APARC
Atmospheric Processes And their Role in Climate

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Source: Fabrizio Vignali, PMOD/WRC

Welcome to the latest edition of the APARC Newsletter. This time, our cover features the MeteoSwiss measurement facilities at PMOD/WRC in Davos, Switzerland, with Dobson and Brewer spectrophotometers that represent a century of atmospheric observations. The 100th anniversary of stratospheric ozone measurements in Arosa/Davos (1926–2026) is being celebrated on 25 July 2026 in Davos. To mark this milestone, this issue features a comprehensive article looking back at 100 years of continuous ozone observations in Switzerland, highlighting the scientific achievements and the continuing value of this unique long-term record. Another anniversary is reflected in a report from the NDACC Symposium in Virginia Beach, where the network celebrated its 35th anniversary. Finally, a change in APARC leadership is acknowledged as Karen Rosenlof stepped down as Co-Chair after many years of dedicated service, and Paul Kushner is welcomed as the new Co-Chair from 1 July 2026.
We hope you enjoy reading this collection of contributions from across the APARC community.

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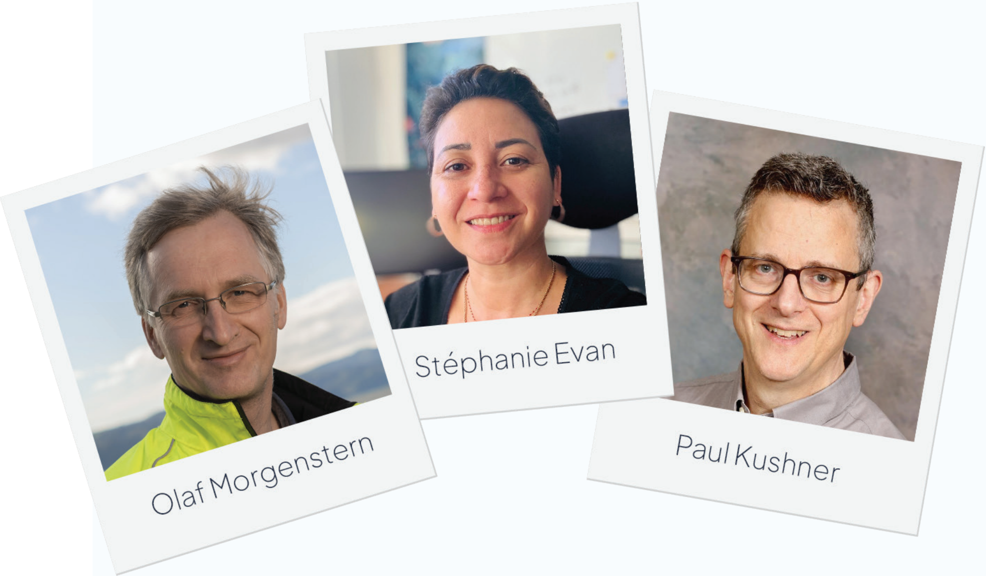
Olaf Morgenstern

Stéphanie Evan

Paul Kushner

We express our gratitude to Karen Rosenlof as her term as APARC Co-Chair draws to a close. Karen's scientific contributions have shaped, and continue to shape, APARC/SPARC science across an exceptional breadth of topics. In 2016, Karen received the Yoram J. Kaufman Oustanding Research and Unselfish Cooperation Award, a distinction that reflects not only her scientific excellence, but also the generosity, dedication and collaborative spirit through which she has inspired, and continues to inspire so many scientists in our community. We are deeply grateful for her steady leadership, vast experience, and deep understanding of the SPARC/APARC community, and we wish her all the best for her retirement. At the same time, we cordially welcome Paul Kushner to the team. His early roots are in APARC science; more recently he has ventured into the troposphere domain and is therefore well placed to help lead APARC into the whole-atmosphere direction that has been the philosophy behind the recent rebranding from SPARC to APARC. We are looking forward to working with Paul.

The recent online WCRP leadership meeting highlighted the evolving context in which WCRP and all its activities, including APARC, are now operating. While the current financial landscape inevitably calls for careful prioritization across WCRP, the need for APARC science remains unquestionable. This situation also invites the climate community to think more broadly about how to sustain research activities, observational capacity, and international coordination beyond traditional research funding programs. As AI and machine learning become increasingly important across weather forecasting, data analysis and climate science more broadly, strong engagement from the community will be essential. As APARC evolves in response to these challenges, it can draw on the scientific expertise, experience, and deep community knowledge that have made it a long-standing and widely recognized activity within WCRP and the broader atmospheric science community.

What makes this moment one of opportunity, rather than only constraint, is APARC's distinctive place within WCRP. APARC is the community that studies the atmosphere as the most immediate and pervasive medium linking all components of the Earth system, where many climate forcings are expressed, mediated, and redistributed, and through which their signals affect the ocean, cryosphere, land surface, and biosphere. For more than three decades, this vantage point has kept APARC at the heart of understanding atmospheric composition change, atmospheric dynamical and climate variability, and the processes, thresholds, and irreversibilities that shape climate risk. APARC was relevant when this science was still emerging; it is relevant now;

and as these questions move increasingly to the centre of climate prediction, risk assessment, mitigation, and adaptation, it will remain so.

It is in this spirit of continuity and shared purpose that the community will come together this fall. The APARC General Assembly (12-16 October, Pune) is going to be the seminal APARC event of the year. A huge thanks to IITM, the organizing team (led by Suvarna Fadnavis) as well as the scientific organizing committee (led by Hella Garny and Jonathon Wright) who have shouldered the burden of getting this conference off the ground. Abstract submission is now closed. If you haven't done so already, please consider attending this important conference. We are looking forward to meeting all of you there.

Personal note from Karen Rosenlof

My term as APARC Co-Chair just ended, after 4.5 years. However, my involvement with SPARC/APARC goes back much longer. My first activity with SPARC was the Water Vapour Assessment (WAVAS) that was completed in 2000 (SPARC report #2); we started working on it in 1996. At the time I was an early career scientist in Boulder, co-working on understanding seasonal cycles in the stratosphere, and there were relatively new satellite measurements to explore, as well as a lot of people interested in processes that dehydrate air going into the stratosphere. After attending an initial meeting at NCAR, and meeting several prominent senior scientists, I somehow got volunteered to be a lead author and worked with Sam Oltmans on the data analysis chapter. It was a wonderful experience for a young scientist, and I love that those types of opportunities still exist within APARC for young scientists. That was the hook that got me involved, and it led to many fruitful collaborations over the past 30 years.


Karen Rosenlof

It's been fun working with Co-Chairs Seok-Woo Son, Amanda Maycock, and Olaf Morgenstern, and I am happy that APARC leadership will continue with Olaf, as well as new Co-Chairs Stéphanie Evan and Paul Kushner. The IPO group has made many things quite easy, and support from WCRP, and in particular from Hindumathi Palanisamy has been very valuable.

I'm sure the new team will do a great job moving APARC science forward. I look forward to seeing the APARC community's future successes, and hope to keep in touch with many of you. And, I thank you all for giving me the opportunity to meet and work with an incredible group of scientists over the years.

Arosa/Davos, 1926–2026:
A Century of Stratospheric Ozone Science

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The year 2026 marks a remarkable milestone in the history of atmospheric science: 100 years of continuous total ozone measurements at Arosa/Davos, Switzerland. What initiated in 1926 as a pioneering effort by a handful of scientists has grown into the world's longest uninterrupted total ozone record, a century-long witness to the evolution of stratospheric ozone. This ground-based Dobson time series has underpinned decades of research into stratospheric ozone variability, long-term trend detection, and the assessment of ozone layer recovery following the Montreal Protocol, and also studies of historical atmospheric dynamics (e.g. Brönnimann et al., 2004, Brönnimann, 2022). Its scientific value lies not only in its length, but also in the sustained homogenization efforts that ensure its consistency (Staehelin et al., 1998, Stübi et al., 2017ab, STOA[1] project). This newsletter highlights both the historical dimension of the timeseries and its future development and invites the reader to look back with curiosity and forward with innovation because the next 100 years of ozone science are just beginning!

To honor this centenary, the atmospheric science community will gather on 25 July 2026 in Davos for a dedicated scientific symposium and a public event, bringing together researchers, instrument experts, decision-makers, and a knowledgeable audience.

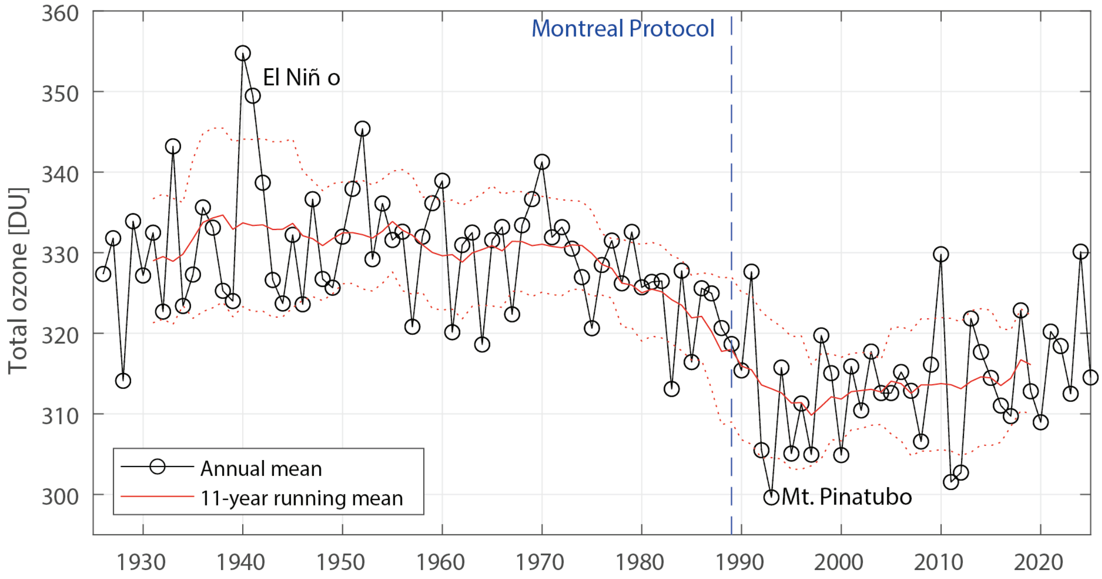

Figure 1: *The world's longest ground-based total column ozone (TCO) observation time series from Arosa/Davos started in 1926. Besides the longtime monitoring for trend analyses, such a long time series also captures rare events such as the extremely strong El Niño event in 1940/1941 or the effect of the volcanic eruption of Mt Pinatubo leading to record-low ozone in 1993. Source: MeteoSwiss.*

History of the timeseries

The ozone record of Arosa/Davos is one of the longest continuous atmospheric measurement series in the world (Figure 1), yet the scientific rationale underpinning these observations has shifted profoundly over the past century.

The program originated in a medical hypothesis. Friedrich WP Götz, a German mathematician and physicist, arrived in Davos to recover from tuberculosis and began investigating whether atmospheric ozone contributed to the therapeutic properties attributed to high-altitude air. Following a disagreement with Davos scientists over instrumental approaches, he relocated to Arosa in 1921 and initiated systematic ozone measurements, first on the roof of the local sanatorium and, from 1926, at the dedicated Villa Firnelicht observatory (Figure 2).

Among the scientists he invited to collaborate was Gordon MB Dobson. He improved the optical instrumental design of a Fery spectrograph (Figure 3) by incorporating two dispersive elements to reduce stray light. This became the Dobson spectrophotometer.

Figure 2: *Villa Firnelicht where measurements were performed from beginning of 1926 until end of 1953, the origin of Lichtklimatisches Observatorium (LKO). Source: MeteoSwiss Archives .*

Using the Arosa Fabry-Buisson spectrometer (instrument on the left in the right hand-side picture), Götz made a landmark discovery during a 1931 expedition to Svalbard (Figure 3, right picture), where the slow movement of the midnight sun compensated for the limited instrumental sensitivity and allowed him to identify the Umkehr effect, enabling ground-based retrievals of the vertical ozone distribution.

Figure 3: *Féry Spectrograph called D2 (on the left picture and in the center of the right hand-side picture on Svalbard). Source: MeteoSwiss Archives.*

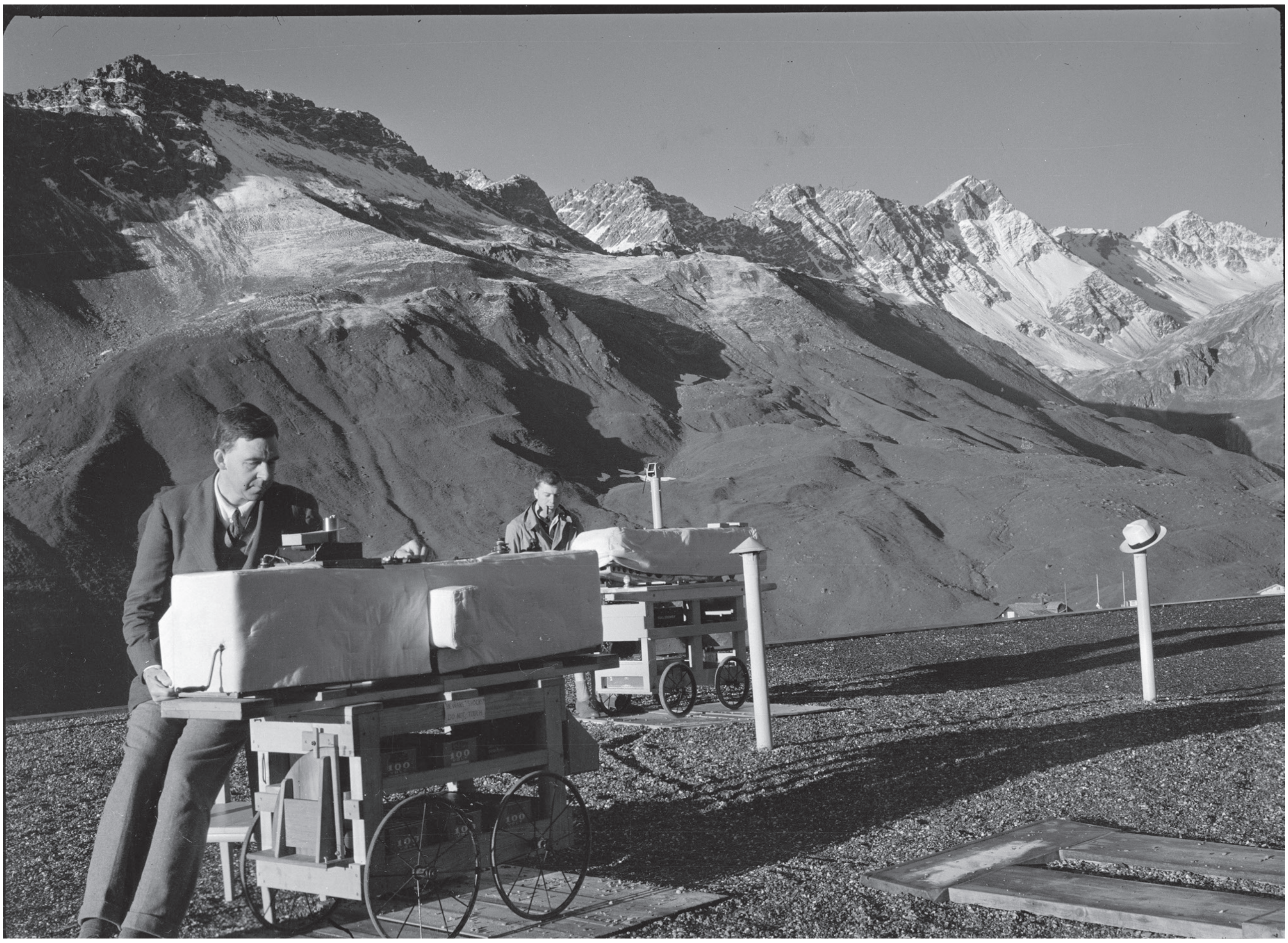

Figure 4: *Dobson and Meetham (behind) taking measurements on the first Umkehr campaign during summer 1932 at the LKO in Arosa. Source: MeteoSwiss Archives.*

The scientific motivation evolved with the times. The advent of antibiotics rendered the medical justification obsolete, and attention shifted toward surface ozone as an air quality indicator, then toward stratospheric ozone as a dynamical tracer for improving weather forecasting under Hans-Ulrich Dütsch. By the 1970s, the emerging evidence for anthropogenic ozone depletion gave the long Arosa/Davos record an entirely new strategic value for trend detection.

In 1988, MeteoSwiss assumed formal responsibility for the program, initiating systematic long-term monitoring supported by IACETH[2] at ETH[3] for scientific quality assurance. Subsequent decades brought progressive automation, the acquisition of Brewer spectrophotometers, and the homogenization of the total column ozone time series in 1998. The current scientific priority remains monitoring the ozone layer evolution from ground (the actual STOA[1] project - a collaboration of PMOD/WRC, MeteoSwiss and BOKU Vienna- is aiming to revisit the data record homogenization) and also tends to shift to understanding how climate change will modulate the future evolution of the recovering ozone layer.

Between 2011 and 2021, the instruments (Figure 5) were transferred from Arosa to the Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center (PMOD/WRC) accompanied by 10 years of parallel measurements to ensure that the homogeneity of the time series is maintained (Stübi et al., 2017ab). This 13 km horizontal and 260 m vertical displacement completed a century-long trajectory from rivalry to institutional fusion between the two sites. Today, the time series is based on 3 automated Dobson and 3 Brewer instruments (Figure 6) in a joint effort of Meteo-Swiss and PMOD/WRC and constitutes a unique dataset underpinning international assessments of stratospheric ozone recovery.

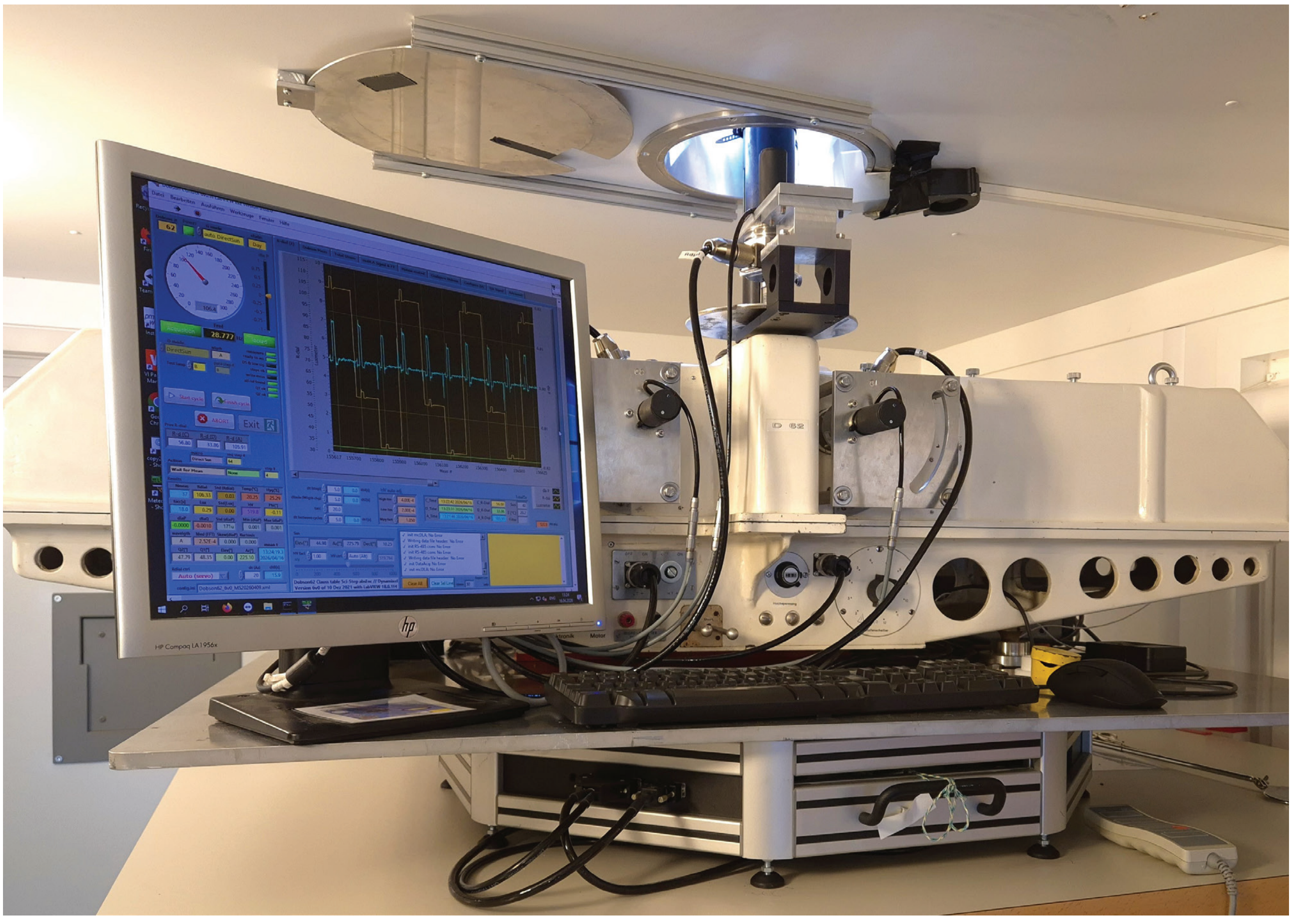

Figure 5: *One automated Dobson spectrophotometer in the container of the measurement facility at PMOD/WRC Davos. Source: Franz Zeilinger, PMOD/WRC*

Figure 6: *The instruments in 2026 with the 3 Brewer spectrophotometers (outside) and the 3 automated Dobson spectrophotometers (in the container) on the measurement platform at PMOD/WRC Davos. Source: Fabrizio Vignali, PMOD/WRC.*

Description of the instruments

The amount of ozone in the atmosphere and its vertical distribution are measured remotely from the ground by spectrophotometry (Dobson and Brewer instruments or array spectrometers), Fourier-Transform Infrared spectrometers, by Lidar instruments, by microwave radiometry or with satellite-based instruments from space, such as SBUV, OMI and MLS. In situ ozone profiles are measured by balloon-borne ozone sounding.

Féry, Dobson and Brewer spectrophotometers

After Fabry and Buisson had elaborated a first ozone spectrograph for scientific applications in the 1910s and early 1920s, the Oxford-based team around G. M. B. Dobson came up with a spectrophotometer called "Féry spectrograph" with a robust design that enabled series production and remote deployment at multiple sites around the world in 1924. The instrument is depicted in the left part of Figure 3. In this picture, light enters the part from the upper right through a Bromine-Chlorine vapour tube to reduce contamination by visible light before the refraction in a so-called Féry prism (at the bottom of the picture) splits the different wavelengths into different light paths which are then imaged on a photographic plate (Figure 7). Before the plate an optical wedge translates the intensity of light at each wavelength to the length of the line visible on the photograph. After a special development of the photographic plate the lengths of these lines was measured at 4-6 wavelengths (half of them strongly/weakly absorbed by ozone) in a dedicated device measuring the transmission through the plate.

In 1926 already, Féry spectrographs started measuring at various locations in Europe and South America. One of them has been deployed to Arosa where it set the cornerstone for the centennial time series at Arosa/Davos. It was operated as a standard

Figure 7: *Photographic plate of March 21, 1942. Each "half-ellipse" is a solar spectrum dispersed by the Fery prism. The 6 spectra are repeated exposures at different solar zenith angles during the same day. The vertical dimension represents light intensity (darkening of the photographic emulsion), and the horizontal dimension represents UV wavelengths. The optical density of the plate darkening was measured at specific wavelengths pairs and compared with a known UV source reference. The TCO was computed from the difference in darkening between the two wavelengths. Source: MeteoSwiss Archives.*

instrument until 1939 with a few occasional observations being continued throughout the entire 1940s. From 1939 on the Arosa/Davos time series was continued with instruments which are referred to as "Dobson" spectrophotometers.

A sketch of a Dobson spectrophotometer is given in Figure 8. As for the Féry instrument, the wavelength splitting occurs by a prism. This time, however, intensities at two wavelengths are directly compared while alternatively (a chopper wheel masks one light path after the other) falling on the same photodetector. To achieve this a second prism is used to recombine the light paths of the two wavelengths to fall on the active surface of the photodetector after having passed through dedicated slits where the beam at the weakly absorbed wavelength can be attenuated by the operator by gradually inserting an optical wedge. The position of this wedge where the intensity of both wavelengths is identical on the photodetector translates to a measurement of the ratio of the atmospheric absorption at the two wavelengths, hence to the ozone content.

Basing the retrieval on a relative measurement helps getting rid of many systematic errors and the use of two prisms forming a double monochromator coupled to the long light path within the instrument greatly reduces the sensitivity to stray light so that Dobson spectrophotometers are highly robust measurement devices. Different wavelengths can be chosen by adjusting quartz plates in the optical path. By using so-called double-ratios, i.e. the ratio between two wavelength pairs in the ozone retrieval can help to get rid of additional atmospheric effects such as scattering. While initially having been designed as instruments for manual operation, the Dobson spectrophotometers sustaining the Arosa/Davos time series have been completely automated in the 2010s keeping the original measurement principle so that full backward-compatibility is guaranteed.

Brewer spectrophotometers were introduced as a compact and automated alternative to the "Dobsons" in the early 1980. There ozone is inferred by the intensity ratio between 4 wavelengths separated by diffraction gratings measured sequentially by a photomultiplier tube. Brewer spectrophotometers exist as double or single monochromator versions with one or two diffraction gratings which lead to different stray-light characteristics.

Today the continuity and stability of the Arosa/Davos time series is ensured by two triads of Brewer and Dobson spectrophotometers which, together with the length of the time series, makes it a benchmark site in the international ozone monitoring system.

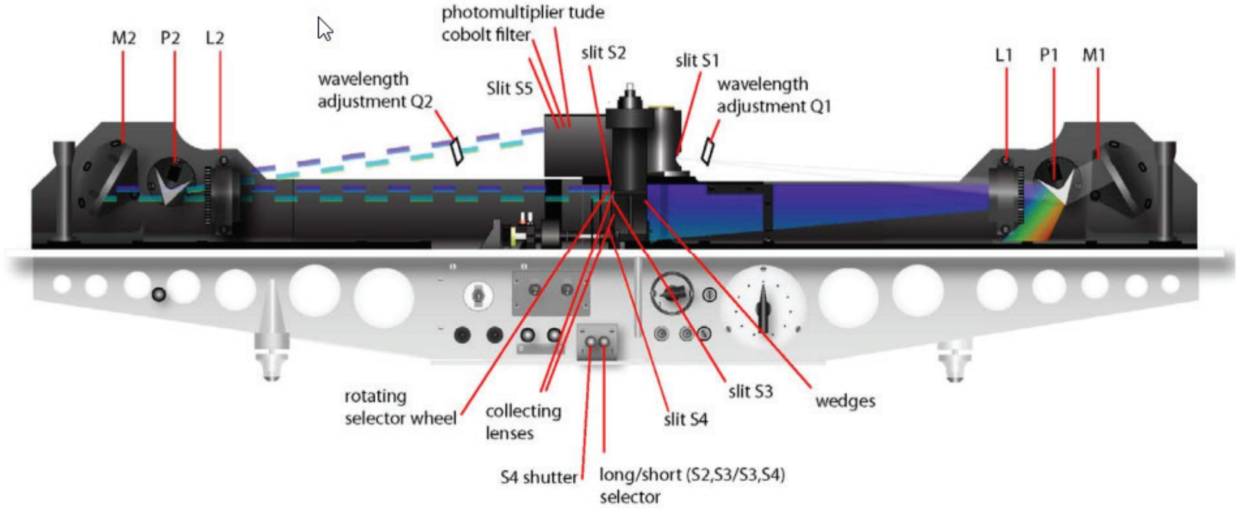

Figure 1. Optical system of the Dobson Spectrophotometer

Figure 8: *Schematic of a Dobson spectrophotometer. The prisms introduce wavelength-dependent diffraction, then the isolation of specific wavelengths of the ozone absorption lines and solar background is achieved by the geometrical placement of slits . The R-dial inserts an optical wedge increasingly absorbing the less absorbed by the atmosphere wavelength until the intensity of both wavelengths signals are equal. From the position of the measured R-dial, the total absorption due to ozone can be calculated. From https://www.o3soft.eu/dobsonweb/messages/revisedNo6NewFigsA.pdf*

BTS Solar spectroradiometer

The BTS-Solar array spectroradiometer is a promising candidate for future monitoring of the total ozone column (TOC) in the atmosphere. Because the instrument is compact, robust, and highly automated, it can be operated with relatively low cost and is easy to ship and install. These practical advantages make it particularly suitable for deployment in regions where traditional ozone-monitoring instruments, such as Dobson and Brewer spectrophotometers, are not available.

Testing of the BTS-Solar for ozone monitoring began in 2014 at the Izaña Observatory in Spain. Since then, the instrument has been evaluated at several research sites, including PMOD/WRC in Davos, Switzerland, since 2018 and it is now used at additional locations worldwide.

Studies at PMOD/WRC have shown that total ozone column values derived from BTS-Solar measurements—using a specialized "double-ratio" retrieval method—can be calibrated against established reference instruments such as the Dobsons or Brewers (Egli et al., 2023). This ensures that the resulting data are consistent with the long-term ozone records maintained by existing monitoring networks including the Arosa/Davos time series. In addition, the instrument records solar spectra between 280 and 440 nanometers, which allows total ozone to be retrieved with measurements that can be directly traced back to laboratory calibration standards (Egli et al., 2022).

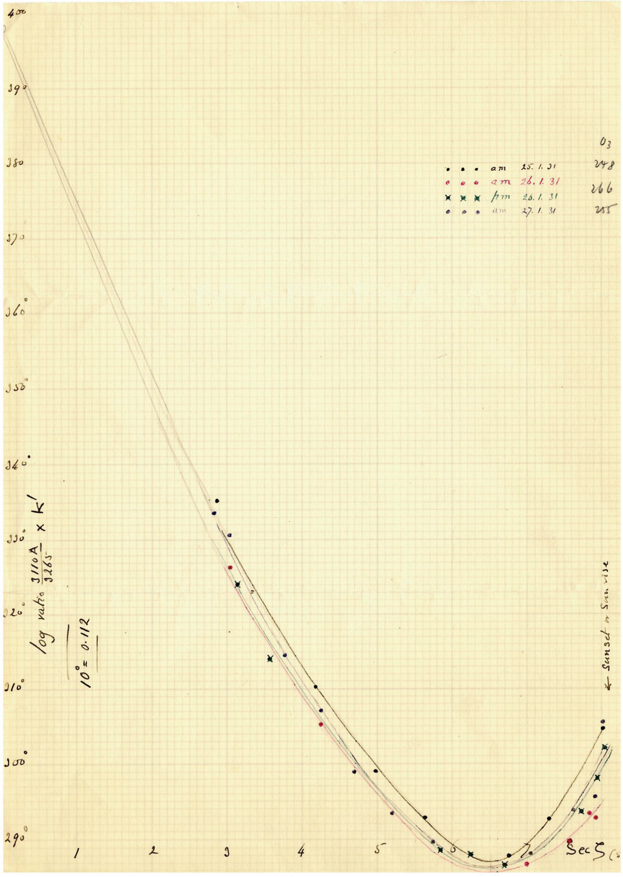

Figure 9: *The probable first Umkehr curves of January 1931 used for ozone profile determination: zenith sky observation (represented by the R dial position in deg) measured as a function of SZA covering sunrise or sunset (SZA is represented by path length "sec theta"). When the sun reaches the lowest elevation angle, the scattering at higher altitudes becomes predominant which causes the reversal (Umkehr). Source: MeteoSwiss Archives.*

Contributions to Ozone research

The Arosa/Davos record served major discoveries on ozone, contributing to each milestone across the century:

Early measurements from 1921–1923 allowed Götz to identify the seasonal cycle of stratospheric ozone at northern mid-latitudes, a springtime maximum and autumnal minimum (Dobson et al., 1926; Staehelin et al., 2018; Staehelin and Viatte, 2019), providing one of the observational pillars of the Brewer–Dobson circulation concept .

1930s: The Umkehr method. Götz's observations (Götz, 1934) at Svalbard and Arosa directly led to the 1934 discovery that ozone peaks at ~20–22 km, not 40–50 km. This is the first reliable vertical ozone profile ever obtained (the related 1st Umkehr curve is shown in Figure 9). This single finding refined the understanding of ozone distribution beyond what the Chapman theory alone could explain (Chapman, 1930) and established vertical ozone sounding as a discipline.

1970s - 1990s: The 50-year length of the Arosa/Davos record was a critical asset in establishing the impact of ODS. It provided a pre-CFC baseline (see Figure 1), allowing researchers to demonstrate unambiguously that the decline, starting around 1970 and discovered with the ozone hole by Farman et al. in 1985, was anomalous. Arosa/Davos data record was part of the core scientific case for the Montreal Protocol.

The discovery of the ozone hole above Antarctica encouraged an expansion of ozone measurements worldwide and the development of more sophisticated instruments, i.e. nowadays Brewer spectrometers, Microwave radiometers, Lidars, FTIRs and BTS.
Total ozone measurements at Arosa are broadly consistent with the long-term evolution of equivalent effective stratospheric chlorine (EESC), showing record low values in the early 1990s (Staehelin et al., 2018; Ozone Assessment, 2022).

1990–present: Trend detection and homogenisation. Together with ozone sondes, lidar, FTIR, MWR and Dobson Umkehr ground based data records, the Arosa/Davos dataset contribute to resolve in which altitude ranges ozone was decreasing and why, separating dynamical from chemical contribution (Staehelin et al., 2001; Steinbrecht et al., 1998; Appenzeller et al., 2000; Brönnimann et al., 2000; Ball et al., 2018; WMO Ozone assessments). The Arosa/Davos timeseries documented the turnaround in stratospheric ozone (Zanis et al., 2006; Harris et al., 2008; Maillard Barras et al., 2022) and is part of broader studies initiatives such as SI2N (Harris et al., 2015) and APARC/LOTUS (Petropavlovskikh et al., 2019; Godin-Beekmann et al., 2022; Sofieva et al., 2026).

The comparison of the unique Arosa total ozone time series from Dobson and Brewer instruments has allowed studies of systematic differences between the two instrument types (see Figure 10) and their long-term behaviour, including quantifying the effect of temperature-dependent ozone absorption cross-sections (Staehelin et al., 1998; Scarnato, 2009; Stübi et al., 2017; Redondas et al., 2014; Gröbner et al., 2021). The TCO timeseries is long enough to allow extreme value statistics studies (Rieder, 2010ab).

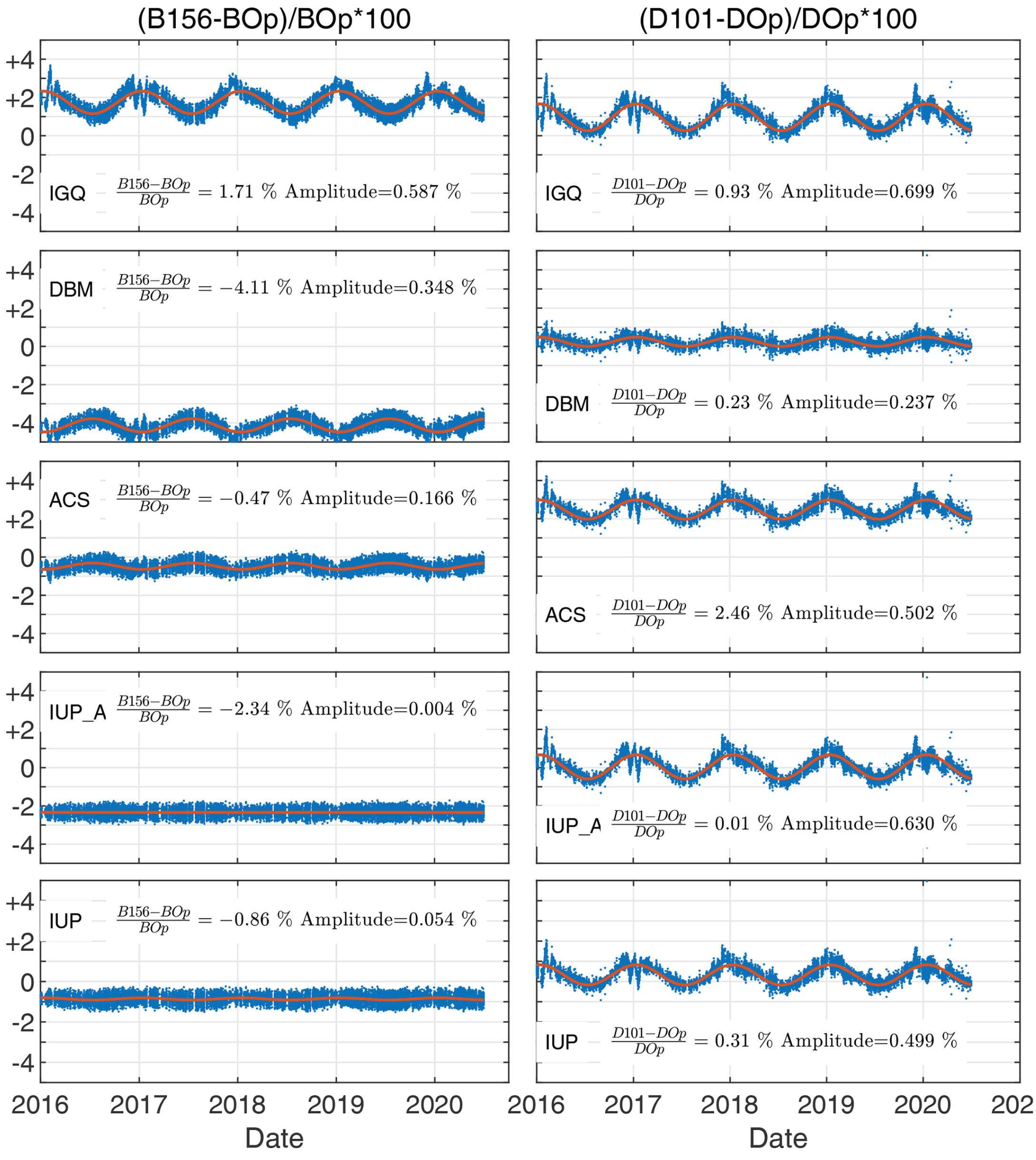

Figure 10: *Relative differences in total column ozone calculated with different ozone absorption cross-sections and effective ozone temperature relative to the operational ozone datasets for Brewer B156 (left panels) and Dobson D101 (right panels). The red curve in the figure represents a sinusoidal fit to the data with a period of 1 year. The average offset and amplitude of the sine wave are also shown. From Gröbner et al., 2021.*

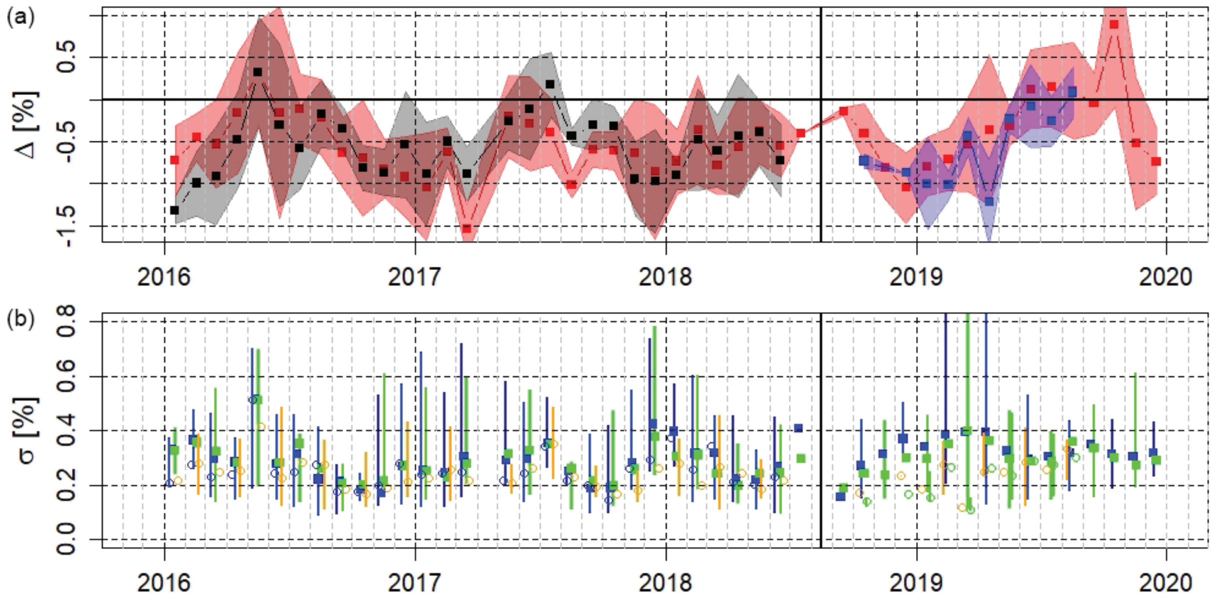

Figure 11: *Time series of the monthly median differences (%) between pairs of Dobson measurements at two different sites over the period 2016–2019 with* D_{062} *at Arosa,* D_{101} *at Davos, and* D_{051} *at Arosa before September 2018 and at Davos after:* $\Delta_{062-101}$ *(red),* $\Delta_{051-101}$ *(black) and* $\Delta_{062-051}$ *(blue). Lower panel: time series of monthly medians of* σ_i*:* σ_{101} *(blue),* σ_{062} *(green) and* σ_{051} *(orange). The shading and the error bars indicate the inter-percentile range* $IPR_{97.5th-2.5th}$*. From Stuebi et al. (2021)*

2010s–2020s: The relocation from Arosa to Davos. The careful transfer of instruments to PMOD/WRC, in which Brewer and the Dobson triads were central, ensures the data record to continue (see Figure 11 taken from Stübi et al., 2018, 2021)

Future evolution: The representativeness of the total column ozone (TCO) measurements from the ground-based instruments located at the Arosa/Davos stations in Switzerland to analyze the global ozone layer behavior in the past and future has been assessed by Rozanov et al. (2021). Models assess a strong dependence of return time of stratospheric ozone on greenhouse emissions. Separating dynamically driven ozone variability from photochemical changes is a distinction that becomes more important as the climate signal grows.
A long-term ground-based record such as the Arosa/Davos allows to follow the slow recovery of the ozone layer and will demonstrate locally the predicted changes (see Figure 12). In combination with the Payerne ozonesonde series, the Payerne microwave radiometer and the Umkehr timeseries, the Arosa/Davos total column record can be partitioned into partial columns allowing future research to attribute trends to specific altitude ranges (STOA[1] project).

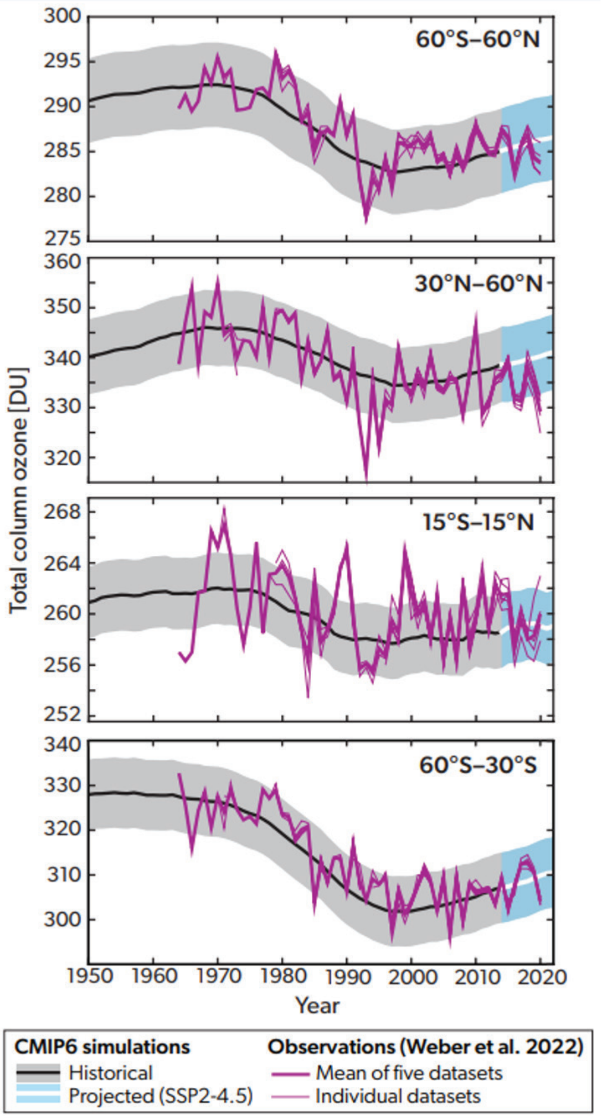

Figure 12: *TCO for the CMIP6 multi-model mean from 1950 to 2022 (historical to 2014 in black and then extended with SSP2-4.5 in white. From WMO, Scientific Assessment of Ozone Depletion: 2022, GAW Report No. 278, 56 pp., Geneva, 2022., Figure 3-20.)*

25th July 2026 celebration event

On July 25, 2026, MeteoSwiss and PMOD/WRC will celebrate 100 years of continuous ozone measurements in Switzerland. The venue for the event will be PMOD/WRC in Davos where the triad of Dobson spectrophotometers is installed. The celebration day will start with a half-day scientific symposium featuring participation and contributions from world-renowned ozone scientists, highlighting the long tradition and longevity of ground-based ozone measurements in Switzerland and in the world. The evening will be dedicated to a public event featuring keynote speakers Tom Peter and Johannes Staehelin from ETHZ, Switzerland (in German). Tours of the measurement facilities will be offered.

Further information on the official website:
https://www.meteoschweiz.admin.ch/klima/klima-der-schweiz/beobachtungen-in-der-atmosphaere/ozon-beobachtung/celebration-of-100-years-of-zone-measurements.html

Notes

1) STOA: Quantifying past, present and future Stratospheric and Tropospheric Ozone over the Alps and Europe, SNF project, 2024-2029

2) IACETH: Institute for Atmospheric and Climate Science of Eidgenössische Technische Hochschule Zürich

3) ETH: Eidgenössische Technische Hochschule Zürich

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San Francisco, CA, USA
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7th WGNE Workshop on Systematic Errors
Pune, India
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FISAPS - Gravity Waves Symposium

Aurélien Podglajen[1], **Riwal Plougonven**[1], **Hye-Yeong Chun**[2], **Corwin Wright**[3], **Laura Holt**[4], **Marvin Geller**[5]

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DATES:
9 - 13 June 2025

MEETING VENUE:
Yonsei University, Seoul, South Korea

NUMBER OF PARTICIPANTS:
96 presentations (from 10 countries)

SCIENTIFIC COMMITTEE:
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Marvin Geller, Laura Holt,
Riwal Plougonven, Corwin Wright

LOCAL ORGANIZING COMMITTEE:
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YONSEI UNIVERSITY

APARC
Atmospheric Processes
And their Role in Climate

The Gravity Waves and FISAPS Symposium was held from 9 to 13 June 2025 at Yonsei University in Seoul, Republic of Korea, bringing the two communities together for a joint meeting of 96 presentations from 10 countries, in oral, poster and flash-talk formats. It continues a series of meetings organized by the two APARC (formerly SPARC) activities: the Gravity Wave Symposia, most recently in Honolulu, USA (2012), at Penn State, USA (2016) and Frankfurt, Germany (2022), and the FISAPS (Fine-Scale Atmospheric Processes and Structures) activity on high vertical-resolution radiosonde data, whose earlier workshops were held in Kyoto, Japan, (2017), Kühlungsborn, Germany (2018) and Boulder, USA (2023).

Section 1 : FISAPS

1a. Methodology of turbulence detection from various platforms

The FISAPS activity was initiated to leverage the full potential of high vertical-resolution radiosonde data (HVRRD) collected worldwide by operational meteorological agencies, coordinating its archiving and improving access to these records. Analyzing turbulence from this data remains at the core of the activity. Because of the small scales involved and the indirect nature of the measurements, however, free-atmospheric turbulence remains difficult to quantify. A central thread at the meeting was the efforts to develop new methods and evaluate existing ones.

Various approaches to infer the properties of turbulence (such as energy dissipation rate) were discussed, including the Thorpe method and its limitations (**R. Wilson, M. Geller**), a minimum-Richardson-number approach (**H.-C. Ko**) or a static-instability method comparing observed and hydrostatic pressure profiles (**P. Šácha**). These physics-based methods can be benchmarked against Direct Numerical Simulations of isotropic turbulence (**A. Doddi**). Another approach is to make machine-learning estimates from radiosondes trained against radar (**M. Kohma**).

Other platforms extending the picture provided by radiosondes were also discussed: in-situ rocket soundings in the mesosphere and thermosphere (**B. Strelnikov**), STRATEOLE-2 long-duration balloons (**F. Juge**), and radar profiling at boundary layer levels (**J. Guo**) in the tropical lower upper troposphere, revealing Kelvin-Helmholtz billows near convection (**A. Kottayil**).

1b. Aviation turbulence, its modeling and forecast

One of the most relevant platforms for turbulence studies is aircraft, due to the direct nature of their measurements of eddy dissipation rates and the underlying threat turbulence poses for aviation safety. Over East Asia, high-altitude in-situ measurements from the NASA DCOTSS campaign demonstrate a link between turbulence and composition (**S.-H. Kim**). Besides science campaigns, a climatology of turbulence at flight level is now available from the hundreds of millions of archived EDR reports from commercial aircraft and can be used to assess turbulence predictors from reanalyses (**T. Kaluza**).

On the forecasting side, combination of commercial aircraft detections with satellite observations of deep convection enables to characterize convectively-induced turbulence (**S.-H. Baek**), and, using machine learning, to estimate turbulence intensity at multiple levels (**Y. Lee**).

1c. Turbulence variability and generating processes

Finally, the long time series of measurements now available enables investigations of the climatology and time variability of turbulence and the physical nature of its sources. This enables building local (e.g., in the lower troposphere over South Korea, **Y.-S. Lee**) and close-to global climatologies (**H.-Y. Chu**n), acknowledging their limitations. A 21-year tropical radiosonde database showed the turbulent fraction of the lower stratosphere to be strongly modulated by the QBO and tied to specific equatorial Kelvin-wave phases (**R. Atlas**). The turbulence-aviation connection was placed in a changing climate through a routing analysis of 44 years of ERA5 (**J. H. Kim**).
Various sources of turbulence were mentioned and investigated in the presentations using models and observations, including fog in the boundary-layer scale (**J. Kim**), inertial instability and Kelvin-Helmholtz billows near clouds (**J. H. Lee**), gravity-wave modulation of Kelvin-Helmholtz instabilities in the mesosphere and lower thermosphere (**T. Mixa**), and tropical convection (**F. Juge, A. Kottayil**).

Section 2 : Gravity Waves

2a. Observations

Obtaining quantitative constraints on the atmospheric gravity wave field from observations continues to be an important goal for the community. The range of scales of gravity waves makes the observation of the spectrum challenging, with efforts to combine different sources of information very valuable: in situ, radar and lidar observations provide detailed, fine-scale information. These document properties of the gravity wave field such as upward and downward propagation (**Y. Tian**), variability in time (**P. Ghosh**), interannual variations over long time records (**J. Jandreau**), intermittency in different locations (**N. Kaifler**), turbulence (**R. Wing, M. Kohma**), or generation from specific mechanisms such as a solar eclipse (**J. Gong**). Combination of instruments and recent campaigns reveal secondary generation (**R. Reichert**), which is absent from the majority of parameterizations of gravity waves. Satellite observations provide a global coverage, and the depth in time of certain records allow to explore the geographical and temporal variations of Mesospheric Inversion Layers (**T. Ayorinde**), and possible trends, raising questions regarding the dynamics driving these variations.

2b. Models : reanalyses, high-resolution simulations, process studies

As their resolution increases, models become a more important source of information on the gravity wave field. An important preliminary step however consists in validating the gravity wave fields that are simulated, and an attractive approach for comparison involves sampling the model as the observational platform samples the atmosphere. Simulations from three high-resolution models of the DYAMOND initiative (Stevens et al, 2019) are sampled as the Atmospheric InfraRed Sounder (AIRS) instrument, allowing a proper comparison (**P. Noble**). Ground-based lidar observations are used to evaluate gravity waves resolved in ICON-UA (ICON Upper Atmosphere), but also enhance the interpretation of measurements, with a larger-scale context

(**I. Strelnikova**). High-resolution simulations inform on the variability of gravity waves and their relation to the underlying flow (**Z. Prochazkova**). Careful investigation of the sensitivity to resolution remains crucial, notably for equatorial waves which can have very small aspect ratios (**M. Bramberger**).

2c. Models : Climate models and parameterizations

The QBO is one of the large-scale circulation features to which gravity wave parameterizations contribute. A detailed investigation of the sensitivity of the QBO to the parameterization of convectively forced gravity waves reveals the respective roles of different hypotheses made in the design of a parameterization, emphasizing in particular the sensitivity to parameters resulting from other parameterized processes, in this case convection (**M. J. Alexander**). Efforts to improve parameterizations include comparison to high-resolution simulations, to be examined with caution (**I. Toghraei**), adapting parameters (launch level, wave intensities) to reduce model biases (**S-Y. Kim**), analysis of their contributions to the variability of the stratospheric circulation and to Sudden Stratospheric Warmings in particular (**D. Hajkova**). Beyond these investigations which remain within the current framework of parameterizations, the inclusion of transience and lateral propagation is shown to improve the representation of gravity waves, and allow impacts on the circulation (e.g. flow reversals above orography) which are otherwise excluded (**F. Jochum**). Inclusion of secondary generation can contribute to alleviate known biases in the modelled polar mesosphere (**I.-S Song**).

2d. Processes and impacts

Over the past decade, the group of **U. Achatz** has developed a Lagrangian gravity wave parameterization, MS-GWaM, which incorporates three-dimensional effects (lateral propagation, horizontal flux convergences) that are absent from classical gravity wave parameterizations. This is used to explore and demonstrate the multiple implications of these non-classical effects on the circulation from the stratosphere to the mesopause. Also neglected in classical parameterizations, is the secondary generation of gravity waves, a process in which nonlinear wave-wave interactions likely play a role (**C. Zülicke**). Wave-mean flow interactions are also considered at larger scales, with the role of in situ excited planetary waves in the sudden warming of the Southern Polar Vortex in 2002 (**J.-H. Yoo**).

Gravity wave variability is proposed as an important driver of some of the variability of the QBO, in particular for descent of the easterly phase (**Y.-H. Kim**). Wave mean flow interactions drive oscillations of the winds at different altitudes throughout the middle atmosphere, as illustrated by the study of abnormally strong easterly winds at the mesopause in the Japan Whole Atmosphere ReAnalysis (JAWARA) by **K. Sato**. Yet, the pathways leading to variability of circulation features that are partly driven by gravity waves remain elusive: as illustration, the connection between stratospheric gravity waves and their convective sources is not as strong as expected, with waves having a significant sensitivity to the background wind conditions (**C. Cullens**).

Novel aspects of projections are finding their way to the field, as the impacts of Stratospheric Aerosol Injection on parameterized convective gravity waves are investigated (**H.-K. Lee**). Studies on the circulation of Mars have also been presented: observations of gravity waves (**S. England**) and contributions of resolved and unresolved waves to the residual mean circulation (**A. Asumi**).

Section 3 : Trends and challenges

3a. Development of Machine Learning

As for many other fields of research, the development of Machine Learning and Artificial Intelligence opens many new possibilities for gravity waves and turbulence. For turbulence, machine learning has been used to estimate intensity from geostationary satellite data over Korea (**Y. Lee**) and to infer energy dissipation rates from radiosondes (**M. Kohma**). A convolutional neural network was used to better identify gravity waves from satellite observations (**H. Okui**), hence extracting more accurate information from existing records. The relationship between the large-scale flow and gravity waves in a given location, as observed by super-pressure balloons, was investigated with Machine Learning (**R. Plougonven**). Work in the broader community has explored and developed the use of Machine Learning to improve or renew parameterizations, raising both fundamental and practical questions including the stability of a data-driven parameterization when run online; applications in a climate different from the one providing the training samples; quality and the completeness of training datasets.

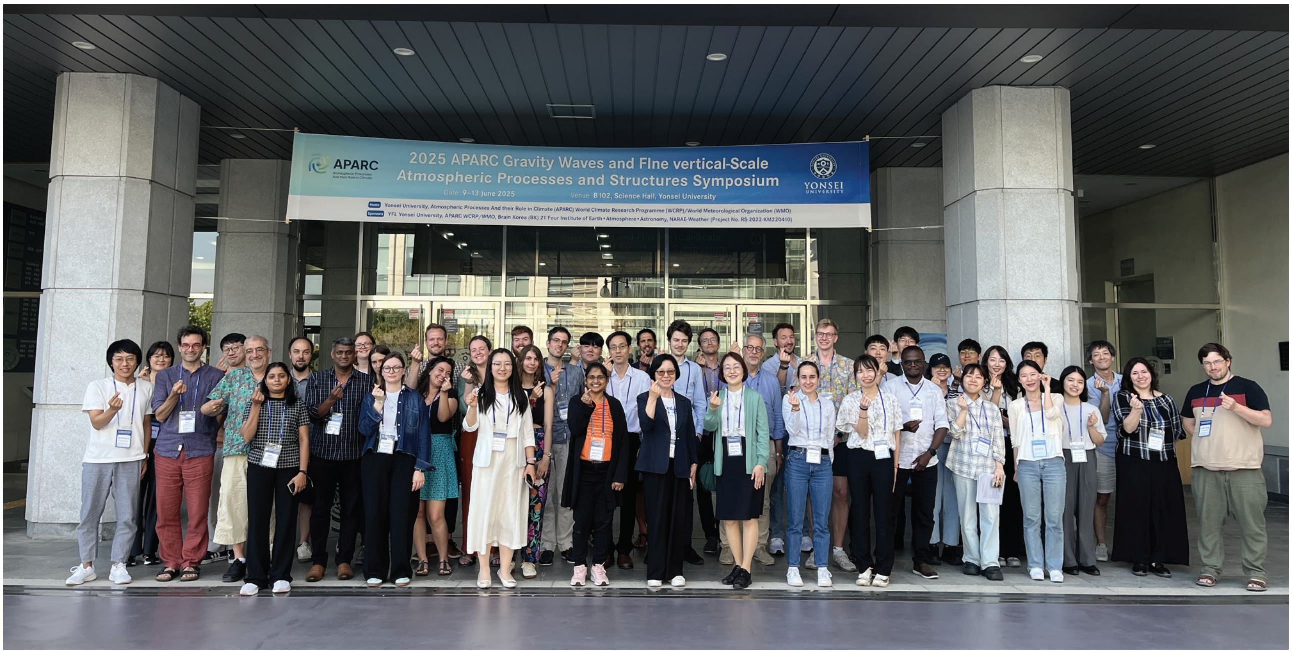

Figure 13: *Group photo taken at the FISAPS - Gravity Waves Symposium.*

3b. Value and usage of continued long observational records

A second highlight from the symposium is the interest and need for long time series to explore atmospheric variability, as well as the concern regarding future gaps in global observations. Several talks addressed how to extend, merge and validate long-term global records. The value of long-term in situ observations of turbulence, from operational radiosonde and commercial aircraft networks was highlighted (**R. Atlas, H-Y. Chun, T. Kaluza**). A special focus was on the satellite records of the gravity wave field, which have been a game-changer for the study of gravity waves (Alexander et al., 2010, and references therein). Topics discussed include prolonging data records by combining various satellite observations such as SABER and GNSS RO (**C. Wright**), and leveraging existing nadir-viewing satellite climatologies to examine long-term changes in stratospheric waves, and assess resolved waves in forecast models through the lens of the observational filter (**N. Hindley, P. Berthelemy**).

In the future, one anticipates a gap in the observation of atmospheric gravity waves with the end of life of a number of platforms. The CAIRT mission, which aimed at limb sounding of the middle atmosphere with horizontal scanning, potentially enabling 3D retrievals of GW properties (**S. Rhode**), in the middle atmosphere, has not been selected within Europe's Earth Explorer program.

3c. Coupling of processes: gravity waves, turbulence, microphysics

Finally, gravity wave parameterizations, along with many others, have developed with a particular focus and goal: providing the appropriate forcing for the circulation in the middle atmosphere to be modelled correctly, at least in climatology. Other implications of gravity waves have not been included in the aims of parameterizations. Several presentations pointed to the coupling with other non-linear processes (microphysics, instabilities, turbulence). In particular, gravity waves are a contributor to tracer transport, notably by inducing turbulence and irreversible mixing (**M. Umbarkar, T. Mixa**). These effects are considered in some new parameterizations (**I. Knop, T. Banerjee**). Gravity waves also impact ice cloud microphysics, as seen in observations (**A. Podglajen**), and efforts are under way to include this in parameterizations (**A. Kosareva, S. Dolaptchiev**).

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NDACC Celebrates 35 Years with an October 2025 Symposium in Virginia Beach, USA

Ryan Stauffer[1], Wolfgang Steinbrecht[2], Irina Petropavlovskikh[3], Martine De Mazière[4], Jeannette Wild[5], Reem Hannun[6], James W. Hannigan[7], Jean-Christopher Lambert[4], Eliane Maillard Barras[8], Elizabeth Asher[3], Thierry Leblanc[9], Sarah Strode[10], Roeland Van Malderen[11], Bärbel Vogel[12], Gerald Nedoluha[13], Henry Selkirk[14]

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[7]National Centers for Atmospheric Research Atmospheric Chemistry Observations & Modeling Lab
[8]MeteoSwiss, Federal Office for Meteorology and Climatology
[9]Jet Propulsion Laboratory, California Institute of Technology
[10]Morgan State University & NASA/GSFC
[11]Royal Meteorological Institute of Belgium (KMI-IRM)
[12]Research Centre Jülich (FZJ), Institute of Climate and Energy Systems
[13]Naval Research Laboratory, Remote Sensing Division
[14]East Aurora, NY, USA

DATES:
27 - 30 October 2025

SCIENTIFIC ORGANISING COMMITTEE:
Jeannette Wild, James Hannigan, Wolfgang Steinbrecht, Jean-Christopher Lambert, Eliane Maillard Barras, Elizabeth Asher, Thierry Leblanc, Martine De Mazière, Sarah A. Strode, Roeland Van Malderen, Bärbel Vogel, Gerald E. Nedoluha, Henry Selkirk

LOCAL ORGANISING COMMITTEE:
Ryan Stauffer, Ruben Delgado, Belinda Denson, Lynn Kennedy, Brianne Milano, Reem Hannun, Jeannette Wild, Irina Petropavlovskikh, Gao Chen, Gerald Nedoluha, Ken Jucks

NUMBER OF PARTICIPANTS:
80 (in-person participants)
60 (online participants)

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CONFERENCE WEBSITE:
https://www.ndacc.org

The NDACC Symposium celebrated 35 years of successful Network for the Detection of Atmospheric Composition Change (NDACC, formerly NDSC [Network for the Detection of Stratospheric Change]) science and operations (see also www.ndacc.org). Up to 80 people attended in person, with about 60 more online. It was the third large meeting of the entire NDACC community, preceded by 10-year and 20-year anniversary symposia in Arcachon, France (2001), and Île de La Réunion, France (2011). Hosted by Hampton University, the Symposium featured six sessions, grouped along NDACC's key objectives.

1. Creating and improving long-term data: Instrumentation, processing and past, present and future data-streams
2. Validating atmospheric measurements from satellites and from other platforms
3. NDACC synergistic environment in support of field campaigns and other chemistry and climate-observing networks
4. Synergistic use of models with NDACC and its Cooperating Networks' data to interpret observations and support model development and verification
5. Linking changes in atmospheric composition, climate, and air quality
6. Oases in the desert: Measurements that address the impending gaps in atmospheric data

The entire program was framed by historical perspective talks from **Susan Solomon** (MIT), **Mike Kurylo** (retired from NASA-HQ), and **Wolfgang Steinbrecht** (DWD), and **Jeannette Wild** (NOAA). All posters were on display throughout the entire symposium.

Figure 14: (Top) Group photo of NDACC Symposium attendees in the Grand Ocean Ballroom of the Sheraton Virginia Beach Oceanfront Hotel. (Bottom) Symposium attendees listening to a presentation by **Wolfgang Steinbrecht**. Photo by Voltaire Velazco.

Session A: Creating and improving long-term data: Instrumentation, processing and providing past, present and future data-streams

The first session focused on the key objective to create and improve long-term atmospheric composition data records. In their invited talk, **Sophie Godin-Beekmann** (LATMOS, Paris) and **Emmanuel Mahieu** (U Liege) presented the ups and downs in the creation of some of NDACCs longest records: the stratospheric temperature and ozone record since the late 1970s and mid-1980s from the lidars at Haute Provence; the very long term spectroscopic measurements from Jungfraujoch in the 1950s. Especially with Fourier Transform Infrared Radiometry (FTIR), in the framework of NDACC, Jungfraujoch has some of the longest atmospheric records covering ozone, chlorine species, and much more. **Alistair Bell** (U Bern) showed what can be done with microwave radiometers, measuring ozone, water vapor, temperature and wind in the upper atmosphere. Using long-term UV-VIS measurements of stratospheric BrO, **Michel Van Roozendael** (BIRA-IASB) showed the success of the Montreal Protocol, with BrO slowly declining over the last few decades. Talks by **Alberto Redondas** (AEMET) and **Luca Egli** (PMOD, Davos) highlighted successes and challenges of ground-based total ozone measurements from well-established Brewer spectrometers to recent BTS spectrometers. **Sergey Shilov** (Bruker Optics) demonstrated the wide range of FTIR measurements currently possible with commercial instruments. After all the remote sensing, **Kate Smith** (U Colorado) presented great results from balloon-borne in situ measurements of stratospheric aerosol. NDACC would be nothing without great stations and PIs and it was very assuring to hear from **Michael Sicard** (LACY, Reunion) about old and new efforts with NDACC instruments at Reunion Island. The session ended with long-term records: **Andrea Pazmino** (LATMOS, Paris) explained trends and variations in 35 years of SAOZ observations of ozone and nitrous oxide, while **Louis Miralliè's** (Meteoswiss, Payerne) topic was the generation of a Bayesian (=most likely) ozone time series from all the different observed data in a region with similar variations. In addition to the talks, more than 15 posters covered topics ranging from long-term trends to specific technical details, and from ozone and water vapor sondes, to lidars, UV-VIS spectrometers, FTIRs and microwave radiometers.

Session B: Validating atmospheric measurements from satellites and from other platforms

Session B focused on the essential role of NDACC measurements in serving as a ground-based reference for the validation of satellite observations. In their invited keynote talk, **Daan Hubert** and **Tijl Verhoelst** (BIRA-IASB) reviewed 50 years of past, present and future NDACC cooperation with atmospheric composition satellite missions. They illustrated how NDSC/NDACC has responded to the evolution of satellite validation needs since the inception of the network, and in particular with the uptake of Earth Observation interoperability frameworks and the adoption of the CEOS Fiducial Reference Measurements Maturity Assessment (CEOS-FRM) as a guide to improve on traceability, uncertainty budget characterization, and satellite validation capacity.

The second part of Session B was devoted to limb and solar occultation profiling of the upper troposphere and middle atmosphere. **Jiansheng Zou** (Toronto U.) et al. presented the validation of ACE-FTS v5.3 ozone profiles with respect to the full suite of NDACC profilers. With the imminent decommissioning of Aura MLS and the aging of the very few limb profilers still in operation, **Nigel Richards** (NASA/GSFC) et al. highlighted that OMPS-LP validation becomes critical as this instrument will likely be one of the only providers of high-resolution global ozone profiles in the close future. **Jun Wang** (Iowa U.) et al. gave a tribute to the SAGE satellite series and highlighted the role of the SAGE III/ISS mission as a reference anchor for multiple-sensor data synergies in the upper troposphere and stratosphere.

The third part of Session B illustrated recent advances of geostationary and hyperspectral nadir missions and on the interoperability of the emerging satellite constellations. In her invited talk **Juseon Bak** (Pusan U.) et al. showed significant progress in the geostationary GEMS ozone profiling algorithm leading to reduced spectral fitting residuals and elimination of the altitude-dependent oscillating biases. In support of multi-satellite data assessments like TOAR-II and LOTUS, **Arno Keppens** (BIRA-IASB) et al. introduced a holistic constellation approach to satellite tropospheric ozone validation, combining harmonization of the tropopause definitions and vertical information content between sounders, and multiple techniques. **Niko Fedkin** (NASA/GSFC) et al. assessed the TEMPO geostationary satellite's capability to monitor oil and gas emissions with NO_2 hourly measurements, demonstrating new diurnal pattern detection capabilities. **Zachary Fasnacht** (SSAI) et al. presented a ML approach enabling monitoring of NO_2 and O_3 at high spatial resolution with the polar-orbiting hyperspectral ocean color instrument PACE OCI. **Thierry Marbach** (EUMETSAT) et al. introduced the agency approach to Cal/Val gap analyses and to Fiducial Reference Measurements.

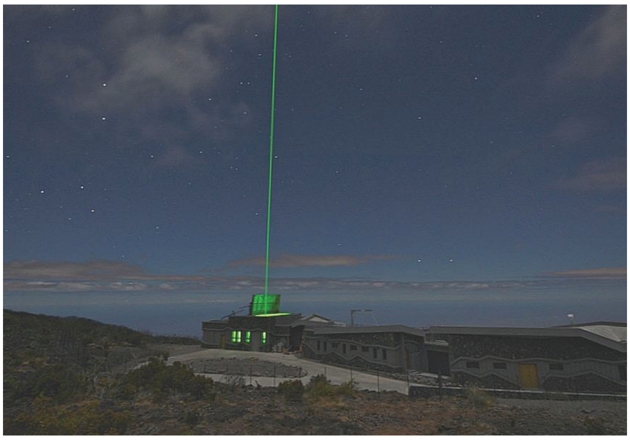

Figure 15: Always a highlight: Photo of an NDACC lidar beam at night. Shown here is the green beam of the temperature lidar at the Maido OPAR station on Reunion Island.

Session B concluded with 14 posters where the essential role of NDACC long-term data records in satellite validation, the potential of new measurement techniques, intercomparison campaigns, and advances in multi-satellite validation methods and services developed in several space agencies and research institutions were highlighted.

Session C: NDACC synergistic environment in support of field campaigns and other chemistry and climate-observing networks

Session C highlighted the importance of NDACC and Cooperating Networks to the scientific community. Keynote speaker **Sergey Khaykin's** (LATMOS) synthesis of the Hunga-Tonga eruption's stratospheric impacts relied heavily on NDACC data, demonstrating how this network is essential for tracking abrupt changes in atmospheric composition, as well as long-term changes. Talks by **Roeland Van Malderen** (KMI-IRM) and **Bärbel Vogel** (FZJ) demonstrated the critical importance of NDACC data global coverage and diversity (sonde, lidar, FTIR) for major international ozone assessments such as the Second Tropospheric Ozone Assessment Report (TOAR-II) and showed that combining models and NDACC observations is a powerful tool for understanding changes in atmospheric composition, respectively. Many other oral and poster contributions to Session C highlighted cooperating ground-based networks (e.g., GRUAN, SHADOZ) or other, newer networks (NOAA B2SAP, NOAA AirCore, PGN) that monitor changes in atmospheric composition (trace gases and aerosol). NDACC and Cooperating Networks are important for satellite validation, exemplified by **Steven Compernolle's** (BIRA-IASB) talk, and for merging satellite records into longer time series. They also provide additional information to global overview from satellites (e.g., a sufficient number of simultaneously measured trace gases to calculate the AOD, aerosol size and number, and improved vertical resolution in the troposphere and lower stratosphere of other trace gas species). In light of impending satellite gaps, leveraging synergies between these networks will be even more critical.

Session D: Synergistic use of models with NDACC and its Cooperating Networks' data for interpretation

The keynote talk for Session D given by **Martyn Chipperfield** (Leeds U.) recalled how the synergetic use of NDACC and limb-viewing satellite observations of tracers like HCl, HF and N_2O together with various CTMs (chemistry-transport models) like TOMCAT and SLIMCAT reveals stratospheric circulation changes and chemical feedback mechanisms in ozone trends. He highlighted the growing importance of NDACC data sets as time series lengthen and for filling the satellite limb-data gap. **Daniele Minganti** (BIRA-IASB) highlighted the use of NDACC FTIR N_2O time series for studying the hemispheric asymmetry of trends in the Brewer-Dobson Circulation, and for capturing the transport anomalies caused by the Hunga-Tonga eruption. **Ivan Ortega** (NCAR) focused on the improvement of NDACC FTIR CH4 datasets for enabling distinct stratospheric/tropospheric column analyses and corresponding model verification support. **Beatriz Herrera** (Toronto U.) analyzed ammonia data from FTIR observations at 22 sites in the network, including background, urban and high-altitude sites, from the high north to southern mid-latitudes, and showed where models can benefit from these data for better capturing the seasonal and diurnal variabilities and long-term trends. **Christian Rolf** (FZJ) presented the open questions as to the impact of UTLS water vapor in current and future climate modelling and the need for increasingly reliable UTLS H_2O observations. **Daniel Rauter** (BOKU U.) highlighted the availability of high-quality UV Spectral irradiance and total ozone observations for more than 30 years over Austria in the NDACC database, and their exploitation for investigating O_3 and UV long-term trends with various applications in environmental, agricultural, medical, climate, and meteorological research. **Megan Lickley** (Georgetown U.) provided insights into the uncertainties associated with the use of atmospheric lifetimes in 1D-box models for estimating emissions of ozone depleting substances measured at the surface. **Ralf Sussmann** (KIT, IMK-IFU) showed investigations of the NOx photochemistry based on NDACC FTIR observations of NO_2 and NO at 5 sites of the network. The poster presented by **Hyungyu Kang** (Kongju National U.) showed the use of daily ozonesonde observations to investigate ozone variability over the Korean Peninsula, and the study of a Stratosphere–Troposphere Exchange event and its dynamical characteristics. **Teagan Knox's** (Oregon State U.) poster discussed UTLS ozone trends as derived from ozonesonde observations at Boulder and the link with observed tropopause trends. **Erin McGee** (Toronto U.) in her poster presented work performed in the Arctic Monitoring and Assessment Programme (AMAP) using data from three TCCON and five NDACC sites and comparisons with model simulations to investigate the variability of short-lived climate forcers in the Arctic. **Sieglinde Callewaert** (BIRA-IASB) used NDACC and TCCON data for methane at Japanese sites to explore the capacity of WRF-GHG in simulating columns and vertical distributions of long-lived greenhouse gases in East Asia.

Session E: Linking changes in atmospheric composition, climate, and air quality

In the session keynote presentation, **Susann Tegtmeier** (Saskatchewan U.) showed that the hemispherically asymmetric ozone trends above 30 hPa can be explained by stratospheric transport rate changes, while halogen changes (e.g. HCl) have enhanced ozone recovery below 30 hPa in SH and delayed it in the NH. **Paul Newman** (UMBC/NASA-GSFC) concluded that year-to-year variations in Antarctic ozone-hole breakup, including recent unusually late breakup events, are mainly driven by large-scale tropospheric waves propagating vertically into the stratosphere. In her contribution, **Simone Tilmes**

(NCAR) showed that, while stratospheric aerosol injection could cool Earth's surface, it may also pose risks to the ozone layer, with significant uncertainties that depend on aerosol type and require further investigation. **Xin Zhou** (Chengdu U.) highlighted that the unprecedented stratospheric water vapor injected by the January 2022 Hunga eruption is being slowly removed through both Antarctic dehydration and stratosphere–troposphere exchange, with potential additional losses in the cold Arctic vortex of early 2025. **Hannah Clark** (IAGOS) talked about how three decades of global aircraft-based IAGOS measurements provide essential long-term data on ozone and water vapor trends—especially in regions lacking in-situ observations—revealing both natural and pollution-driven variability and underscoring the program's growing importance in a changing climate. **Sarah Strode** (Morgan State U./NASA-GSFC) presented a study that uses ozonesonde data and targeted GEOS-GMI model experiments to quantify how lightning, biomass burning, and other changes contribute to interannual and ENSO-driven variability in tropical tropospheric ozone. **Peter Effertz** (CIRES/NOAA-GML) developed station-specific optimized multiple linear regression models to better isolate total ozone recovery signals in ground-based and satellite records, reducing uncertainties and improving prospects for earlier detection of long-term ozone recovery. **Victoria Flood** (Toronto U.) summarized two decades of Toronto Atmospheric Observatory (TAO) atmospheric measurements and recent wildfire-focused analyses, showing how extreme 2023 Canadian fire emissions affected Toronto's air quality. **James Hannigan** (NCAR) refined long-term global measurements and trend analyses of atmospheric carbonyl sulfide (OCS) from 1986–2024, using a global FTIR network to assess its tropospheric and stratospheric variability, drivers, and recent post-2016 decline in order to better constrain the global OCS budget.

Posters from this session focused e.g., on the use of NDACC time series to estimate ozone trends at Boulder, OHP, in the Arctic and Antarctic, compared ozone profiles from multiple data in South Korea, and reported on NDACC UV-VIS or FTIR measurements in the Canadian Arctic, and on the climatological variation of NO_2 using AERONET observations. A thought experiment concluded that ODS-induced ozone depletion could have been first observed as early as 1957, assuming the availability of accurate stratospheric ozone observations from 1950 onward.

Session F: Oases in the desert: Measurements that address the impending gaps in atmospheric data

The final Session F was inspired by the Salawitch et al. (2025) study which highlighted the need for, and the impending absence of, sustained, coordinated, global satellite measurement capabilities of critical atmospheric components such as water vapor, inorganic chlorine species, and tracers of stratospheric transport. **Ross Salawitch** (Univ. Maryland) was the keynote speaker, and he highlighted the role of NDACC observations in understanding long-term changes and stratospheric composition, and their increasing importance given the age of ACE-FTS and the decommissioning of Aura MLS. **Nathaniel Livesey** (JPL) then presented MLS observations since 2004 and showed how these measurements have been central to diagnosing the effect of anomalous events and improving our understanding of long-term variability in stratospheric dynamics and composition. **Peter Bernath** (Old Dominion) introduced observations from ACE-FTS, which has been operating since 2003. He highlighted the capabilities of the ever-expanding suite of stratospheric trace gas and aerosol observations, and more recently winds from the tropopause to the thermosphere, that are provided by ACE. **Nigel Richards** (Univ. Maryland, Baltimore County) discussed the suitability of the Ozone Mapping and Profiler Suite (OMPS) series of instruments to continue the Aura record of ozone measurements and discussed the effect of stratospheric aerosols on OMPS retrievals. **Katrin Müller** (Alfred Wegener) showed how measurements from the Palau Observatory since 2016 in the tropical western Pacific support monitoring of atmospheric composition over a critical region for the transport of tropospheric air into the stratosphere. **Holger Vömel (**NCAR) reported on 20 years of water vapor measurements collected at the Ticosonde station in Costa Rica, highlighting the unique capability to provide in situ monitoring of the tropical water vapor tape recorder. The session returned to satellite-based measurements with a presentation by **Martin Mlynczak** (Space Environment Technologies) on the SABER/TIMED instrument. He pointed out that while this instrument was originally developed for measurements above 60 km, it can continue to provide global measurements of temperature, ozone, and water vapor in the stratosphere. The final speaker was **Lyatt Jaegle** (Univ. Washington) who introduced the Stratosphere Troposphere Response using Infrared Vertically-resolved light Explorer (STRIVE) mission. In February this year, STRIVE was selected by the NASA Earth System Explorers Program for launch in the

2030s. STRIVE has the potential for providing global measurements of many of the species that were highlighted in Salawitch et al. (2025). Finally, there was a discussion on the role of NDACC in helping to fill the gap in data caused by the impending end of life of ACE and Aura MLS.

Session F also received contributions from ten poster presentations covering NDACC FTIR, lidar, balloon, and microwave measurements, OMPS LP water retrievals, GEOS composition assimilation and the NDACC database.

Concluding remarks

Jeannette Wild and **Wolfgang Steinbrecht** wrapped up the symposium with a historical perspective from the beginnings of NDACC as Network for the Detection of Stratospheric Change (NDSC) in the early 1990s, to today's successful NDACC 35 years later. A key conclusion was that "in the end people are the most important asset of NDACC". It seems appropriate to show these people: back in the 1990s in Fig. 16, and just recently in Fig 17.

All Symposium participants were invited to submit a paper to the ACP/AMT inter-journal special issue, "Achievements and Perspectives of the Network for the Detection of Atmospheric Composition Change (NDACC) After 35 Years of Operations." Celebrating the 35th anniversary of NDACC (ndacc.org), this special issue highlights past scientific achievements and outlines the network's updated strategy in response to evolving questions about atmospheric behavior. The featured paper, "The Network for the Detection of Atmospheric Composition Change at 35 Years: Achievements and Future Strategy," provides a comprehensive overview of key research findings aligned with NDACC objectives. Furthermore, it outlines the future of NDACC by examining shifting scientific priorities, growing collaborations with partners and Cooperating Networks, and current gaps in satellite and ground-based observations.

Figure 16: Participants of the 1996 NDSC Steering Committee Meeting in Ny-Ålesund, Svalbard. Photo provided by Justus Notholt.

Figure 17: Except for one person, a different set of people at the 2025 NDACC Steering Committee Meeting in Virginia Beach, USA.

Recent advancements in our understanding of stratospheric age of air: Summary of a workshop in Maria Laach, Germany

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DATES:
10 - 12 December 2025

MEETING VENUE:
Maria Laach, Germany

NUMBER OF PARTICIPANTS:
10

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TP CHANGE

The large-scale stratospheric overturning circulation, referred to as the Brewer-Dobson circulation, plays a primary role in the composition of the stratosphere with subsequent impacts on important issues such as stratospheric ozone recovery, the lifetime and distribution of radiatively important trace gases and aerosols, and on proposed climate intervention scenarios. Chemistry-climate models have consistently simulated a speed up of the mean stratospheric circulation in recent decades and into the future in response to increased greenhouse gas concentrations. One of the only observable metrics of the strength of the Brewer-Dobson circulation is the stratospheric age of air, the time elapsed since air has entered the stratosphere. The age of air can be inferred from measurements of certain long-lived trace gases. Importantly, changes in the observed age of air do not show the stratospheric circulation speeding up as climate models predict. This discrepancy between observations and model projections of potential changes in stratospheric circulation has posed a significant challenge for the stratospheric and climate modeling communities for nearly two decades.

The recent review paper by Garny et al. (2024a) served as both a summary of research on the topic of stratospheric age of air over the past two decades and a catalyst for new studies that have considerably advanced our understanding in a relatively short time. A small workshop in Maria Laach, Germany in December 2025 brought together 10 scientists, including four graduate students, to share and discuss their recent findings relevant to stratospheric age of air, and implications for research on the stratospheric Brewer-Dobson circulation. A key aspect

Figure 18: *Group photo*

of the recent work is the availability of a range of new observations of very long-lived trace gases from various platforms including satellites, balloons and aircraft, that can be used to calculate age of air. This range of age of air-focused trace gas measurements is unprecedented, surpassing even those obtained during the height of stratospheric ozone hole investigations in the 1990s when numerous aircraft missions were undertaken but few balloon flights and no satellite age trace gas measurements were available. The workshop primarily focused on how we are taking and using these new measurements, along with model simulation output, to update our understanding of age of air trends, regional and seasonal variability, calculation techniques and relevance to the stratospheric Brewer-Dobson circulation.

The most extensive new stratospheric measurements of long-lived trace gases have come from the relatively low-cost AirCore sampling on balloon platforms (J. Degen, A. Engel, J. Laube, E. Ray). At least two AirCore sampling programs (U. Frankfurt and NOAA GML) are now providing regular profile measurements of mean age trace gases in the Northern Hemisphere. In addition, AirCore sampling has been utilized in recent intensive mission-oriented campaigns, as for instance during summer 2025 at Juelich, Germany, and even in the Southern Hemisphere in March 2023 and 2024. Recent research also aimed at comparing AirCore measurements with a variety of other sampling types (Schuck et al., 2025; Laube et al., 2025). Aircraft campaigns have continued to provide mean age trace gas measurements through the 2020s from both European and US missions (PHILEAS, DCOTTS, SABRE). These targeted missions give insight into specific seasonal and regional variability in long-lived trace gases, such as around the Asian monsoon (J. Strobel, M. Volk) and in the Arctic (T. Diederich). Moreover, satellite measurements from different instruments (ACE-FTS, MIPAS, MLS) have been used to estimate the global distribution and variability of mean age for the period since 2004 (F. Voet, F. Ploeger, E. Ray). Such mean age estimates from satellite sulphur hexafluoride mixing ratios are typically prone to large scatter which complicates quantification of small long-term changes (Saunders et al., 2025), but new methods including information from other long-lived trace gases have been shown to have the potential to overcome these issues (Voet et al., 2025).

The methods of calculating age of air from trace gases have continued to evolve in response to the more extensive measurements and the use of model output to constrain unknown parameters. As summarized in the Garny et al. (2024a) review paper, the 'convolution' technique is the most common method of estimating mean age and generally has improved accuracy compared to other techniques (A. Engel, H. Garny). When multiple simultaneously measured long-lived trace gases are available, new techniques provide a better constraint on the age calculation and on unknown parameters such as the width of the age spectrum (E. Ray, F. Voet). In the lower stratosphere, where air is relatively young (small mean ages) and the seasonal cycle is important (Degen et al., 2025), multiple trace gases can be used to identify source latitude regions and to be able to use seasonally varying trace gases such as carbon dioxide (Ray et al., 2024).

Open questions and outlook

A key outcome of the workshop was the identification of critical open questions regarding the stratospheric age of air, together with a discussion of the essential tasks required to address them, as summarized below:

- New analysis of existing in-situ trace gas measurements from balloons and aircraft provides new evidence of discrepancies between model simulations and observed long-term changes in the age of air across the Northern hemisphere stratosphere (Ray et al., 2026). While the direction of these differences changes compared to past studies, their significance persists, raising questions about the current understanding of how the stratospheric circulation responds to increasing greenhouse gas levels.

- Available in-situ measurements are sparse in space and time while satellite observations have significant measurement and retrieval uncertainties. Hence, the discrepancies between climate models and observations show the need for more and better observations of long-lived trace gases across the stratosphere. The AirCore technique offers a cost-effective and flexible approach, while new satellite instruments would also be highly beneficial.

- Available satellite observations of long-lived trace gas species from (ACE-FTS, MIPAS, MLS) should be further explored to estimate global age of air distributions, as well as temporal and regional variability therein. Information from other species besides sulphur hexafluoride offers potential to reduce uncertainty in these estimates (Voet et al., in preparation). However, it should be emphasized that only a single instrument (ACE-FTS) is still in orbit and that we are heading towards a satellite data desert (Salawitch et al., 2025).

- Methodological uncertainties need to be further improved to reduce uncertainty in estimates of age of air from measurements of long-lived trace gas species. These uncertainties include regional variations in trace gas sources (particularly for sulphur hexafluoride), parameterizations for chemical sinks (Garny et al., 2024b), as well as assumptions on the age spectrum shape. Retrieving information on the age spectrum directly from trace gas measurements seems to be particularly valuable for this purpose (Voet et al., in preparation).

Several ongoing and planned research efforts aim to address these issues, promising significant new insights from age of air into the stratospheric Brewer-Dobson circulation and its evolution in a warming climate.

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2nd Workshop on the dynamics of Rossby waves, compound extremes and their impacts

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DATES:
19 - 21 January 2026

NUMBER OF PARTICIPANTS:
132 in-person and 50 online

SCIENTIFIC ORGANIZING COMMITTEE:
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LOCAL ORGANIZING COMMITTEE:
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https://sites.google.com/view/dynamics-of-rossby-waves-co/home

SPONSORS:

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The Workshop was held on 19-21 January 2026 in Amsterdam, kindly hosted by VU Amsterdam. We would like to express our sincere thanks to the local organizers for an excellent organization of the workshop and great hospitality.

Support from the WCRP Stratosphere-Troposphere Processes and their Role in Climate and from the XAIDA project enabled the attendance for 6 Early Career Scientists (ECS) and researchers from underrepresented countries. The organizers would like to thank all sponsors for their support.

Meeting overview

The workshop was the 2nd edition of the workshop on "Rossby waves, heatwaves and compound extreme events" taking place in November 2023 at CNR in Bologna, Italy, which was documented in the Bulletin of the American Meteorological Society (BAMS): Lembo et al (2024): "Dynamics, Statistics, and Predictability of Rossby Waves, Heat Waves, and Spatially Compounding Extreme Events", https://doi.org/10.1175/BAMS-D-24-0145.1.

The workshop in Amsterdam expanded the scientific scope and the community to include the societal impacts of circulation anomalies and extreme events. The workshop was attended by a wide range of researchers interested in large-scale atmospheric dynamics, weather and climate extremes and their impacts. Overall, more than 130 in-person participants from over 21 countries attended the meeting, of which around 42% were female.

Figure 19: *The in-person attendees of the workshop.*

The meeting accommodated 36 oral presentations (42% of all speakers were female, and of the 10 invited/keynote speakers 40% were female) and 80 posters. The presentations were organized into 8 sessions. There were sessions devoted to Rossby waves and the atmospheric circulation, compound events and extremes, and impacts of Rossby waves and extremes. Novel topics for this workshop in comparison to its first edition were on the relation between socio-economic impacts and Rossby waves, through their linkage to the science and prediction of compound extreme events.

On 20 January the conference dinner was held in Café Belcampo located at the food court "Food-hallen" in Amsterdam.

Invited talks

There was a total of 10 invited talks. Tim Woolings provided a historical background of the scientific developments linking Rossby waves and station-arity, Hayley Fowler highlighted the importance of Rossby wave breaking for sub-daily rainfall extremes in Europe, Rachel White described quasi-stationary waves in relation to waveguides, highlighting their role for extreme weather, Dim Coumou provided an overview of the EXPECT project, focusing on the

Figure 20: *Scientific organizing committee: left to right: Jacopo Riboldi, Simona Bordoni, Vera Melinda Galfi, Daniela Domeisen, Valerio Lembo*

Figure 21: *Audience during the workshop in one of the lecture rooms.*

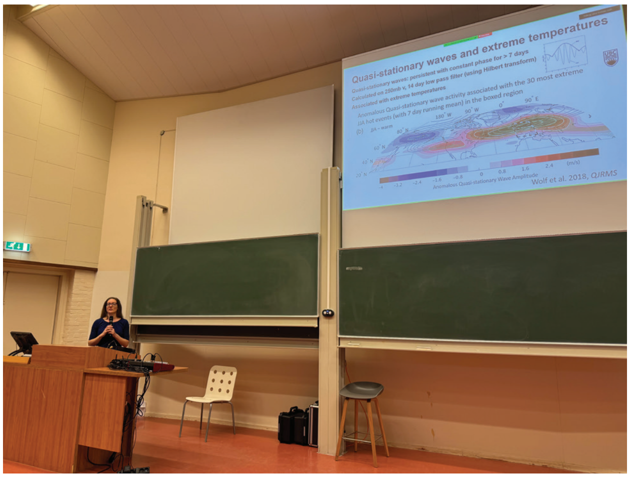


Figure 22: *Keynote talk by Rachel White.*

emergence of trends in the boreal summer circulation. Olivia Martius focused on the modulation of soil moisture anomalies by the upper circulation. Emanuele Bevacqua highlighted how compound extreme events are shaped by climate change. Erich Fischer introduced the topic of "unseen" events as simulated in large ensemble simulations. Vikki Thomson highlighted the importance of multiple event methods for extreme events attribution. Gabriele Messori stressed challenges and opportunities in the study of impacts related to extreme events. Sander Veraverbeke introduced the topic of drivers and impacts of wildfires in boreal forests.

Breakout discussions

The workshop featured three 60-min discussion blocks, linking the three main themes of the workshop into two main questions: the first question focused on the open research gaps at the interface between Rossby wave dynamics and compound extreme weather events, and the second about the challenges of building reliable connections between compounding hazards and socio-economic impacts. Workshop participants contributed to the discussion with the help of the "MentiMeter" application: individual feedback was gathered by allowing 5 quiet minutes for everyone to submit their input, which was then displayed on the main screen to serve as a starting point for further discussion.

Breakout discussion on the link between Rossby waves and compound extremes:

Concerning the first topic, the participants re-emphasized the importance of process understanding as a first necessary step to gain confidence in the modeling and future projection of extreme events, especially in so-far understudied regions like the Global South and the Southern Hemisphere. Furthermore, anthropogenic global warming leads to subtle dynamical changes in the extratropical circulation, for instance by slowly modifying the background flow in which tropopause-level Rossby waves evolve. However, a shared definition of what would constitute such a "background flow" is lacking, posing a major conceptual challenge and hindering our basic understanding of future circulation changes. The discussion also mentioned the lower boundary of the atmosphere, the Earth's surface, with many participants emphasizing the lack of process understanding for land- and ocean-atmosphere interactions in present and future climate. The presence of biases in climate models (e.g., in the upper-level jet stream) further complicates the picture, calling for the necessity to reduce such biases. A possible avenue to achieve this objective might be the use of kilometer-scale models, which have been beneficial to properly represent the process of Rossby wave breaking with the associated consequences in terms of extreme weather at the surface. The enhanced process understanding can then be fed back to models to enhance the predictability of extremes, both at shorter time scales (e.g., via early warning systems based on large-scale flow precursors) and at longer time scales (e.g., via improved storylines of worst-case events). The community also discussed the role that AI models will play in this challenge, pointing out the necessity that such models correctly represent multi-scale energy exchanges involved in the genesis of extreme events.

Breakout discussion on the link between compound extremes and impacts:

The second discussion block clearly pinpointed uncertainty in impact modeling and lack of usable economic/health impact data as major limitations for impact-related research. There is broad agreement that no "silver bullet" exists to tackle these issues: among the discussed ideas to attenuate them is the possibility of improving regulations for public entities to obtain a more consistent impact reporting and facilitate data sharing. Enhancing data quality and availability would also be a way to reduce the large uncertainties in impact modeling. Those impact-specific issues further amplify the uncertainty already present in future climate projections because of model biases and natural/scenario variability, turning impact projections into an extremely challenging task. The discussion also highlighted the importance for the extremes and the impacts communities to talk more to each other, in order to standardize definitions and terminology and to develop a bottom-up characterization of physical drivers starting from the impacts themselves -- which are also, as pointed out, very relevant from the perspective of communication of weather/climate extremes to the broader society.

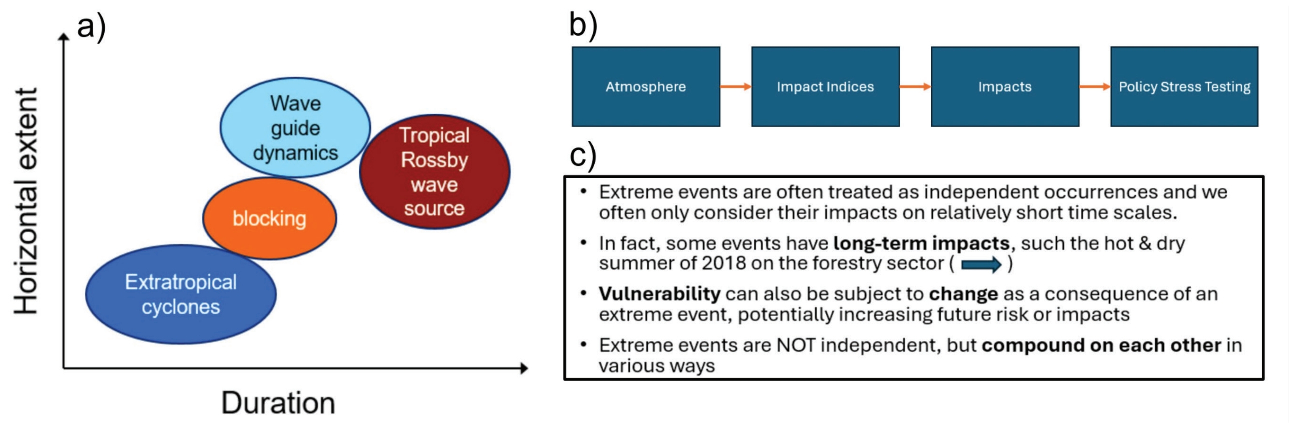
In addition to discussing the detailed responses from the workshop participants, the organizers used an AI summary tool to sort the responses, leading to the following key insights:

- The strongest theme coming out of the workshop is the aim of better predictability of the connection between Rossby waves and extremes, especially via improving model biases and hybrid AI-physics methods.
- The community is ready for follow-up action in terms of regular workshops, hackathons, and community papers.
- The impact work is bottlenecked by fragmented and/or inaccessible data and terminology issues, suggesting that shared datasets and a common language are crucial first steps.

All of these points have been taken up by the community, see the following sections on seed ideas and ongoing and future activities.

Seed ideas

A few weeks before the start of the workshop, the participants were encouraged to propose novel research ideas capable of "bridging gaps" between atmospheric dynamics, compound extremes and impacts. These initial "seed" ideas were pitched during the two discussion sections, and they were then voted on to gauge which research directions were of particular interest to the broader community. Six seed ideas tackling the dynamics-extremes gap and two ideas tackling the extremes-impact gap were proposed, providing concrete examples of the challenges discussed more abstractly during the first part of the discussion sessions.



- Extreme events are often treated as independent occurrences and we often only consider their impacts on relatively short time scales.
- In fact, some events have **long-term impacts**, such the hot & dry summer of 2018 on the forestry sector (➡)
- **Vulnerability** can also be subject to **change** as a consequence of an extreme event, potentially increasing future risk or impacts
- Extreme events are NOT independent, but **compound on each other** in various ways

Figure 23: *A collection of pictures from the most popular "seed ideas" during the Workshop. a) Schematic by W. Wicker depicting how different drivers could project on compounding extremes with different temporal and spatial scales; b) Workflow by L. van Garderen depicting a storyline-based attribution approach with direct connection to policy-relevant stress testing; c) Motivation behind the seed idea by N. Schuhen, emphasizing the lack of systematic analysis of long-term impacts of extreme events.*

The most voted seed idea at the interface between atmospheric dynamics and compound extremes was proposed by Wolfgang Wicker (University of Lausanne, Switzerland): it concerned the connection between known drivers of Rossby wave activity and the magnitude/extent of spatially compounding events, suggesting to compare how each driver affects the co-location and co-occurrence of extremes over northern midlatitudes (Fig. 23a).

The two ideas at the interface between compound extremes and impact-related research were proposed by Linda Van Garderen and Nina Schuhen: both of them obtained ~50% of the votes, speaking for a high interest from the community. The first idea involved a storyline-based attribution approach to bridge different hazards with impact-relevant stress testing, with the aim to help decision-makers in assessing climate change impacts (Fig. 23b). The second idea aims for a framework to systematically characterize the lagged impact of extreme events at often neglected multi-year time scales, extending the concept of temporally compounding extremes (Fig. 23c).

Ongoing and future activities

Based on the input from all workshop participants and especially the discussion sessions, several activities were agreed on as a follow-up of the workshop. The most notable ones are mentioned below:

- Independent collaboration activities as follow-ups to the workshop:
    - a review paper on the connection between Rossby wave breaking and extremes, initiated by Olivia Martius and led by Andries de Vries. This effort is overshadowed by the early passing of Victoria Sinclair, who participated in the workshop and contributed to the early stages of this review
    - an early-career collaboration assessing large-scale atmospheric drivers for compound extremes led by Wolfgang Wicker and Anupama K Xavier
- A perspective paper led by Vera Melinda Galfi is currently in preparation, underlying the importance of understanding the large-scale atmospheric dynamics for the prediction of extreme events and the assessment of its impacts.
- A splinter meeting was organized in May during the European Geosciences Union 2026 in Vienna, gathering the community and discussing next steps; a follow-up of this meeting was held online to accommodate participants and ideas not present at EGU.
- A follow-up of the workshop, in the form of a Summer School in tandem with a next workshop is currently being organized and partially funded by the International Center for Theoretical Physics (ICTP) in Trieste for summer 2027.

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