circulation and its future changes to benefit from the opportunity provided by the availability of DynVarMIP data and to actively use them. If you are interested in using the data or have published an article using the data, please let us know. Contact persons:

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DynVar: Alexey Karpechko (alexey.karpechko@fmi.fi) and Daniela Domeisen (daniela.domeisen@env.ethz.ch)

More information about the project, as well as its current status, can be found from [DynVarMIP's web-site](#). More information about DynVar can be found from the [SPARC web-site](#)

Reference:

Gerber, E.P. and E. Manzini, 2016: [The Dynamics and Variability Model Intercomparison Project \(DynVarMIP\) for CMIP6: Assessing the stratosphere-troposphere system](#). *Geosci. Model Dev.*, **9**, 3413–3425.

Stratospheric Nudging And Predictable Surface Impacts (SNAPSI)

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Over the past several decades the SPARC community has demonstrated that stratospheric variability can have robust and at times potent impacts on weather on a range of timescales. The SNAP community has recently published a pair of papers (Domeisen *et al.* 2020a,b) focusing in part on forecast skill related to Northern Hemisphere sudden stratospheric warmings in forecasts issued by operational forecast models contributed to the S2S database. This work confirms that operational forecast models can to some extent capture the surface impacts of sudden stratospheric warmings, and has demonstrated robust, enhanced subseasonal forecast skill in some regions in the weeks following the stratospheric events. However, this ensemble of opportunity approach only allows for correlative conclusions to be drawn. In particular, because of the diversity of forecast initialisation dates and ensemble generation strategies, and because models are able to forecast these sudden stratospheric warmings with differing degrees of success, the causes of the differences in surface impacts among the modelling systems are unclear.

To address this limitation, SNAP is coordinating a new set of controlled numerical experiments, designed to isolate and quantify the contribution of the stratosphere to forecast skill on subseasonal time scales. These experiments target three recent stratospheric events: two major Northern Hemisphere sudden stratospheric warmings in February 2018 and January 2019, and the unusual near-major sudden warming in the Southern Hemisphere that occurred in September 2019. Each of these events was followed by a surface extreme thought to be connected to the stratospheric anomalies, though the timescale and intensity of the downward propagation differed among the events.

The basic experimental protocol consists of a set of forecast ensembles: (1) a standard, free running forecast ensemble, (2) a 'perfect stratosphere' forecast in which the stratosphere is relaxed towards

the observed evolution, and (3) a 'control' forecast in which the stratosphere is relaxed towards climatology. Further details of the experimental protocol will be described in an article soon to be submitted to a peer-reviewed journal. To date, twelve modelling groups at eleven centers are planning to contribute integrations following this protocol. This will allow for an unprecedented, multi-model comparison of the dynamics underlying the surface responses to sudden stratospheric warmings. Moreover, by including 'counterfactual' forecasts in which the stratospheric circulation remains in a climatological state, the experimental protocol will allow for formal attribution statements to be made regarding the surface extremes that followed the stratospheric anomalies.

The goal is to have the experiments completed by fall of 2021, and the initial analysis will be carried out by a set of community working groups. Anyone interested in participating in the community analysis of these experiments is encouraged to contact Peter Hitchcock (aph28@cornell.edu), Amy Butler (amy.butler@noaa.gov), and Chaim Garfinkel (chaim.garfinkel@mail.huji.ac.il) for further information. We expect initial results to be reported towards the end of 2021 through the first half of 2022. After an initial embargo period, the dataset will be made available to the broader community by the end of 2022.

References

- Domeisen, D.I.V., *et al.*, 2019a: [The role of the stratosphere in subseasonal to seasonal prediction Part I: Predictability of the stratosphere](#). Journal of Geophysical Research: Atmospheres, 124.
- Domeisen, D.I.V., *et al.*, 2019b: [The role of the stratosphere in subseasonal to seasonal prediction Part II: Predictability arising from stratosphere - troposphere coupling](#). Journal of Geophysical Research: Atmospheres, 124.

CCMI-2022: A new set of Chemistry-Climate Model Initiative (CCMI) Community Simulations to Update the Assessment of Models and Support Upcoming Ozone Assessment Activities

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Introduction

The second phase of the Chemistry-Climate Model Validation Activity (CCMVal-2) (Eyring *et al.*, 2008) produced an extensive assessment of the dynamical and chemical aspects of many chemistry-climate models (CCMs) against a wide range of available observations. The main output from that activity took the form of a 400-page report (SPARC, 2010) and provided an important base of information for the 2010 WMO/UNEP Scientific Assessment of Ozone Depletion. CCMs have evolved considerably since CCMVal-2 and while there have been ad hoc assessments of certain aspects of more recent simulations, for example the comparison of ozone trends from simulations performed for the first phase of the Chemistry Climate Model Initiative (CCMI-I; Eyring *et al.*, 2013) with observations as part of the Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) activity (SPARC/IO3C/GAW, 2019), there has not been a comprehensive assessment of models since CCMVal-2. Additionally, since CCMVal-2 many new reanalysis datasets have been produced [e.g., the ECMWF ReAnalyses ERA-Interim (Dee *et al.*, 2011) and ERA5 (Hersbach *et al.*, 2020), the Modern-Era Retrospective analysis for Research and Applications MERRA-2 (Gelaro *et al.*, 2017) and the Japanese 55-year Reanalysis JRA-55 (Kobayashi *et al.*,

2015)]; new merged and harmonized data products have been developed [e.g. the Global Ozone Chemistry And Related trace gas Data records for the Stratosphere GOZCARDS (Froidevaux *et al.*, 2015) and the SPARC-Data Initiative (SPARC, 2017)]; and coordinated data record assessments have been conducted [e.g., the SPARC-Data Initiative, LOTUS and the SPARC Reanalysis Intercomparison Project (Fujiwara *et al.*, 2017)].

In addition, the process for developing the 2022 Scientific Assessment of Ozone Depletion is currently underway and expected to be completed in early 2022. Projections of ozone from CCMI-I (Eyring *et al.*, 2013), were analyzed in Dhomse *et al.* (2018) and were an important resource for the 2018 Ozone Assessment (WMO, 2018). The CCMI-I simulations were based on a scenario of near-surface concentrations of Ozone Depleting Substances (ODSs) from WMO (2010). These CCMI-I simulations also used scenarios for Long-Lived Greenhouse Gas concentrations and ozone and aerosol precursor emissions from CMIP5. With the recent release of new scenarios for CMIP6 the time seems opportune to update projections of ozone. The updates for CMIP6 are also significant in that they include a number of important updates for forcings, including a revised dataset of solar spectral irradiance (Matthes *et al.*, 2017).

Given the length of time since the last comprehensive assessment of chemistry climate models, the tremendous developments of atmospheric reanalysis and other sources of observational data, and the fast-approaching 2022 Ozone Assessment, the IGAC/SPARC CCM1 project has developed a new set of coordinated CCM experiments, called CCM1-2022, to be run by participating modelling centres. One goal of the current set of simulations is to conduct an updated assessment of the current generation of CCMs by revisiting and extending the suite of diagnostics that were performed for CCMVal-2, taking advantage of the development of new reanalysis and observational datasets. A second important goal of the simulations is to provide input for some of the high-profile scientific topics that have been put to the Assessment Panel by the Parties to the Montreal Protocol.

Recognizing the short time available, and the significant resources required to perform these simulations and provide data in the requested format, the number of requested simulations has been kept to a minimum. A historical hindcast simulation covering 1960–2018, referred to as the **refD1** simulation, has been specified using forcing data that reproduces the observed historical record as closely as possible. The hindcast simulation will provide data for an assessment of models against observations using process-oriented diagnostics and test the ability of models to reproduce the observed trends and interannual variability in ozone, particularly over the post-2000 period when ODSs have been slowly declining. To update projections of ozone recovery, a baseline scenario (**refD2**)

has been developed that closely follows the specifications of the CMIP6 SSP2-4.5 scenario (O'Neill *et al.*, 2016) with ODSs from WMO (2018). Following Decision XXXI/2 of the Montreal Protocol on Substances that Deplete the Ozone Layer, which requested 'information and research related to solar radiation management and its potential effect on the stratospheric ozone layer' (UNEP, 2020), a stratospheric aerosol intervention (SAI) scenario has been developed, **senD2-sai**, using the same forcings as the refD2 baseline but with increased specified stratospheric aerosol amounts from 2025 to 2100. These three simulations are all assigned a high priority for participating groups. The general outline of the setup for these three experiments is given in Table 8 with more details provided below.

For modelling groups with sufficient available resources, an additional two scenarios have been developed to investigate different climate change scenarios; a low mitigation scenario following the CMIP6 SSP3-7.0 scenario (**senD2-ssp370**) and a high mitigation scenario following SSP1-2.6 (**senD2-ssp126**).

The analysis of the CCM1-I set of simulations by Dhomse *et al.* (2018) highlighted the confounding effects of internal variability on assessing the timing of the return of ozone column amounts to historical values, typically the value at the year 1980. The problems were particularly significant for the sensitivity scenarios that were specified for CCM1-I, which often were run by only a small set of all participating models and then with only a single simulation from each model.

Exp. Name	Forcing	Period			
		1960 – 2014	2015 – 2018	2019 – 2024	2025 – 2100
refD1	GHGs	CMIP6 Historical	SSP2-4.5 + revised methane		
	ODSs	WMO (2018) + revisions for 2018–2019			
	Ozone/Aerosol Precursors	CMIP6 Historical	SSP2-4.5		
	Open Burning	CMIP6 Historical	GFED4s or repeating avg(2010–2014)		
	SSTs / sea-ice	HadISSTs			
	Ext-T SSI	CMIP6 Extended			
	SAD	CMIP6 Extended			
	QBO	Relaxed to observed winds			
refD2	GHGs	CMIP6 Historical		SSP2-4.5	
	ODSs			WMO (2018)	
	Ozone/Aerosol Precursors	CMIP6 Historical		SSP2-4.5	
	Open Burning	CMIP6 Historical		SSP2-4.5	
	SSTs / sea-ice	Model SSTs - fully coupled or specified from another AOGCM or ESM			
	Ext-T SSI	CMIP6			
	SAD	CMIP6 with CMIP6-recommended extension from 2014			
	QBO	Internally generated or relaxed to extended QBO dataset			
senD2-sai	GHGs				SSP2-4.5
	ODSs				WMO (2018)
	Ozone/Aerosol Precursors				SSP2-4.5
	Open Burning				SSP2-4.5
	SSTs / sea-ice				Repeating avg(2020–2030) from refD2
	Ext-T SSI				CMIP6
	SAD				Specified with effects of SAI
	QBO				Internally generated or relaxed to extended QBO dataset

Table 8: A summary of the specified forcings for the three high priority simulations for CCM1-2022.

By limiting the number of proposed experiments, we are hoping for a more homogeneous participation of models across experiments and the generation of a small ensemble by each model for each experiment. We strongly encourage participating modelling groups to commit to producing a minimum of three ensemble members for each of the experiments and to participating fully across the three high-priority simulations.

A dedicated webpage with links to the experiment description, the data request and ancillary data can be found on the CCMI website at: <https://blogs.reading.ac.uk/ccmi/ccmi-2022/>. Updates as the work progresses will also be found at this location. Detailed specifications for the setup of each of the model experiments are given below.

The refDI hindcast simulation for 1960 - 2018

The model assessment will be based on a small ensemble of hindcast simulations performed using specified SSTs and sea-ice cover for the 1960-2018 period, with a sufficient spin-up prior to 1960 (~10 years) that the stratosphere is properly initialized. As the primary focus of the refDI simulation will be to assess models against observations, the forcing data is based as much as possible on observations, largely using databases developed for CMIP6 and available through the input4MIPs activity. A discussion of the different input4MIPs forcing datasets can be found at <http://goo.gl/r8up3l>.

Long-lived Greenhouse Gases:

Mixing ratios of the long-lived greenhouse gases such as CO₂, CH₄ and N₂O are to be specified following the CMIP6 historical database (Meinshausen *et al.*, 2017) up to 2014 and extended to the end of 2018 following SSP2-4.5 (Meinshausen *et al.*, 2020).

As shown in Figure 13, the specified near-surface methane concentration in all of the SSPs shows an unrealistically large increase over 2016-2017. To avoid introducing this increase into the models the four different versions (produced with different time and latitudinal resolution) of the original SSP2-4.5 methane forcing files have been scaled using a set of monthly-varying, global correction factors to produce new files for 2015 to 2019. These modified methane timeseries are recommended for the refDI simulation and can be found [here](#). We leave it to the individual modelling groups to decide which version they wish to use.

Ozone Depleting Substances

The near-surface mixing ratios of the important Ozone Depleting Substances controlled under the Montreal Protocol (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl₄, CH₃CCl₃, HCFC-22, HCFC-141b, HCFC-142b, Halon-1211, Halon-1202, Halon-1301, Halon-2402, CH₃Br, and CH₃Cl) are to follow a slightly modified version of the WMO (2018) baseline scenario given in Table 6-4 of WMO (2018). The WMO-2018 scenario was based on observed near-surface concentrations until 2017. For the refDI simulation the timeseries for CFC-11, CFC-12, CCl₄, HCFC-22 and CH₃Cl have been revised for 2018 and 2019 based on more recent NOAA/ESRL Global Monitoring Laboratory data, while the original values from WMO (2018) are used for the remaining species. The recommended timeseries of global average near-surface mixing ratios with annual time resolution can be found [here](#).

For models that do not represent all of the specified brominated and chlorinated species, the chlorine and bromine content from missing species should be added to existing model tracers with similar lifetimes to preserve total chlorine or bromine.

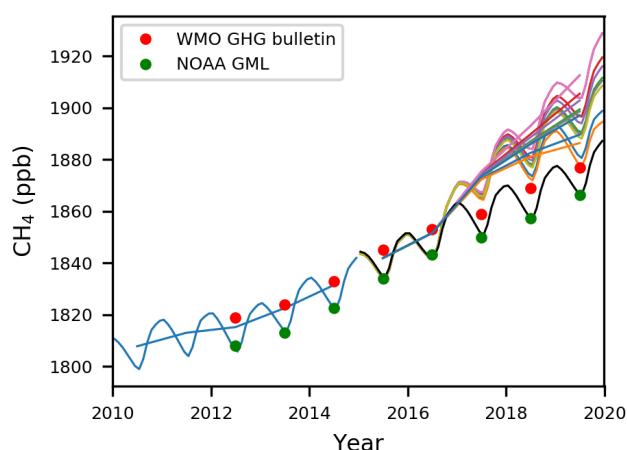


Figure 13: The global average near-surface concentration of methane from the CMIP6 historical period up to 2014 (Meinshausen *et al.*, 2017). From 2015, the same quantity from the four Tier 1 and four Tier 2 SSPs are shown (Meinshausen *et al.*, 2020). Both annual average and monthly average concentrations are plotted. The annual average, global average methane concentration derived from observations are shown for data from the WMO Global Atmospheric Watch Program (WMO, 2020) and the National Oceanic and Atmospheric Administration Global Monitoring Laboratory (NOAA GML) (Dlugokencky *et al.*, 1994). The observations have been used to scale the SSP2-4.5 methane from 2015 to produce the recommended methane forcing file for the refDI hindcast simulation, shown by the black line.

Very Short-Lived Source Gases

As was the case for previous community simulations, we ask modelling groups to account for the additional bromine introduced to the stratosphere by Very Short-Lived Source Gases (VSL-SGs) by explicitly including two of the important VSL-SG species CHBr_3 and CH_2Br_2 . By imposing a near-surface volume mixing ratio of 1.2 ppt each (6.0 ppt of Br) and having these two source gases decompose to inorganic bromine species directly, models should achieve the required 4.5 ppt to 5.0 ppt of bromine from VSL-SGs in the stratosphere. For modelling groups that do not wish to include these VSL-SGs and model tropospheric loss, the model CH_3Br tracer can be increased by a constant 5 ppt in the troposphere.

Note that these experiments do not explicitly consider chlorine-containing VSL-SGs. If groups do include a representation of VSL-SGs containing chlorine we ask them to limit the concentration imposed as a lower boundary condition to a small, constant value. If groups specify a flux boundary condition, we ask groups to zero out the anthropogenic component.

Natural biogenic emissions and lightning emissions of NO_x

These emissions are sensitive to meteorological variability and climate change and it is therefore preferable that models diagnose these emissions online using their own suite of interactive parameterizations. Climatological emissions may provide an acceptable solution for those models with an upper tropospheric/stratospheric emphasis. Lightning emissions are more difficult to specify in an externally consistent manner, but are important to upper tropospheric variability and the tropospheric oxidant balance.

Anthropogenic precursor emissions

The complete set of anthropogenic emissions is to be taken from the [CMIP6 input4MIPs databases](#) for the historical period to 2014 and following RCP2-4.5 until 2018. Emissions from sectors other than open biomass burning (aircraft; non-combustion agricultural emissions; energy; industry; surface transportation; residential, commercial and other; solvents; waste disposal; international shipping) are to be taken from the $0.5^\circ \times 0.5^\circ$ monthly files produced from the Community Emissions Data System (CEDS) as detailed in Hoesly et al. (2018) for the historical period. For 2015 and subsequent years, emissions are to be taken from version 1-1 of SSP2-4.5 (Gidden et al., 2019), which provides emissions as 12 monthly fields for

2015 and 2020 and will need to be interpolated in time to provide emissions for intermediate years.

Open biomass burning emissions

For open biomass burning, emissions are to be taken from version 1.2 of the historical dataset constructed for CMIP6 (BB4CMIP6-1-2) and detailed in van Marle et al. (2017). Take special note that the open biomass burning emissions of NO_x ($\text{NO} + \text{NO}_2$) are expressed as $\text{kg-NO/m}^2/\text{s}$ while the other anthropogenic NO_x emissions are in units of $\text{kg-NO}_2/\text{m}^2/\text{s}$. More information on the CMIP6 historical open biomass burning emissions can be found at <http://globalfiredata.org/pages/ar6-historic/>.

Note that the historical biomass burning emissions includes data for 2015. For 2016 and subsequent years, open biomass burning emissions are to be calculated from the GFED4s database (<https://globalfiredata.org/pages/data/#emissions>), which will provide a consistent extension of the open biomass burning emissions as the CMIP6 historical emissions use GFED4s for years 1997-2015. Note that the GFED4s data is in a significantly different format to that of the CMIP6 emission dataset and, if groups prefer, they may construct a repeating annual cycle of open biomass burning emission from the CMIP6 historical dataset using data from 2010-2014. Avoid including 2015 in the average as this was an extreme burning year in south-east Asia.

Sea surface temperatures (SSTs) and sea ice concentrations (SICs)

The historical simulation uses specified SSTs and SICs, prescribed as monthly mean boundary conditions following the global HadISST1 sea ice concentration and sea surface temperature data set provided by the UK Met Office Hadley Centre (Rayner et al., 2003). The data set can be downloaded from <https://www.metoffice.gov.uk/hadobs/hadisst/index.html>. To prepare the data for use in forcing a model, and in particular to correct for the loss of variance due to time-interpolation of monthly mean data, it is recommended that each group apply the AMIP II variance correction method (see <https://pcmdi.llnl.gov/mips/amip/details/index.html> for details) to the HadISST1 data.

Quasi-Biennial Oscillation (QBO)

While it is possible to internally generate a QBO in models, it is generally not possible to guarantee that the model-generated QBO is in phase with the observed historical variability.

To ensure the model QBO remains synchronized with the historical variability, whether a model is capable of internally generating a QBO or not, we ask modelling groups to relax zonal winds (nudge) in the QBO domain towards the observed historical variations from radiosonde observations. A dataset of monthly average zonal winds for this purpose, covering 1953 - 2019 and based on updated radiosonde measurements following the method of Naujokat (1986) extended to the upper stratosphere, can be found [here](#).

Extra-terrestrial solar flux and solar cycle

The dataset of time-varying extra-terrestrial solar flux produced for CMIP6 contains important revisions to the solar spectrum, including a larger magnitude variation associated with the 11-year solar cycle in the 200 - 400nm region, compared to what has been used for CCMI-I (Matthes *et al.* 2017). We strongly recommend modelling groups adopt the CMIP6 time-varying solar spectral irradiance (SSI) for the calculation of chemistry. For the refD1 simulation the SOLARIS-HEPPA group has produced an extended daily, spectrally resolved solar irradiance that is consistent with the historical forcing dataset produced for CMIP6, but with data to the end of 2019. The dataset also includes atmospheric ionization rates due to mid-energy electrons, solar protons and cosmic rays and, for models that are capable of simulating the indirect effects of particle precipitation through an upper boundary condition on NO_y, there is a package available to calculate the necessary quantities to specify NO_y as an upper boundary condition. More information on the SOLARIS-HEPPA solar forcing dataset can be found at <https://solarisheppa.geomar.de/solarisheppa/ccmi2022>.

Stratospheric aerosol surface area density (SAD)

An extended version of the CMIP6 stratospheric aerosol SAD dataset has been prepared using version 2.0 of the Global Space-based Stratospheric Aerosol Climatology (Kovilakam *et al.*, 2020). This dataset extends to the end of 2018 the version 3-0-0 zonal mean monthly mean stratospheric aerosol SAD produced for the CMIP6 historical period. The format of the data is identical to the CMIP6 data and can be found at: ftp://iacftp.ethz.ch/pub_read/luo/CMIP6_SAD_radForcing_v4.0.0_1850-2018/

Note that aerosol values that appear in the tropo-

sphere are not considered reliable and should not be used. These values are included to allow for a seamless merging of the specified aerosols in the stratosphere with the model representation of tropospheric aerosols and should be ignored for model levels below the diagnosed local tropopause. The file also includes additional aerosol quantities such as mean radius, volume density and H₂SO₄ mass derived from the assumed single mode log-normal aerosol size distribution if required by models. Fields of extinction, single scattering albedo and asymmetry calculated for the specific wavelength bands of individual model radiation schemes are also available at the same web address.

The refD2 Baseline projection simulation for 1960 - 2100

The baseline projection of ozone recovery will be based on a small ensemble of simulations for the 1960 - 2100 period, with a sufficient spin-up prior to 1960 (~ 10 years) that the stratosphere is properly initialized. The baseline projection will follow the SSP 2-4.5 scenario of CMIP6 and will largely follow the same specifications as used for CMIP6. One significant difference is the time evolution of the near-surface concentration of ODSs, which are to be taken from the baseline scenario of WMO (2018) given in Table 6-4 of the 2018 Assessment.

Long-lived Greenhouse Gases

Mixing ratios of the long-lived greenhouse gases such as CO₂, CH₄ and N₂O are to be specified following the CMIP6 historical database (Meinshausen *et al.*, 2017) up to 2014 and extended to the end of 2100 following SSP2-4.5 (Meinshausen *et al.*, 2020). While a modified version of the methane forcing was developed for the 2015 - 2019 period of the refD1 historical simulation, to ensure a smooth transition beyond the period of available observations this data should not be used for the projection simulations.

Ozone Depleting Substances

The near-surface mixing ratios of Ozone Depleting Substances controlled under the Montreal Protocol are to follow the original WMO (2018) baseline scenario as given in Table 6-4 of the report. The recommended file of global average near-surface mixing ratios with annual time resolution for 1949 - 2101 can be found [here](#).

Very Short-Lived Source Gases

As for the refD1 simulation, we ask modelling groups to account for the additional bromine introduced to the stratosphere by VSL-SGs by explicitly including two of the important species, CHBr_3 and CH_2Br_2 , following the same approach as for the refD1 experiment.

Natural biogenic emissions and lightning emissions of NO_x

These emissions are sensitive to meteorological variability and climate change and, as for the refD1 simulation, it is therefore preferable that models diagnose these emissions online using their own suite of interactive parameterizations.

Anthropogenic precursor emissions

The complete set of anthropogenic emissions for the refD2 simulation follows the same specifications as for the refD1, only extended to 2100: emissions are taken from the CMIP6 input4MIPs databases for the historical period to 2014 and follow SSP2-4.5 until 2100.

Open biomass burning emissions

For open biomass burning, emissions over the period to 2014 are specified in an identical manner as for the refD1 experiment. At the end of the historical period, groups should use version 1-1 of the SSP2-4.5 'openburning' emissions files provided for 2015, 2020 and every 10 years after. The available emissions need to be interpolated in time to provide data for intermediate years.

For the scenario simulations groups should not use 2015 from the historical biomass burning emission files, instead taking emissions for 2015 from the SSP2-4.5 dataset. Also note that the open burning emissions for the years 1997 - 2015 are based on year-specific data and, as a result, have considerably larger year-to-year variability than other years. In contrast to the approach in refD1, modelling groups may decide to apply some degree of temporal smoothing before using the open burning emissions in the refD2 simulation.

Sea surface temperatures (SSTs) and sea ice concentrations (SICs)

To avoid potential discontinuities, SSTs and sea ice concentrations should be consistently specified through-

out the entire 1960-2100 period. Depending on the capabilities of each modelling group, SSTs and sea-ice can be specified in a number of different ways:

1. Groups with a CCM fully coupled to a 3-D ocean model should perform coupled ocean-atmosphere simulations. Because of the long time constants inherent in the ocean, these simulations should be started at 1850 from an equilibrium pre-industrial control climate following the standard protocol for historical coupled model simulations with prescribed CO_2 concentrations.
2. CCM groups requiring specified SSTs and sea ice but with a closely related coupled atmosphere-ocean GCM within their institution, should use specified SSTs/sea ice taken from coupled model simulations performed by the related AOGCM. Ideally the AOGCM simulations used to calculate the SSTs and sea ice fields will have been performed following the CMIP6 historical and SSP2-4.5 forcings. If not available, the SSTs and sea ice may be taken from a simulation performed with radiative forcing close to that of the CMIP6 SSP2-4.5 scenario, the CMIP5 RCP4.5 for example. Note that if using specified SSTs and sea ice, different refD2 ensemble members should be performed with sets of SSTs/sea ice derived from different ensemble members of the AOGCM.
3. Groups that do not have access to a coupled atmosphere-ocean GCM within their institution should use SSTs/sea ice from one of the combined historical/SSP2-4.5 simulations available in the CMIP6 archive. If using specified SSTs and sea ice, different refD2 ensemble members should be performed with sets of SSTs/ sea ice taken from different ensemble members of the chosen CMIP6 model.

If specifying monthly average SSTs and sea ice, to correct for the loss of variance due to time-interpolation of monthly mean data it is recommended that each group apply the AMIP II variance correction method (see <https://pcmdi.llnl.gov/mips/amip/details/index.html> for details).

Quasi-Biennial Oscillation (QBO)

For models that do not internally generate a QBO, a dataset of monthly average tropical winds has been created by extending the historical record derived from observations (Naujokat, 1986) from March 2019 to December 2100.

Models that do not internally generate a QBO should relax (or nudge) zonal winds in the QBO domain towards this record. The recommended ascii data file of monthly tropical zonal winds to 2100 can be found [here](#) and additional supporting information can be found on the [CCMI website](#).

Modelling groups that are able to internally generate a QBO in the configuration being used for the refD2 experiment may choose to nudge to the specified QBO timeseries or allow their QBO to run freely as they see fit.

Extra-terrestrial solar flux and solar cycle

For the future scenario simulations we recommend using the original CMIP6 dataset (Matthes *et al.* 2017), version 3.2, as it will correctly transition between the observation-based historical portion of the record and the projections of solar activity to 2100. Datasets with daily and monthly-average total and spectrally-resolved solar irradiance data are available. More information on the SOLARIS-HEPPA CMIP6 solar forcing dataset can be found at <https://solarisheppa.geomar.de/cmip6>.

Stratospheric aerosol surface area density (SAD)

The extended version of the CMIP6 SAD dataset for the refD1 experiment is identical to the original CMIP6 dataset except for some minor differences following the Pinatubo eruption. For the scenario simulations, we recommend using the extended SAD, but follow the CMIP6 recipe to extend the record to 2100. The time-evolving SAD would be used to the end of 2014, then over a 10-year period the SAD would transition from a repeating annual cycle of 2014 data to a repeating annual cycle of monthly average SAD constructed from the 1850-2014 average.

The senD2-sai projection simulation for 2025 - 2100

The purpose of the CCMI-2022 stratospheric aerosol intervention (SAI) experiment (senD2-sai) is to explore the impact of an enhanced stratospheric aerosol burden on stratospheric chemistry and transport. SAI is a proposed climate intervention approach to increase the stratospheric aerosol burden to reflect some of the incoming solar radiation, thus cooling the Earth's surface and counteracting anthropogenic climate change. This experiment

requires all models to use the same prescribed transient stratospheric aerosol distribution that is continuously increasing with increasing greenhouse gas forcing, while assuming that the imposed aerosol layer would offset the warming by future GHG emissions, therefore keeping the tropospheric climate (global average near-surface temperature) relatively constant. Since different models will produce a different climate response using the same aerosol distribution, this experiment requires prescribing a repeating annual cycle of SSTs derived from a multi-year average of the model SSTs around the start of the SAI and maintained for the duration of the period when SAI is applied. The senD2-sai simulation will branch from the refD2 scenario performed by each group at the point in time when SAI is started, assumed to be January 1, 2025. Therefore, groups will need to ensure they are able to restart the refD2 simulation at January 1, 2025 using specified SSTs and sea-ice irrespective of how SSTs and sea-ice were calculated for the refD2 simulations. In keeping with the design of the experiment, the repeating annual cycle of specified SSTs and sea-ice from 2025 onwards should be calculated as the 2020-2030 average of the SSTs and sea-ice from the corresponding refD2 simulation. If groups performed the refD2 simulation with a coupled atmosphere-ocean model, specified SSTs and sea-ice calculated from the refD2 simulation as just described must be used for the senD2-sai simulation. Please also ensure that other aspects of the model setup (e.g., resolution, number of model levels) remains identical for both the refD2 and senD2-sai simulations.

The senD2-sai scenario will run for 2025-2100 using identical forcings to those used for the refD2 scenario, with the exception of the SSTs/sea-ice as just described and the specified stratospheric aerosol. The specified stratospheric aerosol fields of the original refD2 simulation will be replaced with transient stratospheric fields that have been calculated by CESM2(WACCM6) using a feedback control algorithm (Tilmes *et al.*, 2018, 2020) to ensure that SSTs in CESM2(WACCM6) remained at 2025 values. Further details of the specified SAD dataset for the senD2-sai experiment are provided on the [CCMI website](#).

Alternate radiative forcing scenario simulations for 1960 - 2100

The refD2 and senD2-sai simulations are assigned high priority as they directly address headline scientific issues identified for the 2022 Ozone Assessment.

For groups that have the necessary capacity, additional scenarios have also been defined with a lower priority. The senD2-ssp370 experiment follows the CMIP6 SSP3-7.0 scenario. The SSP3-7.0 scenario is one with low climate mitigation and high emissions of tropospheric ozone and aerosol precursors (Rao et al, 2017). The SSP3-7.0 scenario was also one of the central scenarios for AerChemMIP simulations (Keeble et al., 2021) and would provide an important link between AerChemMIP and the CCM1-2022 simulations.

The other experiment, senD2-sspl26, follows the CMIP6 SSPI-2.6 scenario, which represents a high climate mitigation scenario designed to explore the effects of a low future climate forcing. The SSPI-2.6 scenario will also produce a tropospheric climate similar to that produced in the senD2-sai simulation with geoengineering, thus providing an interesting comparison of two possible paths to a similar level of climate warming.

Forcings for SSP3-7.0 and SSPI-2.6

Both senD2-ssp370 and senD2-sspl26 should follow the CMIP6 specifications for the corresponding SSP scenario with the same exceptions as were noted for the refD2 scenario compared to SSP2-4.5; the near-surface concentrations of ozone depleting substance should follow the WMO (2018) baseline scenario and a QBO, either internally generated or through relaxation to the provided tropical wind profile, should be included.

Requested Model Output

An excel version of the data request can be found [here](#). Output from this simulation will be collected in netCDF version 4 format files that are compliant with the Climate and Forecast (CF) standard. Note that the specifics of the requested variables have been harmonized as much as possible with those requested for CMIP6, including aspects such as variable names, units and the set of constant pressure surfaces for zonal average fields.

The use of CMOR, specifically CMOR3, for conversion to netCDF is strongly encouraged. CMOR tables for all requested output in the JSON format used by CMOR3 can be found at <https://github.com/cedadev/ccmi-2022>. Model output are to be submitted to a central archive at the Centre for Environmental Data Analysis (CEDA) in the United Kingdom. More details on the directory structure and

the construction of filenames can be found [here](#).

Diagnostic Tracers

We ask modelling groups to include two diagnostic tracers in their simulation. The first is the standard 'Age of Stratospheric Air' tracer (meanage), defined as the mean time that a stratospheric air mass has been out of contact with the well-mixed troposphere. Different approaches can be used to estimate the mean age, though we recommend a tracer that is continually reset to zero in the troposphere and allowed to increase in value everywhere at a rate equal to the passage of time in the model.

The second diagnostic tracer is the 'Stratospheric Ozone' tracer (o3strat), that is set equal to the model ozone for all grid points above the local tropopause, decays with the odd oxygen chemical loss rate in the troposphere and deposits at the surface with the deposition velocity of ozone. We strongly recommend that groups use a common method to calculate the chemical loss of o3strat by specifying a first-order loss process with a chemical loss frequency given by

$$f_{o3strat} (s^{-1}) = \frac{k_A[O(^1D)][H_2O] + k_B[OH][O_3] + k_C[HO_2][O_3]}{[O_3]}.$$

The loss frequency is calculated at each model grid point using the local reaction rates (k_A , k_B and k_C) and local species concentrations, denoted by the square brackets. Here k_A is the reaction rate constant for $O(^1D) + H_2O \rightarrow 2OH$; k_B is the rate constant for $OH + O_3 \rightarrow HO_2 + O_2$; k_C is the rate constant for $HO_2 + O_3 \rightarrow OH + 2O_2$.

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Short report of the ESA Ozone_cci+ User Workshop

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DATES:

16- 17 March 2021

ORGANIZING COMMITTEE:

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MEETING VENUE:

online

NUMBER OF PARTICIPANTS: >100

SPONSORS:



WEBSITE:

<https://events.spacepole.be/event/121/>

The European Space Agency Climate Change Initiative (ESA-CCI) aims to realise the full potential of the long-term global Earth Observation archives that ESA, together with its member states, has established over the past 30 years. The Ozone_cci User Workshop was held on Tuesday 16 and Wednesday 17 March 2021 through 2 half-day virtual sessions via Webex.

This workshop focused on the generation and exploitation of CCI's harmonised multi-decadal Climate Data Records (CDRs) of atmospheric ozone observations suitable to assess long-term changes in total ozone and its vertical distribution, and their interaction with climate change. Its aim was to bring together scientists involved in the generation of ozone CDRs, data users of ozone CDRs, and the broader ozone community, in order to present the state of the art in ozone CDR production, and to discuss results from major CDR users. Topics addressed included stratospheric and tropospheric ozone assessments, research on the upper troposphere and lower stratosphere (UTLS) region, evaluation of climate modelling results, data assimilation and reanalysis. Another important aim of the workshop was also to collect and update user requirements for CDRs from current and future Earth Observation (EO) missions, and to discuss remaining challenges for the generation of ozone CDRs.

The workshop was attended by just over 100 international participants on both days. The presentations and their abstracts as well as a more detailed report are available on the [workshop website](#).

Ozone_cci data characteristics and availability

The first day of the workshop program started with presentations by the CCI team of the ozone climate data records in the CCI portfolio. Further, it was explained how the ozone CDRs are created within Ozone_cci, and data main characteristics and data availability were discussed, together with an overall assessment of data quality.

A welcome note was given in the beginning by **Christian Retscher**, representative from ESA on the ESA CCI programme. Among others, he mentioned that more than 10 years of research on ozone CDRs have been successfully carried out.

Many ozone CDRs are now available, which were presented and discussed in this workshop.

Michel van Roozendaal presented an introduction to the ESA project Ozone_cci, which was started as part of the ESA Climate programme on Climate Change with the ambition for high quality climate data records on Essential Climate Variables. Currently, 21 ECVs are addressed in the programme, in close collaboration with the Copernicus Climate Change Service (C3S) led by ECMWF. The Ozone_cci project provides the pre-operational development for the operational climate services. All Climate Data Records are open access.

Melanie Coldewey-Egbers presented the GOME-type Total Ozone Climate Data Record (GTO-ECV) based on GOME/ERS-2, SCIAMACHY/Envisat, GOME-2 (MetOp A/B) and TROPOMI/Sentinel-5P including monthly means on 1x1 degrees spatial resolution covering 25 years. A few scientific highlights on the use of the GOME-type Total Ozone CDR based on the most recent CDR using the GODFITv4 algorithm were presented.

A detailed quality assessment of the Level-2 and Level-3 total ozone column data records (GODFITv4) using the ground-based networks with excellent correlation were presented by **Katerina Garane**. The CDRs shown cover the period from July 1995 (GOME) to the end of 2020 for the subsequent ESA satellite instruments for total ozone column observations. The Level-3 climate data record (GTO-ECV) in the C3S, currently covering 25 years, is in close agreement to the Level-2 CDRs, with no significant drifts over time. It was concluded that both Level-2 and Level-3 Total Ozone products fulfil the requirements in terms of bias uncertainty and long-term stability.

As shown in an overview of the Ozone_cci ozone profile CDRs from nadir sensors, given by **Richard Siddans**, Nadir UV sensors and Nadir IR sensors both provide tropospheric ozone as well as stratospheric ozone products. Quite a few papers emerge from these data sets and some recent studies related to biomass burning events were highlighted. The longest IASI-based CDRs currently cover close to 15 years since the launch of the first IASI instrument on the MetOp-A platform.

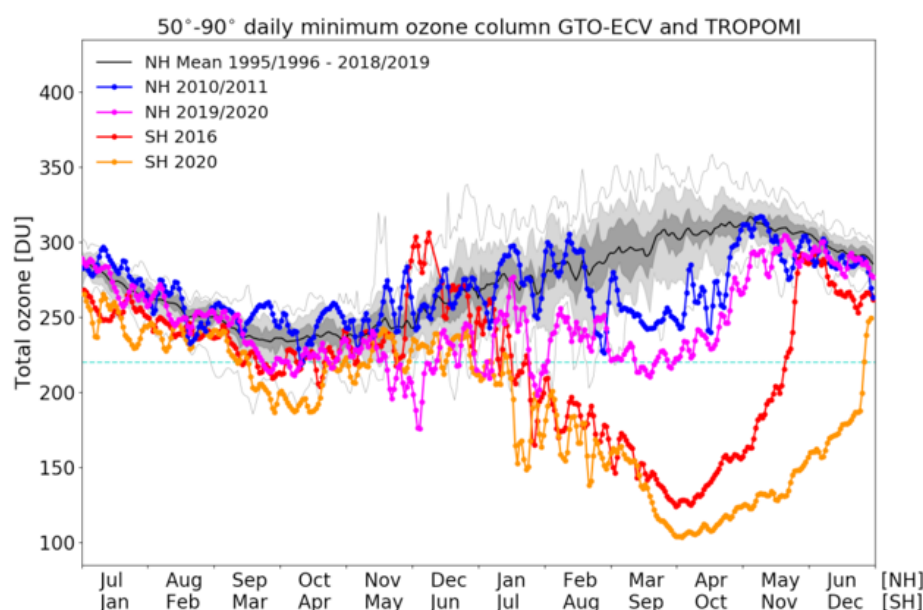


Figure 14: Annual cycle of the daily minimum total column ozone values in the north polar region (50°-90°N) and in the south polar region (50°-90°S) derived from the European satellite data record GOME-type Total Ozone Essential Climate Variable (GTO-ECV) from July 1995 to June 2019 and from TROPOMI/Sentinel-5 Precursor data from July 2019 to December 2020. The thick black line shows the GTO-ECV mean annual cycle in the north polar region and the thin black lines indicate the corresponding maximum and minimum values for the complete time period starting in 1995. The grey shadings denote the 10th and 90th percentile (light grey) and the 30th and 70th percentile (dark grey), respectively. The blue and magenta lines show the minimum values in the north polar region in the years 2010/2011 and 2019/2020. The red and orange curves show the minimum values in the south polar region in the years 2016 and 2020, respectively. The Southern Hemisphere data are shifted by 6 months. Update from Dameris et al. (2021).

An in-depth analysis of the quality assessment of the Level-2 and Level-3 nadir ozone profile CDRs was given by **Arno Keppens**. Various validation data sources were considered including the ground-based networks of WOUDC, SHADOZ, NDACC (a.o.). Biases and drifts of the nadir sensor derived CDRs relative to ozone sondes were shown as function of altitude.

Viktoria Sofieva presented an overview of the Level-2 and Level-3 ozone profile CDRs based on Limb and Occultation sensors including MIPAS, GOMOS, SCIAMACHY, OMPS-LP and ACE-FTS. Harmonized individual and merged CDRs were presented ultimately covering the period 1984 to 2020, including SAGE II data (a.o.).

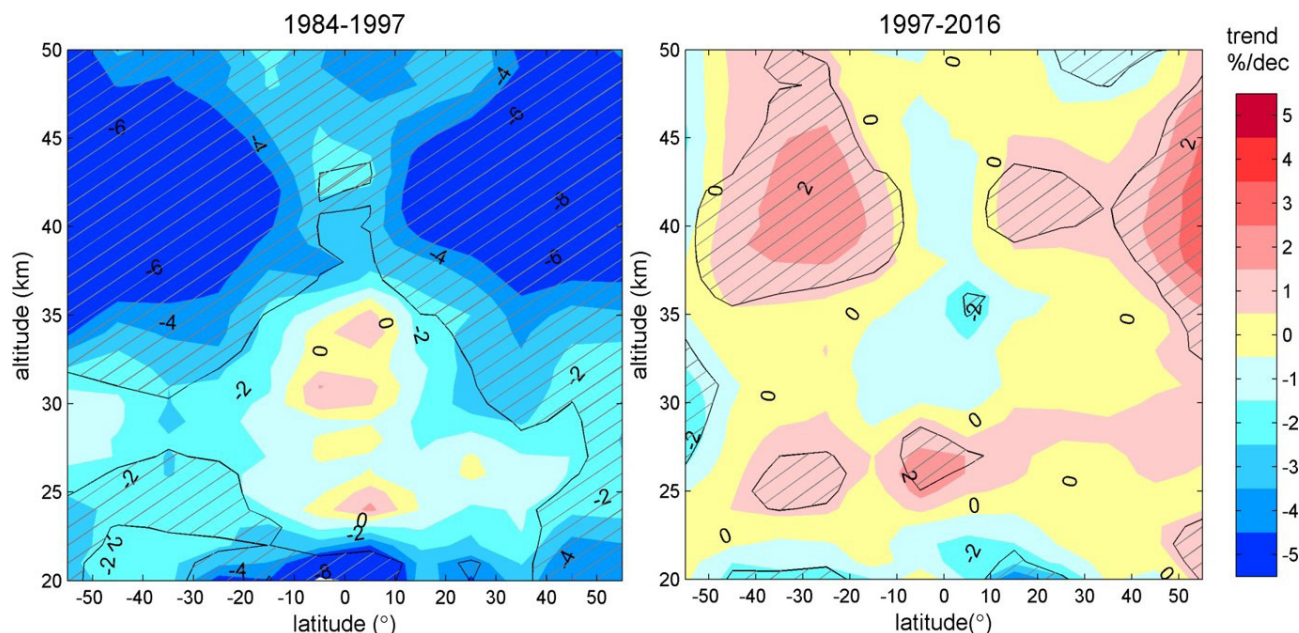


Figure 15: The ozone trend (% decade⁻¹) for different latitudes for 1984-1997 (left) and 1997-2016 (right). Shaded areas show regions where trends are statistically different from zero at the 95% level. Reproduced from Sofieva et al. (2017).

Recent results on altitude-dependent and regional ozone trends were presented in order to evaluate (the presence of significant) ozone recovery.

A detailed quality assessment of the Ozone_cci Limb ozone profile CDRs by independent ground-based networks was discussed by **Daan Hubert**. Results on bias, dispersion and drift were reported for a set of instruments and the derived CDRs. For Level-3 CDRs covering the 2001 - 2019 time period the granularity of the data record is most coarse because limb-based profiles are merged and gridded mostly to zonal monthly mean profiles. Recommendations on how to make best use of the Ozone_cci CDRs were given.

The user requirements in relation to data validation and quality assessment was introduced by **Jean-Christopher Lambert**. Validation requirements include aspects on the data products including e.g., altitude registration and important diagnostics such as averaging kernel, viewing geometry and many other quantities that affect retrievals. Lessons learnt with respect to validation, and remaining challenges were discussed, as well as validation requirements for upcoming satellite missions such as Altius and the observations from geostationary platforms.

The discussion at the end of Day 1 was moderated by **Jean-Christopher Lambert** and **Viktor Sofieva**. It was remarked that the long-term GOME-type nadir-based profile data records might

become more and more valuable for trend studies. However earlier limitations w.r.t. stability of shortest UV bands and the limited vertical resolution in nadir were also highlighted. This is particularly critical in the UTLS. Moreover, other species as measured e.g., by MLS are also needed to understand ozone chemistry.

While merged and gridded data sets are a logical choice for many users including chemistry-climate modelers, for other applications such as assimilation individual instrument-specific Level-2 data records qualify best. Continuation from reanalysis to near-real time data provision with only weeks to at most a month delay would prevent sudden changes in the prolongation of existing reanalysis records. The use of a data set in assimilation is further dependent on its uniqueness and long-term consistency (do not change versions too often). Bias and stability are very important in the evaluation of data set performance within the assimilation framework.

Representativeness in validation was considered important. Concurrently the need to increase the frequency and spatial coverage of validation data was pointed out, raising questions on how to ensure their sustainability. It was stressed that a more structural cooperation is needed across agencies. Finally, the potential impact on satellite validation of the recently reported post-2013 drop-off in total ozone at some stations of the ozone sonde network was highlighted.

Research applications of the Ozone_cci climate data records

The second day of the workshop focused on the use of Ozone_cci data in various studies and frameworks. The presentations were given by invited external researchers on selected scientific topics and international initiatives to which Ozone_cci climate data records provide important contributions.

Birgit Hassler in her presentation emphasized the specific need of consistent long-term data sets for ozone research. She introduced the main research questions of the upcoming 2022 WMO/UNEP Ozone Assessment, as well as the overall timeline of the report preparation. She pointed out where ESA-CCI ozone data was already used in analyses for previous WMO/UNEP Ozone Assessments, the SPARC project LOTUS (Long-term Ozone Trends and Uncertainties in

the Stratosphere), and the Tropospheric Ozone Assessment Report (TOAR).

In his talk, **Wolfgang Steinbrecht** focused on trends in total column and stratospheric ozone. While ground- and space-based observations show that the large ozone decline from the 1970s to the 1990s has been stopped thanks to the international ban of ozone depleting substances by the Montreal Protocol and its amendments, so far only the regions of largest ozone depletion, the upper stratosphere and the Antarctic ozone hole, show clearly improving trends. The slope of the expected recovery is about three times slower than the fast decline from the 1970s to the 1990s.

In her presentation of an assessment of tropospheric ozone by TOAR-II, **Jessica Neu** introduced the intercomparison of time series from multiple satellite instruments undertaken as part of TOAR-I, which shows substantial differences in

the net change in ozone over the past decade. In TOAR-II the possible sources of differences in these datasets are discussed and methodologies will be developed for quantifying expected differences in the ability of each product to better capture long-term variations in tropospheric ozone.

Based on OCTAV-UTLS, **Peter Hoor** mentioned that the ozone distribution in the UTLS is affected by the Brewer-Dobson Circulation (BDC) as well as transport across the tropopause and the jets. Complications arise particularly from the short-term variability of the tropopause and jet locations, which introduce variability in the ozone distribution. Examples of the remapping of the observations in jet- or tropopause-based coordinates with the JETPAC tool using MERRA-2 reanalysis data demonstrate a reduction in the ozone variability.

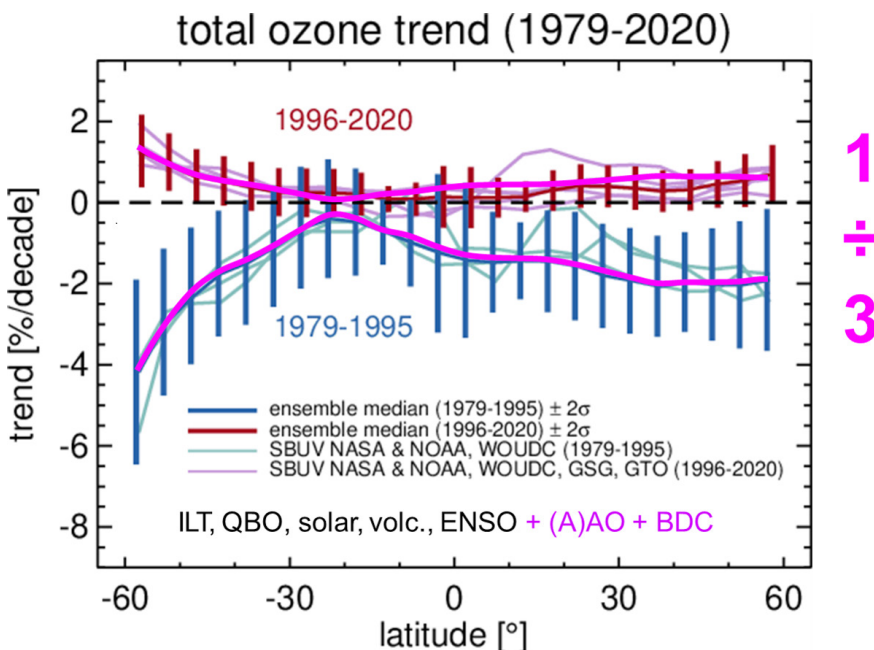


Figure 16: Total ozone trends as a function of latitude, and for the two periods 1979 to 1995 (blue colours, negative trends), and 1996 to 2020 (reddish colours, positive trends). Trends were estimated by multiple linear regression, using proxies for independent linear trends, QBO, solar cycle, volcanic aerosol, El-Nino/Southern Oscillation, Arctic and Antarctic Oscillation (AO and AAO), and strength of the Brewer-Dobson Circulation (BDC). The thin lines show observed trends from individual merged satellite data sets. The thick lines with error bars show the latitude dependent trends of the median of the different merged satellite datasets. From the long-term increase and decline of effective equivalent stratospheric chlorine loading (EESC), a fast increase until 1995, and a three times slower decline since 1996, one might expect a 3 to 1 ratio also for the ozone trends. The magenta lines in the figure show that simulated and observed ozone trends indeed follow this expectation, provided dynamical proxies are included in the multiple linear regression (AO, AAO, BDC). Update from Weber et al. (2018) and WMO (2018).

Stacey Frith showed a comparison of GTO-ECV and MERRA-2 including further plans. The adjusted MERRA-2 product combines the high spatial and temporal resolution of the MERRA-2 assimilation with the long-term consistency of the SBUV merged satellite record. The consistency between both products spatially and in time was discussed.

The results of an interesting comparison of observational ozone data to chemistry-climate models were discussed by **Hella Garny**. At time periods shorter than about 2 decades, internal variability strongly influences ozone trends and therefore complicates conclusions on (dis-)agreement between modelled and observed time series. In the lower stratosphere observational data indicate a decline in ozone mixing ratios in a broad latitudinal region extending well into the mid-latitudes, while models predict an ozone decline only in the tropics, but an increase in mid-latitudes. Possible reasons explaining this discrepancy are reviewed, including a possible misrepresentation of chemistry in models.

Finally, **Antje Inness** explained the CAMS current and planned ozone data assimilation activities. In addition to meteorological reanalyses, reanalyses of the atmospheric composition have been emerging in the last decade. The recently produced CAMS reanalysis CAMSRA can be used to assess ozone anomalies, e.g., related to the ozone hole. The importance of good quality, long term datasets as input for (future) reanalysis activities was stressed, including the CAMS-II reanalysis production, which is scheduled to start in 2023 and the ERA6 reanalysis scheduled to start in 2024.

The discussion at the end of Day 2 was moderated by **Michiel van Weele** and **Martin Dameris**.

The importance of the continuation of research activities within Ozone_cci was stressed, as well as the ongoing cooperation on the creation, inter-comparison and analysis of the ozone CDRs deriving from the different space agencies.

The workshop participants consider the user needs on forecast and reanalysis as important as feeding long-term monitoring needs. Further, the participants stressed the continued need for independent validation data records.

Continuation of limb observation capacity is required to mitigate important drawbacks of nadir-based ozone vertical profile-based trends for the UTLS vertical resolution and instrument stability at the shortest UV bands.

For the potential production of data sets in non-standard coordinates (useful for attribution studies), attention was drawn on a proper error propagation in the production of such climate data records.

In his concluding remarks, **Christian Retscher** stressed the importance of the ozone ECV project for the European Space Agency. Based on the presentations given during the two days of the workshop, it is clear that the project has gained a high visibility at the international level.

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Multi-species analysis key for testing chemistry-transport models in the upper-troposphere and lower stratosphere (UT/LS)

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The earth's environment of land, ocean and atmosphere are intricately linked. Many changes at the land and ocean surfaces affect the earth's atmosphere, in terms of radiation budget by changing chemical composition. Thus, it is well recognised that we need an improved understanding of the distribution of short-lived and long-lived chemical species covering the troposphere (altitude range of about 0 - 15 km) and stratosphere (altitude range of about 15 - 45 km) in particular (Figure 17). The variability in species of different atmospheric lifetimes show distinct features arising from transport processes in the troposphere and stratosphere, their photochemical transformations and spatio-temporal behaviours in emissions on the Earth's surface. The time and space variability scales of chemical constituents are usually short near the surface, resulting in large heterogeneity in concentrations, which are relatively homogenous with increasing altitudes up until the upper troposphere (UT), and further smoothens out in the lower stratosphere (LS). For example, by utilizing the wider representativeness of the middle-to-upper troposphere, the CO₂ seasonal surface fluxes at the hemispheric scale was linked with the middle tropospheric CO₂ data, which was used for deriving a robust metric on biosphere-CO₂ response due to climate change over a period 1958-2011 (Graven *et al.* 2013).

Long-term (about a full annual cycle or longer) measurements of carbon dioxide (CO₂), methane (CH₄), along with many other species, are made in the UT region over South Asia by the Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container (CARIBIC) programme (Schuck *et al.* 2010). By using multi-species observations and a chemical-transport model, it was possible for the first time, to clarify the opposite phase of CO₂ and CH₄ seasonal cycles that are essentially driven by the opposite phases of surface fluxes under the influence of monsoon (Patra *et al.* 2011). Contrary to CO₂ and CH₄ whose anthropogenic emissions reside primarily in the Northern Hemisphere, it was also found that methyl chloride (CH₃Cl) with strong natural tropical emissions shows very dif-

ferent atmospheric distribution pattern in the UT/LS (Umezawa *et al.* 2015). The UT/LS play a special role in transporting bromine (Br) containing very short-lived species (VSLS), but large uncertainty in model transport prove accurate estimation difficult based on sparse observations of bromoform (CHBr₃) and dibromomethane (CH₂Br₂) (Hossaini *et al.* 2016). Recent multi-tracer observation campaigns covering densely all tropospheric altitudes over a wide geographical area between the north and south poles have improved our understanding of chemistry-transport-emission processes in species distribution (Wofsy 2011; Patra *et al.* 2014; Baier *et al.* 2020).

Atmospheric chemistry-transport models (ACTMs) are improved for better simulation of chemical species distribution in the troposphere and the stratosphere, but it has been challenging to find observable metrics for evaluations of how well various processes are represented in such models. A recent study (Bisht *et al.* 2021) has used a maximum of four well-studied long-lived greenhouse gases (GHGs) simultaneously, as measured by the Comprehensive Observation Network for TRace gases by Air-Liner (CONTRAIL) programme (Sawa *et al.* 2015). Bisht *et al.* (2021) firstly explain the observed variabilities in the UT/LS region by using known spatial-temporal patterns of surface fluxes, and then probe the uncertainties in the ACTM developed at JAMSTEC. The JAMSTEC's MIROC4-ACTM is based on general circulation Model for Interdisciplinary Research on Climate, version 4.0 (Watanabe *et al.* 2008). They have analysed GHGs observations between Australia – Japan – Europe of the Japan Airlines (JAL) commercial flight corridor. The CO₂ seasonal cycle in the UT, with winter-spring maximum and summer-autumn minimum, in different latitude bands of the northern hemisphere is primarily governed by propagation of the seasonality in its surface biospheric fluxes. The model suggests that the CH₄ seasonality is largely driven due to loss by reaction with hydroxyl (OH) in low latitudes (10° S-10° N), overwhelming the seasonal changes in the tropical CH₄ emissions.

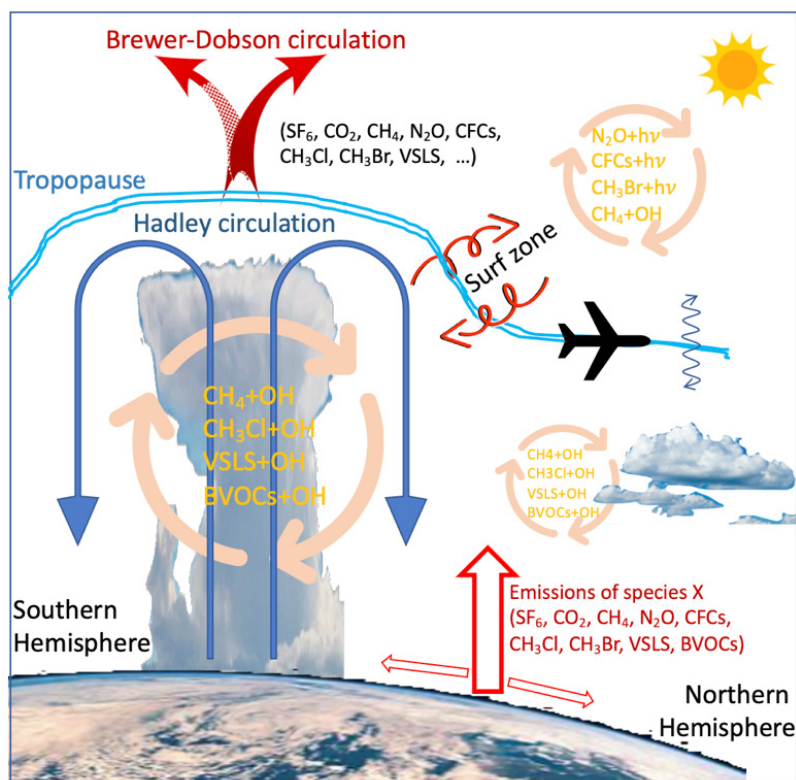


Figure 17: Schematic diagram of primary emissions of chemical species on the earth's surface (open arrows in red), and their simplified chemical (text within the circular arrows in brown) and dynamical interactions (curved or spiral arrows) in the troposphere before escaping to the stratosphere. The species with intermediate to long lifetimes of months to years in the atmosphere are able to cross the tropopause barrier in significant amounts through the tropical upwelling (Hadley circulation) and the extratropical surf zone. Species are redistributed in the stratosphere by the Brewer-Dobson circulation. The size of the circular arrow in the tropical troposphere (region of the Hadley circulation), midlatitude troposphere or in the stratosphere depicts relative loss rates of these chemical species mainly by chemical reaction with hydroxyl radical (OH) and photolysis by ultraviolet radiation (hν) in the stratosphere. Commercial airliners, like those used for atmospheric measurements (e.g., CARIBIC and CONTRAIL), usually cruise in the tropopause region at mid-high latitudes and in the UT in the tropics.

The seasonality in sulphur hexafluoride (SF₆) and nitrous oxide (N₂O) is generally weak in the troposphere. The JAMSTEC's ACTM simulates the observed features in all the 4 species quite well, confirming the above-mentioned processes.

Bisht *et al.* (2021) further show that the MIROC4-ACTM simulations have important deviations from the observations in the LS region. In this study, the UT and LS are separated based on a newly formulated PV (potential vorticity) threshold, a meteorological measure of altitude, by locating the maximum gradient with altitude. Vertical profile comparisons of all the 4 species show that ACTM better simulate the photo-chemically inert CO₂ in all seasons in the LS region, suggesting a realistic representation of the Brewer-Dobson circulation (an upwelling circulation from the tropical LS to the deep stratosphere and subsequent downwelling in the mid-high latitudes, as depicted in Figure 17). The observed SF₆, CH₄ and N₂O concentrations

exhibit pronounced seasonal variability in the LS with a minimum in spring-summer and a maximum in autumn-winter. MIRCO4-ACTM reproduces these seasonal variations well during September-March, whereas it overestimates the species concentrations during May-August. To explain the seasonal variabilities of the long-lived species in the LS, the mean "age of air" derived from CO₂ is used. Age of air is defined as the time for an air parcel to travel from the Earth's surface (location of emissions) to various layers of the atmosphere. It is found that, in the older air regime, the model mixes UT and LS air more vigorously than that can be derived from observations in the months of May-July, along the Japan-Europe flight tracks.

The MIROC4-ACTM simulated mean age of air distributions for January suggest that the shallower branch of Brewer-Dobson circulation brings older air from the middle-upper stratosphere to the LS observation locations in the northern high latitudes.

At the same time, during July, the cross-isentropic transport brings younger tropospheric air to the extratropical LS, most likely through the surf zone (Figure 17). The long-term regular measurements from commercial aircraft at cruising altitudes are providing valuable information for atmospheric model validation; however, we envisage that more campaigns using the world's high-altitude research air-

craft (e.g., NASA ER-2, DLR HALO, Russian Geophysica) will cover wider latitudes and altitudes, which would further strengthen model developments in the crucial UT/LS transition zones. Such model improvement along with new data is of particular interest to the application of satellite and ground remote sensing observations for sources and sinks estimation of greenhouse gases by inverse modelling.

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