pmod wrc

Annual Report
Jahresbericht 2021

Front Cover: View of PMOD/WRC during the IPC-XIII intercomparison which ran from 27 September to 15 October 2021. The 5th Filter Radiometer Comparison (AOD) (FRC-V) and the 3rd International Pyrgeometer (IR) Comparison (IPgC-III) took place at the same time. Image credit: Paola Russo.

Das PMOD/WRC ist eine Abteilung der Stiftung Schweizerisches Forschungsinstitut f. Hochgebirgsklima und Medizin in Davos, Schweiz.

The PMOD/WRC is a department of the Swiss Research Institute for High Altitude Climate and Medicine (SFI) in Davos/Switzerland.

Physikalisch-Meteorologisches Observatorium Davos/ World Radiation Center (PMOD/WRC)
Dorfstrasse 33,
7260 Davos Dorf
Schweiz

Tel. +41 (0)81 417 51 11
www.pmodwrc.ch

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Physikalisch-Meteorologisches Observatorium Davos und Weltstrahlungszentrum PMOD/WRC

Unsere Mission

Wir sind ein international anerkanntes Kalibrierungszentrum für meteorologische Strahlungsinstrumente. Zu diesem Zweck entwickeln wir Strahlungsinstrumente, sowohl für den Einsatz am Boden, als auch satellitengetragen im Weltraum. Unsere Forschung konzentriert sich auf den Einfluss der solaren Strahlung und der Sonnenaktivität auf das Klima der Erde und dessen Atmosphäre.

Geschichte des PMOD/WRC

Das Physikalisch-Meteorologische Observatorium Davos (PMOD) erforscht seit seiner Gründung im Jahr 1907 den Einfluss der solaren Strahlung auf das Klima der Erde. Im Jahr 1926 schloss sich das Observatorium dem Schweizerischen Forschungsinstitut für Höhenklima und Medizin Davos an und ist seither Teil dieser Stiftung. Auf Antrag der Weltorganisation für Meteorologie (WMO) beschloss der Bundesrat 1970 die Finanzierung eines Kalibrierungszentrums für Strahlungsmessungen als Beitrag der Schweiz an das Weltwetterbeobachtungsprogramm der WMO. In der Folge wurde das PMOD mit der Errichtung und dem Betrieb des World Radiation Center (WRC) beauftragt.

Kernaktivitäten

Das World Radiation Center unterhält den Primärstandard für die solare Bestrahlungsstärke, der aus einer Gruppe von hochpräzisen Absolutradiometern besteht. Als Reaktion auf weitere Anfragen der WMO wurde 2004 ein Kalibrierungszentrum für Instrumente zur Messung der langwelligen atmosphärischen Strahlung und 2008 ein Kalibrierungszentrum für spektrale Strahlungsmessungen zur Bestimmung der atmosphärischen Trübung eingerichtet. Seit 2013 wird auch das Weltkalibrierzentrum für UV von unserem Welt-Strahlungszentrum betrieben.

Heute besteht das Welt-Strahlungszentrum aus vier Abteilungen: Solare Radiometrie (WRC-SRS), Infrarot-Radiometrie (WRC-IRS), atmosphärische Trübung (WRC-WORCC) und UV-Radiometrie (WRC-WCC-UV).

Das PMOD/WRC ist vollständig in den Europäischen Verband der nationalen Metrologieinstitute (EURAMET) und in den Rahmen des Bureau International des Poids et Mesures (BIPM) integriert. Das PMOD/WRC ist assoziiertes Mitglied von EURAMET und wurde im September 2002 durch METAS beim Bureau Internationale des Poids et Mesures (BIPM) als designiertes Institut (DI) für die Grösse "Solare Bestrahlungsstärke" im Rahmen des CIPM-MRA gemeldet.

Wir entwickeln und bauen Radiometer, die zu den genauesten ihrer Art auf der Welt gehören und sowohl am Boden als auch im Weltraum eingesetzt werden. Diese Instrumente sind auch käuflich zu erwerben und werden seit langem von den Wetter-und Klimadiensten weltweit eingesetzt. Darüber hinaus haben wir ein globales Netz von Stationen zur Überwachung der atmosphärischen Trübung mit Präzisionsfilterradiometern ausgestattet, die vom PMOD/WRC entwickelt wurden.

Die im Weltraum gesammelten Daten (Radiometrie und Solar Imaging) sowie die Bodenmessungen werden in Forschungsprojekten zum Klimawandel und zur Sonnenaktivität ausgewertet. Zu diesem Zweck haben wir ein eigenes globales Chemie-Klimamodell entwickelt, mit dem wir die Beziehung zwischen Sonne und Erde unter besonderer Berücksichtigung der mittleren Erdatmosphäre und der Ozonschicht untersuchen. Diese Forschungsaktivitäten und unsere internationalen Kooperationen sind weltweit anerkannt.

Schliesslich unterrichten wir an der ETH Zürich sowohl auf Bachelor- als auch auf Masterstufe innerhalb des Departements Physik und des Departements für Umweltsystemwissenschaften.

Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center PMOD/WRC

Mission

Our core mission is to serve as an international calibration center for meteorological radiation instruments. To this end, we develop radiation instruments for use on the ground and in space. Our research focuses on the influence of solar radiation and solar activity on Earth’s climate and its impact on the Earth's atmosphere.

PMOD/WRC History

Since its establishment in 1907, the Physikalisch-Meteorologisches Observatorium Davos (PMOD) has been studying the influence of solar radiation on the Earth’s climate. In 1926, the Observatory joined the Swiss Research Institute for High Altitude Climate and Medicine Davos and has since become part of this foundation. At the request of the World Meteorological Organization (WMO), the Federal Council decided in 1970 to finance a calibration center for radiation measurement as Switzerland’s contribution to the World Weather Watch Programme of the WMO. Following this decision, PMOD was commissioned to establish and operate the World Radiation Center (WRC).

Core Activities

The World Radiation Center maintains the primary standard for solar irradiance, which consists of a group of high-precision absolute radiometers. In response to further requests from WMO, a calibration center for atmospheric longwave radiation instruments was established in 2004, and the calibration center for spectral radiance measurements to determine atmospheric turbidity was established in 2008. Since 2013, the World Calibration Center for UV has also been operated by the World Radiation Center.

Today, the World Radiation Center consists of four sections: Solar Radiometry (WRC-SRS), Infrared Radiometry (WRC-IRS), Atmospheric Turbidity (WRC-WORCC), and UV Radiometry (WRC-WCC-UV).

PMOD/WRC is fully integrated into the European Association of National Metrology Institutes (EURAMET) and into the framework of the Bureau International des Poids et Mesures (BIPM). PMOD/WRC is an associated member of EURAMET and was nominated in September 2002 by METAS at the Bureau Internationale des Poids et Mesures (BIPM) as the designated institute (DI) for the quantity "solar irradiance" within the framework of CIPM-MRA.

We develop and build radiometers that are among the most accurate of their kind in the world and are used both on the ground and in space. These instruments are also available for purchase and have long been used by Meteorological Services worldwide. Furthermore, a global network of atmospheric turbidity monitoring stations is equipped with precision filter radiometers developed by PMOD/WRC.

Data collected in space (radiometry and solar imaging) and by means of ground measurements are analysed in research projects on climate change and solar activity. For this purpose, we have developed our own dedicated global chemistry-climate model, devoted to investigating the Sun-Earth relationship with particular focus on the Earth’s middle atmosphere and ozone layer. These research activities and our international collaborations are recognised worldwide.

Last but not least, we carry out teaching at both, the bachelor and master level at ETH Zürich, hosted within the Department of Physics and the Department of Environmental Systems Science.

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Einleitung

Louise Harra

Obwohl die Pandemie bis ins Jahr 2021 andauerte, arbeiteten die Mitarbeiter weiterhin auf innovative Weise daran, die exzellente Arbeit des Physikalisch-Meteorologischen Observatoriums Davos und des Welt-Strahlungszentrums (PMOD/WRC) sicherzustellen.

Eine der grossen Veranstaltungen in diesem Jahr war der 13. Internationale Pyrheliometer-Vergleich, der gleichzeitig mit dem 3. Internationalen Pyrgeometer-Vergleich und dem 5. Filter-Radiometer-Vergleich stattfand. Diese Vergleiche finden normalerweise alle 5 Jahre statt und sollten eigentlich im Jahr 2020 stattfinden. Dank der hervorragenden Teamarbeit aller Abteilungen des Instituts und der monatelangen Vorbereitungen konnte die Veranstaltung mit 52 Teilnehmern aus 22 Ländern erfolgreich durchgeführt werden.

Auch im Bereich der Raumfahrt haben wir ein ereignisreiches Jahr hinter uns: Die ESA-Mission Solar Orbiter hat ihre Reisephase erfolgreich abgeschlossen, die ersten wissenschaftlichen Ergebnisse wurden veröffentlicht, unser Instrument auf der chinesischen Mission Fengyun-3E wurde gestartet und unser Instrument auf der ESA/NASA-Sonde SOHO ist seit 26 Jahren in Betrieb.

Die Zusammenarbeit mit der ETH-Zürich, Institut für Teilchenphysik und Astrophysik (IPA), wird fortgeführt, mit Beteiligung an der Lehre und Projektstudenten und Zusammenarbeit in der Technologie.

Die sechs Kernbereiche, in denen das PMOD/WRC tätig ist, sind:

- Welt-Strahlungszentrum: dient als internationales Kalibrierungszentrum für meteorologische Strahlungsinstrumente und entwickelt Strahlungsinstrumente für den Einsatz am Boden und im Weltraum.
- Weltraumprojekte: Entwicklung von Instrumenten zur Bildgebung und Strahlungsmessung der Sonne.
- Technologie: Grundlage für das Design und die Entwicklung der Instrumente für Messinstrumente am Boden und im Weltraum.
- Klimawissenschaft: Erforschung des Einflusses der Sonnenstrahlung auf das Klima der Erde.
- Sonnenwissenschaft: Erforschung der Ursachen der Sonnenaktivität.
- Lehrtätigkeit: Durchführung von Lehrveranstaltungen auf verschiedenen Stufen an der ETH-Zürich.

Im Jahr 2021 konnten wir viele wichtige Erfolge verbuchen. Hier sind einige Highlights:

- Der 13. Internationale Pyrheliometervergleich (IPC-XIII) fand im September 2021 statt. Daneben fanden der 5. Filter-Radiometer-Vergleich (FRC-V) und der 3. internationale Pyrgeometer-Vergleich (IPgC-III) statt. *Siehe Seiten 12, 13, 14*.

- Verbesserungen am kryogenen Solar-Absolut-Radiometer (CSAR) wurden fortgesetzt, und dieses Instrument nahm ebenfalls an der IPC-XIII teil.

- Die chinesische Raumsonde Fengyun-3E wurde im Juli 2021 erfolgreich gestartet. Das PMOD/WRC-Instrument, Joint Total Solar Irradiance Monitor Digital Absolute Radiometer (JTSIM-DARA), ist an Bord und betriebsbereit. *Siehe Seite 23.*

- Das Instrument Digitale Absolute Radiometer (DARA) der ESA-Mission Proba-3 wurde an die Raumsonde geliefert. *Siehe Seite 17.*

- Die Mission Solar Orbiter hat während ihrer Reisephase erfolgreich mehrere Vorbeiflüge an der Erde und der Venus durchgeführt, um in die endgültige Umlaufbahn zu gelangen und den wissenschaftlichen Betrieb aufzunehmen. Die ersten wissenschaftlichen Arbeiten wurden veröffentlicht. *Siehe Seite 28.*

- Wir wurden für die Phase A der Studie eines extrem ultravioletten Bildgebers für die NASA-Mission Solaris finanziert.

- Ein neuer Kurs „Sonne, Sterne und Planeten“ wurde an der ETH Zurich als Blockkurs gestartet.

- Das ESA-Komitee für das Wissenschaftsprogramm hat unsere Teilnahme an der Überwachung der spektralen Bestrahlungsstärke der Sonne für die japanische Mission Solar-C genehmigt. *Siehe Seite 18.*

- Julian Gröbner und Natalia Kouremeti gewannen den Professor Dr. Vilho Väisälä Award für ein „Herausragendes Forschungspapier über Instrumente und Beobachtungsmethoden“, 27. Verleihung (2020), für ihr Paper über das Präzisions-Sonnenspektroradiometer.

- Wir haben die Genehmigung erhalten, die Phase A der Studienarbeiten für die ESA-Mission TRaceable Radiometery underpinning Terrestrial and Helio-studies (TRUTHS) zu beginnen. *Siehe Seite 19.*

- Der endgültige Transfer der Instrumente von Arosa nach Davos ist abgeschlossen - damit ist die Messung der Ozon-Messreihe für die Zukunft gesichert. *Siehe Seite 43.*

- Die Aufrüstung des Netzwerks der Präzisionsfilter-Radiometer von Global Atmosphere Watch (GAW) wurde im Jahr 2021 fortgesetzt.

- Unsere wissenschaftlichen Publikationen gehen weiter - mit einem Zitationsindex von mittlerweile über 2000 pro Jahr. *Siehe Seite 25.*

- Öffentliche (persönliche) Veranstaltungen starteten langsam im Jahr 2021 mit der Teilnahme an der Davoser Mäss, einer offenen Veranstaltung entlang der Hauptstrasse in Davos. Das PMOD/WRC hatte dort einen Stand.

Ich möchte diese Gelegenheit nutzen, um allen Mitarbeitern des Instituts für ihre harte Arbeit und ihr Engagement in der Zeit der Pandemie zu danken, sowie dem Kuratorium und der Aufsichtskommission für die kontinuierliche Begleitung und Unterstützung. Meine Kolleginnen und Kollegen an der ETH Zürich haben die Arbeit in Zeiten der Pandemie, einschließlich des Unterrichts, ruhig organisiert, so dass alles zeitgerecht ablaufen konnte - auch das hat außergewöhnliche Arbeit, Initiative und Planung erfordert.

Eine Collage mit einigen der Erfolge ist rechts abgebildet.

Abbildung 1: Von links oben nach rechts unten: Teilnehmer der IPC-XIII, der Start des Fengyun-3E-Satelliten, die Lieferung des letzten Containers von Arosa nach Davos für die Fortsetzung der Ozon-Zeitreihe, das DARA-Radiometer in einer von der Heliostat-Anlage des PMOD/WRC beleuchteten Vakuumkammer, eine künstlerische Darstellung des Vorbeiflugs des Satelliten Solar Orbiter an der Venus.

Figure 1: From top left to bottom right: attendees at the IPC-XIII, the launch of the Fengyun-3E spacecraft, the delivery of the last container from Arosa to Davos for the continuation of the ozone time-series, the DARA radiometer in a vacuum chamber illuminated by the Heliostat facility at PMOD/WRC, an artist's impression of the fly-by of Venus by the Solar Orbiter spacecraft (image credit: ESA).

Introduction

Louise Harra

Although the pandemic continued into 2021, staff continued to work in innovative ways to ensure that work carried on at the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in an excellent way.

One of the big events that took place this year was the 13th International Pyrheliometer Comparison, which ran simultaneously with the 3rd International Pyrgeometer Comparison and the 5th Filter Radiometer Comparison. These comparisons normally take place every 5 years and should have taken place in 2020. With the great teamwork across all sections of the institute, and many months of preparation, it took place successfully with the attendance of 52 participants from 22 countries.

We have had an eventful year also in space, with the ESA Solar Orbiter mission successfully completing its cruise phase, and the first science results out, our instrument on the Chinese mission Fengyun-3E being launched and our instrument on the ESA/NASA SOHO spacecraft being operational for 26 years.

The collaboration with ETH-Zürich, Institute for Particle Physics and Astrophysics (IPA), continues with involvement in teaching and project students and collaboration on technology

The six core areas that PMOD/WRC undertake are:

- World Radiation Center: serve as an international calibration center for meteorological radiation instruments and develop radiation instruments for use on the ground and in space.

- Space projects: develop instruments for imaging and radiation measurements of the Sun.

- Technology: underpin the design and development of instruments for ground and space measurements.

- Climate science: research the influence of natural and anthropogenic activity on Earth's climate.

- Solar Science: research the causes of solar activity.

- Teaching: carry out teaching at different levels at ETH-Zurich.

There have been many key successes during 2021. Here are a few highlights:

- The 13th International Pyrheliometer Comparison (IPC-XIII) took place in September 2021. Alongside that was the 5th Filter Radiometer comparison (FRC-V) and the 3rd International Pyrgeometer Comparison (IPgC-III). *See pages 12, 13 and 14.*

- Improvement on the Cryogenic Solar Absolute Radiometer (CSAR) continued, and this instrument also took part in IPC-XIII.

- The Chinese Fengyun-3E spacecraft was successfully launched in July 2021. The PMOD/WRC instrument, Joint Total Solar Irradiance Monitor Digital Absolute Radiometer (JTSIM-DARA), is onboard and operational. *See page 23.*

- The Digital Absolute Radiometer (DARA) instrument on the ESA PROBA-3 mission was delivered to the spacecraft. *See page 17.*

- The Solar Orbiter mission has successfully carried out several fly-bys of Earth and Venus during its cruise phase to get into the final orbit and start science operations. The first science papers were published. *See page 28.*

- We were funded for the phase A study of an extreme ultraviolet imager for the NASA Solaris mission.

- A new course, "Sun, stars and planets", started at ETH Zurich as a block course.

- The ESA science programme committee approved our participation on the Solar Spectral Irradiance Monitor (SoSpIm) for the Japanese Solar-C mission. *See page 18.*

- Julian Gröbner and Natalia Kouremeti won the Professor Dr Vilho Väisälä Award for an “Outstanding Research Paper on Instruments and Methods of Observation”, 27th granting (2020), for their paper on the Precision Solar Spectroradiometer.

- We were approved to start the phase A study work for the ESA TRaceable Radiometry underpinning Terrestrial and Helio-studies (TRUTHS) mission. *See page 19.*

- The final transfer of instruments from Arosa to Davos took place - ensuring the future measurement of the ozone time-series. *See page 43.*

- The upgrade of the Global Atmosphere Watch Precision Filter Radiometer (GAW-PFR) network continued during 2021.

- Our scientific publications continue - with the citation index now reaching over 2000 per year. *See page 25.*

- Public (in person) events slowly started in 2021, with participation in the Davoser Mäss, which is an open event along the main street in Davos. PMOD/WRC had a stand there.

I would like to take this opportunity to thank all the staff at the institute for their hard work and dedication throughout the time of the pandemic, and the Board of Trustees and Supervisory Commission for continuing guidance and support. My colleagues at ETH Zurich organised the pandemic teaching in an excellent way – this has also taken exceptional work, initiative, and planning. We are hopeful of a 2022 that becomes more normal.

A collage of some of the successes is shown on page 7.

World Radiation Center / Operational Services

Quality Management System, Calibration Services, Instrument Sales

Ricco Soder, Wolfgang Finsterle, and Julian Gröbner

Calibration and Measurement Capabilities (CMCs)

As in the previous two years, PMOD/WRC has 8 different CMCs listed in the Key Comparison Database (KCDB) of the Bureau International de Poids et Mesure (BIPM). These include:

- Responsivity, solar irradiance pyranometer (1)
- Responsivity, solar irradiance pyrheliometer (1)
- Responsivity, solar irradiance broadband detector (4)
- Responsivity, solar spectral irrad. solar spectroradiometer (2)

Depending on the instrument's wavelength range the CMCs belong to the different WRC calibration sections.

Organisation and Human Resources

No changes occurred in personnel regarding functions or responsibilities within the QMS (Figure 1).

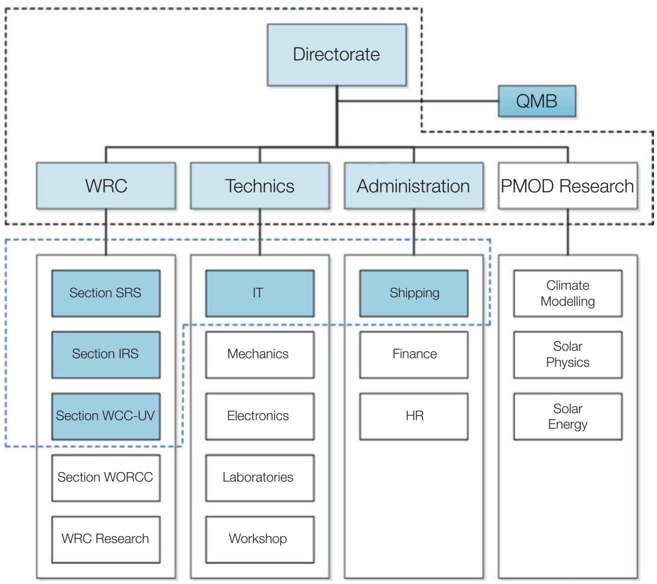


Figure 1. PMOD/WRC Quality Management System (QMS) - organisational chart. The WRC-SRS, WCC-UV, and WRC-IRS sections (in blue), perform calibrations according to the EN ISO/IEC standard 17025.

Activities

Even though the COVID-19 pandemic still had a strong impact on our working life at PMOD/WRC, we were able to participate in several inter-laboratory comparisons and held the IPC-XIII intercomparison (including FRC-V and IPgC-III) which had to be postponed in 2020. The quality management system and documentation of our calibration sections was successfully peer-reviewed by METAS, the Swiss National Metrology Institute, in June 2021. This audit was also the last milestone, which had to be achieved to complete the requirements of the postponed transition phase towards the revised standard, ISO 17025:2018. Furthermore, QM related Documentation of all WRC-sections was updated and continuously developed throughout the year. Training of staff was performed in accordance with a section-specific training schedule.

The establishment of a new service category and CMC for atmospheric longwave irradiance was discussed (through the EURAMET TC-Chair) at the CCPR WG CMC meeting on 21 October 21 2021 for the audience of RMOs TC Chairs and RMO CMC experts.

The proposal was assessed positively, noting that further information should be supplied by PMOD/WRC, such as clarification on the option for the traceability chain, and information where the expertise lies at CCPR to review a possible CMC submission of this quantity. Such a CMC also implies that the designation of PMOD/WRC as a designated institute of METAS will need to be extended to encompass this new quantity.

Calibration Services

In 2021, the four WRC calibration sections (SRS, IRS, WCC-UV and WORCC) calibrated a total of 243 instruments, which is the second highest amount ever. This increase of 75 instruments, or almost 45% compared to last year, was mainly driven by the IPC-XIII and IPgC-III intercomparisons.

Solar Radiometry Section (WRC-SRS)
The WRC-SRS section calibrated a total of 98 instruments in 2021. Whereas the number of pyranometer calibration slightly increased to 77, the number of pyrheliometer calibrations significantly decreased to 21. This drop can be explained by the fact that IPC-XIII took place in 2021 and, as usual, no certificates were issued for the participating pyrheliometers. Due to a discrepancy regarding the stated level of uncertainty, only 93 pyrheliometer certificates were issued with the CIPM logo.

Infrared Radiometry Section (WRC-IRS)
The WRC-IRS section performed 70 pyrgeometer calibrations in 2021 and increased the number of calibrations by 46. As already mentioned, this was due to the IPgC-III intercomparison (see Fig. 3).

Atmospheric Turbidity Section (WRC-WORCC)
The WRC-WORCC section calibrated 19 Precision Filter Radiometers (PFR) against the WORCC Triad standard. In addition, six Precision Solar Spectroradiometers (PSR) were calibrated against a reference standard, traceable to the German national metrology institute. WRC-WORCC organised the FRC-V intercomparison (see Figure 4). A total of 36 certificates were issued by WRC-WORCC.

World Calibration Center for UV Section (WRC-WCC-UV)
A total of 29 UVB broadband radiometers were calibrated by the WRC-WCC-UV section. This resulted in 84 certificates which typically cover different measurement units. Furthermore, WRC-WCC-UV performed five lamp/diode calibrations, and 14 spectrometers were calibrated against the QASUME travelling reference. These calibrations resulted in 21 certificates, where 12 certificates were issued with the CIPM logo. Jakob Föller started in February 2021 as a new member of technical personnel in the science department in the WRC sections, WORCC and WCC-UV.

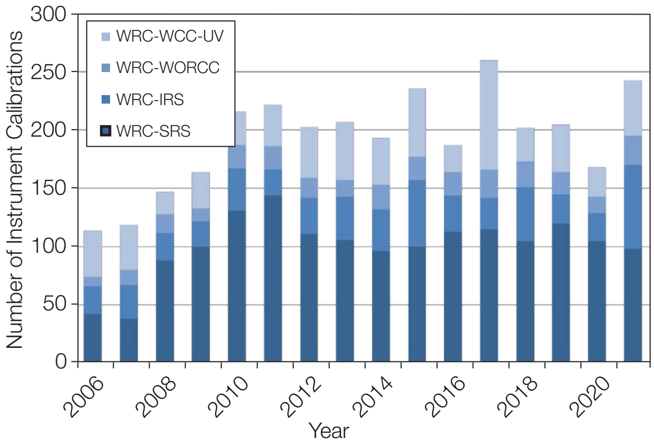


Figure 2. Statistics of instrument calibrations at PMOD/WRC 2006 - 2021. Note that one instrument can result in more than one calibration certificate.

Figure 3. Participants from the IPgC-III on the PMOD/WRC roof platform in Autumn 2021. From left to right: Christian Thomann (PMOD/WRC), Julian Gröbner (PMOD/WRC), Stefan Wacker (DWD, Germany), and Ibrahim Reda (NREL, USA).

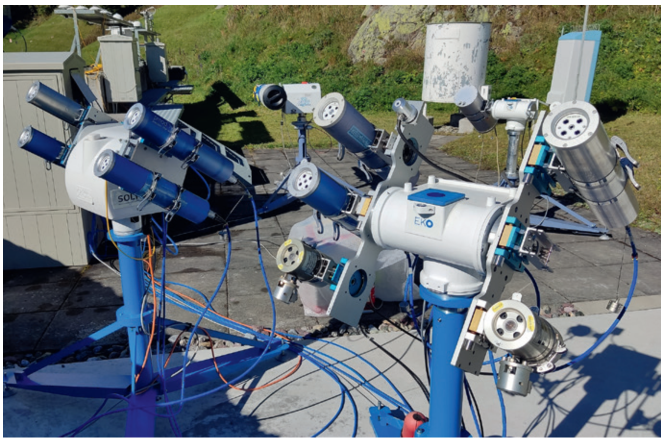


Figure 4. View of Precision Filter Radiometers (PFRs) during the FRC-V intercomparison at PMOD/WRC in Autumn 2021.

Instrument Sales

In 2021, PMOD/WRC sold one Precision Filter Radiometer (PFR). The low volume of instrument sales was due to several reasons. The first reason was that the production and sale of PMO6-cc absolute cavity pyrheliometers was outsourced to Davos Instruments (https://www.davos-instruments.ch/) several years ago. Davos Instruments have developed a new generation, the PMO8 series, along with a new control unit. PMOD/WRC will continue to be responsible for the calibration of absolute cavity pyrheliometers against the World Standard Group. As a result, these type of radiometers have not appeared in the sales statistics of Figure 5 as of 2020.

The second main reason for the lack of instrument sales in 2021 was the continuing global Covid-19 pandemic. Despite the IPC-XIII, FRC-V and IPgC-III intercomparisons which took place at PMOD/WRC in September - October 2021, the uncertainty due to the pandemic remained, and did not result in increased sales.

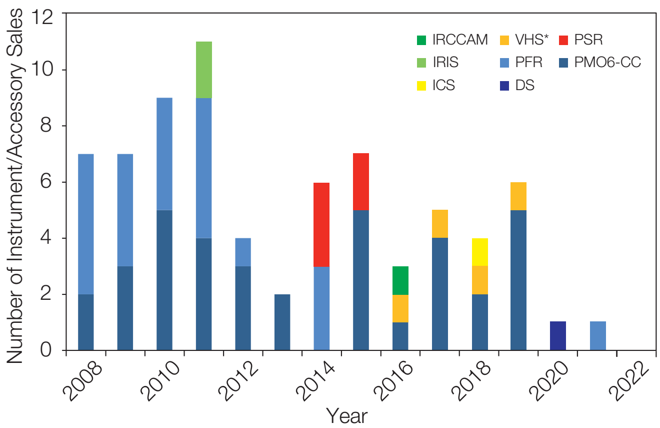


Figure 5. Number of PMOD/WRC instrument sales from 2008 up to and including 2021: i) IRCCAM = Infrared Cloud Camera, ii) VHS = Ventilated Heating Systems, iii) PSR = Precision Spectroradiometer, iv) IRIS = Infrared Integrating Sphere Radiometer, v) PFR = Precision Filter Radiometer, vi) PMO6-CC = absolute cavity pyrheliometer, vii) ICS = Irradiance Calibration System, and viii) DS = Diffuser System for UV spectroradiometers.

**Note: VHS sales/year shown as a single unit for ease of interpretation. Actual VHS units sold: 2016 = 7; 2017 = 2; 2018 = 36; 2019 = 5.*

Solar Radiometry Section (WRC-SRS)

Wolfgang Finsterle

The Solar Radiometry Section (SRS) of the WRC maintains and operates the World Standard Group (WSG) of Pyrheliometers which represents the World Radiometric Reference (WRR) for ground-based total solar irradiance measurements. The SRS operates the ISO 17025 certified calibration laboratory for solar radiometers (pyrheliometers and pyranometers). During the 2021 calibration season, 108 certificates were issued compared to 95 in 2020. The 13th International Pyrheliometer Comparison IPC-XIII was held from 27 September to 15 October 2021. IPCs are normally held every five years. They are used to disseminate the WRR and provide the ultimate validation of the stability of the WSG.

In 2021, the SRS/WRC calibrated 108 radiometers: These consisted of 16 absolute solar radiometers, 77 pyranometers, and 15 pyrheliometers with a thermopile sensor. The number of certificates thus almost reached the pre-pandemic level. The WSG was operated on 78 days, including 12 days during IPC-XIII. The Cryogenic Solar Absolute Radiometer and Monitor for Integrated Transmittance (CSAR/MITRA) were successfully upgraded and participated in the IPC-XIII.

Preparations for the IPC-XIII intercomparison started in Spring 2021, and the final decision to proceed was made in June. Although international travel restrictions were still active for many countries, close to 80 individuals registered for the intercomparison. Eventually, 52 participants from 32 institutions representing 22 countries were able to take part in IPC-XIII. An additional four institutions sent only their pyrheliometers to be operated by WRC-SRS staff. The WRC-SRS offered this service as an exception for PMO6 and PMO8-type pyrheliometers to also enable participation for institutions from countries who were still banned from international travel in 2021. In total, 105 pyrheliometers participated in IPC-XIII (Figure 1). The weather conditions were quite favourable with measurements being possible on 12 days during the 3-week period. The results from IPC-XIII will be published in a final report.

Figure 1. IPC-XIII participants are getting ready to take measurements on a sunny day (28 September 2021).

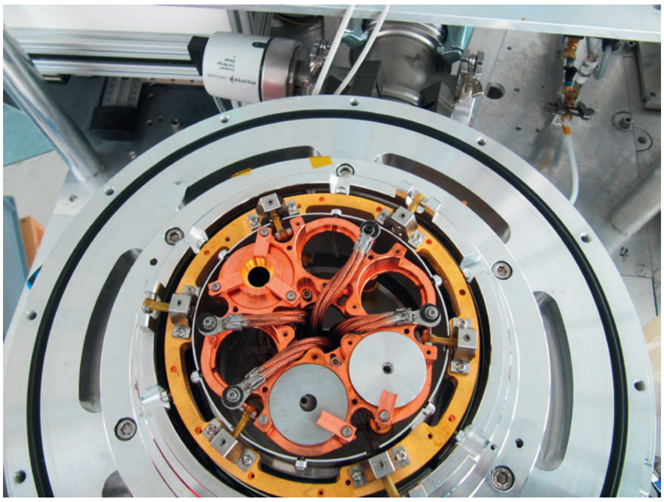


Figure 2. The CSAR vacuum tank was opened to service the heat-links between the reference block (copper structure) and the cold finger of the cryo cooler. The measuring cavity is in the 11 o'clock position on this photograph. The copper straps connect the reference block to the cold finger (not visible). During normal operation the reference block is at ~25 - 35 K, the intermediate stage (gold coated ring) is at ~70 K.

The IPC-XIII symposium was held during cloudy days. The symposium was held in a hybrid format; all presentations were live-streamed on the internet and pre-recorded presentations were shown from authors who could not participate in person.

On 5 July 2021, the WRC-SRS calibration laboratory was audited by METAS. Three non-conformities were found and 1 recommendation was issued. All issues were resolved by the end of the year.

The CSAR cryo-cooler and vacuum system were serviced in preparation for IPC-XIII (Figure 2). MITRA was upgraded with a third receiver to better compensate for changes in ambient temperature. The new MITRA receivers are of the flat-sensor type which was originally developed by PMOD/WRC together with Davos Instruments AG for their latest absolute solar radiometer, PMO8. CSAR and MITRA operated flawlessly during IPC-XIII, although windy conditions may have influenced the absolute accuracy of the MITRA transmission measurements. The results will be published in the IPC-XIII final report.

A new data acquisition computer was commissioned before IPC-XIII. Together with the old system, which is still operational, the new system provides technical redundancy for the WRC-SRS calibration laboratory. For additional redundancy, a new tracker controller was designed and built by the PMOD/WRC technical department. This new system is now in the testing phase and will be commissioned during 2022.

Infrared Radiometry Section (WRC-IRS)

Julian Gröbner, Christian Thomann, and Stephan Nyeki

The Infrared Radiometry Section of the WRC maintains and operates the World Infrared Standard Group of pyrgeometers (WISG) which represents the world-wide reference for atmospheric longwave irradiance measurements.

The WISG serves as an atmospheric longwave irradiance reference for the calibration of pyrgeometers operated by institutes around the world. The WISG has been in continuous operation since 2004, and consists of four pyrgeometers which are installed on the roof platform of PMOD/WRC. The measurements of the individual WISG pyrgeometers with respect to their average are shown in Figure 1 for the period 2004 to the end of 2021. As can be seen in the figure, the long-term stability of the WISG is very good, with measurements of the four pyrgeometers within ±1 Wm^{-2} over the whole time period.

The third International Pyrgeometer Comparison (IPgC-III) was organised together with the IPC-XIII and the Filter Radiometer Comparison (FRC-V) from 27 September to 15 October 2021 at PMOD/WRC. A total of 28 participants with 40 pyrgeometers were present during IPgC-III. In addition, four IRIS radiometers (two from PMOD/WRC, one from BOM, Australia and one from DWD, Germany) and four ACP radiometers from NREL, US (2), DWD, Germany (1), JMA, Japan (1) were operated during clear-sky nights to establish a new reference for longwave irradiance measurements traceable to SI. During 71 clear sky nights IRIS-2 and IRIS-4 measured alongside the WISG, yielding more than 9300 coincident measurements. Of these, more than 6400 coincident measurements were obtained on 24 days during conditions when values of the integrated water vapour were larger than 10 mm. The observed average difference between the WISG and IRIS was -4.3 Wm^{-2} with a standard deviation of 1.2 Wm^{-2}, which is consistent with the results published in Gröbner et al. (2014).

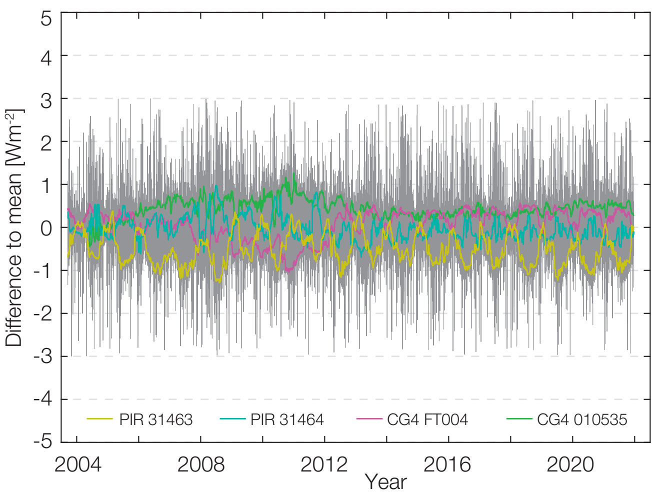


Figure 1. Night-time atmospheric longwave measurements of the WISG pyrgeometers relative to their average. The coloured lines represent a 30-day running mean of each WISG pyrgeometer, while the grey-shaded area represents daily averages.

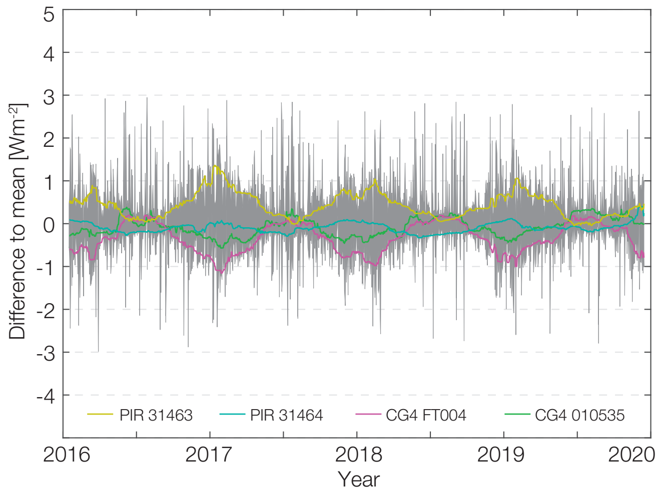


Figure 2. Night-time atmospheric longwave measurements of the WISG pyrgeometers relative to their average using the updated WISG calibration coefficients. The consistency between the four WISG pyrgeometers during the calibration season (approximately March to October) has been improved compared to the previous configuration as shown in Figure 1.

The measurements and analysis from the collocated ACP#96 on loan from NREL are ongoing. A WMO report will be published later in 2022.

The Ad-Hoc Committee for the IPgC-III was established on 29 September 2021 to supervise the progress of the IPgC and to evaluate the status and stability of the WISG. Based on the analysis performed by PMOD/WRC, it recommended the updating of the calibration factors of the WISG according to the following procedure:

- The coefficients k_1, k_2, k_3 were updated by calculating mean coefficients from the 2015 to 2020 blackbody calibrations.
- Then, a new responsivity was retrieved for each WISG radiometer by an outdoor comparison to the other three WISG pyrgeometers using these new coefficients.

The consistency of the WISG has been improved with the new coefficients, in particular during the calibration season in summer, while the overall irradiance level of the WISG is maintained throughout the year, as shown in Figure 2. Furthermore, the updated coefficients also improve the consistency of the WISG during daytime.

The Ad-Hoc Committee endorsed the updated WISG coefficients and recommended to the president of INFCOM of the WMO to approve the implementation of the updated WISG coefficients as of 1 January 2022.

References: Gröbner, J., Reda, I., Wacker, S., Nyeki, S., Behrens, K., Gorman, J.: 2014, A new absolute reference for atmospheric longwave irradiance measurements with traceability to SI units, J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD021630

Atmospheric Turbidity Section (WRC-WORCC)

Stelios Kazadzis, Natalia Kouremeti, and Julian Gröbner

The Atmospheric Turbidity Section of the WRC maintains a standard group of three Precision Filter Radiometers (PFR) that serve as a reference for Aerosol Optical Depth (AOD) measurements within WMO. WORCC also operates the Global Atmospheric Watch PFR (GAW-PFR) network for AOD and collaborates with other global aerosol networks.

The World Optical depth Research and Calibration Center (WORCC) calibration hierarchy is based on the WORCC reference. The WORCC reference is defined as the average of three (Triad) well-maintained precision filter radiometers (PFRs) that are located at Davos, Switzerland. In addition, instruments operating at high mountain stations such as Mauna Loa (USA) and Izaña (Canary Islands, Spain) perform Langley calibrations, and are transported (one instrument every six months) to WORCC/Davos in order to check the Triad stability with an independent instrument. No changes were applied to the Triad data set after analysing the Langley transfer-related measurements.

Annual quality assured data from GAW-PFR stations were updated and submitted to WDCA. In 2021, six instruments from the GAW-PFR network and 13 customer instruments, all part of the extended GAW-PFR network, were calibrated against the reference Triad at Davos. In addition, three precision spectroradiometers were calibrated at WORCC.

ACTRIS-RI (Aerosols, Clouds and Trace gases Research Infrastructure) is a pan-European initiative to consolidate permanent and long-term observations of aerosols, clouds and trace gases at distributed National Facilities. WORCC is participating in ACTRIS-CARS (Center for Aerosol Remote Sensing), providing a permanent traceability link between ACTRIS AOD measurements and the WMO primary AOD references. During 2021, measurements of WORCC reference instruments and CARS sunphotometers at OHP (France) and Izana (Spain: see Figure 1) were conducted (see: https://www.actris.eu/index.php/news-events/news/wmo-criteria-aod-traceability-are-met-actrisaeronet-europe-and-gawpfr-wmo-networks).

Within the QA4EO project, WORCC scientists have been collaborating with ESA, CNR (Italy) and NOA (Greece), investigating NO_2 spatio-temporal variability and its effect on the retrieval of AOD at 440 nm.

WORCC is involved in the activities of the Metrology of Aerosol Optical Properties (MAPP) project. Calibration of PFR and spectroradiometric direct sun measurements linked with the SI scale through metrological institutes were conducted. The retrieved AOD measurements were compared and evaluated against the WORCC Triad.

WORCC has continued the collaboration with AERONET Europe and SKYNET Europe and Asia. WORCC activities were presented in the SKYNET Workshop (September 2021 – online). Collaboration

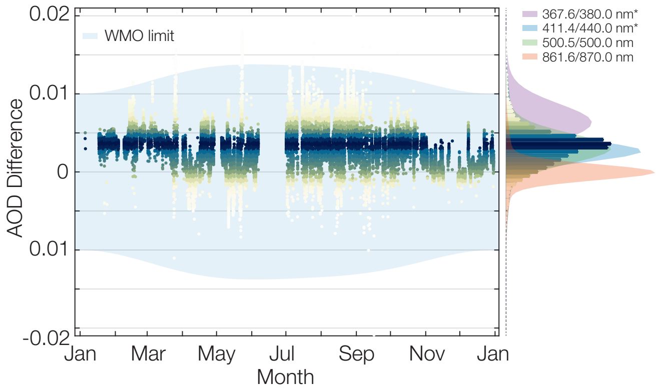


Figure 1. AOD differences derived from ACTRIS-CARS, CIMEL and PFR at Izana, Spain in 2021. Differences are shown for four wavelengths. PFR AODs have been calculated at CIMEL wavelengths using the PFR-derived spectral dependence. The light blue area represents the WMO limits: 96 - 100% of data are within those limits depending on the AOD wavelength.

with AERONET Europe has also continued through the activities of MAPP and ACTRIS-RI projects.

Concurrent with the 13th International Pyrheliometer Comparisons (IPC-XIII) and the 3rd Pyrgeometer Comparison (IPgC-III), the 5th Filter Radiometer Comparison (FRC-V) was held at Davos, Switzerland. Instruments belonging to different AOD global networks were invited. The comparison took place at PMOD/WRC from 27 September to 15 October, 2021. A total of 29 filter radiometers and spectroradiometers from 11 countries participated in FRC-V. The objective of this comparison, supported by WMO, was to compare different instruments belonging to different global or national networks in order to quantify the main factors that are responsible for possible deviations. The whole activity aims towards a homogenisation of AOD measurements on a global scale. Measurements from each instrument were compared with the WORCC PFR Triad.

In 2021, the production of a new PFR series continued. The new PFR series has been designed to be fully compatible with the existing data acquisition systems, and includes improvements based on current technology and the 21 years of experience since the first PFR series in 1998. Instruments from this new series were evaluated during FRC-V.

A PhD student, Xinyuan Hu, started her work at PMOD/WRC in collaboration with the ETH Dept. of Physics.

Overviews of WORCC results were presented at various workshops and meetings. Such meetings included: i) the Scientific Aerosol Group for Aerosols, ii) the Expert team of Atmospheric Composition Measurement Quality, iii) ACTRIS-CARS members, iv) the FRC-V Symposium, v) the SKYNET workshop, and vi) the Sorbetto-2 Summer school organised online in September 2021.

World Calibration Centre for UV (WRC-WCC-UV)

Julian Gröbner, Gregor Hülsen, and Luca Egli

The objective of the World Calibration Center for UV (WCC-UV) of the WMO Global Atmosphere Watch (GAW) is to assess the data quality of the Global GAW UV network and to harmonise the results from monitoring stations in order to ensure representative and consistent solar UV radiation measurements on a global scale.

The traceability of spectral solar UV irradiance to SI is established through the yearly measurements of seven transfer standard 1 kW tungsten halogen incandescent lamps, which are occasionally recalibrated at the Physikalisch-Technische Bundesanstalt (PTB) against the primary spectral irradiance standard, a high temperature blackbody.

The measurements of this reference lamp-set are used to transfer the irradiance scale to several internal secondary standards and working standard lamps that are used throughout the year to calibrate the radiometers and spectroradiometers used at PMOD/WRC for measurements of solar irradiance. One important aspect in this process is the stability assessment of these reference lamps as they represent the WMO reference for solar UV irradiance. As shown in the panels of Figure 1, the relative deviations of each of these lamps with respect to the average is very stable with deviations over the last 15 years of less than 0.5%. The long-term stability of the average, calculated as the standard error of the mean, is 0.1%.

After two years without quality assurance site visits, due to the COVID pandemic, three solar UV irradiance comparisons with the transportable reference spectroradiometer, QASUME, were conducted in 2021. In June, we visited the headquarters of the Agencia Estatal de Meteorología (AEMET). It was the 7th audit in Madrid, Spain, after 2009, 2011, 2013, 2015, 2017 and 2019. In June, we organised the 9th visit to the Agenzia Regionale per la Protezione dell Ambiente (ARPA) in Valle d´Aosta, Italy.

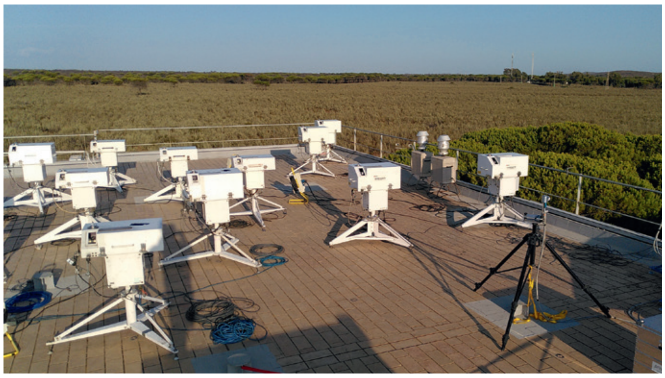


Figure 2. View of the measurement platform at the Istituto Nacional de Technica Aeroespacial (INTA). The input optic for direct and global irradiance measurement of QASUME can be seen on the tripods and sun-tracker on the right-hand side of the image.

The second main activity during 2021 was the participation in the 16th Regional Brewer Calibration Center – Europe (RBCC-E) campaign. Both, global and direct spectral irradiance measurements were carried out in September in El Arenosillo, Spain (Figure 2). The global UV irradiance spectra recorded by QASUME provided the reference data for the participating 14 Brewer spectrophotometers. Direct solar UV irradiance measurements were used to derive total column ozone values which were compared to the reference data from the reference Brewer #185 operated by the Izaña Atmospheric Research Center, AEMET.

Results of all the QASUME site audits and reports of the campaigns can be found on the WCC-UV website: www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/.

At Davos, calibration activities were unaffected by the Covid pandemic, so 29 UV broadband radiometers were calibrated as well as three spectral irradiance tungsten halogen standards, one photodiode and one spectroradiometer system.

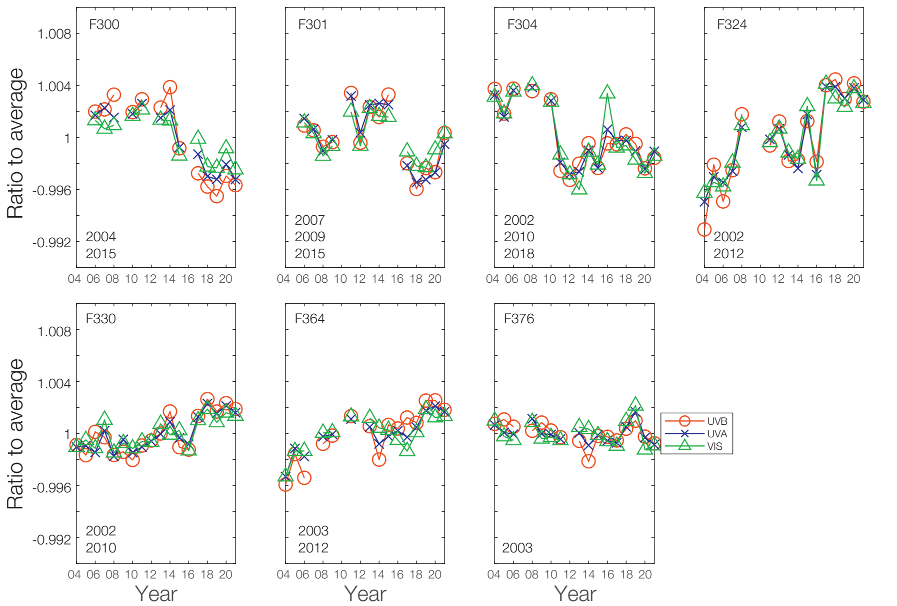


Figure 1. Ratio of each reference transfer standard to the grand average since 2004 for three wavelength bands in the UV-B (280 nm to 315 nm), UV-A (315 nm to 400 nm), and VIS (400 nm to 500 nm). The year of the recalibration at PTB is shown in each panel.

Section Ozone: Total Ozone Column and Umkehr Measurements

Julian Gröbner, Herbert Schill, Franz Zeilinger, and Luca Egli

Operational Total Ozone Column and Umkehr measurements are performed at PMOD/WRC with three Dobson and four Brewer spectrophotometers to monitor the stratospheric ozone layer, hence extending the world's longest continuous total ozone time-series at Arosa and Davos, Switzerland.

Stratospheric ozone measurements in Arosa stopped on 17 February 2021 after almost 95 years. The last two instruments (Dobson D062 and Brewer B040) were subsequently transferred to Davos, where direct sun (total ozone) and Umkehr (vertical profiles) measurements are continuing with three Dobson instruments (D051, D062 and D101) and four Brewers (B040, B072, as well as B156 from Meteoswiss and B163 from PMOD/WRC). Dobson D051 is mainly dedicated to Umkehr measurements, and therefore only occasionally used for direct sun observations to compare with D101 and D062, thereby forming a so-called Triad.

At the end of March 2021, the Dobson housing from Arosa was flown by helicopter to Davos and added to the existing two Dobson container housings (Figure 1).

The 15th Regional Brewer Calibration Campaign for Europe (RBCC-E) was held at PMOD/WRC from 6 - 16 July 2021 with the support of MeteoSwiss and the Global Atmosphere Watch (GAW) programme. The following operations were performed by the RBCC-E during the intercomparison: i) ozone calibration against the RBCC-E travelling reference (B185), ii) compilation of the calibration histories of the instruments, and iii) evaluation of the Level 2 Eubrewnet ozone data for the period in-between intercomparisons.

Besides the travelling reference and the four Davos Brewers, two instruments from the Brewer manufacturing company, Ott Hydrotechnics (formerly Kipp & Zonen) from Delft (Netherlands), participated in the campaign. The weather conditions were not ideal for calibration, with rain during the second half of the campaign. However, our instruments did not require any maintenance.

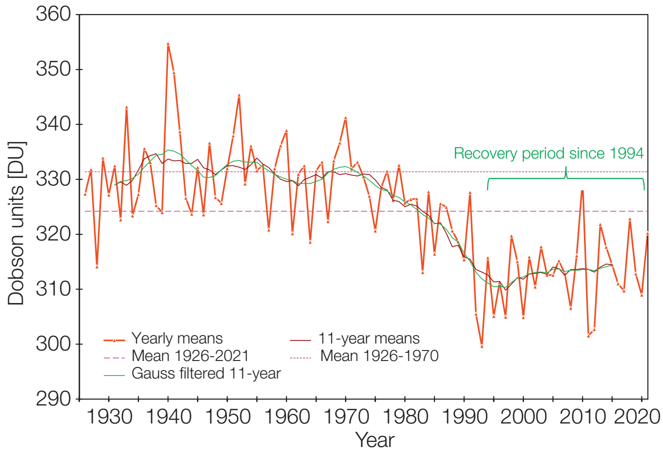


Figure 2. Yearly (red), 11-year (burgundy; Gaussian-filtered) and 11-year (light green) averages of the homogenised total ozone column in Dobson units at Arosa and Davos.

Therefore around 150 nearly simultaneous measurements with the B185 reference instrument were conducted. Total ozone values of all Davos Brewers were within ±1% compared to the reference instrument during the initial calibration days, which reflects the careful maintenance of the spectrophotometers on our site.

With the shutting down of the Lichtklimatisches Observatorium (LKO) in Arosa in February 2021, Dobson D101 (at PMOD/WRC since January 2016) again became the reference instrument for the long-term homogenised total ozone series. From November 2013 until the end of 2020, D062 was used as the local reference of the Triad. With a yearly average of 320 Dobson Units (DU) in 2021, about 10 DU higher than in the previous year, the small recovering trend in the stratospheric ozone layer since 1994 seems to be continuing (Figure 2). The days and the number of measurements are similar to previous years, except for Dobson D062 which was not in operational service between mid-February 2021 (transfer from Arosa) and mid-April 2021 (housing ready). On the other hand, D051 was more often used to conduct direct sun measurements.

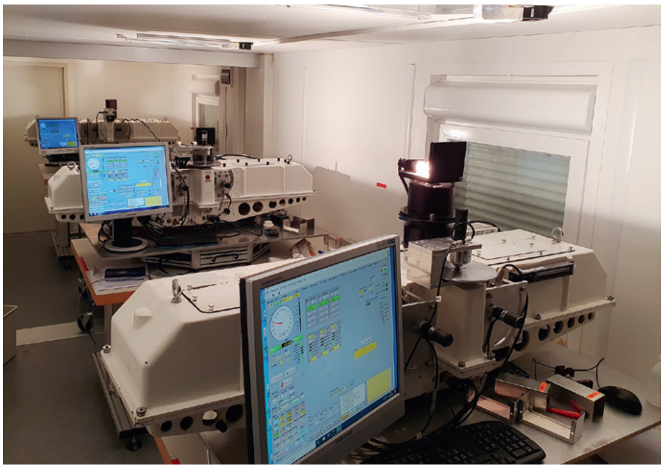


Figure 1. A triple-unit container houses the three fully-automated Dobson spectrophotometers at PMOD/WRC.

Figure 3. Brewer spectrophotometers during the 15th Regional Brewer Calibration Campaign (RBCC-E) in front of the PMOD/WRC.

Instrument Development

Space Missions in the Build Phase

Andrea Alberti, Valeria Büchel, Wolfgang Finsterle, Matthias Gander, Margit Haberreiter, Louise Harra, Silvio Koller, Patrik Langer, Leandro Meier, Daniel Pffifner, Werner Schmutz, Marcel Spescha, Daniel Tye, and Liviu Zambila

PMOD/WRC is involved in five Space missions at different design and development stages up to finalisation. DARA (onboard the ESA PROBA-3 mission) is a 3-channel absolute radiometer designed for the long-term stable and highly accurate measurement of Total Solar Irradiance, which is fully traceable to SI. SoSpIM, an extreme UV Solar Spectral Irradiance Monitor for the Japanese Solar-C mission, is in its first design steps and due to be launched in 2027. CSAR, part of the ESA TRUTHS (Traceable Radiometry Underpinning Terrestrial- and Helio- Studies) mission, is a cryogenic absolute radiometer to be launched in 2029. LUCI, the Lagrange EUV Coronal Imager is a potential remote sensing instrument onboard ESA's space weather mission to the L5 Lagrange point. S-EUVI was a Phase A study for a US consortium mission proposal for the SOLARIS mission. S-EUVI is an adapted version of LUCI.

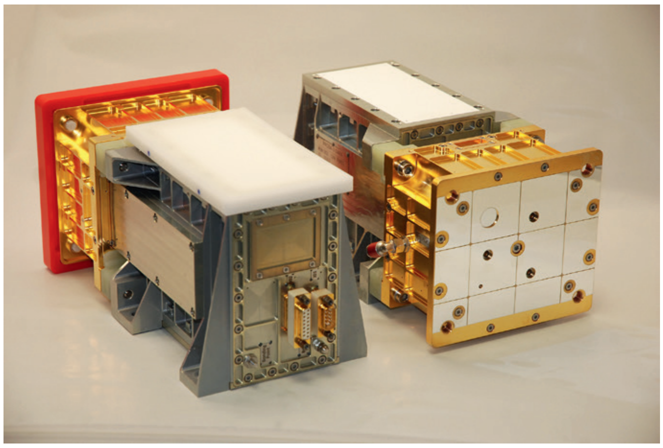


Figure 2. DARA Flight Spare (left, with protective covers) and DARA Flight Model (right).

DARA onboard PROBA-3

Both instrument flight units, the DARA Flight Model (FM) and the Flight Spare (FS), were already fully assembled in 2019 and most of the required qualification tests were performed in that year. However, some remaining tasks concerning the instrument qualification included: i) correlation of the vibration test results with the structural analysis output, and ii) thermal test findings with the thermal analysis.

Another mandatory check was to verify if any of the optical elements had moved during the vibration tests. This would result in a deviation of the optical axis in relation to the built-in alignment mirror, which is used as an optical reference during instrument mounting on the PROBA-3 spacecraft. For this purpose, we were able to use the existing infrastructure of the World Radiation Center at PMOD/WRC. In the optics laboratory (see Figure 1), the angular-dependent response of the radiometer was used to determine the line-of-sight of the receiver cavities which were then compared to the alignment mirror. The results were highly satisfactory and hence proved the mechanical design, the manufacturing precision and instrument assembly process.

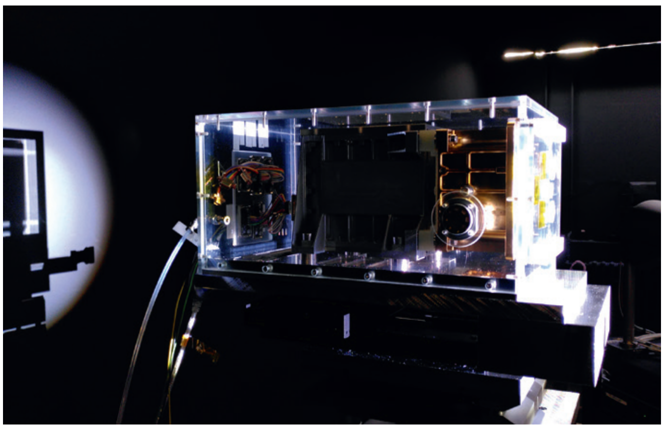


Figure 1. DARA Flight Spare. Pointing verification test in the optics laboratory at PMOD/WRC.

In parallel, the DARA FM (Figure 2) was prepared for delivery. The same tests as mentioned above were repeated on the FM, but at reduced levels, meaning for example lower vibration loads, smaller temperature ranges and/or reduced testing times. We again used the University of Bern facilities for vibration and thermal tests (Figure 3), and performed an electromagnetic compatibility test at a private test lab.

Due to the pandemic, one of the most important steps had to be continually delayed until we were no longer able to wait. The final end-to-end calibration campaign at the Laboratory for Atmospheric and Space Physics (LASP; Boulder, USA) was actually foreseen to be attended by PMOD/WRC technical staff. However, the plans had to be modified, so the instrument and ground support equipment were shipped to LASP. The calibration task itself required our staff to have highly flexible working hours. Every day, or night, several video calls were necessary so that complex tasks could be completed. In this manner, the calibration campaign was successfully concluded. We received great support from LASP and thanks to their experience, DARA was in careful and capable hands.

The LASP calibration campaign concluded the major activities on the FM. In a final step, PMOD/WRC had to verify some minor details, such as: i) accurate mass and centre of gravity measurements, ii) mechanical interface flatness, and iii) other aspects. Afterwards, it was time to prepare the FM for final delivery. A final cleaning step of the exterior surfaces was conducted in the PMOD/WRC clean-room and all the mounting parts, tools and instruction manuals were prepared for shipment.

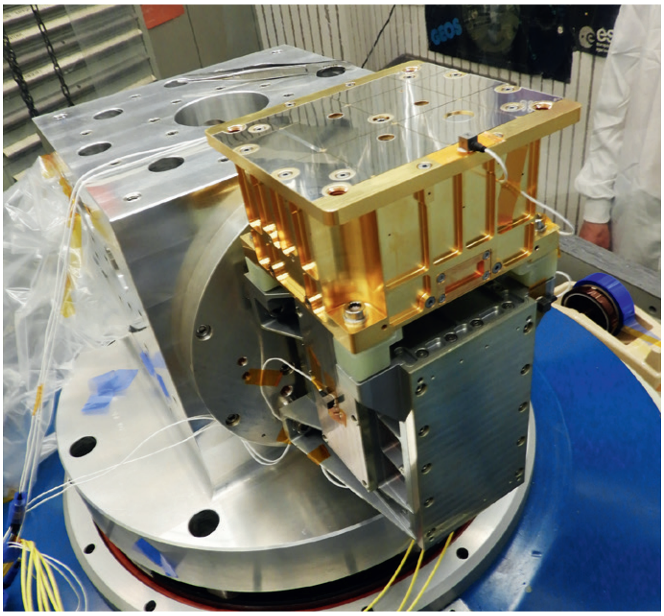


Figure 3. DARA EQM Flight Spare mounted on the vibration shaker at the University of Bern. Similar tests were also performed on the Flight Model.

At the end of November 2021, the DARA FM was taken to QinetiQ Space NV (Antwerp, Belgium), which is responsible for integration of the different PROBA-3 occulter spacecraft units. Together with ESA and QinetiQ, all the customs declarations were organised and we finally transported the instrument ourselves to QinetiQ. Again, system compatibility tests with the spacecraft simulator were conducted and the instrument was handed over to QinetiQ staff.

The spacecraft itself is not yet fully assembled and final instrument integration is foreseen to be finished by the end of 2022. PMOD/WRC activities with respect to DARA are now finished. An End-Item-Data Package is to be concluded and our commercial sub-contractor needs to provide and mount the instrument multi-layer insulation. The PROBA-3 launch date is currently foreseen for Q3/Q4 in 2023.

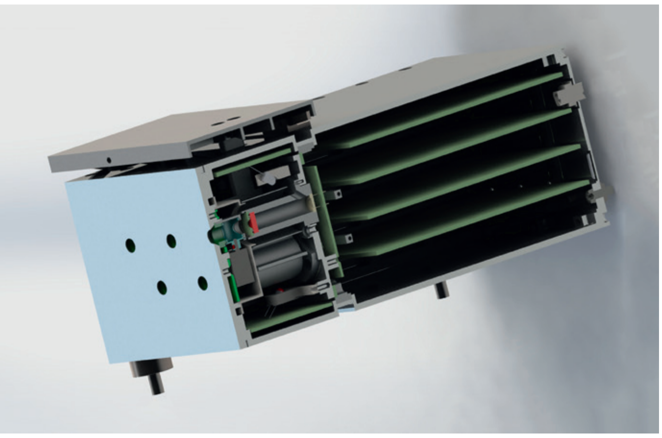


Figure 4. Model cross-section of the EUV Solar Spectral Irradiance Monitor (SoSpIM) onboard the future JAXA-led SOLAR-C mission.

SoSpIM onboard Solar-C_EUVST

Solar-C_EUVST is the next Japanese solar physics mission to be developed with significant contributions from US and European countries. The mission carries an Extreme UV (EUV) imaging spectrometer with a slit-jaw imaging system called EUV High-Throughput Spectroscopic Telescope (EUVST) as the mission principal payload. EUVST is designed to take a fundamental step towards answering how the plasma universe is created and evolves, and how the Sun influences the Earth. In 2020, SOLAR-C_EUVST was down-selected as the fourth in the series of the competitively chosen M-class mission to be launched with an Epsilon launch vehicle in 2027. The mission underwent the Mission Design Review in 2021.

The second instrument onboard SOLAR-C_EUVST is the Solar Spectral Irradiance Monitor (SoSpIM, Figure 4; Harra et al., 2021) and is led by PMOD/WRC. It will provide "Sun-as-a-star" spectral irradiance measurements over two bands that overlap with EUVST, the Short EUV and Lyman-Alpha bands. This provides both scientific and cross-characterisation capabilities. SoSpIM and EUVST will work hand-in-hand. While EUVST will deliver spectral observations from the chromosphere to the corona, tracking the energy flow on small spatial scales, SoSpIM will measure the integrated irradiance over the bands of interest, not just those within the EUVST field-of-view. The SoSpIM instrument provides the connectivity between the flare processes captured in detail on the Sun by EUVST and the impact of those irradiance changes in different layers of the Earth's atmosphere.

The SoSpIM Phase A2B development kicked-off in November 2020 after confirmation of SSO PRODEX funding support. During 2021, the SoSpIM instrument architecture was defined, the required specifications were detailed, and the principal interfaces with the Solar-C_EUVST were also defined. The instrument's thermo-mechanical structure concept was also defined. SoSpIM sub-systems were defined and specified. Special attention was given to performance-relevant sub-systems, such as:

i) The Cold Trap for contamination management.
ii) The Digital Acquisition board for accurate acquisition.
iii) The control board and onboard software steering the instrument operations.

The Preliminary Design Review (PDR) is planned in Q1/2023 in alignment with the Solar-C mission PDR and its outcomes. During this definition period, several industry work packages and related tasks will be defined and specified. Swiss Industry will be invited to participate in the instrument consortium and provide different sub-units to SoSpIM. The implementation of an EM is planned in 2023 - 2024.

References: Harra L., et al.: 2021, A Spectral Solar Irradiance Monitor (SoSpIM) on the JAXA Solar-C space mission, SCOSTEP PRESTO Newsletter Vol. 27.

CSAR / TRUTHS

The mission, Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS), is conceived by the UK's National Physical Laboratory (NPL) and being developed by ESA on behalf of the UK and other partner nations across Europe. The implementation of TRUTHS is led by Airbus UK with an international core team of industries and institutes. The TRUTHS spacecraft (Figure 5) will carry three main payloads: the Hyperspectral Imaging Spectrometer (HIS), the Cryogenic Solar Absolute Radiometer (CSAR) as well as the novel On-Board Calibration System (OBCS).

The TRUTHS payloads are working jointly to provide measurements of incoming solar irradiation and of the radiation reflected from Earth back out into space as traceable International System of Units. These two observations will be used to evaluate the energy-in to energy-out ratio. These measurements will allow changes in Earth's climate to be detected faster, and they will be used to calibrate data from other satellites. In effect, TRUTHS will be a "metrology standards laboratory in space", setting the "gold standard" for climate measurements. Furthermore, TRUTHS would contribute to the Global Climate Observing System, the Committee on Earth Observation Satellites, the World Meteorological Organisation, the Copernicus Climate Change Service and the Group on Earth Observations by offering an important element of an international space-based climate observing system proposed in the Strategy Towards an Architecture for Climate Monitoring from Space.

As part of the ESA mission development, TRUTHS successfully passed Phase A (feasibility study phase) in Q3/2021 into Phase B1 (early design phase). The success of Phase B1 in Q2/2022 will lead to the adoption of the mission by ESA in 2022, heading toward a mission launch around 2029. During 2021, PMOD/WRC was involved in the development of the TRUTHS mission. Firstly, PMOD/WRC was engaged in supporting the engineering of the Cryogenic Solar Absolute Radiometer (CSAR), with focus on the performance aspects of the cryogenic measurement block and on the radiometer metrology electronics, in close collaboration with NPL.

In addition, PMOD/WRC was engaged in the pre-development of one of the voltage references. This is of central functionality in a TSI radiometer. Its performance directly propagates along the measurement chain. The challenging mission goals require thorough solution screening, design of test-boards and testing to ensure the proposed solution will achieve the needed performance stability by mission end-of-life. PMOD/WRC aims to support the successful TRUTHS mission Phase AB1 close-out as led by AIRBUS UK that will lead to the mission implementation phase starting in 2023.

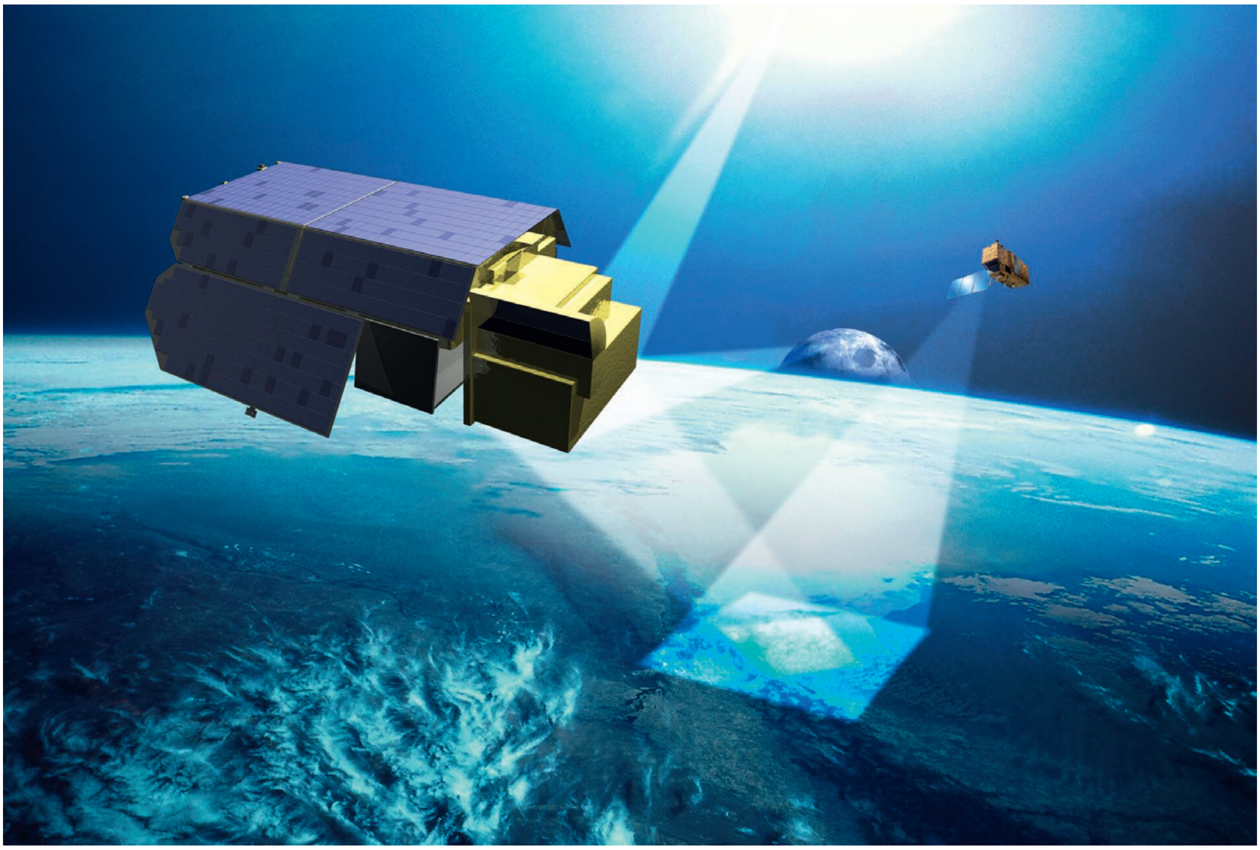


Figure 5. Artist's representation of the TRUTHS Spacecraft (Image credit: ESA).

LUCI onboard Lagrange

The Lagrange EUV Coronal Imager (LUCI) is one of the potential remote sensing instruments onboard ESA's space weather mission to the L5 Lagrange point. During previous project phases, the LUCI consortium was led by Centre Spatial de Liège (CSL, Belgium) and had the following members: i) CSL, ii) Royal Observatory of Belgium (ROB; Belgium), and iii) PMOD/WRC.

In the first months of the year, the ongoing Pre-Development Phase I was successfully completed. This phase mainly comprised of engineering activities on the front-end electronics (FEE; Figure 6) and thermo-mechanical (Figure 7) designs. Progress was made towards the upcoming hardware phase of the LUCI structural and thermal model and the FEE electrical functional model. In addition, the PRODEX Pre-Study was successfully finished over the course of the year. The aim of this study was the early involvement of Swiss industry.

The mission payload management was transferred from ESA to the spacecraft prime contractor, Airbus Defense and Space (ADS). To enable the smooth familiarisation of ADS with the instruments, the LUCI consortium participated in several workshops. In the framework of this transfer, an ITT for phases B2/C/D was published by ADS regarding the payload instruments. For the LUCI instrument, an industry prime contractor was introduced to link the consortium to the new mission organisation. The instrument prime candidates submitted their proposals together with the existing consortium and complemented it with additional members. The collaboration with Swiss industry during the proposal writing was intensive, but also productive and fruitful. Thales Alenia Space Switzerland (TAS-CH) was finally selected as the LUCI instrument prime contractor.

In parallel to the proposal for B2/C/D, a contract change was submitted in reply to a request from ESA. The objective of this contract change was to bridge the time to the kick-off of phase B2. As of the second quarter of the year, no contract was in place to cover LUCI activities. Therefore, all activities, except proposal writing and support to Swiss industry, had to be interrupted by PMOD/WRC from mid-2021 onward. The bridging phase and B2 were supposed to have been kicked-off a few months later. Since both phases were postponed at a mission level, no further technical progress was made.

The mission situation and the schedule concerning the remote sensing instruments remained unclear at the end of the year. The status of the project has become challenging. Nevertheless, PMOD/WRC and the strengthened consortium concluded the year with great anticipation for the continuation of the project and the upcoming collaboration with TAS-CH as the new LUCI instrument prime contractor. The mission, formerly named "Lagrange", was renamed to "Vigil" after a public competition published by ESA in early 2022. As of spring 2022, the LUCI instrument is no longer one of the core instruments on Vigil.

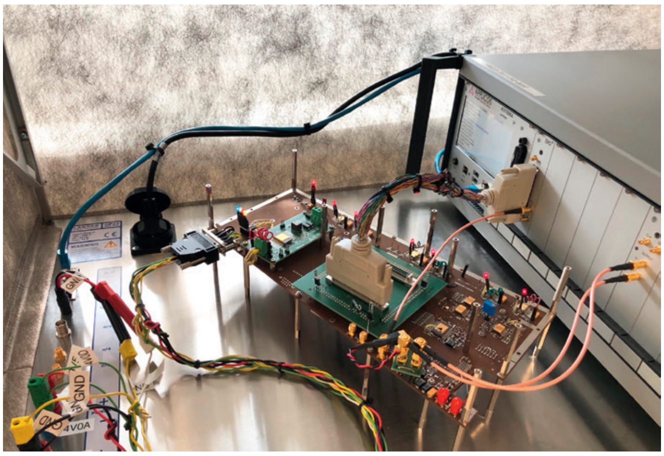


Figure 6. LUCI Front End Electronics - breadboard of analogue electronics during first tests.

S-EUVI onboard Solaris

Solaris is a NASA solar polar mission of discovery to address fundamental questions about the Sun and heliosphere that can only be answered from a high latitude (polar) vantage point. Solaris will be the first mission to obtain sustained coverage of the solar interior and atmosphere from high latitudes, uniquely and comprehensively investigating the global Sun and heliosphere.

Solaris will transform our understanding of the solar activity cycle and the global heliosphere through direct imaging of the solar poles and the ecliptic-plane corona viewed at all longitudes simultaneously. It will use a Jupiter fly-by, and achieve an inclination of 55° above the ecliptic, and have a 3-month pass about the solar poles.

PMOD/WRC is involved in the EUV Imager instrument, building on the development of the LUCI instrument for the Lagrange mission. The concept study report was submitted to NASA in Autumn 2021 followed by a review. It was in competition with four other missions for the next phase. Unfortunately, it was not selected this time, but the team will continue to develop the mission concept to be submitted for the next opportunity.

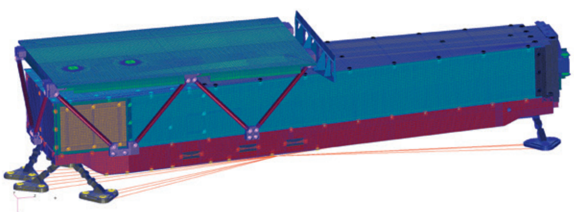


Figure 7. LUCI thermo-mechanical design - Finite Element Model.

Space Missions in the Operations Phase

Wolfgang Finsterle, Manfred Gyo, Margit Haberreiter, Louise Harra, Silvio Koller, Jean-Philippe Montillet, Daniel Pfiffner, and Elena Podladchikova

PMOD/WRC is involved in the operations of instruments onboard seven operational spacecraft. The ESA SOHO mission was launched back in 1995, and the PMOD/WRC instrument, Variability of solar IRradiance and Gravity Oscillations (VIRGO) is still operational. The ESA PROBA-2 mission which was launched in 2001, hosts the LYRA instrument with PMOD/WRC involvement, measuring the solar spectral irradiance. The Compact Lightweight Absolute Radiometer (CLARA) is a payload onboard the Norwegian NorSat-1 micro-satellite and is a new generation of radiometer to measure the Total Solar Irradiance (launched in 2017). The ESA/NASA Solar Orbiter mission, which was launched in 2020 has ten instruments onboard, two which have PMOD/WRC involvement. The Chinese JTSIM mission was launched in July 2021 and our Digital Absolute Radiometer (DARA) instrument is onboard.

We have operational, calibration and scientific responsibilities of all the instruments we have been involved in developing. These include irradiance measurements (VIRGO, LYRA and CLARA), and more recently, imaging and spectroscopic measurements. We have been funded through Karbacher Fonds to support these efforts since the end of 2019.

VIRGO onboard SOHO

The VIRGO experiment on board the SOHO spacecraft has been providing total and spectral solar irradiance measurements almost continuously since February 1996. Over the years, the active sensors have lost some sensitivity. Backup sensors are being used from time to time in order to track the degradation of the active sensors. A novel method to correct for long-term sensor degradation was developed and implemented with the VIRGO Total Solar Irradiance (TSI) time-series.

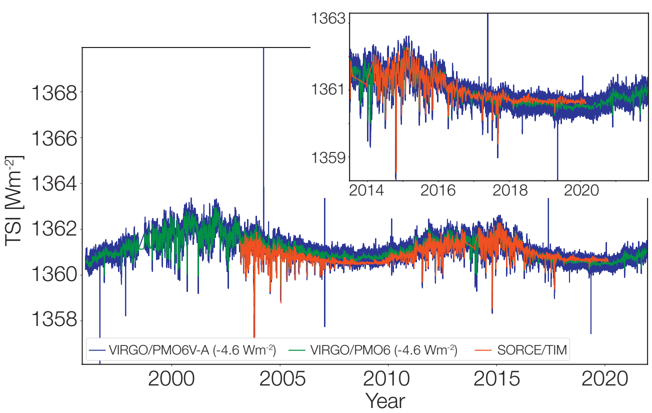


Figure 1. The degradation corrected PMO6-VA (blue) and the PMO6-V composite (PMO6-VA + PMO6-VB, green). For comparison, we also show the SORCE/TIM time-series (red). The inset zooms in on the period of the last solar minimum in 2019 (Finsterle et al., 2021).

The sensor degradation has been a long-standing issue with Total Solar Irradiance (TSI) measurements on spacecraft. The classical approach to assess and correct sensor degradation was based on deep technical knowledge of the radiometer, understanding of the physical and optical processes that make up the measurement process, and how they might change with time or when the sensor is exposed to the harsh environment in space (e.g. Fröhlich, 2003).

Together with three MSc students of Computer Sciences at ETH Zurich we developed a novel approach to correct instrumental degradation based on data science methods (Finsterle et al., 2021). We use machine learning and data fusion to:

- Determine the common degradation curve of the active and backup channels based on their different exposure rates.
- Combine the measurements from the active and backup channels into a single TSI time-series.

In addition, we assume that the degradation curve is monotonically decreasing. This assumption is obviously not suitable to describe the phenomenon of the "early increase", an apparent gain in sensitivity that was observed mainly in PMO6-type radiometers during their first couple of days in space. The “early increase” of the VIRGO PMO6 radiometers is therefore still corrected with the classical method. We are trying to relax the requirement of monotonically decreasing degradation curve in a future version of our algorithm.

The resulting new version of the degradation-corrected VIRGO PMO6 TSI time-series is shown in Figure 1. As a first scientific result, the new time-series shows no secular trend in the TSI level between the solar minima of 2008 and 2019.

The data pipeline for the VIRGO data on the SOHO archive is currently being updated to make the new data version available to the science community (https://soho.nascom.nasa.gov/data/archive/).

Thanks to its data focused nature and independence of the technical specifics of the radiometer, our new method can be readily used to correct TSI measurements from other space experiments. The method will be applied to correct the degradation in CLARA on NORSAT-1, DARA on JTSIM/FY-3E and the future DARA on PROBA-3.

References:

Finsterle, W., Montillet, J.P., Schmutz, W., Šikonja, R., Kolar, L., Treven, L.: 2021, Scientific Reports, 11, doi.org/10.1038/s41598-021-87108-y

Fröhlich, C., 2003, Metrologia, 40, doi.org/10.1088/0026-1394/40/1/314

CLARA onboard NorSat-1

The Compact Lightweight Absolute Radiometer (CLARA) onboard NorSat-1 was launched on 14 July 2017 and began measurements on 21 August 2018 (Walter et al., 2020). After the failure of a reaction wheel on the NorSat-1 platform on 13 May 2018, a new platform operation scheme was implemented, and CLARA became operational again in November 2019.

The CLARA processing pipeline has been validated and updated. The improvements include a verified pointing filter taking into account the off-pointing of the CLARA cavities with respect to the Precision Sun Sensor (PSS), an improved implementation of the electrical calibration, and a data filter based on the upper limit of the heat sink temperature gradient at the time of each irradiance measurement. In addition, the validated angle-dependent radiative loss due to the non-homogeneous reflectivity of the cavities, the temperature dependent radiative loss from the cavities to deep space, and the radiative contribution of the precision aperture are considered in the data processing pipeline. Figure 2 shows the latest version of the CLARA Total Solar Irradiance (TSI) time-series at a daily resolution compared to the VIRGO Level-2 dataset (Finsterle et al., 2021). From November 2020 onward, CLARA nicely followed the increasing solar activity. However, from March to November 2020, CLARA measured significantly lower TSI values. The reason for this is currently under investigation.

Besides TSI, CLARA also measures the terrestrial outgoing longwave radiation from the nightside of Earth. Figure 3 shows the monthly running mean of the outgoing terrestrial flux.

CLARA was operational until August 2021, when a second reaction wheel stopped working, this time due to a problem with the wheel software. After software development by UTIAS, the upgraded firmware was uploaded to the spacecraft in February 2022 and the reaction wheel is now functional again. Due to ongoing performance tests of the platform, CLARA is not yet operational at the time of writing.

Acknowledgement: MH acknowledges funding from the Karbacher Fond.

References: Finsterle W., Montillet J.P., Schmutz W., Šikonja R., Kolar L., Treven L.: 2021, The total solar irradiance during the recent solar minimum period measured by SOHO/VIRGO, Nature Sci Rep., 11(1), 7835, doi: 10.1038/s41598-021-87108-y

Walter, B., Andersen, B., Beattie, A., Finsterle, W., Kopp, G., Pfiffner, D., Schmutz, W.: 2020, First TSI results and status report of the CLARA/NorSat-1 solar absolute radiometer, Proc. Int. Astron. Union, 14(A30), 358-360, doi:10.1017/S1743921319004617

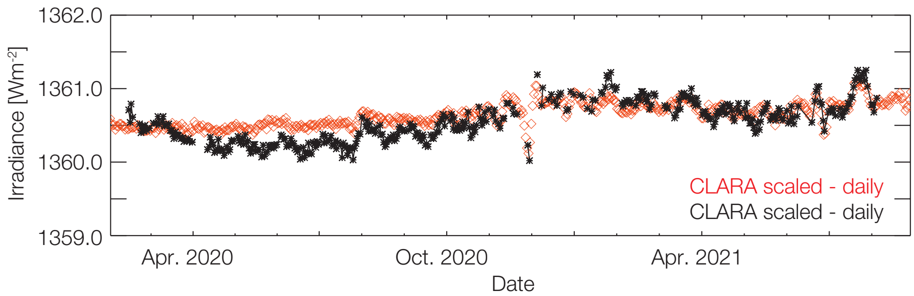


Figure 2. CLARA TSI time-series (black crosses) compared to the VIRGO Level 2 PMOA TSI measurement (red diamonds). Both datasets are shown with a daily resolution.

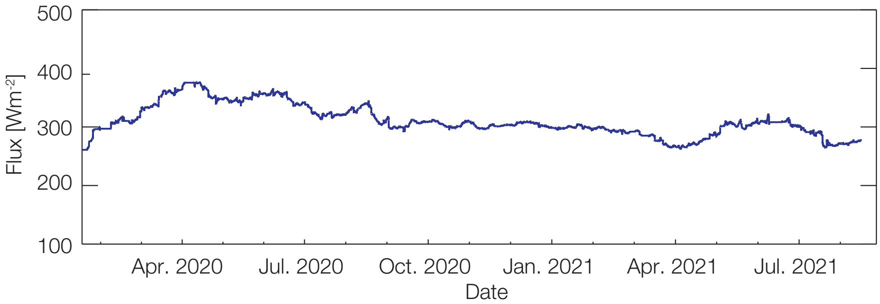


Figure 3. Monthly running mean of the outgoing longwave radiation flux as observed with CLARA.

Solar Orbiter

PMOD/WRC are involved in two instruments on Solar Orbiter. The first is the Extreme Ultraviolet Imager (EUI; Berghmans et al., 2021) which consists of three telescopes that are optimised to image the solar atmosphere at the Lyman-α wavelength (121.6 nm, temp. ~30000 K) and in the Extreme UV (EUV; 17.4 nm and 30.4 nm, temperatures of ~1 MK and 0.08 MK, respectively).

The second is the Spectral Imaging of the Coronal Environment (SPICE). The SPICE instrument is an EUV imaging spectrograph designed to remotely characterise plasma properties of the solar corona.

The instruments were successfully commissioned in 2020, and the mission is in cruise phase. During this phase, the remote sensing telescopes are mostly off but have five check-out windows. Data from these periods is being used to understand the calibration and behaviour of the instruments. The first perihelion (0.55 A.U.) was in June 2020, which provided spatial resolutions of 400 km. When we reach the operational phase at a perihelion of 0.3 A.U., this will improve by a factor of nearly two. First data from SPICE has also been published, highlighting the range of spectral lines available to extract plasma parameters on the Sun (Fludra et al., 2021).

Planning involves Solar Orbiter specific operations, and coordination with other facilities such as Parker Solar Probe, Hinode, Interface Region Imaging Spectrograph and ground-based telescopes. Trials were made during the cruise phase to coordinate data, and detailed plans are underway for the operational phase.

The EUV imagers operate in synoptic mode outside of the science phases (30 days per orbit), and this allows the determination of flare and coronal mass ejection sources, which is particularly useful as the Sun's activity is increasing towards the next solar maximum.

References:

Berghmans, D., Auchère, F., Long, D.M., Soubrié, E., Mierla, M., Zhukov, A.N., Schühle, U., Antolin, P., Harra, L., et al.: 2021, Extreme-UV quiet Sun brightenings observed by the Solar Orbiter/EUI, Astron. Astrophys., 656, 4, doi:10.1051/0004-6361/202140380

Fludra, A., Caldwell, M.E., Giunta, A.S., Grundy, T.W., et al.: 2021, First Observations from the SPICE EUV spectrometer on Solar Orbiter, Astron. Astrophys., 656, 38, doi:10.1051/0004-6361/202141221

JTSIM-DARA onboard FY-3E

FY-3E is an Earth observation satellite by the Chinese Meteorological Administration (CMA). The satellite also carries the Joint Total Solar Irradiance Monitor experiment that consists of two solar radiometers, one from the Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP, China) and the Digital Absolute Radiometer (DARA) from PMOD/WRC.

The PMOD/WRC radiometer was already delivered to CIOMP in 2020 for integration on the Joint Total Solar Irradiance Monitor (JTSIM) instrument suite, shown in Figure 4 (see next page). Our instrument JTSIM-DARA on the Fengyun-3E (FY-3E) satellite was successfully placed into the planned orbit onboard a Long March 4C carrier rocket on 5 July 2021 (Figure 5). The FY-3E satellite is the world's first early-morning-orbit meteorological satellite for civil use.

The commissioning of the radiometer started shortly after the satellite was placed in the planned orbit and was successfully completed after one month. The instrument is healthy, all temperatures, currents and voltages are nominal, and within their tolerances.

To-date the instrument is fully operational. It performs all nominal and backup measurements autonomously and then sends readings to the ground station. From there, PMOD/WRC receives the data every few weeks for analysis. It is planned to automate the data chain and analysis in 2022.

Figure 5. Fengyun-3E launch from the SLS-2 launch site at the China Jiuquan Satelite Launch Centre. Image credit: ECNS.ch.

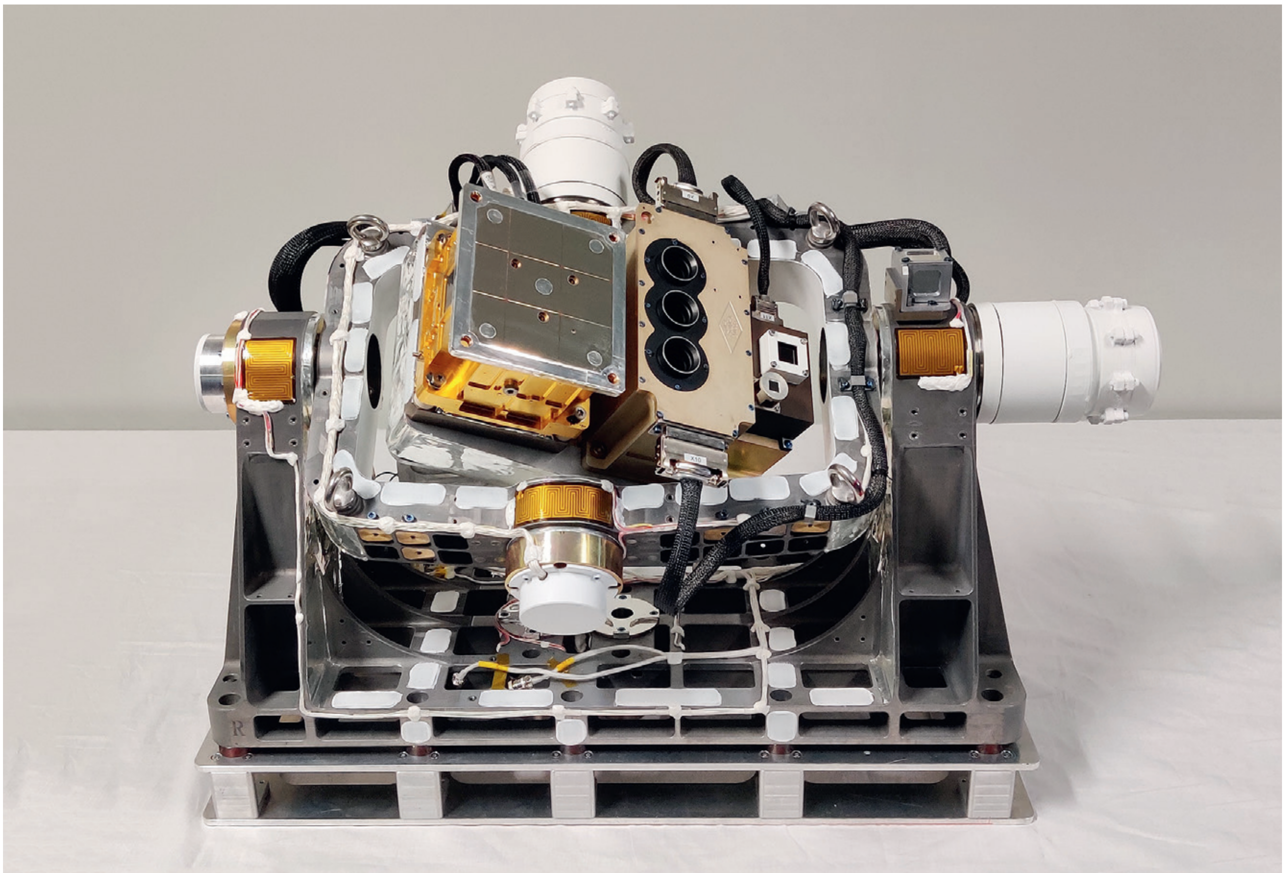


Figure 4. JTISM-DARA sensor head (centre left) integrated into the JTSIM solar tracker.

Scientific Research Activities

Overview

Louise Harra

Projects at PMOD/WRC are related to solar radiation in which we address questions regarding the radiation energy budget in the terrestrial atmosphere, as well as problems in solar physics in order to understand the mechanisms concerning the variability of solar irradiance. Hardware projects at our institute are part of investigations into Sun-Earth interactions which involve measurements of solar irradiance.

The choice of projects to be conducted at the institute is governed by the synergy between the know-how obtained from the Operational Services of the World Radiation Center and other research activities. The same instruments are built for space-based experiments as are utilised for ground-based measurements. In addition, with the involvement in Solar Orbiter, the instrumentation extends to imaging and spectroscopy. The research activities can be grouped into four themes: climate modelling, atmospheric physics, development of reference instruments for meteorological radiation measurements and solar physics.

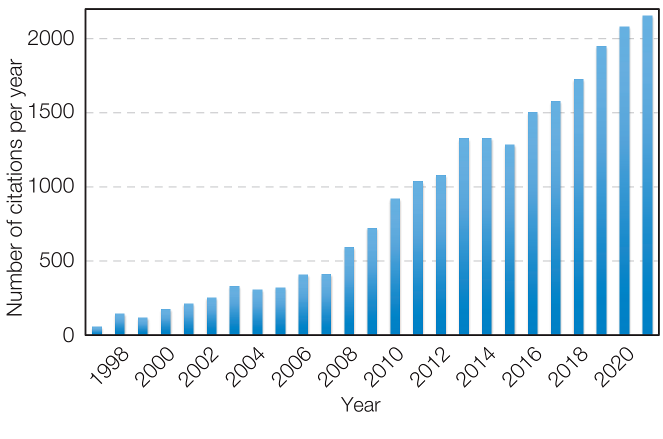
The majority of research activities are financed through third party funding. During 2021, there were a range of funding sources which included projects supported by the Swiss National Science Foundation, Karbacher Fonds, Innosuisse, European COST action, Meteoswiss, European H2020, ESA, and EURAMET. These funding sources supported four PhD thesis projects, four post-doctoral positions and two instrument scientists.

Swiss participation in ESA's PRODEX programme (PROgramme de Développement d'Expériences scientifiques) funds the hardware development of space experiments. The institute's six PRODEX projects paid for the equivalent of three technical department positions.

In the area of climate modelling, our research is concerned with both long and short-term changes in the Earth's atmosphere. The ozone layer evolution is being modelled and predicted. The impact of solar protons on the ionosphere has been assessed and particularly strong historical events are analysed. In addition, work is proceeding on understanding the outgoing radiation at the top of the Earth's atmosphere with the NorSat-1 CLARA mission. The climate group is also modelling different scenarios for the Sun from the current day Sun to a highly active mode. The Solar physics focus is on the Solar Orbiter mission following its launch in February 2020. These topics cover the creation of the slow and fast solar wind, and are carried out in collaboration with an array of other space and ground-based missions including NASA's Parker Solar Probe, the Solar Dynamics Observatory and JAXA's Hinode mission.

The institute's infrastructure and most of its overheads are paid for by the operational service of the World Radiation Center. We are proud of the fact that at the PMOD/WRC, the Center's services are based on research that is state-of-the-art in their respective fields. The data from new instruments are being analysed, such as the new spectroradiometer which measures from 500 nm to 1.7 µm and a lunar Precision Filter Radiometer (PFR). The accuracy of measurements are constantly being improved, and ensuring that long-term datasets can be actively used such as the Arosa/Davos ozone measurements. The long-term operation of the global aerosol optical depth monitoring network GAW-PFR has been secured with the development of a new generation of PFRs to replace the fleet of original network instruments constructed more than 20 years ago. The research carried out at PMOD/WRC is intertwined with the instrumentation, both ground and space-based. In addition, a transfer of knowledge on solar radiation is being carried out through the development of a short-term forecast model of solar energy.

PMOD/WRC's citations for refereed publications are shown below. They now exceed over 2000 citations each year.



Number of annual citations to articles including an author with a PMOD/WRC affiliation. Up to March 2021, there were a cumulative total of 21,508 citations to 655 articles included in Thomson Reuter's Web of Science. The articles were selected using the search criteria address = (World Rad C*) OR (PMOD* NOT PMOD Technol* OR pmodak) OR (Phys* Met* Obs*).*

Sources of the Slow Solar Wind: Upflows in Active Regions

Louise Harra and Krzysztof Barczynski

The origin of the slow solar wind is not yet understood. The slow solar wind fluctuates significantly with time, unlike the fast solar wind that is relatively steady. One source of the slow solar wind are the regions at the edges of active regions that have persistent upflows in the hot corona. We discuss how they are formed, where jets of plasma are observed throughout active regions, and the challenges of linking the remote sensing data to the in-situ.

The upflow regions at the edges of solar active regions have been observed consistently with the Hinode EUV Imaging Spectrometer that probes the corona spectroscopically. These are thought to be a contributor to the solar wind and also acceleration of particles (Harra et al., 2021). One mystery is how they are actually formed. Joint observations between three spacecraft in March/April 2019, allowed us to investigate the early stages. We analysed the spectroscopic data to detect the upflow, and the imaging data was analysed to trace the signature right back to the emergence of the active region. Figure 1 shows the data from the spectrometer on Hinode. The upflows are at the edges of the active region, even from early in its lifetime. The upflows form quickly and very low in the atmosphere, and the trigger is associated with a small-scale eruption that opens up a magnetic field (Brooks et al., 2021). This is consistent with the onset of the radio noise storm observed by the Parker Solar Probe space mission. Our work demonstrates that even when an active region is small, has just formed, and is not related to flaring, it can contribute to solar energetic particles and the solar wind. This contribution continues for most of its lifetime. This is an output of the International Space Science Institute team, led by Harra entitled "Getting closer to the Sun than ever before".

Solar active regions are rich in coronal jets; the collimated plasma flows into the outer part of the solar atmosphere. The particles, originated from the coronal jets, release into the solar wind. Odermatt et al. (2022) use high-resolution satellite observations obtained with the Solar Dynamics Observatory to study the distribution of the jet in five active regions. For the first time, they show that the jets mainly occur at the edge of the active region and avoid the centre of the active region. Moreover, the coronal jets prefer the vicinity of the strong, leading sunspots. The number of jets in the active region is independent of the average magnetic field flux and average magnetic field flux of the whole active region. In summary, our work demonstrates the basic characteristics of the spatial and temporal distribution of jets in active regions. Using simultaneous satellite observations from the Interface Region Imaging Spectrometer and Hinode, we investigate the solar atmosphere's plasma properties. We determine the mechanisms of the plasma upflow at the active region edges (Barczynski et al., 2021). We then analyse ten active regions (Barczynski et al., 2022) to determine the efficiency of the different mechanisms: (1) the reconnection between the closed loops and open magnetic field line – 90%, (2) the reconnection between the small-scale chromospheric loops and open magnetic field lines – 5% and (3) plasma escape along open magnetic field lines – 5%.

One of the key aspects to link in-situ measurements of the solar wind with remote sensing images and spectroscopy on the surface is through coronal magnetic field modelling. This allows the locations of where the magnetic field is open to be assessed. An output of Harra's ISSI team is the assessment of different global coronal models by constraining them with multiple independent observables (Badman et al., 2022). The metrics chosen for comparison are the locations of coronal holes, locations of the streamer belts and the magnetic structure measured in-situ both close-up by Parker Solar Probe and at 1 A.U. distance. Badman et al. (2022) summarise the strengths and weaknesses of the models and develop a framework to compare models.

References:

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Odermatt, J., et al.: 2022, Spatial distribution of jets in solar active region, submitted to Astron. Astrophys.

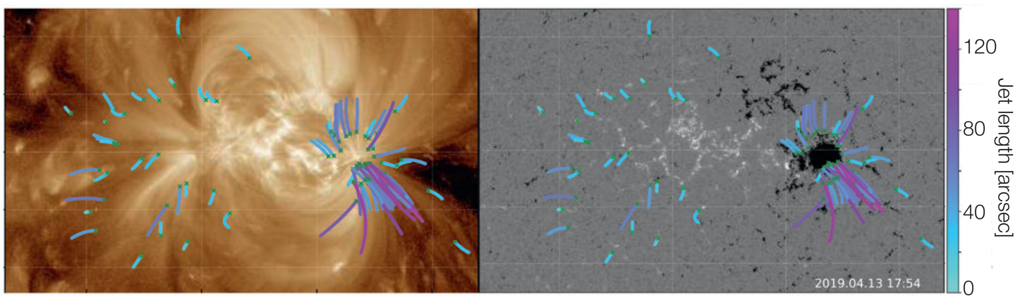

Figure 2. The coronal intensity map (left) and photosphetic magnetogram (right) of an active region obtained with the Solar Dynamics Observatory. The blue-violet lines show the colour-coded jet length and position in the active region.

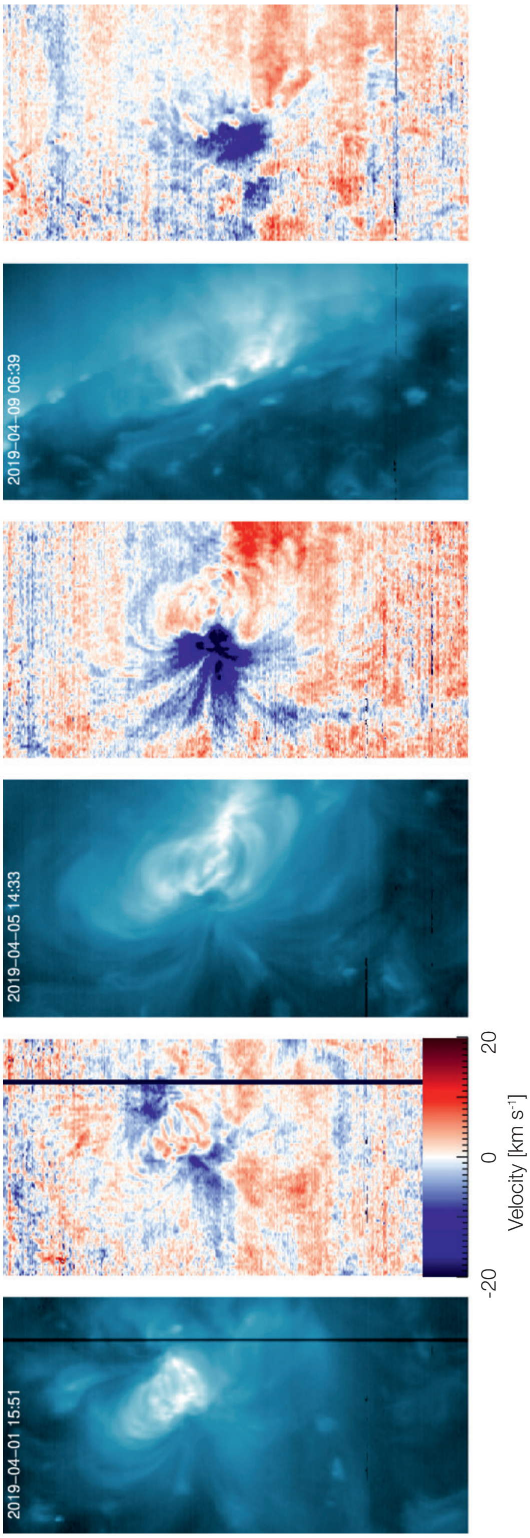

Figure 1. The Hinode EUV Imaging Spectrometer data with the intensity shown as white/blue and the Doppler velocity shown as red and blue with a colour bar. Three consecutive times are shown from 1 April to 9 April. Strong blue-shifts are seen on both the east and west side of the active region at all times (Brooks et al., 2021).

Small-Scale Energy and Plasma Releases in the Quiet Sun

Louise Harra and Conrad Schwanitz

The small-scale energy and plasma releases that are observed in the quiet Sun and coronal holes are important for understanding how the outer atmosphere is heated and how the solar wind is formed. We focus on two types of phenomena - the smallest coronal energy releases ever observed by Solar Orbiter and a new type of small-scale release of plasma that is observed through the measurement of spectral blue-shifts in the solar corona and is not seen as a significant intensity enhancement.

The smallest ever energy releases (known as "camp-fires") in the corona were observed by the Extreme Ultraviolet Imager (EUI) onboard Solar Orbiter in 2020 during a check-out window when the spacecraft was at a distance of 0.55 astronomic units from the Sun (Berghmans et al., 2021). Different physical characteristics have been determined including the heights of these small features - this has not been possible before. The different viewpoints of different spacecraft (Solar Orbiter vs Earth orbiting spacecraft) provided an opportunity to measure the heights of these small structures using stereoscopy (Zhukov et al., 2021). The heights were found to be between 1000 - 5000 km. This provides additional constraints for models. These small features are also observed by the spectrometer onboard Solar Orbiter and the first observation paper has been published (Fludra et al., 2021). Figure 1 shows the range of spectral lines available with the Spectral Imaging of the Coronal Environment (SPICE) spectrometer.

We investigated whether some of the switchbacks captured during the first encounter of the Parker Solar Probe mission are of coronal origin by correlating the switchback in-situ signatures with imaging and spectroscopic observations at their expected coronal footpoints (de Pablos et al., 2022). We found, through spatial analysis, that the proton temperature and density of the switchbacks are correlated with convective cell sizes. This is of potential interest as the small brightenings observed by Solar Orbiter were also located dominantly at the edges of these convective cells. In addition, we are studying small-scale coronal upflows. While our previous research has shown that even weak coronal features can cause strong upflows (Schwanitz et al., 2021), our current focus is to understand the driving mechanisms of small upflows. To do so, a combination of different datasets from Hinode, Interface Region Imaging Spectrograph, Solar Dynamics Observatory (SDO) and the ground-based solar telescope, GREGOR, are used. We can determine whether the flows seen in the corona are generated high in the corona by, for example, interchange magnetic reconnection or arise from beneath by, for example, magnetic flux emergence or cancellation. Figure 2 shows an example of an event from our observing campaign that used multiple instruments. This work is preparatory work for the science phases of the Solar Orbiter mission where we will combine magnetic field data with coronal data.

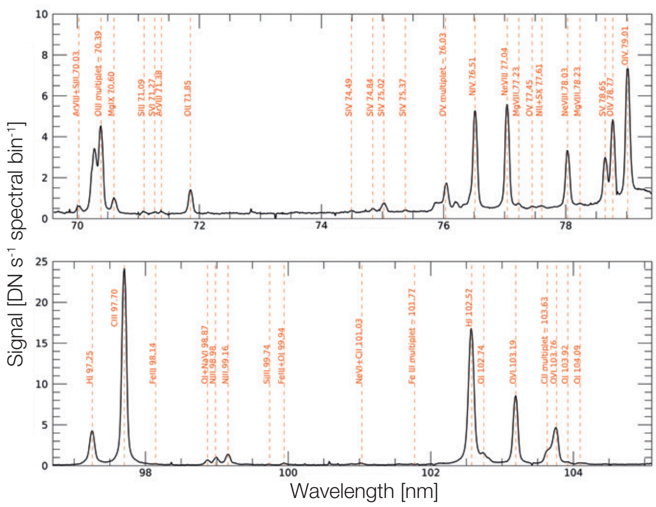

Figure 1. Spectra from the Solar Orbiter spectrometer (SPICE) showing the short (top) and long (bottom) wavelength bands. From Fludra et al. (2021).

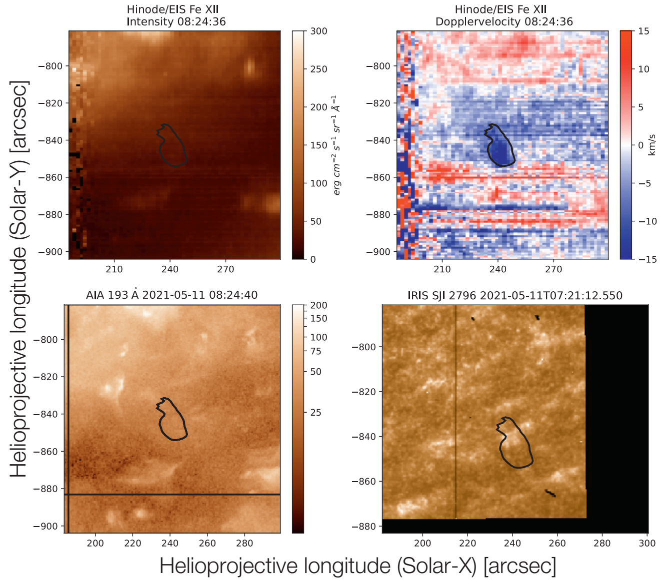

Figure 2. An upflow is identified as a blueshifted region in a Hinode/EIS doppler velocity map (top-right). This feature is then further analysed with observations from SDO/AIA (bottom left) and the Interface Region Imaging Spectrograph (bottom right).

References:

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Zhukov, A., et al.: 2021, Stereoscopy of extreme UV quiet Sun brightenings observed by SOlar Orbiter/EUI, Astron. Astrophys., 656, 35. doi:10.1051/0004-6361/202141010

Solar Atmosphere Radiative Transfer Model Comparison Based on 3D MHD Simulations

Margit Haberreiter in collaboration with NSO and NCAR (USA), and University of Oslo (Norway)

The reconstruction of the solar spectral irradiance (SSI) on various time-scales is essential for the understanding of the Earth's climate response to the SSI variability. The driver of the SSI variability is understood to be the intensity contrast of magnetic features present on the Sun with respect to the largely non-magnetic quiet Sun. However, different spectral synthesis codes lead to diverging projections of SSI variability. In this study, we benchmark three different radiative transfer codes based on 3D magneto-hydrodynamic simulations and carry out a detailed analysis of their performance. This comparison is important in order to understand the sources of uncertainty for irradiance reconstruction models.

We have determined the emergent intensity from 3D magneto-hydrodynamic (MHD) simulation snapshots for a non-magnetic case (hydrodynamic, HD), and two magnetic cases with a magnetic field strength of 100 G and 200 G. The intensity calculations were carried out using the PMOD/WRC radiative transfer COde for Solar Irradiance (COSI; Haberreiter et al., 2008; Figure 1), the RH code (Uitenbroek, 2001) and the MURaM radiation scheme (Vögler et al., 2005).

We find that while the absolute intensities produced by the codes agree very well, systematic differences of the code performance can be identified from the distribution functions. In particular, the RH code produces slightly wider distributions. The RH and MURaM calculations agree very well in the low-intensity range, while RH and COSI match very well at higher intensities. While the pixel-to-pixel differences of the codes can vary by several percent, the averaged intensities for the RH code versus MURaM differ by up to 1.4%, and COSI versus RH and MURaM by ~3 - 4%, respectively.

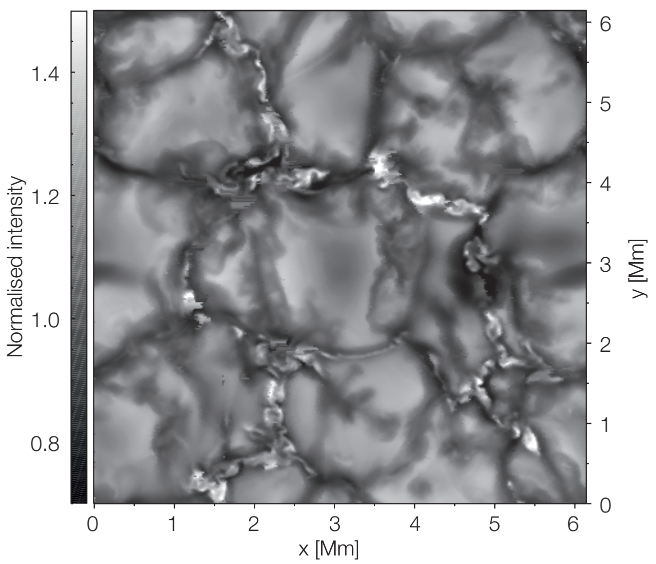

Figure 1. Normalised intensity calculated with COSI from a 3D MHD simulation with 200 G magnetic field strength. From Haberreiter et al. (2021).

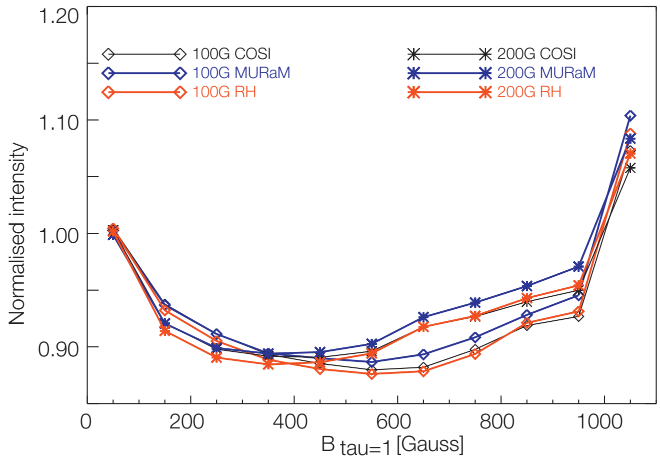

Figure 2. Normalised intensity as a function of absolute magnetic field strength in each grid point of the MHD simulation snapshot calculated with COSI (black), MURaM (blue), and RH (red) codes. Haberreiter et al. (2021).

Furthermore, we investigated how well the codes reproduce the intensities for different magnetic field strengths at the $\tau = 1$ layer (Figure 2). Here, we find the differences between the codes to be about 1 - 2% for the 100-G snapshot and about 2 - 3% for the 200-G snapshot. The overall shape of the change in intensity as a function of magnetic field strength is similar to previous work.

For the COSI and RH calculations we carried out an 8-point averaging of the cell corners of the MHD grid onto the cell centers, as done in the MURaM code. In addition to ensuring consistency, this technique also removes fringes that appear when using the original MHD grid with RH and COSI. While we focused in this study on computing intensities, it is likely that this technique should also be considered for polarised radiative transfer as well. Tests performed using snapshots interpolated on the vertical grid suggest that MHD simulations with substantially higher resolution in the vertical τ-scale might not cause this issue.

Acknowledgements: We thank the International Space Science Institute, Berne, Switzerland for hosting the International Team on Modeling Solar Irradiance with 3D MHD simulations, led by Serena Criscuoli. MH acknowledges support by Daniel Karbacher.

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Total Solar Irradiance (TSI) Data Analysis

Jean-Philippe Montillet, Wolfgang Finsterle, Margit Haberreiter, Daniel Pfiffner, and Silvio Koller

We have developed different algorithms to: i) produce a new Total Solar Irradiance (TSI) composite time-series using observations recorded by successive satellite missions launched since 1978 to present, and ii) process new observations recorded by the JTSIM-DARA radiometer from the latest missions launched in space onboard the Chinese FY3E satellite.

The new 41-year TSI Composite produced by PMOD/WRC

Since the late 1970s, successive satellite missions have been monitoring the Sun's activity by recording the Total Solar Irradiance (TSI). Some of these measurements have lasted for more than a decade. It is then mandatory to merge them to obtain a seamless record whose duration exceeds that of the individual instruments. Climate models can be better validated using such long TSI records which can also help provide stronger constraints on past climate reconstructions (e.g., back to the Maunder minimum) (Egorova et al., 2018; Shapiro et al., 2011). We have developed a 3-step method based on data fusion, including a stochastic noise model to take into account short and long-term correlations characterising the composite noise within the TSI observations.

The first step relies on data fusion of multiple observations recorded by various missions, and based on a Bayesian framework and Gaussian processes. Our new composite spanning the last four decades is obtained in a second step by daisy-chaining the sub-timeseries resulting from the first step. The last step is the application of wavelet filtering to correct some unwanted correlations in the fused observations (i.e. bandwidth noise). The robustness of our approach is guaranteed via careful modelling of the TSI observations during the data fusion process. The comprehensive description of the algorithm is discussed by Montillet et al. (2021).

Compared with previous products (Dewitte and Nevens, 2016; Dudok de Wit et al., 2017; Fröhlich, 2006) scaled at the nominal TSI value of ~1361 Wm^{-2}, the difference in terms of the mean value over the whole timeseries is <0.2 Wm^{-2}. Similar results are obtained when comparing the various composites in terms of solar minima. Note that Figure 1 shows the new TSI composite timeseries. We also model the frequency spectrum of this 41-year TSI composite timeseries with a Generalised Gauss-Markov model to help describe an observed flattening at high frequencies. It allows us to fit a linear trend to these TSI timeseries by joint inversion with the stochastic noise model via a maximum-likelihood estimator. Our results show that the amplitude of such a trend is ~ -0.004 ± 0.004 Wm^{-2}yr^{-1} for the period 1980 - 2021. These results are compared with the difference of irradiance values estimated from two consecutive solar minima. We conclude that the trend in these composite timeseries is mostly an artefact due to the coloured noise.

Data Analysis of the observations recorded by DARA onboard the JTSIM-DARA / FY-3E mission

The JTSIM-DARA radiometer onboard the FY-3E satellite, was successfully launched on 5 July 2021. Since August 2021, PMOD/WRC together with CIOMP have performed several tests to check the observations recorded by the JTSIM-DARA radiometer in space and to compare with the pre-flight calibration values

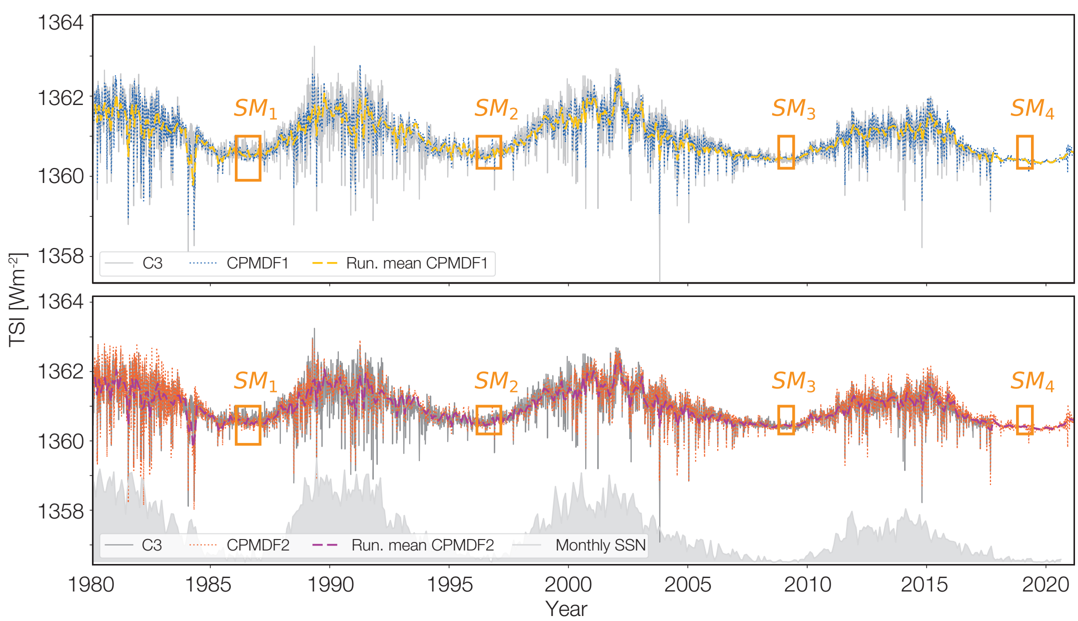

Figure 1. The new composite (CPMDF1, blue) without and with wavelet filtering (CPMDF2, orange) based on merging 41 years of TSI measurements. For comparison, C3 (Fröhlich, 2006) is also shown (grey line). A 30-day running mean of CPMDF1 is shown as a yellow/purple dash line. The orange boxes are associated with the solar minima (SM). For context the monthly sunspot number is also displayed.

(Song et al., 2021). The general processing focusses on converting the raw observations recorded by the instrument (Level-0) to irradiance measurements (Level-2). Level-2 observations are corrected for various factors (e.g., shutter aperture, reflectance, diffraction, the World Radiometric Reference factor, etc). Thus, this processing allows a check of several corrections such as the phenomena corresponding to the repetition of the satellite orbit, the Earth-Sun distance, and the doppler effect, also called orbital correction. Another correction is the deep space or dark correction. During space measurements, the cavity exchanges radiation with a different thermal background in the shutter-open case, where the cavity radiates to deep space, compared to the closed case where the cavity's thermal emission may be reflected by the gold-coated interior of the shutter (Walter et al., 2017). Once all the corrections have been performed, the TSI timeseries for the JTSIM-DARA instrument with its three cavities, is as shown in Figure 2. The first light for JTSIM-DARA is estimated at about 1361.22 ± 0.17 Wm^{-2} for the main cavity (Cavity B), and 1361.18 ± 0.15 Wm^{-2} for the back-up cavity (Cavity C).

TSI webpage: www.pmodwrc.ch/en/research-development/solar-physics/tsi-composite/

SOHO/VIRGO webpage: www.pmodwrc.ch/en/research-development/space/soho

Acknowledgement: JPM and MH acknowledge funding by Daniel Karbacher.

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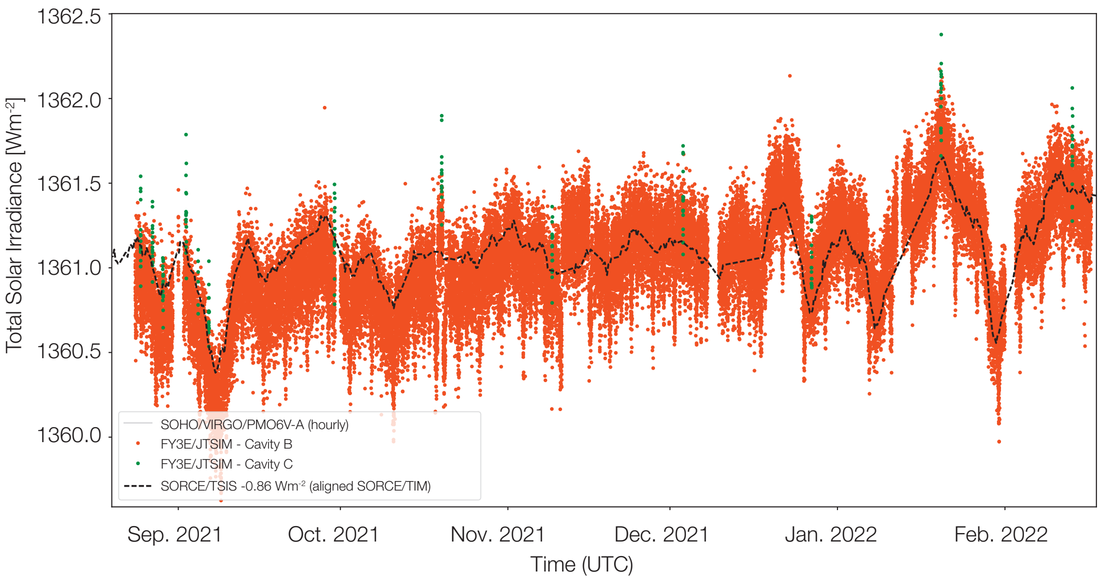

Figure 2. Estimated and corrected values of the irradiance for the different cavities of the JTSIM-DARA radiometer. For comparison, we have added the TSIS/TIM data aligned on the TIM/SORCE dataset following the comparison in Finsterle et al. (2021).

Climate Implications of the Sun Transition to High Activity Mode (CISA)

Tatiana Egorova, Eugene Rozanov, in collaboration with Alexander Schapiro and Anna Shapiro, MPI-S (Germany)

It was suggested that the Sun could go through an epoch of high magnetic activity which would lead to unexpected behaviour of the solar irradiance (Shapiro et al., 2020). A noticeable 0.9% drop in the Total Solar Irradiance (TSI) will be accompanied by a large increase of the ultra-violet (UV) irradiance. In the CISA project, we analyse possible consequences of the Sun transition to a high magnetic activity mode on the terrestrial atmosphere.

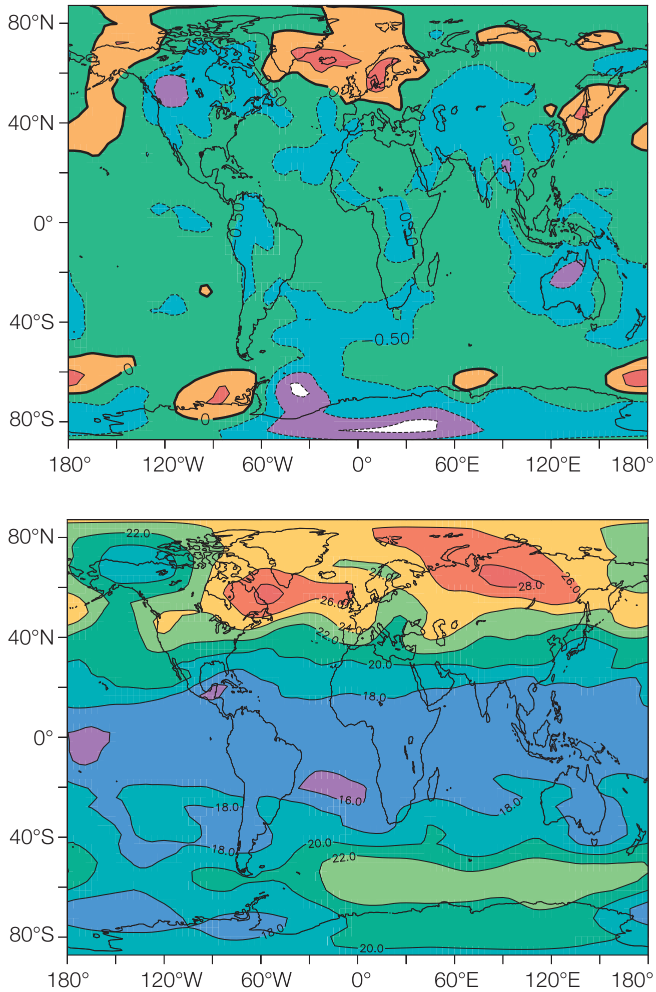

Figure 2. Geographical distribution of the change in surface temperature (upper, in K) and total ozone (lower, in DU).

In the first year of the CISA project, we prepared several scenarios for changes in the solar spectral irradiance (SSI) during the transition of the Sun to more active states, and simulated climate and ozone layer changes caused by the suggested Sun transition. We have prepared SSI data for three cases: (1) reference present day Sun, (2) Sun in medium activity mode, and (3) Sun in highly active mode. We used the SOCOL model with an interactive ocean (MPIOM) and performed two 60-year long time-slice experiments. In the reference run, we prescribed monthly SSI for the year 2000 (solar activity maximum). In the second (experiment) run, we applied monthly SSI for the Sun after its transition to a more active state. Figure 1 shows the near-surface temperature for the normal (black line) and high solar activity (red line) cases. Transition to the higher activity mode cools down the Earth by about 0.5 K as expected from a Total Solar Irradiance (TSI) drop of 4.418 Wm^{-2}.

Figure 2 demonstrates the geographical distribution of the differences for surface temperature (upper) and total ozone (lower) for the last 10 years of the experiment. Pronounced cooling is visible mainly over the land masses, however over the ocean it is somewhat smaller. The positive values over Northern Europe and Greenland are not expected because Arctic amplification should lead to more significant cooling over the high latitudes.

For total ozone, the response is positive everywhere but less intensive in the tropical area and with maximum values (30 DU) over Siberia and the North Atlantic. The results that have been obtained from the experiments are theoretically expected because higher levels of UV radiation lead to a pronounced increase in stratospheric and total ozone. For the surface climate, the results are not obvious because we obtained cooling for global and annual mean values but at the same time, we observe large warming (about 1K) over Northern Europe. This feature can be related to stratospheric ozone changes, but we cannot prove this hypothesis without additional experiments that are planned for the second year of the project.

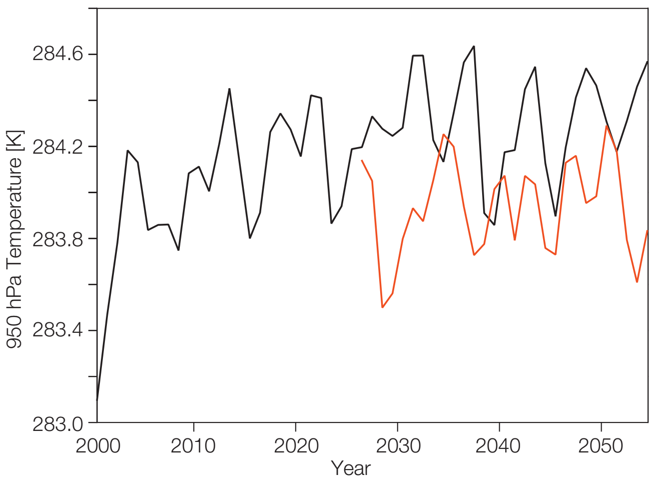

Figure 1. Evolution of the near-surface temperature at 950 hPa. Results are shown for the reference (black) and high Sun magnetic activity mode (red).

Acknowledgment: The study was funded by the SNSF project POLE (200020_182239) and supported by CSCS under projects S-901 (ID 154) and S-1029 (ID 249). The CISA project is also funded by the Swiss Karbacher Fond.

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The Role of the Montreal Protocol in Sustainable Recovery of the Ozone Layer and Climate

Tatiana Egorova, Jan Sedlacek, Eugene Rozanov, Timofei Sukhodolov, and Arseniy Karagodin

To understand the past and project the future behavior of the ozone layer, the PMOD/WRC Climate Group is working on the SNF project, POLE. Here we describe the progress during the third year of the project and present an on-going analysis of the simulations performed using the AOACCM SOCOLv4.0 model, with and without Montreal Protocol and its Amendments (MPA) limitations on the production of halogen-containing ozone-destroying substances (hODS).

During the third year of the POLE project, we completed three ensemble members each for a reference run and for a run without Montreal Protocol limitations using the new Atmosphere-Ocean-Aerosol-Chemistry-Climate Model (AOACCM) SOCOLv4.0 (Sukhodolov et al., 2021) driven by all recommended forcings for the 1980 - 2100 period. Here we analyse the benefits of the Montreal Protocol for several essential climate variables such as surface air temperature, precipitation, and cloud cover. The analysis of the model results is carried out on the mean ensemble of three members, with and without considering the MPA restrictions.

Figure 1 shows regional effects of MPA regulations for surface air temperature for annual mean values for the time period 2080 - 2099. We obtained statistically significant additional warming of up to 8 K in the Arctic region by the end of the 21st century without MPA. The use of additional ensemble members for the analysis led to a decrease in the amplitude of the warming compared to our previous analysis. However, despite this, warming due to hODS remained dramatic and statistically significant.

In a warmer climate, we expect more water vapour in the atmosphere, and consequently substantial changes in precipitation intensity. Figure 2 shows the geographical distribution of precipitation and cloud cover changes. We obtained a very pronounced contrast between dry and wet areas. The cloud cover decreases in extratropical latitudes of both hemispheres and increases in the tropical and high latitudes of the world without the Montreal Protocol.

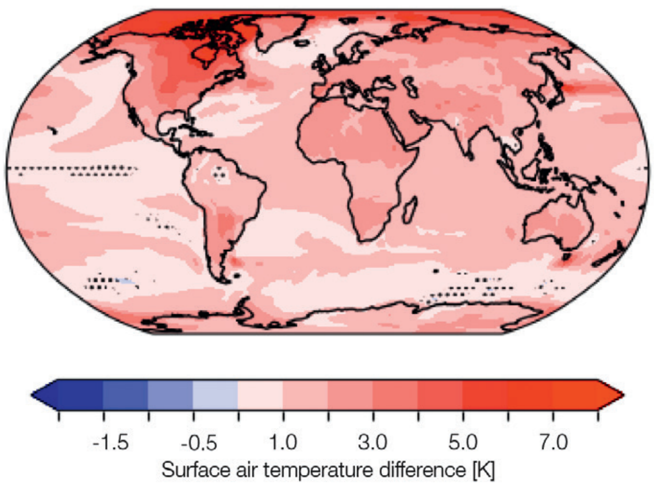

Figure 1. Geographical distribution of the annual mean difference of the surface air temperature between scenario and reference simulations, averaged over the time period 2081 – 2099 (in K). Colours represent the areas where the statistical significance exceeds the 95% level.

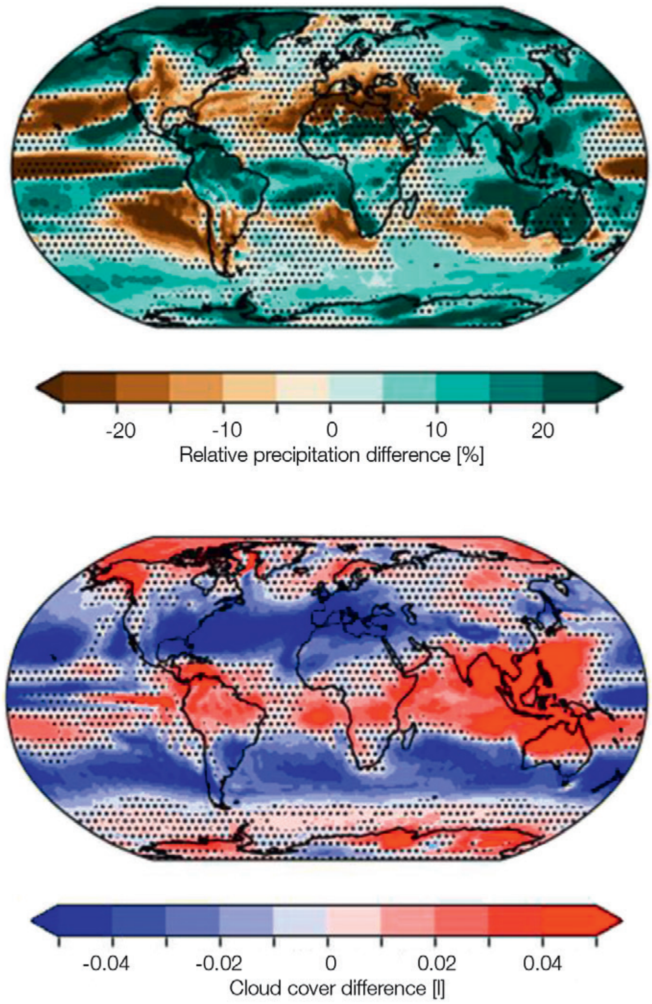

Figure 2. Geographical distribution of the annual mean difference in precipitation and cloud cover between scenario and reference simulations averaged over the time period 2090 – 2100 (in %). Areas without shading show where the difference is statistically significant at the 95% level.

Acknowledgment: The study was funded by the SNSF project, POLE (200020_182239), and supported by CSCS under projects ID S-901 and ID S-1029.

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Iodine Chemistry Simulated with SOCOL-AERv2-I and its Effect on Ozone

Arseniy Karagodin, Eugene Rozanov, Timofei Sukhodolov, Tatiana Egorova in collaboration with IAC ETH Zurich, SNRC (Spain), University of York (United Kingdom), and University of Colorado, Boulder (USA)

In this study, we present a new version of the SOCOL-AERv2 chemistry-climate model (CCM) supplemented with iodine chemistry. We conducted 20 years of 10-ensemble experiments to assess the validity of the simulated iodine and to quantify the effects of iodine on ozone.

Our understanding of the role of iodine chemistry in ozone depletion is limited due to its extremely low concentration (~1 pptv) and the lack of observations. In addition, despite some advances in iodine chemistry modelling, the available results have a wide range of atmospheric iodine values and it is still difficult to conclude which results are closer to reality. At the same time, the ozone depletion efficiency of iodine-containing species on a per-molecule basis is hundreds of times higher than that of chlorine (Saiz-Lopez et al., 2012). Cuevas et al. (2018) argued that the atmospheric iodine loading must have increased by at least a factor of three since the 1950s. Therefore, iodine chemistry remains suspected of affecting the stratospheric ozone recovery.

In this work, we developed a new version of CCM SOCOL-AERv2, extended with iodine chemistry. The main purpose of this study is to test the chemistry of iodine and evaluate the effect of iodine chemistry on stratospheric ozone detection. The iodine chemistry scheme includes 61 gas-phase and 4 heterogeneous chemical reactions involving iodine. The detailed description of iodine chemistry scheme in SOCOL-AERv2-I and conducted experiments are reported by Karagodin-Doyennel et al. (2021). Figure 1 shows the vertical distributions of total inorganic gas-phase iodine I_y. In the troposphere, the iodine level decreases toward the poles and far from the iodine source regions. In the lower stratosphere over middle-to-high latitudes, the I_y distribution demonstrates a maximum of more than 1.15 pptv in the Northern Hemisphere and about 1 pptv in the Southern Hemisphere due to the inhomogeneous meridional transport.

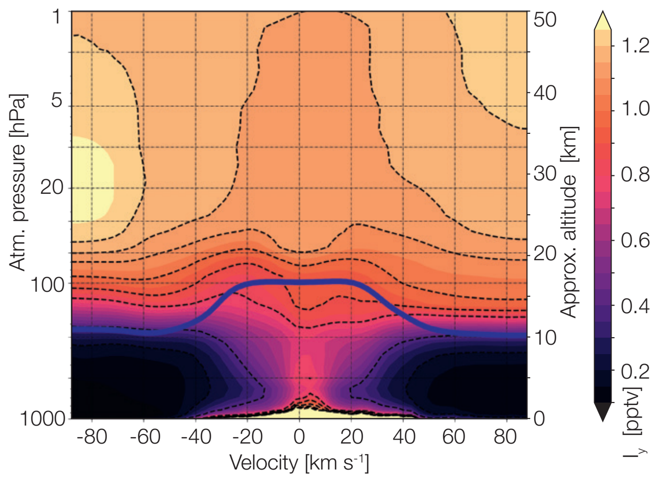

Figure 1. The vertical distribution of the ensemble-mean modelled zonal-mean of total inorganic gas-phase iodine (I_y) simulated with SOCOL-AERv2-I, averaged for the 2000-2009 period. Blue solid line: annual mean tropopause height.

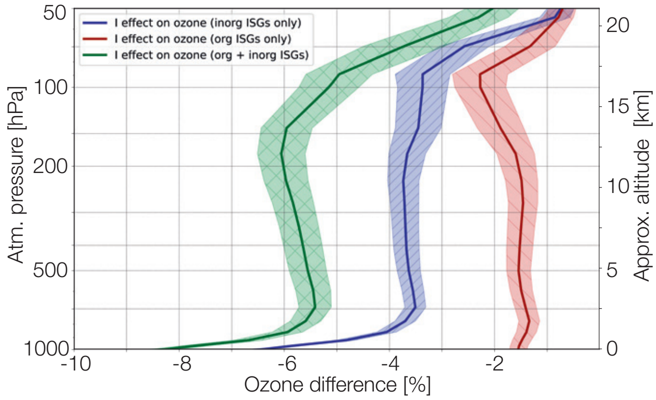

Figure 2. Ensemble-mean modelled vertical profiles of O_3 reduction by iodine from organic, inorganic, and total surface emissions averaged over the tropics (20°N-20°S) for the 2000-2009 period. Red curve: difference in O_3 relative to the control run (0 × iodine), if only organic iodine source gases are considered; blue curve: a percentage difference in O_3 relative to the control run (0 × iodine), if inorganic iodine source gases are only considered; green curve: percentage difference in O_3 relative to the control run (0 × iodine), if both organic and inorganic iodine source gases are considered. Shading represents a standard deviation of ensemble members. The results have a confidence level more than or equal to 95%.

The effect of organic vs inorganic iodine sources on tropical ozone is addressed in Figure 2. In the lower troposphere, the iodine from inorganic emissions is responsible for ~75% of the total iodine effect on ozone, and the contribution of iodine from organic sources is ~25%. In the upper troposphere and lower stratosphere, the difference in contributions of two types of iodine sources shrinks, and impact becomes similar at a height of about 50 hPa. Thus, our results show the importance of better characterising iodine levels in the atmosphere and its contribution to ozone depletion. Nevertheless, the further improvement of iodine chemistry in CCMs and the necessity of improving global measurements of iodine chemistry, especially in the upper troposphere and lower stratosphere, will increase the accuracy of estimates of the iodine contribution to ozone reduction. In addition, better predictions of future ozone evolution will also be possible.

Acknowledgment: The study was funded by the SNSF project POLE (200020_182239) and supported by CSCS under projects ID S-901 and ID S-1029.

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Influence of Solar Irradiance on Future Climate

Jan Sedlacek, Timofei Sukhodolov, Tatiana Egorova, Arseniy Karagodin, and Eugene Rozanov

We use conservative and declining solar activity scenarios to prescribe the spectral solar irradiance evolution for 21st-century climate simulations with the Earth System Model, SOCOLv4. The difference between the two simulated climate states on a global scale are very small and not significant. However, on seasonal and regional scales there could be some significant changes towards the end of the century.

Solar irradiance is the dominant energy source on Earth. For the Climate Model Intercomparison Project (CMIP), which is the basis for the Intergovernmental Panel on Climate Change Assessment Report (IPCC AR), several forcings such as greenhouse gas concentrations, solar irradiance and so on are proposed to compare the results from different climate models. In the 5th CMIP phase, a perpetual repetition of the solar cycle 23, which lasted from 1998 until 2008, was proposed as the 11-yr solar cycle forcing. For the 6th CMIP phase a new approach was taken by Matthes et al. (2017). Different plausible scenarios of the future evolution of the solar cycles were produced using statistical methods, which consider past variations.

We force the SOCOLv4 model (see Sukhodolov et al. (2021) for a description) with a "middle-of-the-road" scenario in greenhouse gas evolution (SSP-4.5). SOCOLv4 is a fully interactive Earth System Model with atmosphere, ocean, and land components including a biogeochemical cycle in the ocean, and aerosol and chemistry modules in the atmosphere. The model is forced with two different solar forcings (Figure 1) and three ensembles are computed for each forcing. The REF forcing depicts the most conservative evolution of future solar irradiance and the EXT describes a possible scenario with some decline of solar activity.

On a global scale, the changes induced by the different solar irradiance are very small. For example, the change in global mean temperature from 1980 to 2100 is about 2 K due to changes in greenhouse gases. The temperature difference due to solar irradiance changes at the end of the century is only about 0.05 K, i.e., two orders of magnitude smaller. However, on seasonal and regional scales, the climatic changes can be statistically significant.

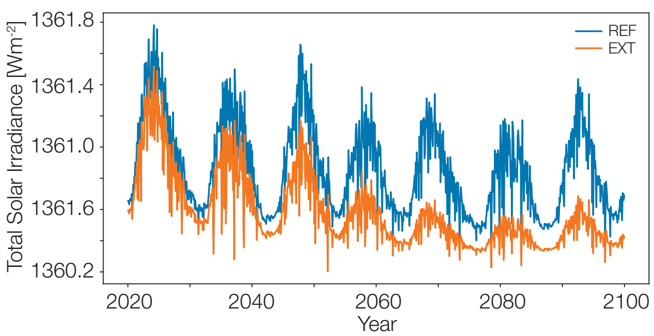

Figure 1. Total solar irradiance forcing used for the simulations. The blue line denotes the reference forcing (REF) and the orange line depicts the low forcing scenario (EXT).

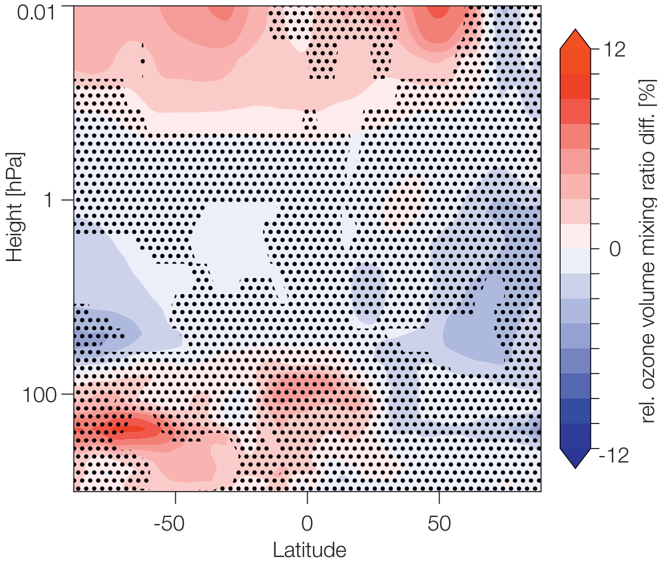

Figure 2. Latitude-height ozone changes in % for the month of December from 2080 and 2099 between the different solar forcings. The dots show no significant changes according to the IPCC AR6 definition.

One of these regional mechanisms which is visible in the simulation is explained by the example of a climatological December month at the end of the century (Figure 2). The figure shows the relative change of zonal mean ozone from the South Pole to the North Pole. In the mesosphere (above 1 hPa), there is an increased amount of ozone mainly due to weaker UV radiation, leading to less intensive hydrogen oxide production from water vapour. In the stratosphere, there is a decrease in ozone due to the intensification of the dominant oxygen photolysis, while at the stratopause and in the troposphere (below ca. 300 hPa) most of the changes are dynamically driven. These changes in ozone induce changes in temperature and thus temperature gradients which in turn trigger dynamical changes in the atmosphere.

The impact of the two different solar forcings on future climate can be described in general terms as the changes expected and observed during an 11-yr solar cycle when comparing low and high activity time periods. Most mechanisms are dynamically driven which have large variability and thus are more difficult to detect. Further work will focus on identifying these mechanisms and investigating more precisely what the exact impacts will be.

Acknowledgment: The study was funded by the SNSF project POLE (200020_182239) and supported by CSCS under projects ID S-901 and ID S-1029.

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Investigation of Sulphate Aerosol Modelling Uncertainties in the Frame of the ISA-MIP and VolRes Activities

Timofei Sukhodolov and Eugene Rozanov in collaboration with IAC ETH Zurich, VolRes and ISA-MIP communities

With our aerosol-chemistry-climate model, SOCOL-AER, we are participating in two international activities focussed on the atmospheric sulphur budget and volcanic eruptions: Interactive Stratospheric Aerosol Model Intercomparison Project (ISA-MIP) and the Volcano Response plan (VolRes). ISA-MIP explores the uncertainties in processes that govern the stratospheric aerosol layer evolution in order to improve models, while VolRes is a plan of a fast scientific response in case of a new strong volcanic event, which also involves modelling. Here, we present some updates from both activities.

ISA-MIP. Large magnitude tropical volcanic eruptions emit sulphur dioxide and other gases directly into the stratosphere, creating a long-lived volcanic aerosol cloud which scatters incoming solar radiation, absorbs outgoing terrestrial radiation, and can also affect composition and dynamics of the stratosphere. We investigated the Mt Pinatubo eruption in 1991, the largest volcanic eruption of the last 100 years, comparing simulations within the ISA-MIP HErSEA experiment (Historical Eruptions SO_2 Emission Assessment). This experiment allowed interactive stratospheric aerosol simulations of the volcanic aerosol cloud with common upper, mid and lower estimate amounts and injection heights of SO_2 in order to better understand known differences among modelling studies. Results from five participating models and five experiments are shown in Figure 1. Detailed analysis of different aerosol parameters and comparison with available observations revealed that model differences in the treatment of aerosol chemistry and microphysics are not sufficient to explain differences in results among models, implying that a further step would be to look at the differences in stratospheric dynamics. This work has already been presented at the EGU 2021 conference (Quaqlia et al., 2021) and is currently in preparation for publication.

VolRes. If a strong eruption happens, in order to predict its potential effects and their duration the model would rely on emission parameters derived from observations, but it would first have to be driven by the observed dynamical fields (so-called "nudging" mode). To identify whether this can introduce any side effects, we performed three sets of runs: free-running (Free1 - 3) with nudged winds (NdgW), and with nudged wind and temperature fields (NdgWT), results of which are presented in Table 1. We found that the sulphur burden in the fully nudged set-up (NdgWT) was enhanced on average by 9.6% in the stratosphere and 12.7% in the whole atmosphere, which is due to several factors. First, differences in the cloud formation and precipitation favour aqueous phase oxidation of SO_2 in free running simulations, which promotes wet aerosol scavenging, while gas phase oxidation dominates in nudged simulations. Second, convective activity appears to be stronger in nudged simulations, which leads to an increased troposphere-to-stratosphere flux of sulphur-containing species (also seen in OCS). We showed, that this effect can be avoided by only nudging toward horizontal winds (NdgW), which provides a smoother transition from the nudged to the free running regime, although for the price of a less dynamically constrained model. These results are published in Brodowsky et al. (2021).

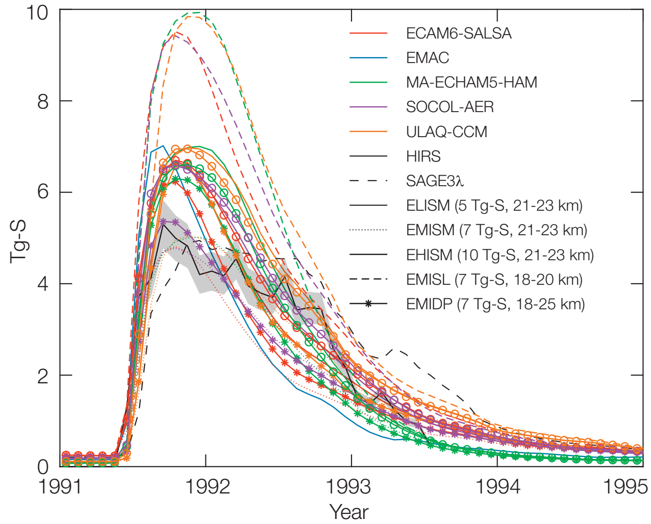

Figure 1. Global stratospheric sulphate burden after Pinatubo from five models (ECHAM6-SALSA, EMAC, MA-ECHAM5-HAM, SOCOL-AER, ULAQ-CCM) in 5 ISA-MIP experiments (ELISM, EMISM, EHISM, EMISL, EMIDP) and two observational estimates (HIRS, SAGE3λ).

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Table 1. The large-scale and convective precipitation as well as aerosol and OCS burdens for the free running model versus NdgW and NdgWT. Alll values are means over the time period from 2008 to 2012.

Simulations	Large-scale precipitation (10^{-5} kg/m^2 s)	Convective precipitation (10^{-5} kg/m^2 s)	Tropospheric aerosol (H_2SO_4; 10^8 kg S)	Stratospheric aerosol (H_2SO_4; 10^8 kg S)	Stratospheric OCS (10^8 kg S)
Free1	1.22 ± 0.04	2.08 ± 0.08	6.73 ± 0.97	2.29 ± 0.53	2.86 ± 0.15
Free2	1.22 ± 0.03	2.08 ± 0.07	6.80 ± 1.08	2.35 ± 0.54	2.84 ± 0.15
Free3	1.22 ± 0.03	2.08 ± 0.07	6.77 ± 0.99	2.19 ± 0.40	2.86 ± 0.15
NdgW	1.10 ± 0.06	2.13 ± 0.07	6.77 ± 0.90	2.38 ± 0.52	3.14 ± 0.19
NdgWT	1.05 ± 0.04	2.20 ± 0.08	7.59 ± 1.14	2.51 ± 0.52	3.33 ± 0.18

Quantifying Present and Near-Future Rocket Launch Impacts on the Stratosphere

Timofei Sukhodolov and Eugene Rozanov in collaboration with the School of Physical and Chemical Sciences, University of Canterbury (Christchurch, New Zealand)

The rate of rocket launches around the world is accelerating, driven by the rapid global development of the space industry. However, the cumulative effects of orbital launch vehicle emissions on the stratosphere are poorly understood. We have used a new quantitative inventory of stratospheric-based rocket emissions in the present and in the near future to simulate the effects on ozone using our global chemistry-climate model, SOCOLv4. We found that the present day emissions do not cause any identifiable impact, while the future emissions might reach the levels that are dangerous for the ozone layer.

Individual rocket launches deposit potentially significant quantities of soot, alumina, nitrogen oxides (NO_x), reactive chlorine (Cl), carbon dioxide, and water vapour (H_2O) into the stratosphere. With an 8% year-on-year growth in the number of space launch activities over the last decade, determining the ongoing effects of rocket emissions on the ozone layer is paramount. Our collaborators from the School of Physical and Chemical Sciences have compiled a new inventory of the rocket emissions of the above-mentioned species considering the type of engines and fuel used in different spaceports, as well as current and future launch cadence plans. Two emission databases have been compiled: one representing the present day, and the second one assuming a maximum launch cadence (120/year) for every spaceport.

To estimate the impacts on ozone, we have used our Atmosphere-Ocean-Aerosol-Chemistry-Climate model SOCOLv4 (Sukhodolov et al., 2021). Thirty-year long experiments were performed in a time-sliced mode for conditions in the year 2030. Since currently SOCOLv4 does not include interactive alumina and soot aerosols, and carbon dioxide emissions are clearly too small to produce an impact, we have so far only considered the emissions of NO_x, Cl, and H_2O. Distribution of spaceports around the world can be seen in Figure 1. The majority are located in the Northern Hemisphere (NH), while there is only one spaceport in the Southern Hemisphere (New Zealand). Several spaceports are located in the tropical area, which allows them to effectively influence both hemispheres.

Figure 1. Spaceport locations around the world.

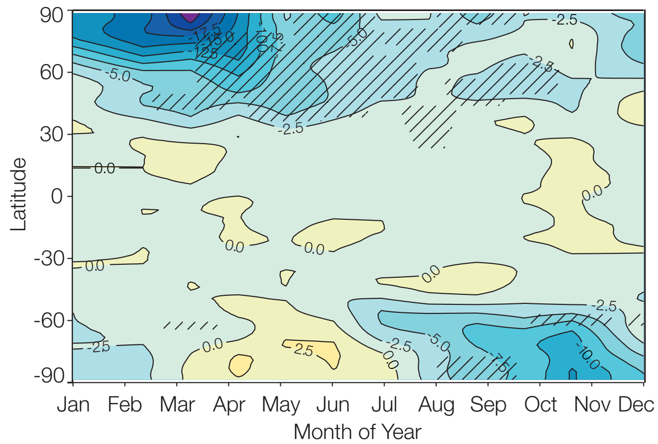

Figure 2. Total ozone column change due to future rocket emissions of H_2O, NO_x, and Cl. Hatched areas are statistically significant at a 95% confidence level.

Our results showed that the present day rocket emissions do not cause any significant impact on the ozone layer. However, results from the second scenario, implying further launch cadence growth, suggest that the future space industry might become a new danger for the ozone layer. Total ozone column changes in the second scenario are presented in Figure 2. Additional ozone depletion is statistically significant in both hemispheres and is mostly confined to the mid and high-latitude regions, and winter and spring seasons. Depletion is also stronger in the NH, which is defined by the larger amount of spaceports. The magnitude of the extra depletion for the NH is comparable to the historical ozone decline due to anthropogenic emissions of halogens in 1975 - 1995 (Dhomse et al., 2018).

We also found that the main effect comes from the emission of chlorine, while effects of NO_x and H_2O are rather minor. The mechanisms, therefore, are very similar to the historical ozone depletion in the past: namely, decrease of ozone throughout the upper stratosphere, where the gas-phase chlorine catalytic cycle of ozone destruction is the most efficient, as well as the intensification of the polar ozone holes due to heterogeneous chemistry on the polar stratospheric clouds. The latter is clearly seen in Figure 2, as the maximum signal during Austral and Boreal springtime.

A paper describing the new emission databases and our simulation results is currently in preparation. Our next step would be to upgrade SOCOLv4 by including soot and alumina modules and to estimate their effects as well. These particles can also affect the stratospheric chemistry, while they can also induce extra heating in the stratosphere.

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Historical Ozone Trends Simulated with ESM SOCOLv4

Arseniy Karagodin, Eugene Rozanov, Timofei Sukhodolov, Tatiana Egorova, and Jan Sedlacek in collaboration with IAC ETH Zurich

We present recent historical ozone trends simulated with the Earth system model (ESM), SOCOLv4, with a focus on extratropical lower stratospheric ozone. We applied a dynamical linear model (DLM) to the reference experiment from six-ensemble members to estimate changes in ozone during two intervals: the ozone depletion (1985 - 1997) and ozone recovery (1998 - 2018) phases. The model shows reasonable ozone changes. However, the observed negative ozone changes for the last two decades are still hardly captured in the model.

Over the last decades, there has been a marked recovery of stratospheric ozone following the phasing out of the production of ozone-depleting substances under the Montreal Protocol and its Amendments (MPAs). While the recovery of total column ozone is observed, partial recovery of ozone is uncertain. Recent studies claim that the lack of recovery is due to the continuous decline in extratropical ozone in the lower stratosphere (Ball et al., 2018).

Here, we analyze the ozone from reference experiment simulated with Earth system model SOCOLv4 for the period 1985-2018. The reference means that the experiment was performed using the standard (historical) conditions. The standard conditions were initiated from the MPI-ESM1.2 restarts for atmospheric dynamics and physics and the SOCOLv3 run for chemistry. The detailed model and experiment descriptions can be found in the SOCOLv4 validation paper (Sukhodolov et al., 2021).

To estimate the ozone trend and exclude the influence of well-known forcings of ozone variability, we applied the dynamical linear model (DLM). We used proxies of ozone variability such as Solar F 30 index, zonal wind (quasi-biennial oscillation) at 30 and 50 hPa, El Niño / Southern Oscillation, stratospheric aerosol optical depth, Arctic and Antarctic oscillations, as well as the seasonal cycle.

Figure 1 illustrates ozone changes for the ozone depleting and recovery phases from the ensemble-mean SOCOLv4 reference experiment. During 1985 - 1997, the decrease in ozone caused by halogen ozone-depleting substances is estimated to be more than 5% for the lower stratosphere and it reaches a maximum in the Southern high latitudes. In the upper stratosphere, the simulated decline in ozone is ~4 - 5% caused by enhancement of the ClO_x catalytic cycle efficiency. In the troposphere, the model shows a strong increase in tropospheric ozone over the tropics of more than 5%, which might be due to the increase in ozone precursors and, in particular, NO_x by lightning activity, whose continuous increase is caused by global warming. Overall, we see a marked decrease in stratospheric ozone during 1985 - 1997. For the 1998 - 2018 interval, tropospheric ozone continues to increase, especially in the tropics. In the upper stratosphere, the statistically significant recovery of about 3 - 4%, resulting from a decline in halogen levels, is well-captured by the model. The lower stratospheric ozone trends are uncertain because of a poor statistical significance in this region. At high latitudes, some signs of recovery are seen. Note that the observed statistically significant negative changes in

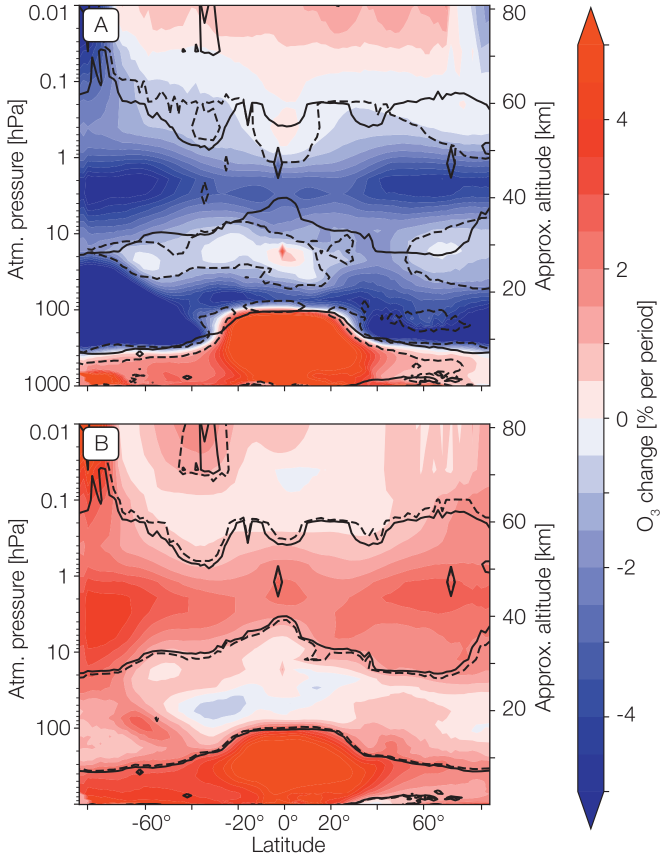

Figure 1. Latitude-pressure ozone changes in % per period in the ensemble-mean SOCOLv4 reference experiment. A) Ozone-depleting phase (1985 - 1997); B) ozone-recovery phase (1998 - 2018. The solid line represents a 95% probability of changes; The dashed line represents a 90% probability of changes.

extratropical ozone recently shown by Ball et al. (2018) are hardly represented in the ensemble-mean experiment. This might be due to complicated dynamics that create a significant difference between ensemble members. In addition, the DLM tool may not be effective in correctly estimating ozone changes due to components with natural variability such as the QBO. Nevertheless, there is an urgent need to investigate the cause of the decline in extratropical ozone, and the use of models in these studies will continue.

Acknowledgment: The study was funded by the SNSF project POLE (200020_182239) and supported by CSCS under projects ID S-901 and ID S-1029.

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Contribution of Ozone Depletion to Climate Change due to Uncontrolled CFC Production

Timofei Sukhodolov, Tatiana Egorova, Jan Sedlacek, Eugene Rozanov, and Arseniy Karagodin

In a series of modelling experiments, we have explored further the climate effects avoided due to the Montreal Protocol. Our results suggest that additional warming from chlorofluorocarbons (CFCs) would bring the climate warming rate from the moderate "Middle of the Road" ssp4.5 scenario to the levels of the extreme "Fossil-fueled Development" ssp8.5 scenario, while the depletion of ozone compensates about 0.5 K of extra warming by the end of the century. Depletion of ozone also significantly perturbs the stratospheric circulation and, thus, the stratosphere-troposphere dynamical coupling.

Within the framework of our SNSF project, POLE, we looked in detail at how the future climate would evolve in the absence of the Montreal Protocol and its amendments. We performed runs with the Montreal Protocol under the moderate ssp4.5 emission scenario (Ref) and the extreme scenario ssp8.5 (Ref_ssp8.5), as well as without the Montreal Protocol under ssp4.5 (NoMP). To distinguish between the direct greenhouse effects of CFCs and the effects from the ozone depletion, we perfomed an additional model run, where increasing CFCs were active only chemically but not radiatively (NoMP_noRadCFC).

The evolution of the global mean surface temperature in the 21st century is presented in Figure 1. Our results showed that without the Montreal Protocol, the warming rate under the ssp4.5 scenario would be as large as the warming rate under the ssp8.5 scenario. This effect comes mostly from the greenhouse effect of CFCs in the troposphere. The difference between the Ref and the NoMP_noRadCFC runs allows the global radiative effects of the depleted ozone layer to be estimated, which is about 0.5 K by the end of the century, and results from the reduced absorption of terrestrial radiation by ozone in the troposphere. A dramatic depletion of the ozone layer would also significantly affect the temperature regime of the stratosphere, since absorption of solar ultraviolet (UV) radiation by ozone is the main source of energy in this region. This is shown in Figure 2a as zonally mean differences between NoMP and Ref. The stratosphere becomes colder mostly in the regions of strong UV absorption, which is the sunlit stratopause and the tropical-subtropical stratosphere.

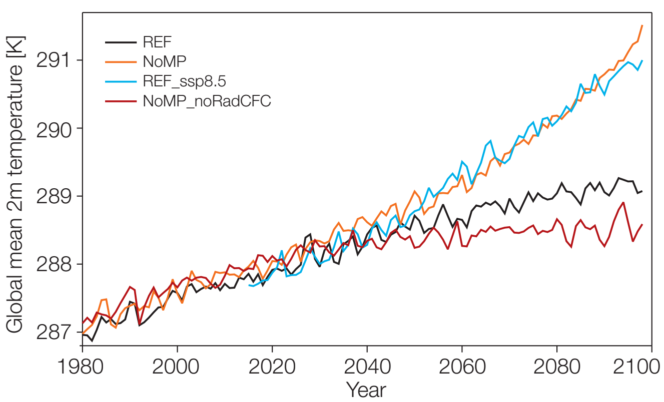

Figure 1. Evolution of the global mean surface temperature from four experiments with SOCOLv4.

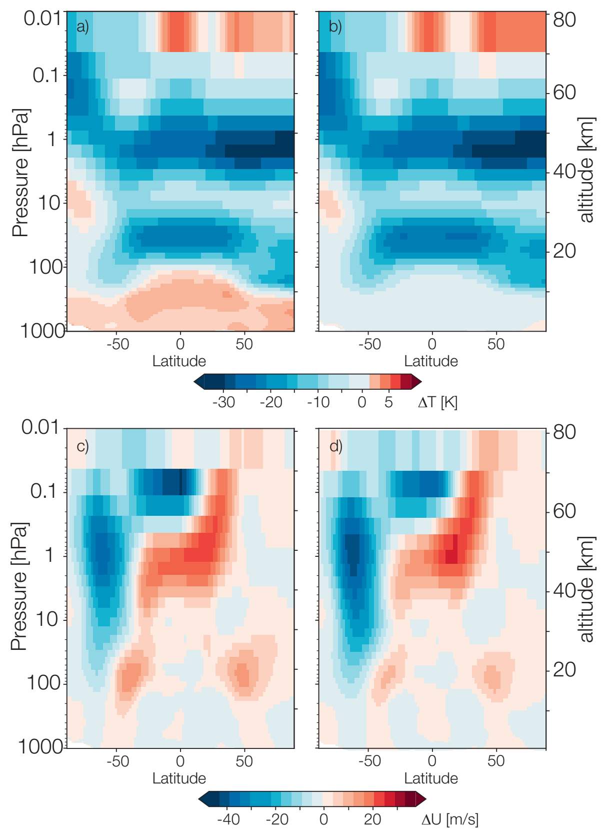

Figure 2. June-July-August 2080-2100 zonal mean differences in temperature (upper row) and zonal wind (lower row) between the runs with and without the Montreal Protocol.

Temperature fluctuations are always a pre-requisite for changes in circulation, which is also shown in Figure 2c as the difference in zonal wind speed. Reduction of the meridional temperature gradient throughout the stratosphere leads to a strong deceleration of the polar vortex. The stratosphere is dynamically coupled to the troposphere and strong fluctuations of the polar vortex intensity are known to affect the tropospheric circulation modes such as southern annular mode (SAM) and northern atlantic oscillation (NAO). However, given a strong warming from CFCs in the troposphere (Figure 2a), such effects would be difficult to identify. NoMP_noRadCFC and Ref pairs of runs help to avoid this issue, since the CFC warming effect in the troposphere is excluded (Figure 2b), while stratospheric perturbation of the polar vortex induced by the ozone depletion is very similar to the standard NoMP case. Our next step would be to look at the surface dynamical effects arising from the stratosphere.

Acknowledgment: The study was funded by the SNSF project POLE (200020_182239) and supported by CSCS under projects ID S-901 and ID S-1029.

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Distribution of ^{14}C in the Atmosphere Simulated with CCM SOCOL-AER2-BE

Eugene Rozanov, Timofei Sukhodolov in collaboration with the Cosmic Ray group (University of Oulu, Finland)

We simulated carbon-14 production in the atmosphere for different conditions using the chemistry-climate and isotope production models. Here we present computed zonal distributions (tropical, subtropical, and polar regions) of the ^{14}C production in the stratosphere and troposphere.

The carbon-14 isotope (^{14}C) is produced by cosmic rays mostly in the middle to low atmosphere and then participates in complicated transport and deposition processes in the troposphere or stratosphere. The fraction of stratospheric to tropospheric production depends on the spectrum (origin) of cosmic rays, geomagnetic shielding, and the tropopause height. ^{14}C is continuously produced by highly energetic galactic cosmic rays (GCR) and sporadically by less energetic solar energetic particles (SEPs). The production reaches its maximum at high geographical (geomagnetic) latitudes due to the lack of geomagnetic shielding. However, the zonal distribution of the production in tropospheric and stratospheric regions, which is needed for the understanding of the isotopes' transport and deposition for climate reconstruction, has not been well characterised yet.

Figure 1 illustrates ^{14}C production in atmospheric zones important for large-scale transport and deposition of the isotopes calculated with the chemistry-transport model, SOCOL-AER2-BE (Golubenko et al., 2021), and production model, CRAC (Poluianov et al., 2016). The computations were performed for four solar activity scenarios:

1) Production by GCR during a solar-cycle minimum with solar modulation potential (phi = 400 MV).
2) Production by GCR during a solar-cycle max. (phi = 1100 MV).
3) SEP event with the hardest known spectrum (GLE 5, 23 Feb. 1956).
4) The strongest known soft-spectrum SEP (GLE 24, 4 Aug. 1972).

The results can be summarised as follows.

– For GCR (scenarios I and II), the global fraction of stratospheric production is 50 - 60% which is smaller than previously estimated at 370% (e.g., Yoshimori, 2005), implying that the tropospheric production is significantly more important than thought earlier. In particular, the tropospheric production dominates in the tropical regions. This important change is most likely related to more accurate modelling, particularly for the heavier particles, performed here.
– Accordingly, all zones are equally important for the cosmogenic isotopes produced by GCR that requires a full modelling of their transport.
– The results of the relative percentage of zonal productions do not change much for solar-minimum and solar-maximum GCR conditions (scenarios I and II respectively), while only the global production rates change by 15 - 20% over a solar cycle.
– For SEP scenarios III and IV, most of the ^{14}C atoms are produced in the polar (>60% and >80% for hard and soft spectrum events, respectively). Carbon-14 production by SEPs

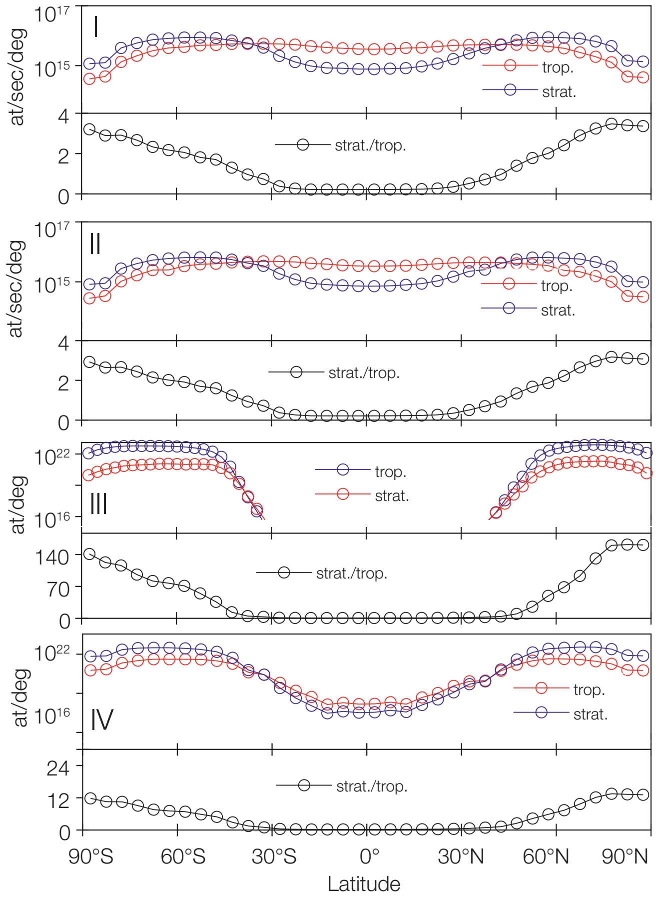

Figure 1. Zonal mean production rates of ^{14}C for the four scenarios. Upper sub-panels depict the stratospheric (blue) and tropospheric (red) zonal mean (per latitude degree) production rates, while lower panels show the stratospheric-to-tropospheric production ratio.

in the tropical zone is small (<0.05%) and can be neglected.
– Accordingly, for simple estimates, the polar stratospheric production of ^{14}C can be assumed for SEP events, within the accuracy of the assumption, to be within 10 - 20%.
– The results presented here are computed for the modern-epoch geomagnetic field (epoch 2000). Similar results for other archaeomagnetic models will be studied in a forthcoming work.

These results can be used for a parametric fast estimate, without explicit modelling of the relation between ^{14}C production and deposition.

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Angular Response Measurements of Solar Radiometers in the MAPP Project

Julian Gröbner, Jakob Föller, and Gregor Hülsen in collaboration with CNRS (France) and the University of Valencia (Spain)

Solar filter radiometers measure the direct solar irradiance and scattered solar radiation at different narrowband spectral channels in order to retrieve aerosol properties from these measurements. One important parameter in the retrieval process of aerosol properties is the knowledge of the field-of-view of these radiometers. The full field-of-view was measured for two solar filter radiometers participating in the Joint Research Project Metrology for Aerosol Optical Properties (MAPP) and representing instruments from two global aerosol monitoring networks.

Aerosol optical properties such as the single scatter albedo are retrieved from inverting measurements of the direct solar irradiance and of the scattered radiation from different angles in the sky hemisphere to retrieve the scattering and absorption characteristics of the aerosol particles present in the atmosphere. The aerosol retrieval model used by the AERONET network requires a conversion factor based on a laboratory calibration of the radiance measurement of the filter radiometer, combined with a top-of-the-atmosphere solar spectrum, resulting in an uncertainty of the order of several % in the retrieved aerosol properties, especially in the ultraviolet, where the signal from the integrating sphere calibration is very weak. The new procedure developed in the MAPP project aims to reduce the uncertainties of this conversion factor to less than 1%, using laboratory-based measurements of the field-of-view to calculate the conversion factor between direct irradiance and radiance measurements.

The measurements were performed in the angular responsivity facility of the PMOD/WRC optical laboratory using a point source with an angular size of 0.2° (Hülsen et al., 2022). Angular resolved scans of the full field-of-view were obtained for all channels with a resolution of better than 0.05°, covering the field-of-view of both investigated instruments which have an area of 1.3° x 1.3° and 1.0° x 1.0° for the CIMEL #1270 Radiometer and the POM01-UV Prede radiometer, respectively. Figure 1 shows the corresponding field-of-view measurements for both instruments at the 675 nm wavelength channel.

The full field-of-view is obtained by integrating the angular response measurements shown in Figure 1. The field-of-view at 675 nm is 0.3784 x 10^{-3} sr and 0.2344 x 10^{-3} sr for the CIMEL and POM radiometer, respectively. The associated expanded uncertainties (k = 2, representative of a 95% coverage interval) are estimated at 0.3%.

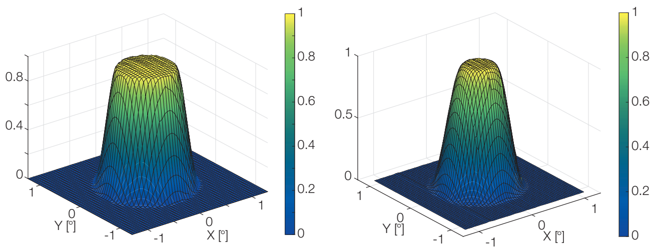

Figure 1. Field-of-view measurements at the 675 nm channel of the CIMEL #1270 filter radiometer (left) and the POM01-UV radiometer (right).

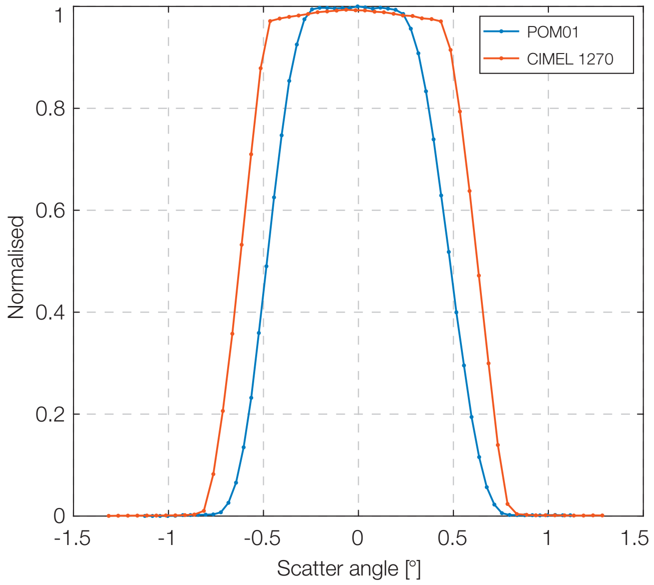

Figure 2. Field-of-view transect at the 675 nm channels of the CIMEL #1270 filter radiometer and the Prede POM01-UV.

As can be seen from these measurements, the field-of-view of the POM is significantly smaller than that of the CIMEL, as shown in Figure 2 where the transects of these field-of-view measurements are compared.

The measurements shown in Figure 2 also highlight the inhomogeneity of the field-of-view of the CIMEL radiometer, which poses significant constraints on the solar pointing accuracy of the radiometer during direct solar irradiance measurements. Similarly, the very narrow field-of-view of the POM radiometer means that when measuring the sun with an angular size of 0.5°, the pointing tolerances are also extremely demanding to avoid a roll-off of the signal during direct solar measurements. When the field-of-view measurements are convolved with the angular size of the solar disk, then a pointing uncertainty of 0.05° results in an uncertainty of the direct solar irradiance measurement of 0.1% and 0.2% for the CIMEL and POM radiometers, respectively.

Acknowledgments: This work has been supported by the European Metrology Program for Innovation and Research (EMPIR) within the joint research project 19ENV04 MAPP "Metrology for aerosol optical properties". EMPIR is jointly funded by the EMPIR participating countries within EURAMET and the European Union.

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Direct Solar Spectral Irradiance Measurements with the QasumeIR Spectroradiometer

Gregor Hülsen and Julian Gröbner in collaboration with Gigahertz Optik GmbH

The new QasumeIR spectroradiometer, developed within the EMPIR project 19ENV04 MAPP, has been used for spectral solar direct irradiance measurements since May 2021. The measurements were compared to various spectroradiometers in the wavelength range from 500 nm to 1.7 µm. After initial discrepancies, measurements between QasumeIR and collocated spectroradiometers agreed to within better than 2%.

The new spectroradiometer, QasumeIR, was installed on the PMOD/WRC roof in May 2021 and continuously recorded direct solar irradiance until Dec. 2021 (Figure 1). The initial solar scans were used to optimise the measurement scheme in terms of accuracy vs. scanning time. First, the solar spectrum was recorded in its whole wavelength range. This was later modified to higher resolution scans of different parts of the solar spectrum to have a faster scanning time of 6.5 min. and a better overlap with filter radiometers. The QasumeIR data was compared to measurements from the QASUME spectroradiometer in the small wavelength overlap of the two instruments (500-550 nm). The average agreement between the data is within ±1%, but a variability above ±5% was found on some days. Second, the aerosol optical depth was derived and compared to Precision Filter Radiometer data from WORCC. Larger inconsistencies were found in the infrared (IR) wavelength region.

Since September 2021, two BTS spectroradiometers (BTS uvvis and BTS visir, Gigahertz Optik GmbH) have been simultaneously measuring alongside the QASUME instruments (Figure 1). The intercomparison also showed large differences of up to 7% in the IR. Therefore, an outdoor absolute calibration experiment was performed during nighttime on the PMOD/WRC roof (Figure 2). The experiment revealed that a calibration error was introduced by the straylight blocking baffle used for the laboratory measurements. It was found that the high reflectivity of the black anodised surface of the baffle at wavelengths longer than 700 nm was the cause. Figure 3 shows that the anodised baffle increases the irradiance through increased reflections by up to 7% with respect to the measurements without a baffle.

Figure 1. Direct solar irradiance spectroradiometers installed on the sun trackers on the PMOD/WRC roof platform. The QASUME and QasumeIR instruments are at the front and two BTS instruments at the back.

Figure 2. Outdoor calibration of QasumeIR using a 1000 W FEL-type irradiance standard. The measurements are not affected by straylight from the surroundings.

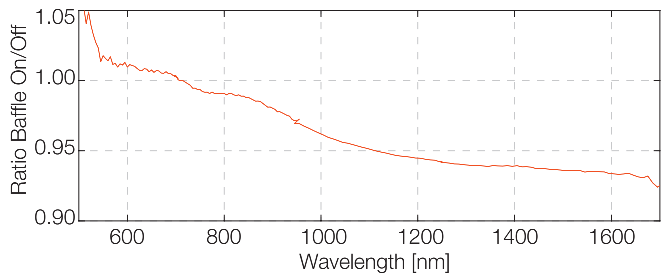

Figure 3. Effect of the original straylight-reducing baffle required for laboratory irradiance calibrations.

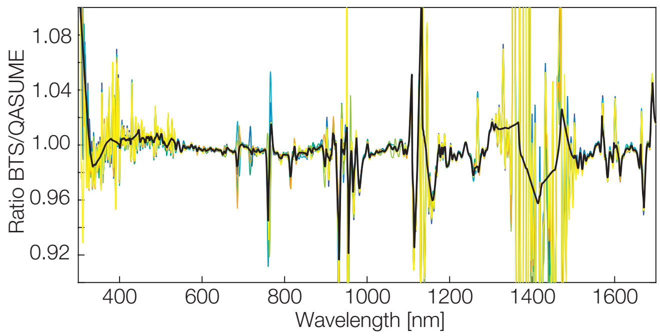

Figure 4. Intercomparison of BTS to QASUME on a clear-sky day (10 Oct. 2021). The mean (black line) over all scans during the day has a variability less than ±1% except for the water absorption bands at around 1400 nm.

The baffle was newly coated with MAP-PU1 paint, which has very good absorption properties from the UV to the IR. Using the outdoor responsivity calibration, the intercomparison of the spectroradiometers is in very good agreement. Figure 4 shows the ratio on a single day using composites of QASUME/QasumeIR and BTS uvvis/BTS visir. Larger uncertainties remain in the 500-600 nm range where the system is very sensitive to measurement errors of the dual channel amperometer in use. An upgrade of this device is currently in development by the manufacturer (Bentham, UK).

Acknowledgment: The project 19ENV04 MAPP has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

95 Years of Dobson Spectrometer Ozone Measurements

Herbert Schill

With the transfer of the last two spectrophotometers in mid-February 2021 from Arosa to Davos, the world's longest record of stratospheric ozone measurements at the Lichtklimatisches Observatorium (LKO) Arosa came to its end and continued at PMOD/WRC. In 1926, F.W. Paul Götz began measurements, in close collaboration with G.M.B. Dobson from Oxford University, with a Dobson spectrometer using photo plates to obtain tracks of the UV signal at different wavelengths. Arosa always profited from the instrumental developments of Dobson, changing to a photoelectric instrument in 1939, and spectrometers using a photomultiplier tube from 1949. Götz always ensured that a sufficient period of parallel measurements were conducted.

After a few months in 1919 – 1920 at the "Observatorium Dorno", the predecessor institute of the PMOD, F.W. Paul Götz moved to Arosa. In 1926, Götz founded the "Lichtklimatisches Observatorium" (LKO) in his newly-built house “Firnelicht”, which was equipped with a Fabry–Buisson type of solar spectrophotometer. In the same year, he began a close collaboration with G.M.B. Dobson, an Oxford physicist and meteorologist. Arosa thus became one of six worldwide stations to house one of the first series of Dobson spectrophotometers (Figure 1). Due to financial constraints, only one measurement per day was usually conducted during these pioneer years, weather permitting. The resulting photo plates were sent to Oxford for development from which the total ozone column was calculated. Results were compared with other stations of the early Dobson network and led to first detailed insights of the temporal and spacial characteristics of the ozone layer of the northern hemisphere mid-latitudes.

In 1939, the International Ozone Commission gave LKO the instrument, Dobson D007 with photoelectric detection. This instrument was much easier to handle and allowed more measurements than before. As a result, the immediate calculation and control of the results was now possible. Again, 10 years later, the first Dobson spectrophotometer equipped with a photomultiplier to measure the signal was put into operation in Arosa. This Dobson instrument (D015) was in use until 1992 when it was replaced by Dobson D062. D015 was therefore in operation during the International Geophysical Year (IGY), running from 1957 - 1959, when a worldwide network of instruments was established.

Figure 1. The historical photo shows the photo-plate based Dobson D2 on the right, together with other instruments from Götz on the roof platform of his house "Firnelicht" in Arosa.

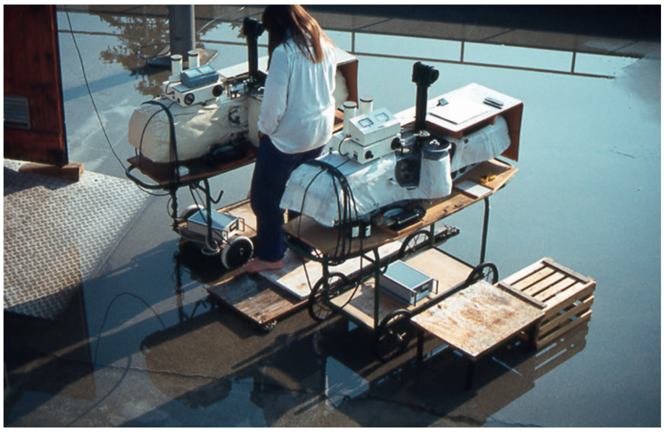

Figure 2. Manual direct sun measurements with Dobsons D015 and D101 performed by a station employee in 1982, after a cloudburst which led to the measurement plattform on the house “Steinbruch” to be temporarily under water. (Photo: H. Schill).

Götz died in 1954, and after a period of uncertainty, covered by his assistant Dr. Gertrud Perl, the LKO was led by Prof. Hans-Ulrich Dütsch of the Laboratory for Atmospheric Physics at ETH Zurich (LAPETH), who kept this position until after his retirement in 1985. In 1967, a second Dobson spectrophotometer (D101) was installed at LKO. With this instrument, permanent parallel measurements of the ozone layer were realised until the present (Figure 2). A few years later, in the early 1970s, a third Dobson was brought in, mainly for experiments in automated operation mode. The first task was observing the total ozone column from the late 1980s, when MeteoSchweiz took over the LKO from ETH Zurich for measuring vertical profiles using the so-called Umkehr method, developed by Götz and others around 1929. This is still the main task of D051 today, although on very clear days the instrument joins D101 and D062 to form an instrument Triad. All three Dobson instruments were fully automated during the period 2012 - 2014 under the lead of Dr. René Stübi (MeteoSwiss, Payerne) for their last period at the LKO Arosa. Since then, they have been housed in a weather-protected container for measurements (see Figure 1, page 16).

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Stübi, R., Schill, H., Klausen, J., Maillard Barras, E., Haefele, A.: A fully automated Dobson sun spectrophotometer for total column ozone and Umkehr measurements. Atmos. Meas. Tech., 14, 5757–5769, 2021 https://doi.org/10.5194/amt-14-5757-2021

Solar Radiation/Energy Research at PMOD/WRC

Stelios Kazadzis, Xinyuan Hou in collaboration with the National Observatory of Athens (Greece), MINES ParisTech (France), D-USYS-Institute for Atmospheric and Climate Science ETHZ Zurich

PMODWRC is participating in various EU-funded projects related to solar radiation/energy research. Specifically, these projects are investigating the effects of various atmospheric parameters such as aerosols and clouds on solar radiation.

Project E-Shape (https://e-shape.eu/) (EuroGEO Showcases: Applications Powered by Europe) has received funding from the European Union's Horizon 2020 Research and Innovation Programme, (April 2019 - March 2023) with the aim of bringing together Earth observation and in-cloud capabilities into services for decision-makers, citizens, industry and researchers. PMOD/WRC is leading the pilot study on solar radiation and energy forecasting. During 2021, solar forecasting and the effects of dust have been expanded for India (Masoom et al., 2021), and literature studies have shown dust events affecting solar energy production by up to 40%.

In addition, a solar ultraviolet (UV) nowcasting service has been developed. UVIOS (UV-Index Operating System) exploits a synergy of radiative transfer models with Earth observation satellite data in order to derive a solar UV index in real-time. Such inputs include: cloud properties from EUMETSAT satellite data in real-time, aerosol optical depth forecasts from the Copernicus Atmospheric Monitoring Service, total column ozone forecasts, and surface albedo and elevation data. (Figure 1). Results have been validated for a number of stations including Davos (Kosmopoulos et al., 2021).

During the EU-COST action InDust (International Network to Encourage the Use of Monitoring and Forecasting Dust Products, 2018-2021) a database for dust aerosol optical depth has been derived with the use of satellite and model data. PMOD/WRC has started working towards assessing solar radiation changes due to total and dust only aerosol attenuation. In this direction an analysis of total and dust aerosol trends in global scale has been published in collaboration with Un. of Patras, Greece (Logothetis et al., 2021).

PMOD/WRC is also participating in the EU-funded project EIFFEL (Revealing the role of GEOSS as the default digital portal for building climate change adaptation & mitigation applications, 2021 - 2024). The project aims to exploit existing GEOSS and external datasets contributing to Europe's efforts towards the implementation of the Paris Agreement for Climate Change. Solar radiation/energy research, amongst other research areas, is included in a pilot study of photovoltaic (PV) penetration in an urban area with a demonstration study in the Attica region, Greece. Cadastral archives, inclination and orientation aspects and shadowing effects, are used to calculate the solar energy availability at a building and neighborhood levels. Results will include reporting the solar availability for a choice of PV orientations, available surface areas and PV materials for the region and a building-scale database and interactive map. PMOD/WRC is involved in this research as part of the work of a new PhD student Xinyuan Hou who started in May 2021.

PMOD/WRC began to participate in December 2021 as a partner in the EU project, Excelsior (Excellence Research Centre for Earth Surveillance and Space-Based Monitoring of the Environment). PMOD/WRC aims to contribute towards the development of The Cyprus Solar Radiation Laboratory aiming to establish an excellence hub for conducting basic and applied research and innovation related with solar radiation measurements and modelling. In addition, it is contributing to the thematic clusters of Environment and Climate, Resilient Society, and Big Earth Data Analytics (Fountoulakis et al., 2021).

Long-term projections of solar power have been investigated in collaborations with ETH Zurich scientists from the Institute of Atmospheric and Climate Sciences, using the Coupled Model Intercomparison Project (CMIP6) dataset. Climate change impacts on solar power generation and its spatial variability in Europe have been studied (Hu et al., 2021).

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Masoom, A., et al.: 2021, Forecasting dust impact on solar energy using remote sensing and modeling techniques, Solar Energy, 228, 317-332, doi.org/10.1016/j.solener.2021.09.033

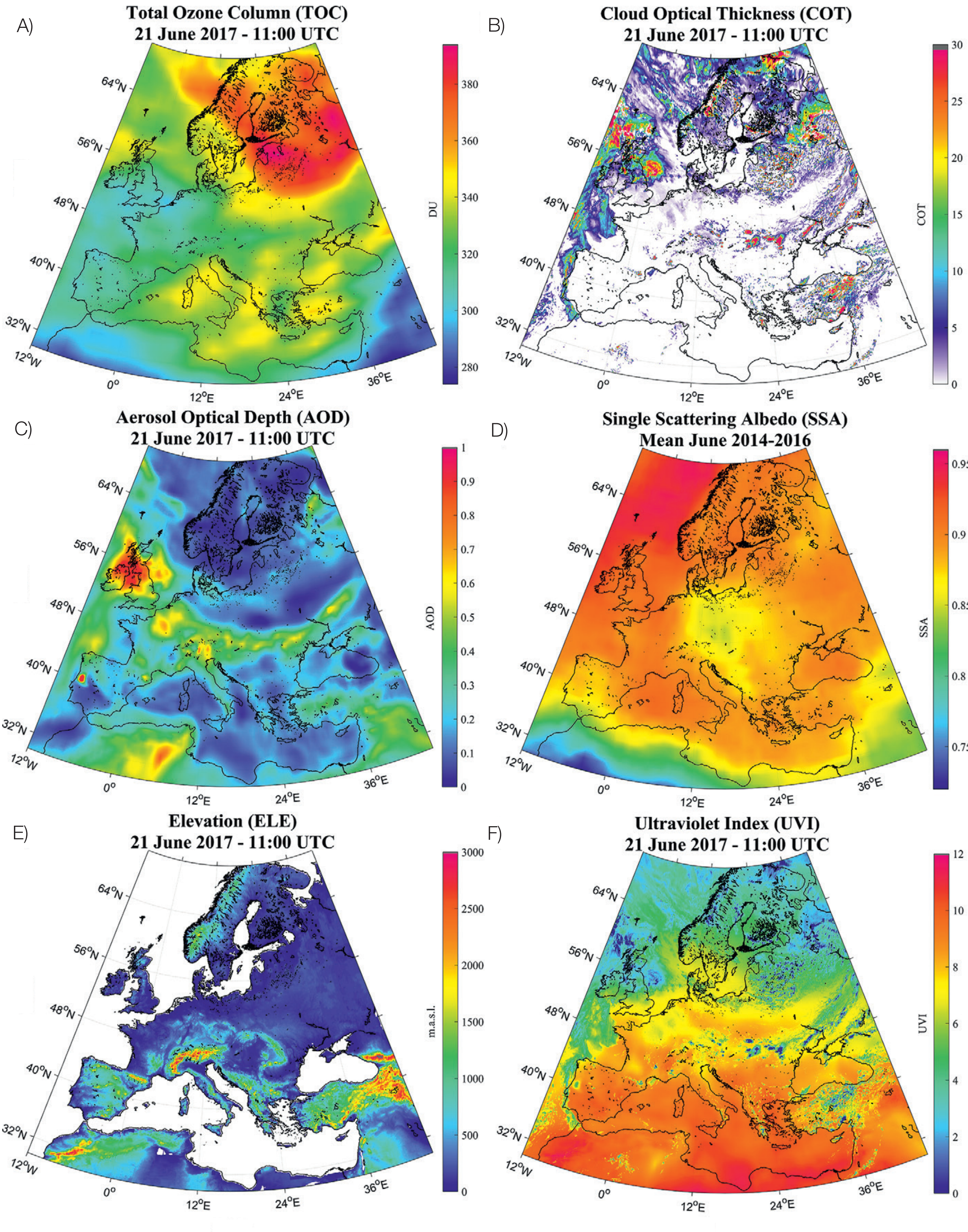

Figure 1. An example of the UVIOS inputs (a-e) and output (f) based on the UVIOS modelling technique demonstrated for the 21 June 2017 at 11:00 UTC.

Characterisation and Performance of the Lunar-PFR

Natalia Kouremeti, Stelios Kazadzis, and Julian Gröbner in collaboration with PTB (Germany)

The Lunar PFR was developed at PMOD/WRC in 2014 with the primary aim to monitor the aerosol optical depth at Ny-Ålesund (Norway) during the polar winter, contributing to arctic haze studies. The instrument has been calibrated in the PMOD/WRC facilities since 2016 in frequent time intervals with uncertainties of 4 - 6%. In 2021, in the framework of the EMPIR 19ENV04 MAPP project, the instrument was characterised at the Physikalisch-Technische Bundesanstalt (PTB; Germany) with an uncertainty <0.5%. The calibration procedures and their comparison are presented.

Atmospheric aerosols are known to impact the climate, but they still represent one of the largest uncertainties in climate change studies. Nighttime Aerosol Optical Depth (AOD) measurements could provide valuable information for the climatology of aerosols in high latitude stations, where direct sun measurements are not possible throughout the year. For example, in the northern hemisphere they can be used for monitoring the arctic (aerosol) haze during polar winter.

The Lunar Precision Filter Radiometer (Lunar-PFR) is a standard PFR instrument with enhanced sensitivity, that has been developed at PMOD/WRC and is based on experience from the Sun-PFR. The Lunar-PFR measures at four wavelengths (412, 500 and 862 nm), while the sensor is temperature-stabilised at 20°C. The instrument has been characterised five times using the radiometric calibration laboratory facilities at PMOD/WRC over the last five years, showing excellent stability within 1%. The calibration procedure of the Lunar-PFR at PMOD/WRC is based on the determination of the relative spectral responsivity of the four PFR channels using a pulsed OPO-laser system, while the irradiance reference is a tungsten halogen lamp, calibrated at PTB. The technical challenges that increase the uncertainties of the calibration are related to the non-linear behaviour of the PFR when exposed to the laser pulsed radiation and the gain determination which links the laboratory and lunar measurements. Moreover, the expanded relative uncertainty of the irradiance standard (lamp) used in this type of calibration is 2 - 3%, depending on the wavelength.

The calibration of a Sun-PFR at the PTB state-of-the-art facilities was conducted in 2018 and 2021 with uncertainties less than 0.5% (k = 2). Combined with top-of-the-atmosphere solar spectra

Table 1. Results from the characterisation at PTB in November 2021, as well as a comparison to the last calibration in 2020 at PMOD/WRC and between the two types of calibration, TULIP vs Lamp.

2021			Differences in		
TULIP			TULIP vs Lamp	2020	
δ (nm)	s (Wm^{-2})	U_s (%, k = 2)	δs (%)	δλ (nm)	δs (%)
861.75	12.96	0.26	-0.10	0.2	-1.4
501.39	9.78	0.25	-0.10	1.1	0.8
411.95	10.88	0.27	-0.30	0.8	5.1
675.39	6.80	0.18	0.20	0.1	-2.5

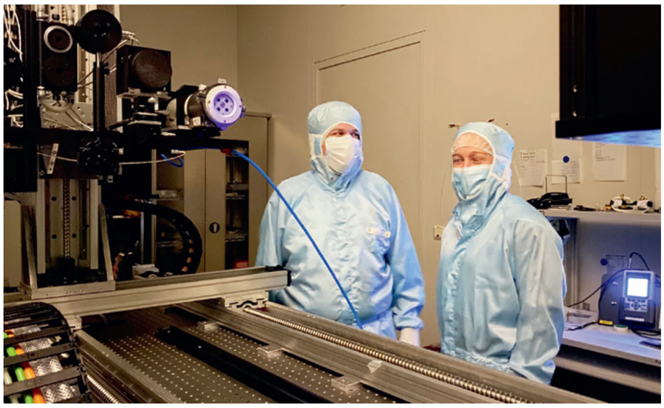

Figure 1. Lunar-PFR in the clean room of the TULIP calibration facility at PTB.

from QASUMEFTS (Gröbner et al., 2017) and TSIS-1 (Coddington et al., 2021), this led to an SI-traceable AOD retrieval which was in excellent agreement with the WMO AOD references (Kouremeti et al., 2021). Taking advantage of the experience gained from the sunphotometer, we applied the same calibration methodology to the lunar instrument. A 2-week measurement campaign at the PTB facilities was organised and supported by the PTB and MAPP projects. The spectral responsivity of the Lunar-PFR was determined at the TUnable Lasers In Photometry (TULIP) setup based on a fs-OPO system. The radiation source was a quasi-cw laser system, measured with a calibrated 3-element trap detector and equipped with a calibrated aperture, giving an uncertainty better than 0.1%. In the TULIP setup, the reference plane of the PFR was determined against the reference detector, introducing a minor correction of 0.5 mm to the pre-defined value based on the inverse square law. The gains of the PFR were also measured. The highest correction was 0.13% for lunar (maximum) to laboratory (minimum) gain ratio. The TULIP calibration was followed by a lamp calibration similar to that performed at PMOD/WRC. The differences between the two different calibration methods were less than 0.3%, which is well within the estimated uncertainties. The centroid wavelength (λ), the responsivity (s) and its uncertainty (U_s) are shown in Table 1 along with the differences with respect to lamp calibrations in 2020 and 2021. The observed differences of -2.5 - 5% are due to differences in the relative spectral responsivities. These results will be used in re-analysis of the PMOD/WRC calibrations providing top-of-atmosphere lunar irradiance values with uncertainties better than 1%.

Acknowledgements: The authors would like to especially thank Saulius Nevas and his team P. Schneider, K. Schwind, S. Pape, P. Sperfeld for the amazing collaboration and one more state-of-the-art calibration campaign. This work has been supported by the EMPIR within the joint research project EMPIR 19ENV04 MAPP "Metrology for aerosol optical properties".

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Total Column Ozone Retrieval from the Array Spectroradiometer, Koherent, by Applying the Double Ratio Technique

Luca Egli and Julian Gröbner in collaboration with MeteoSwiss

Novel array spectroradiometers can select direct solar irradiance in the UV band at hundreds of different wavelengths to be measured within seconds. In the INFO3RS project of the Swiss Global Atmosphere Watch programme (GAW-CH), a new system for total column ozone (TCO) measurements based on an array spectroradiometer, Koherent, was developed and tested at PMOD/WRC. Measurements at different wavelengths allow the selection of the best wavelength pairs in the UV band to retrieve TCO with the double ratio technique in analogy with the Brewer and Dobson TCO retrieval. A long-term comparison in Davos shows that TCO from Koherent is within >0.5% compared to values from Brewer and Dobson instruments.

Koherent is based on a fibre-coupled BTS-2048-UV-S-F array spectroradiometer commercially available from Gigahertz Optik GmbH. The spectroradiometer is connected to a lens-based imaging telescope mounted on a sun tracker on the measurement platform at PMOD/WRC measuring direct irradiance in a wavelength band between 300 nm and 350 nm (Zuber et al., 2021). The system has been continuously operated since 2019, providing data with almost no technical failures.

The post-processing was performed off-line with the following steps: a) converting the raw-counts of the readings to irradiance using laboratory and in-situ calibration with the world reference for UV radiation, QASUME, b) spectrum homogenisation using the MatSHIC software developed at PMOD/WRC, and c) retrieving TOC with the well-established double ratio technique from the Brewer algorithm (see Gröbner et al., 2021). Different to the Brewer or Dobson algorithms, the following wavelengths have been selected to obtain the best performance from Koherent: i) wl_1 = 310 nm, ii) wl_2 = 322 nm, iii) wl_3 = 330 nm, and iv) wl_4 = 345 nm. The rectangular slit functions having a full-width-half-maximum of 1 nm (for wl_1 and wl_2) and 4 nm (for wl_3 and wl_4). In analogy to the retrieval method of the Dobson (Gröbner et al., 2021), the irradiances at the four wavelengths are equally weighted when applying the double ratio technique.

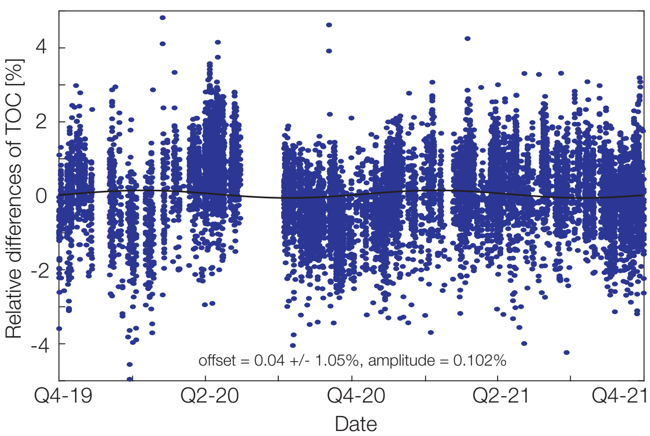

Figure 1. Relative differences of TCO between Koherent and the Brewer 156 double monochromator.

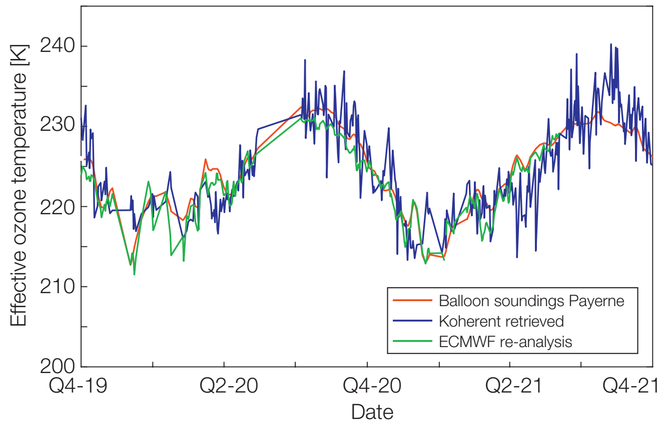

Figure 2. Effective ozone temperature from Koherent.

The Brewer and Dobson retrievals require an extraterrestrial constant, which is either derived by Langley-Plot calibrations or by intercomparison with a reference instrument. The double ratio retrieval from Koherent developed here, only requires a published extraterrestrial solar spectrum measured in space. Finally, the algorithm was driven by effective ozone temperatures from balloon soundings in Payerne, Switzerland, and the new ozone absorption cross-sections proposed by WMO. The comparison of Koherent with Brewer 156 and Dobson 101, from October 2019 to October 2021 in Davos, reveals that Koherent shows an average relative difference of 0.11% with a seasonal amplitude of 0.23% (Brewer) and 0.13% (offset) and 0.42% (amplitude) for the Dobson, respectively (Figure 1).

When applying the standard wavelength settings of the Brewer and Dobson (Gröbner et al., 2021), the offsets are significantly larger than when choosing the custom wavelength selected here. However, the differences of TCO between the double ratio retrieval using the standard Brewer and Dobson wavelength settings, correlate with the effective ozone temperature measured by the balloon sounding. This correlation allows the effective ozone temperature to be retrieved by a parameterisation of the differences between the Brewer and Dobson wavelength TCO retrieval. Figure 2 shows the retrieved effective ozone temperature compared to balloon soundings and EMCWF re-analysis data, indicating that daily effective ozone temperatures can be determined within 3.4 K.

Acknowledgment: This research was supported by the ESA project QA4EO, grant no. QA4EO/SER/SUB/09) and by GAW-CH MeteoSwiss (project INFO3RS, grant no. 123001926).

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Extending the Calibration Traceability of Longwave Radiation Time-Series (ExTrac)

Stephan Nyeki and Julian Gröbner in collaboration with MeteoSwiss, European Commission Joint Research Centre (Ispra, Italy), Alfred Wegener Institute (Bremerhaven and Potsdam, Germany)

The Baseline Surface Radiation Network (BSRN) is an archive of high quality traceable data going back to the early 1990s for several BSRN stations. However, raw data for longwave surface radiation has not been stored in the BSRN archive, and may no longer be accessible from the stations themselves. The main aim of the ExTrac project is to develop a method to recover raw data from longwave measurements and to ensure their availability for future use when a number of traceability and instrumental issues have been resolved by the research community.

The Baseline Surface Radiation Network (BSRN; bsrn.awi.de) is one of several international networks to coordinate the measurement and archiving of surface radiation data. Amongst other parameters, downward longwave surface radiation (DLR) time-series using pyrgeometer instruments from BSRN stations are also archived. Many of these time-series are traceable to the World Infrared Standard Group of pyrgeometers (WISG), established in 2004 and maintained by PMOD/WRC. Although this has led to better global homogenisation of DLR time-series and has considerably increased their reliability and accuracy, a number of traceability and instrumental issues still remain to be resolved by the research community (e.g. Gröbner et al., 2014; Nyeki et al., 2017).

The project, Extending the Calibration Traceability of Longwave Radiation Time-Series (ExTrac), is focused on developing a methodology that can be applied to archived BSRN DLR time-series to recover raw data. This would avoid the need to recover raw data from station archives themselves, which may not be available due to information technology issues or the loss of a knowledge-pool. The aim is to prevent the loss of legacy data and ensure their availability for future use when traceability and instrumental issues (e.g. CIMO, 2018) in this field have been resolved.

Pyrgeometer raw data (voltage U, and body and dome temperatures, T_b and T_d) can be accurately recovered if no more than one parameter is missing. As the equation to determine DLR is non-linear, recovering U, T_b and T_d from archived DLR is therefore not possible. However, a promising method would be to determine proxy values of T_b and T_d using measured BSRN ground temperature (T_{2m}; temperature at a height of 2 m).

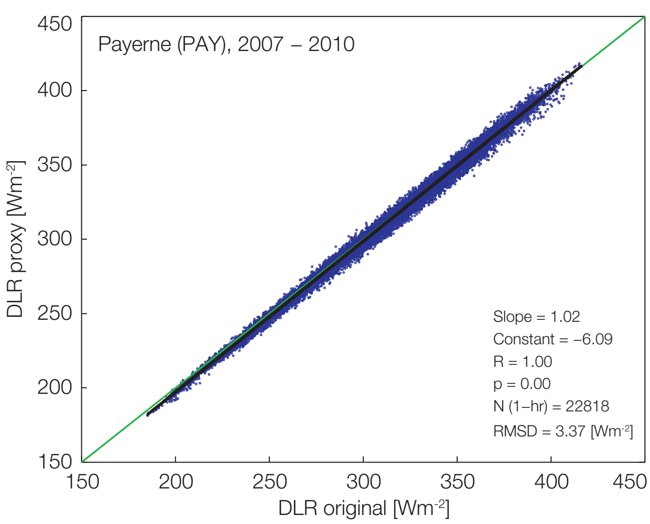

Figure 1. Comparison of DLR_{proxy} with $DLR_{original}$ at the BSRN Payerne station for the period from 2007 to 2010.

Table 1. BSRN station details and root-mean-square deviation (RMSD) values for basic and refined models. BSRN stations: Georg von Neumayer (GVN), Ny Alesund (NYA), Payerne (PAY), Sonnblick (SON), South Pole (SPO), and Syowa (SYO). Pyrgeometer radiometer types: E = Eppley, K&Z = Kipp & Zonen.

Station	Location	Time-series	Pyrgeo. type	Basic model (Wm^{-2})	Refined model (Wm^{-2})
GVN	Antarctica	2006-2015	E	4.6	2.3
NYA	Svalbard	2006-2019	E	4.3	2.1
PAY	Switzerland	2007-2010	E	12.5	3.4
		2011-2015	K&Z	10.6	2.0
SON	Austria	2013-2015	K&Z	28.0	5.7
SPO	Antarctica	2008-2017	E	26.4	4.4
SYO	Antarctica	2011-2019	K&Z	6.6	5.7

Raw data from several BSRN stations (see Table 1) was therefore acquired to investigate the feasibility of this approach. A "basic" model was first developed by directly substituting T_{2m} for T_b. When DLR (1-hr mean) from this approach was compared with the original DLR from BSRN, the root-mean-square difference (RMSD) values ranged from 4.3 to 28.0 Wm^{-2}. This compares to a current uncertainty in DLR of ±5.4 Wm^{-2}. While T_{2m} is a satisfactory choice for some stations, there is large potential for further improvement.

The dependence of T_b - T_{2m} and T_d - T_{2m} on meteorological and radiation parameters (1-min. resolution from BSRN archives) was therefore investigated, and used at each BSRN station to train a refined algorithm. This gave the proxy values, $T_{b\,proxy}$ and $T_{d\,proxy}$, which were found to depend to varying degrees on: i) global shortwave radiation, ii) wind speed at a height of 2 m, iii) T_{2m} itself, and iv) cloud fraction. Figure 1 illustrates a comparison of DLR_{proxy}, calculated using T_{bproxy} and T_{dproxy}, with original DLR from the BSRN archives. RMSD values, also shown in Table 1, decreased to the range 2.0 - 5.7 Wm^{-2} for 1-hr mean values. The next task will be to investigate RMSD values for 10-min and even 1-min values.

Acknowledgment: We thank GCOS Switzerland for financially supporting this project.

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PMOD/WRC Workshop Renovation

Christian Thomann and Pascal Schlatter

After the main building was extensively renovated from 2010 to 2012, a request was submitted to the BBL (Federal Office for Buildings and Logistics) in 2016 to renovate the workshop floor. After an extensive planning phase, construction began on 21 Feb. 2022.

In March 2016, the BBL commissioned the company, DIAG in Davos, to draw up a preliminary study for the renovation of the workshop floor. The goal is to design the floor to bear current payloads, as well as having low-vibration properties and being thermally insulated from the subsoil. The old floor, originally a school gymnasium exercise floor, is made of wood, while the building services no longer meet today's safety requirements.

In order to meet the above-mentioned requirements, four variants were considered:

- Reinforce and insulate the existing floor with wooden panels.

- Reinforce and insulate the existing floor with concrete.

- Demolition of the existing floor and introduction of a new concrete slab with insulation.

- Demolition of existing floor and installation of concrete elements with insulation.

The third option was finally chosen. On 8 May 2019, former director Werner Schmutz, signed the official BBL application. This was approved and the first on-site meeting took place on 16 Oct. 2019. The BBL, under the direction of Nicole Ritschard, commissioned the architects company, Hartmann, to renovate the old schoolhouse.

Since the old schoolhouse is a historic building, the cantonal monument preservation authorities joined the planning phase. A key requirement was that the workshop needed ground-level access with a width of 2.50 m. The question then was where to construct this without changing the character of the building. After careful consideration of various options, the existing door in the front part of the west facade was considered to be the best solution. The door will be replaced with a replica of the original door (Figure 1). Thus, the prominent entrance of the southern facade (Figure 2) will be retained. The old wooden panelling in the interior will also be carefully dismantled, restored, and reinstalled as soon as the structural work is finished.

Figure 1. Renovation in 1975 of the former schoolhouse. PMOD/WRC moved into the building in 1976.

Figure 2. The current workshop entrance.

During the project phase, there was a short stoppage in mid-2020 because the new director, Prof. Dr. Louise Harra, obtained funding for new science projects, and as a result the number of employees increased. This resulted in a growing need for office space. The idea to build an extension to the workshop and convert the gymnasium into laboratories and offices then arose. However, the need for additional office space was subsequently covered by renting additional premises that were already owned by the SFI DAVOS Foundation.

In spring 2021, the project documentation with an estimated cost of CHF 1,140,000, was approved and signed. This allowed the planners to start the detailed planning, and the building application appeared in the Davos Newspaper on 22 August 2021. The project was approved by the authorities without any problems. Offers were obtained from builders, and most of the work was given to companies in Davos.

A tent for the temporary workshop was erected in Feb. 2022 and dismantling of the old gymansium floor began on 21 Feb. 2022. The conversion should be completed by the end of July so that we can move into the newly renovated workshop in August.

Publications and Media

Refereed Publications

Arola, A., Wandji Nyamsi, W., Lipponen, A., Kazadzis, S., Krotkov, N. A., Tamminen, J.: 2021, Rethinking the correction for absorbing aerosols in the OMI- and TROPOMI-like surface UV algorithms, Atmos. Meas. Tech., 14, 4947-4957, https://doi.org/10.5194/amt-14-4947-2021

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Administration

Personnel Department

Barbara Bücheler

The year 2021 began well for staff at PMOD/WRC.

The biggest event in 2021 for us was IPC-XIII, our international calibration campaign, which started on 26 September and lasted for three weeks. The event was opened by Dr. Wolfgang Finsterle with an ice-breaker aperitif in the foyer of Hotel Victoria, Davos, on 26 September. On 27 September, IPC-XIII was officially opened by Dr. Anthony Rea, Director of the WHO Infrastructure Department. In total, 52 participants from 22 countries took part at PMOD/WRC despite the strict Covid measures which were in force internationally as well as locally. Normally the IPC campaigns take place every 5 years but had to be postponed by a year due to the outbreak of the Covid pandemic in 2020. During IPC-XIII, symposia were held, which were also actively attended online by scientists who were unable to travel. Parallel to IPC-XIII, the 5th Filter Radiometer Comparison (AOD) (FRC-V) and the 3rd International Pyrgeometer (IR) Comparison (IPgC-III) also took place.

The 50th anniversary of the World Radiation Center (WRC) took place on 26 November 2021. The opening talk was given by Dr. Bertrand Calpini (Meteoschweiz), followed by Dr. Walter Ammann (SFI), Dr Isabelle Rüdi (WMO) , Prof. Dr. Louise Harra and finally the Davos mayor Philip Wilhelm. The celebration continued with a lunch and a cake with an image of the PMOD/WRC.

During 2021, the last instruments for measuring ozone were moved from Arosa to Davos. This important climate variable has been measured in Graubünden for over 100 years. The continuation of the ozone measurements in Davos is now secured.

We were also able to look forward to an increase in the workforce in 2021. Throughout the year, numerous MSc students e.g. Iga Józefiak, Jonas Odermatt, Dennis Kunz, Jakob Föller and the BSc student, Christina Brodowsky, carried out research projects with us. Our PhD students continued their research: Andrea Battaglia, Arseni Doyennel, Hannah Collier, Angelos Karanikolas, Kyriakoula Papachristopoulou and Conrad Schwanitz. In May, we welcomed a new PhD student, Xinyuan Hou, and in Autumn, two visiting students, Dimitry Gankin and Nerobelov Georgii, joined us from the University of St. Petersburg.

At the beginning of the year, Andrea Alberti joined the Technical Department as a project manager in space projects, followed by Leandro Meier who joined as a development engineer in space electronics in May 2021.

Also in May, a research scientist Jan Sedlacek joined the climate group for the POLE project.

The ozone project at the Arosa site ended at the end of May. We would like to thank Verena Danuser for her hard work.

We are very pleased that our MSc student Jakob Föller joined us as a scientific technical employee. His predecessor Mark Baker, left PMOD/WRC in January 2021.

We are also happy that we were able to welcome back Yanick Schoch, our former electronics engineer graduate, for a 3-month special assignment in the summer.

We hired Linus Luzi, our new electronics apprentice, in August.

Thanks to the dedicated help of our civilian conscripts, we were again able to realise a wide range of projects this year. Florian Zurfluh started in January, followed by Manuel Rohner, Christian Marty, Daniel Raimundo, David Schweizer, Micha Vontobel and Ueli Honauer.

We have once again managed to achieve our goals with our motivated and committed scientists and technicians, despite the ongoing pandemic. We would like to thank everyone who has supported us on our way.

Scientific Personnel

Prof. Dr. Louise Harra	Director, affiliated Prof. at ETH-Zürich, Solar Physics researcher
Prof. Dr. Werner Schmutz	PI DARA/Proba-3 Scientist, physicist
Dr. Krzysztof Barczynski	Postdoc, Solar Physics Group, physicist
Dr. Luca Egli	Scientist, WCC-UV and Ozone Sections, physicist
Dr. Tatiana Egorova	Scientist, Climate Group, climate scientist
Dr. Natalia Engler	Instrument Scientist, group WRC-SRS
Dr. Wolfgang Finsterle	Co-Head WRC, Head WRC-SRS, physicist
Dr. Julian Gröbner	Co-Head WRC, Head WRC-Sections IR radiometry, WORCC, WCC-UV and Ozone Section, physicist
Dr. Margit Haberreiter	Project manager/scientist, L5-LUCI, instrument scientist WRC-SRS.
Dr. Gregor Hülsen	Scientist, WCC-UV Section, physicist
Dr. Stylianos Kazantzis	Scientist, WORCC Section, physicist
Dr. Natalia Kouremeti	Scientist, WORCC Section, physicist
Dr. Jean-Philippe Montillet	TSI instrument scientist, geoscientist
Dr. Stephan Nyeki	Scientist, WRC-IRS Section, physicist
Dr. Elena Podladchikova	Instrument scientist, Solar Orbiter SPICE and EUI
Dr. Eugene Rozanov	Scientist, Head of Climate Group, physicist
Herbert Schill	Scientist, Ozone Section, environmental scientist
Dr. Jan Sedlacek	Scientist, Climate Group, climate scientist (since 05.2021)
Dr. Timofei Sukhodolov	Scientist, Climate Group, climate scientist
Andrea Battaglia	PhD student, ETH Zurich, FHNW
Hannah Collier	PhD student, ETH Zurich, FHNW
Arseni Doyennel	PhD student, 3rd year, ETH Zurich
Nerobelov Georgii	PhD student, St. Petersburg, Russia
Angelos Karanikolas	PhD student, 2nd year, WRC-WORCC Section
Kyriakoula Papachristopoulou	PhD student, NKU Athens, Greece
Conrad Schwanitz	PhD student, 3rd year, ETH Zurich
Xinyuan Hou	PhD student, 1st year, ETH Zurich (since 05.2021)
Jakob Föller	MSc student, ETH Zurich (06.2020 – 01.2021)
Iga Józefiak	MSc student, University of Geneva (05.2021 – 06.2021)
Dennis Kunz	MSc student, ETH Zurich
Jonas Odermatt	MSc student, ETH Zurich
Christina Brodowsky	BSc student, ETH Zurich (05.2021 – 06.2021)
Dimitry Grankin	BSc Student, St. Petersburg, Russland

Technical Personnel

Silvio Koller	Co-Head Technical Department, Project Manager Space
Daniel Pfiffner	Co-Head Technical Department, Project Manager Space
Edoardo Andrea Alberti	Project Manager Space (since 01.2021)
Lloyd Beeler	Electronics Engineer, MSc
Valeria Büchel	Project Manager L5-LUCI
Christian Fringer	Electronics Apprentice, 4th year
Matthias Gander	Electronics Engineer, BSc
Manfred Gyo	Electronics Engineer, MSc
Patrik Langer	Mechanical Engineer, MSc
Linus Luzi	Electronics Apprentice 3rd year (since 08.2021)
Nic Matthes	Polymechanic Apprentice 3rd year
Leandro Meier	Electronics Engineer (since 05.2021), BSc

Pascal Schlatter	Mechanic, Head of Workshop, Safety Officer
Yanick Schoch	Electronics Technician (01.06 - 31.08.2021)
Marco Senft	IT System Administrator
Marcel Spescha	Technician Mechanics
Daniel Tye	System Engineer Space Projects
Fabrizio Vignali	IT System Administrator
Liviu Zambila	Structural Engineer, MSc

Technical Personnel within the Science Department

Mark Baker	Technical Employee (until 15.01.2021)
Jakob Föller	Technical Employee (since 02.2021)
Ricco Soder	Calibration Scientist, Quality Systems Manager
Christian Thomann	Technician
Franz Zeilinger	Technicical Engineer, BSc

Administration

Barbara Bücheler	Head Human Resources / Finances / Administration
Sotirios Filios	Administration, Apprentice, 3rd year
Irene Keller	Administration, Import/Export
Angela Lehner	Administration, Book-Keeping
Christian Stiffler	Accountant
Dario Tannò	Administration, Apprentice, 3rd year

Personnel in Arosa

Verena Danuser	Observer and maintenance ozone measurement station (until 31.05.2021)

Caretaker(s)

Maria Sofia Ferreira Pinto	General caretaker, cleaning
Fatima Da Conceicao Alves D.C.	General caretaker, cleaning (back-up)

Civilian Service Conscripts

Florian Zurfluh	17.08.2020 – 13.01.2021
Manuel Rohner	18.01.2021 – 26.03.2021
Christian Marty	29.03.2021 – 10.06.2021
Daniel Raimundo	14.06.2021 – 13.08.2021
David Schweizer	13.09.2021 – 04.12.2021
Micha Vontobel	01.11.2021 – 14.01.2022
Ueli Honauer	06.12.2021 – 08.06.2022

Lecture Courses, Participation in Commissions

Louise Harra	Member of the Advisory Board of the Solar Physics journal Secretary of the Swiss Committee on Space Research Board of Davos Science City Chair of ESA Heliophysics User archive committee Member of Board of Reviewing Editors for Science Journal Subject editor for Proceedings of the Royal Society A: Mathematical, Physical & Engineering Sciences Chair of ISSI science board Ministerial position on management committee of Armagh Observatory and Planetarium Risk and Audit committee of Armagh Observatory and Planetarium Co-chair of the Scientific Advisory Board of the MPS Member of the ESA space science advisory council Co-PI of EUV Imager, co-I of SPICE on Solar Orbiter Co-I on the NASA Interface Region Imaging Spectrograph mission PI of SoSpIM instrument on the JAXA Solar-C mission Member of selection panel for editor for the Solar Physics journal Member of the ESA Athena Independent Science Review Team External member of the SNF evaluation commission Postdoc Mobility in the area of Mathematics and Engineering Sciences Lecture course: The Sun, Stars and Planets - Properties, Processes and Interactions, D-PHYS, ETHZ, (block course, June 2021) Lecture course: Astronomical instrumentation, Autumn semester, (Schmid/Harra/Sterke), D-PHYS, ETHZ Lecture course: Space research and exploration, Autumn semester, D-PHYS, ETHZ.
Werner Schmutz	Honorary Member of the International Radiation Commission (IRC, IAMAS) PI of DARA on PROBA-3 Co-I of EUV and SPICE instruments on Solar Orbiter
Wolfgang Finsterle	Chair of ISO-TC180/SC1 (until October 2020) Member of WMO ET-RR
Julian Gröbner	Member of the Dobson Ad-Hoc Committee, http://www.o3soft.eu/dobsonweb/committee.html, since 2021 Member of the expert team on atmospheric composition measurement quality and QA-Central facilities of the WMO, since 2020 Member of the scientific advisory group for Ozone and UV in the Global Atmosphere Watch programme of the WMO (as of 2016) Chair of the Scientific Committee of the Conference "New Developments and Applications in Optical Radiometry" (NEWRAD), since 2014 Member of the Swiss Global Atmosphere Watch Programme managed by Meteoswiss, since 2005. Member of the Expert Team on radiation references the Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT) of the WMO, since 2014 Member of the Baseline Surface Radiation Network (BSRN) and Chair of the Infrared Working Group, since 2006 Member of the Regional Brewer Scientific Group - Europe (RBCC-E, 2005- ongoing). Chair of WG4, UV Calibration of Brewer spectrophotometers", since 1999 Elected member of the International Radiation Commission, and Chair of the Working group on solar UV radiation, IAMAS, since 2009 Member International Ozone Commission, IAMAS, since 2016

Eugene Rozanov	Co-chair of SCOSTEP PRESTO project Member of SWISS SCOSTEP Committee Member of MDPI “Atmosphere” journal editorial board Member of RAS “Physics of the Atmosphere and Ocean” editorial board
Margit Haberreiter	President Swiss Society for Astronomy and Astrophysics Vice President European Geophysical Union Member Swiss National SCOSTEP Committee Topical Editor Annales Geophysicae Member of the UN COPUOS Expert Team on Space Weather Swiss Delegate to WMO’s IPT-SWeISS Co-I of EUI and SPICE on Solar Orbiter Lead ISSI International Team “Towards the determination of the Earth Energy Imbalance from Space” Reviewer for Advances in Space Research, Solar Physics
Stylianos Kazantzis	Member of the International Radiation Committee (IAMAS-IRC) Member of the Scientific Advisory Group for Aerosols of WMO (WMO-SAG) Member of the Expert Team on Measurements Quality of the World Meteorological Organization. Member of the Global Atmospheric Watch, Swiss panel Member of Atmospheric Chemistry and Physics journal editorial board. Member of MDPI Atmosphere journal editorial board Lecture course: Solar UV Radiation, J. Grobner and S. Kazadzis, ETHZ, MSc Atmos. & Climate Science
Olena Podladchikova	Expert Evaluator of Marie-Curie fellowships Expert Evaluator of National Science Foundation (NSF-US) scientific grants Expert Evaluator of HORIZON, EU projects including ERC grants and ESA projects Member of Hellenic Astronomical Society Member of MDPI “Atmosphere” journal editorial board Expert Evaluator for Russian Science Foundation (RSF) mega-grants panel Board member of Frontiers in Astronomy and Space Sciences
Timofei Sukhodolov	Guest editor of the research topic “The evolution of the stratospheric ozone” in the journal, Frontiers in Earth Science Member of the SPARC project “High Energy Particle Precipitation in the Atmosphere”, HEPPA-3 Member of the ISSI-based group "Relativistic electron precipitation and its atmospheric effect" Member of the SPARC activity “Interactive stratospheric aerosol model intercomparison”, ISA-MIP Co-PI of the SOCOLv4 model, SPARC activity “Chemistry-climate model initiative phase 2”, CCMI-2 Lecture course: Weather, climate, and society, BOKU-Met, Vienna, Austria
Luca Egli	Member IAMAS International Radiation Commission (since 2016)
Natalia Engler	Member of Expert committee of Swiss National Competition 2021 "Schweizer Jugend forscht!"
Andrea Alberti	Advisor for the Space4Impact non-profit initiative Expert Evaluator for the Bench2Biz international workshop for young and aspiring entrepreneurs Expert for the 1st Cassini Hackaton / Swiss Chapter Expert Evaluator for the Space2Earth Accelerator for startups and scale-up businesses

Public Seminars given at PMOD/WRC (most talks were given online)

16 Feb. 2021	Mark Cheung, LMSAL, USA *Monitoring the Solar Corona with Physics-Informed Machine Learning*
23 Mar. 2021	Laura Hayes, Dublin, Ireland *Solar flares and their effects on the Earth's lower ionosphere*
13 Apr. 2021	Durgesh Tripathi, IUCAA, Pune, India *The Aditya mission*
11 May 2021	Vishal Upendran, IUCAA, Pune, India *Impulsive heating in the quiet corona*
30 Jun. 2021	Matt Owens, University of Reading, UK *The heliospheric magnetic field*
6 Jul. 2021	Karina von Schuckmann, Mercator International, France *The Earth energy imbalance: A view on the Earth heat inventory*
7 Jul. 2021	George Doschek, NRL, USA *A life in solar spectroscopy*
12 Jul. 2021	Norman Loeb, NASA Langley Research Center, USA *Tracking Earth Energy and Climate*
Sep - Oct 21	45 seminars organised by PMODWRC during IPC-XIII, FRC-V, IPgC-III
23 Nov. 2021	Paul Young, Lancaster University, UK *Ozone, UV, the carbon cycle, climate, and the World Avoided by the Montreal Protocol*
7 Dec. 2021	Jim Klimchuk, NASA GSFC, USA *Coronal heating*

Meetings, Symposia, Workshops, Public Events (selected highlights)

22 Feb. 2021	Webinar on: "The challenges of the Solar Orbiter mission", for Akademische Raumfahrt Initiative Schweiz (ARIS), https://aris-space.ch/, Louise Harra.
16 Apr. 2021	The Advisory Commission (Aufsichts-Kommission) meeting.
22 Apr. 2021	"Davos weiss mehr: Wie funktioniert Weltraumforschung", webinar for Davos audience, Louise Harra and Conrad Schwanitz.
26 Apr. 2021	Webinar on "'Fascination with the Sun", Louise Harra.
April 2021	Organisation of EGU21 Session ST4.1 “Advances in Solar Irradiance and Earth Radiation Budget Measurements”, Convenor: Margit Haberreiter.
13 May 2021	Webinar on: "Solar Energy Applications and the Effect of Dust Aerosols", Stelios Kazadzis.
5 Jul. 2021	Mini-lecture series on the Sun filmed for the Massolit learning resources for schools https://www.massolit.io, Louise Harra
18 Jul. 2021	Board of Trustees (Stiftungsrat) meeting.
12 Aug. 2021	Public talk about: "Climate Change and the Summer Weather", Jan Sedlacek.
27 Sep. - 15 Oct. 2021	Organisation of IPC-XIII, FRC-V, IPgC-III Symposium, Margit Haberreiter.
13 - 15 Sep. 2021	Sorbetto-2 Summer School, Stelios Kazadzis.
30 Sep. 2021	The Advisory Commission (Aufsichts-Kommission) meeting.
3 - 9 Oct. 2021	Quadrennial Ozone Symposium, “Environmental and Human Health Effects of Atmospheric Ozone and UV”, Co-Convenor: Julian Gröbner.
9 Oct. 2021	PMOD/WRC stand at Davoser Mäss.
4 Nov. 2021	Louise Harra, Inaugural Lecture at ETH Zurich.
18 Nov. 2021	Talk at Zürich Physical Society, "Getting close to the Sun", Louise Harra.

Bilanz per 2021 (inklusive Drittmittel) mit Vorjahresvergleich

Aktiven	31.12.2021 CHF	31.12.2020 CHF
Flüssige Mittel	2'091'765.44	2'299'714.29
Forderungen	88'338.15	554'591.15
Delkredere	0.00	-20'450.00
Aktive Rechnungsabgrenzungen	830'857.44	321'545.64
Delkredere Drittmittel	-300'000.00	0.00
Warenvorräte	1'000.00	0.00
Total Aktiven	2'711'961.03	3'155'401.08

Passiven		
Verbindlichkeiten	411'312.45	172'514.85
Kontokorrent Stiftung	0.00	157.20
Passive Rechnungsabgrenzung	1'236'259.55	1'619'194.15
Rückstellungen	840'000.00	1'205'000.00
Eigenkapital	224'389.03	158'534.88
Total Passiven	2'711'961.03	3'155'401.08

Erfolgsrechnung 2021 (inklusive Drittmittel) mit Vorjahresvergleich

Ertrag	CHF	CHF
Beitrag Bund Betrieb WRC	1'489'200.00	1'489'200.00
Beitrag Bund (BBL), Unterhalt Gebäude	77'922.60	134'861.52
Beitrag Kanton Graubünden WRC	509'268.00	509'268.00
Beitrag Kanton Graubünden für ETH Prof.	240'000.00	240'000.00
Beitrag Gemeinde Davos	664'191.00	664'191.00
Beitrag Gemeinde Davos, Mieterlass	160'000.00	160'000.00
Dienstleistungsauftrag MeteoSchweiz OZON	272'003.40	270'799.25
Dienstleistungsauftrag WMO Genève	21'881.00	10'940.50
Overhead SNF	44'461.40	55'820.60
Overhead Projekte	49'580.00	0.00
Instrumentenverkäufe	41'650.00	5'578.00
Reparaturen und Kalibrationen	233'009.33	168'816.12
Ertrag Dienstleistungen	63'498.51	94'769.68
Übriger Ertrag	827.85	1'771.85
Finanzertrag	0.00	162.40
Ausserordentlicher Ertrag	0.00	19'069.58
Drittmittel	2'488'050.19	1'991'252.70
Bildung Delkredere Drittmittel	-300'000.00	0.00
Total Ertrag	6'055'543.28	5'816'501.20

Aufwand		
Personalaufwand	4'711'968.30	4'249'169.06
Investitionen Observatorium	197'407.75	161'618.63
Investitionen Drittmittel	1'300.95	43'093.50
Unterhalt Gebäude (Beitrag Bund)	77'922.60	134'861.52
Unterhalt	63'751.55	80'379.40
Verbrauchsmaterial Observatorium	55'335.07	39'740.30
Verbrauchsmaterial Drittmittel	299'541.94	172'571.75
Verbrauch Commercial	104'688.70	100'218.50
Reisen, Kurse	45'763.80	33'082.10
Raumaufwand/Energieaufwand	259'488.70	212'764.50
Versicherungen, Verwaltungsaufwand	116'357.57	112'538.00
Finanzaufwand	7'459.24	1'508.45
Übriger Betriebsaufwand	62'806.71	95'056.10
Ausserordentlicher Aufwand	896.25	1'381.03
Total Aufwand	6'004'689.13	5'437'982.84
Jahresergebnis vor Bildung/Auflösung Rückstellungen	**50'854.15**	**378'518.36**
Auflösung Rückstellungen	15'000.00	80'000.00
Bildung Rückstellungen	0.00	400'000.00
Jahresergebnis	**65'854.15**	**58'518.36**
	6'055'543.28	5'816'501.20

Abbreviations

AERONET	Aerosol Robotic Network, GSFC, USA
AOACCM	Atmosphere-Ocean-Aerosol-Chemistry-Climate Model
AOD	Aerosol Optical Depth
BIPM	Bureau International des Poids et Mesures, Paris, France
BSRN	Baseline Surface Radiation Network of the WCRP
CCM	Chemistry-Climate Model
CIMO	Commission for Instruments and Methods of Observation of WMO, Geneva, Switzerland
CIOMP	Changchun Institute of Optics, Fine Mechanics and Physics
CIPM	Comité International des Poids et Mesures
CLARA	Compact Light-weight Absolute Radiometer (PMOD/WRC experiment onboard the NorSat-1 micro-satellite mission)
CMA	Chinese Meteorological Administration
CMC	Calibration and Measurement Capabilities
CME	Coronal Mass Ejections
COSI	Code for Solar Irradiance (solar atmosphere radiation transport code developed at PMOD/WRC)
COST	European Cooperation in Science and Technology
CSAR	Cyrogenic Solar Absolute Radiometer (PMOD/WRC research instrument)
DARA	Digital Absolute Radiometer (PMOD/WRC experiment onboard the ESA Proba-3 formation flying mission)
EAGLE	Entire Atmosphere Global Model
ECV	Essential Climate Variable
EMRP	European Metrology Research Programme
ESA	European Space Agency
EUI	Extreme Ultraviolet Imager (PMOD/WRC participation in EUI, onboard the Solar Orbiter mission)
EUV	Extreme Ultraviolet region of the light spectrum
FM	Flight Model
FRC	Filter Radiometer Comparisons, held at PMOD/WRC every 5 years
FS	Flight Spare
FY-3E	Chinese weather satellite, Fengyun-3, to be launched in the near future
GAW	Global Atmosphere Watch, a WMO Research Programme
GCM	General Circulation Model
GCR	Galactic Cosmic Rays
HAMMONIA	Hamburg Model of the Neutral and Ionized Atmosphere
HEPPA	High Energy Particle Precipitation in the Atmosphere (SPARC activity)
IACETH Zurich	Institute for Climate Research, ETH Zurich, Switzerland
IPC	International Pyrheliometer Comparisons, held at PMOD/WRC every 5 years
IPgC	International Pyrgeometer Comparisons, held at PMOD/WRC every 5 years
IRCCAM	Infrared Cloud Camera (PMOD/WRC research instrument)
IRIS	Infrared Integrating Sphere Radiometer (PMOD/WRC research instrument)
IRS	Infrared Section of the WRC at PMOD/WRC
ISO/IEC	International Organisation for Standardisation/International Electrotechnical Commission
ISO 17025	General requirements for the competence of testing and calibration laboratories
JTSIM-DARA	Joint Total Solar Irradiance Monitor – DARA (experiment onboard the Chinese FY-3E mission)
LUCI	Lagrange EUV Coronal Imager (experiment onboard the ESA LAGRANGE mission)
METAS	Federal Office of Metrology, (Eidgenössisches Institut für Metrologie), Bern-Wabern, Switzerland
MITRA	Monitor to Determine the Integrated Transmittance (PMOD/WRC research instrument)

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MRA	Mutual Recognition Arrangement
NASA	National Aeronautics and Space Administration, Washington DC, USA
NIST	National Institute of Standards and Technology, Gaithersburg, MD, USA
NorSat-1	Norwegian Satellite-1
NPL	National Physical Laboratory, Teddington, UK
NREL	National Renewable Energy Laboratory, Golden, CO, USA
PFR	Precision Filter Radiometer (manufactured by PMOD/WRC)
PMO6-cc	Type of absolute cavity radiometer (previously manufactured by PMOD/WRC)
POLE	Past and Future of the Ozone Layer Evolution
PROBA	ESA Satellite Missions (PROBA-1 to 3)
PRODEX	PROgramme de Développement d'Expériences scientifiques, ESA
PSR	Precision Spectroradiometer (manufactured by PMOD/WRC)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Germany
QASUME	Quality Assurance of Spectral Ultraviolet Measurements in Europe
QMS	Quality Management System
SCNAT	Swiss Academy of Sciences
SFI	Schweiz. Forschungsinstitut für Hochgebirgsklima und Medizin, Davos, Switzerland
SIAF	Schweiz. Institut für Allergie- und Asthma-Forschung, Davos, Switzerland
SNSF	Swiss National Science Foundation
SOCOL	Combined GCM and CTM Computer Model developed at PMOD/WRC→
SoHO	Solar and Heliospheric Observatory (ESA/NASA space mission)
SOLARIS	Solar Influences on Climate (SPARC activity, joined with HEPPA as SOLARIS-HEPPA)
Solar Orbiter	SolO; An ESA mission to conduct solar research (PMOD/WRC are participating with the EUI and SPICE instruments)
SPARC	Stratosphere-troposphere Processes And their Role in Climate (A core project of the World Climate Research Programme)
SPE	Solar Proton Events
SPICE	Spectral Imaging of the Coronal Environment (PMOD/WRC participation in SPICE, onboard the Solar Orbiter mission)
SRS	Solar Radiometry Section of the WRC at PMOD/WRC
SSI	Solar Spectral Irradiance
TEC	Total Electron Content
TSI	Total Solar Irradiance
VHS	Ventilation Heating System (manufactured at PMOD/WRC)
VIRGO	Variability of Solar Irradiance and Gravity Oscillations (PMOD/WRC experiment onboard the SOHO mission)
WCC-UV	World Calibration Center for UV in the WRC of the PMOD/WRC
WDCA	World Data Centre for Aerosols, NILU, Norway
WISG	World Infrared Standard Group of pyrgeometers (maintained by WRC-IRS at PMOD/WRC)
WMO	World Meteorological Organisation, a United Nations Specialised Agency, Geneva, Switzerland
WORCC	World Optical depth Research and Calibration Center of the WRC at PMOD/WRC
WRC	World Radiation Center at PMOD/WRC, composed of the Sections: IRS, SRS, WCC-UV, and WORCC
WRR	World Radiometric Reference
WSG	World Standard Group of pyrheliometers (realises the WRR; maintained by WRC at PMOD/WRC)

Annual Report 2021

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Dorfstrasse 33, 7260 Davos Dorf, Switzerland
Phone +41 81 417 51 11
www.pmodwrc.ch