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MeteoSwiss

Technical Report MeteoSwiss No. 280

1st Swiss National GAW/GCOS Symposium 2021 White Paper

GAW-CH and Swiss GCOS Offices

ISSN: 2296-0058

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1st Swiss National GAW/GCOS Symposium 2021 White Paper

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Final review by: **Thomas Stocker** on behalf of the GCOS Switzerland Steering Committee.

Recommended citation:

MeteoSwiss: 2022, 1st Swiss National GAW/GCOS Symposium 2021: White Paper, *Technical Report MeteoSwiss*, **280,** 33 pp.

Editor:

Federal Office of Meteorology and Climatology, MeteoSwiss, © 2022

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Executive Summary

The Global Atmosphere Watch (GAW) and Global Climate Observing System (GCOS) are international activities to coordinate long-term systematic observations of the composition of the atmosphere and the climate system as well as regularly assess the status of global climate observations and produce guidance for their improvement. They also facilitate services in the areas of climate, air quality and health. Switzerland implements GAW and GCOS programmes through GAW-CH and GCOS Switzerland. Both national programmes are coordinated by MeteoSwiss and implemented in partnership with a network of research and environmental institutions (Appendix A). In addition, Switzerland makes a substantial contribution to the global programmes by supporting international data and calibration centres (Appendix B).

The first joint Swiss National GAW and GCOS Symposium was held in Bern, and via livestream, on 13-14 September 2021. Recent achievements were presented with the aim to identify key observational gaps, and spark ideas for future initiatives to be promoted by GAW-CH and GCOS Switzerland. This event aimed at discussing the bigger scientific picture by structuring the sessions along the Earth System cycles for carbon, energy, and water. A total of 18 invited international and national experts gave comprehensive presentations and engaged in moderated panel discussions. They highlighted the role of consistent observations and continuous research for a better understanding of the Earth System across the water, energy and carbon cycles, and talked about the importance of linking scientific GAW and GCOS achievements to services for society. These contributions were complemented by 21 poster presentations of current GAW-CH and GCOS Switzerland activities, encompassing research work, systematic monitoring, and central facilities contributing to the global programmes. The closing panel, composed of representatives of the top-level management of major Swiss environmental institutions and moderated by Thomas Stocker, University of Bern, was to give an overall appraisal of the Swiss GAW and GCOS programmes and provide guidance for their implementation. From an overarching strategic perspective, the high-level closing panel recommended the programmes to consider:

- tackling the inherent interdisciplinarity of Earth System monitoring by innovative, silo-overcoming collaboration addressing individual cycles as well as across all cycles;
- continuing to strive for sufficient high-quality observational data and to encourage efforts to combine in-situ and remote sensing observations, as well as integrate them into modelling frameworks and reanalyses;
- enhancing the transfer of knowledge by more strongly communicating experience and lessons-learnt of the Swiss experts;
- promoting the development and delivery of added-value climate and air-quality services and effective climate communication.

The moderated panel discussions following each of the scientific cycle sessions, on the other hand, served to condense the main scientific messages and allowed the audience that followed the Symposium in live streaming to interact and give input. Observing and evaluating changes in regional and local-scale cycles were seen as valuable avenues. The discussions included a focus on the major known drivers of the cycles such as aerosols, clouds and the surface fluxes, soil carbon content and

its variability, and the cryospheric component. Emphasis was laid on the need for combined O_2/CO_2 measurements, and modelling studies for specifying CO_2 monitoring systems for in-situ versus remote sensing measurements. Finally, the interactive exchange touched upon how to refine the linkage between observations, research, services and society. The following thoughts were offered to the Swiss GAW and GCOS programmes for consideration in their current and future implementation efforts:

Innovation and silo-breaking collaboration across cycles: Exploration of new approaches and methods should be facilitated more strongly. Also, joint efforts are needed to ensure the continued development of existing observing systems and ideally to close critical measurement gaps. Next-generation numerical weather and climate prediction models simulate an increasing number of Earth System elements and should be recognised, utilised and exploited as a natural platform for collaboration.

Approaches to constrain individual and overall fluxes and processes: Overall fluxes within the carbon, energy and water cycles should be explored individually, but also across the cycles. This will help close their balance globally by reducing sources of uncertainties, and identifying calibration and reprocessing needs. New types of uncertainties arise with the possibility of thresholds or tipping points that might be reached under further global warming. Early warning systems can only be designed on the basis of robust and long-term observations. Targeted analyses on a specific focus across all cycles, for example, on mountain areas, should be pursued. This requirement is complementary to single Essential Climate Variables (ECV) observation studies but could be supported through GCOS or GAW.

Data maintenance and sustainability: Quality control, traceability and a sound documentation for global-, regional- and national-scale measurements are critically important and must be assured continually. In addition, the importance of regular re-evaluation of historical data sets is important in order to increase their stability and robustness and guarantee their best possible consistency and compatibility.

Data integration and research: Progress towards a more comprehensive observation coverage should be sought by improving the link between the in-situ, remote sensing, modelling and re-analysis communities. Achievement of a global-scale balance for carbon, energy and water fluxes, cross validation of datasets, and the definition of observational requirements should be performed at different scales, possibly with the help of the setup and promotion of supersites. The cryosphere is notoriously under-observed at the global scale, especially in high-mountain areas.

Knowledge transfer: There is the clear need to transfer knowledge from science to society, and questions remain how to connect the full range from observations and science via climate services to climate communication. 'Climate Indicators' should play a more prominent role for creating such a dialogue; hence the recommendation to extend the current set of GCOS Global Climate Indicators. Knowledge transfer, especially to less developed countries around the globe, is a great opportunity for making the GAW and GCOS programmes more valuable at the global scale. New avenues to most efficiently transfer and export knowledge should be explored. WMO Chief Scientist Jürg Luterbacher underscored that the world can learn a lot from Switzerland.

Contents

1 Introduction

1.1 Context and Motivation

Based on the WMO Global Atmosphere Watch[1] (GAW) programme launched 1989, and the co-sponsored[2] Global Climate Observing System[3] (GCOS) programme launched in 1992 as a requirement of the IPCC, the Swiss Federal Council has mandated MeteoSwiss to implement these two programmes at the national level, respectively in 1994 and 2006. The goal of this engagement is to contribute to the global-scale systematic observation of the chemical composition of the atmosphere as well as of a large number of essential climate variables (ECVs). In order to fulfill this mandate, MeteoSwiss has established the GAW-CH[4] and the Swiss GCOS[5] Offices and tasked them to coordinate the implementation of the national programmes through a network of national partners.

The wish for closer collaboration between the Swiss GAW and GCOS programmes led to the idea to organise a first joint symposium. Consistent with the current WMO Strategy 2020-2023[6] and the current GCOS Implementation Plan[7] (GCOS 2016), the meeting agenda was shaped along the Earth System cycles for carbon, energy and water with the goal to promote a more holistic approach and trigger interdisciplinary collaborative efforts. In particular, Goals 2 and 3 of the WMO Strategy focus on Earth System observation and prediction along with targeted research to improve the understanding of the Earth System in view of enhanced service provisions at the national as well as at the global level. In addition, the goals in Chapter 5 of the GCOS Implementation Plan focus on the observation-based closure of the Earth System cycles and budgets. High quality, fit-for-purpose, traceable long-term and continuous measurements feeding a continuous global data exchange, underpinned by data management and data processing mechanisms, are at the heart of the GAW and GCOS programmes. A global research community provides leverage with fundamental advances in the understanding of the Earth System, leading to improved policy-relevant advice and predictive skill at all timescales.

A high-quality and long-term global climate observation system is the prerequisite for assessing the global water, energy and carbon cycles. However, the closure of regional budgets or even the detection of human-induced changes cannot be provided by measurement methodologies alone. The symposium, therefore, was to consider the integration of ground- and satellite-based observations with models in multidisciplinary and international collaborations. Communicating these complex relationships in a way that promotes acceptance is a central challenge. Integrative and easily understandable climate indicators such as the Earth Energy Imbalance (EEI) can serve as a fundamental metric for climate warming, but do require a coordinated effort across a wide variety of disciplines of the Earth System.

[1] https://public.wmo.int/en/programmes/global-atmosphere-watch-programme

[2] World Meteorological Organization (WMO), Intergovernmental Oceanographic Commission (IOC) of UNESCO, United Nations Environment Programme (UN Environment), International Council of Science (ISC)

[3] https://gcos.wmo.int

[4] http://www.meteoswiss.ch/gaw

[5] http://www.gcos.ch

[6] https://library.wmo.int/doc_num.php?explnum_id=9939

[7] https://library.wmo.int/opac/doc_num.php?explnum_id=3417

The 1st Swiss National GAW/GCOS Symposium pursued a threefold goal: (i) to present the achievements of the national programmes; (ii) to identify significant gaps and open questions in the description and understanding of the carbon, energy and water cycles in terms of observations and modelling; and (iii) to assess to what extent, and in what form, the Swiss GAW and GCOS communities can best contribute to further the understanding and description of the Earth System in the years to come.

1.2 GAW-CH in Brief

Launched in 1989, the Global Atmosphere Watch programme (GAW) is a partnership of over 100 countries to monitor the composition of the atmosphere. The programme supports a worldwide network of selected monitoring stations for measuring greenhouse gases, ozone, UV radiation, aerosols, reactive gases and precipitation chemistry with high and known quality around the globe. Systematic data management and quality assurance is a central part of GAW (Fig. 1). The GAW Implementation Plan[8] (GAW 2017) provides the guidelines for the Swiss GAW-CH programme. The GAW-CH Office at MeteoSwiss coordinates and supports about a dozen institutions (Appendix A) that carry out the Swiss national GAW activities, including monitoring and research, and six central facilities (Appendix B) for calibration and quality assurance of the global network. GAW provides the atmospheric chemistry component of GCOS.

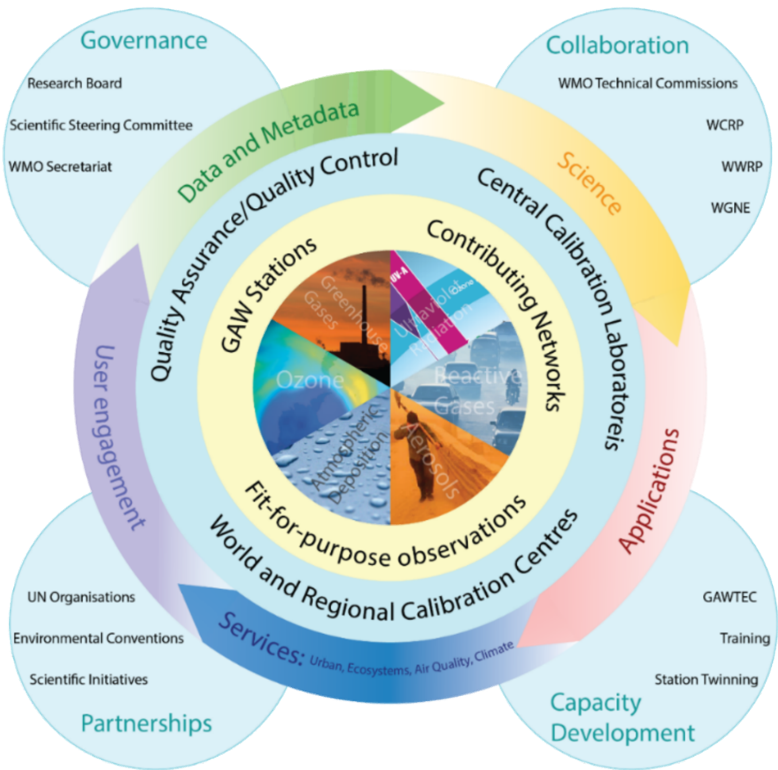

Figure 1: Key elements of the GAW Programme's Research Enabling Atmospheric Composition Services.

[8] https://public.wmo.int/en/resources/library/wmo-global-atmosphere-watch-gaw-implementation-plan-2016-2023

1.3 GCOS Switzerland in Brief

The Global Climate Observing System (GCOS) was established in 1992 to globally coordinate climate observation and to provide users with the data and information needed to address climate-related concerns. Today, within the framework of GCOS Switzerland, high quality data on 33 Essential Climate Variables[9] (ECVs, Fig. 2) are being continuously collected, processed and made available to the public (MeteoSwiss 2018). GCOS Switzerland also includes six international calibration and data centers, three of which are shared with GAW-CH (Appendix B). The systematic observation of ECVs and the operation of international centres in Switzerland is facilitated by the common effort of 28 National Partner Institutions (see Appendix A) and coordinated by the Swiss GCOS Office at MeteoSwiss. The GCOS Switzerland Strategy 2017-2026 (MeteoSchweiz 2017) is based on the GCOS Implementation Plan (WMO 2016) and provides the framework for actions to be implemented by the entirety of the Swiss GCOS community.

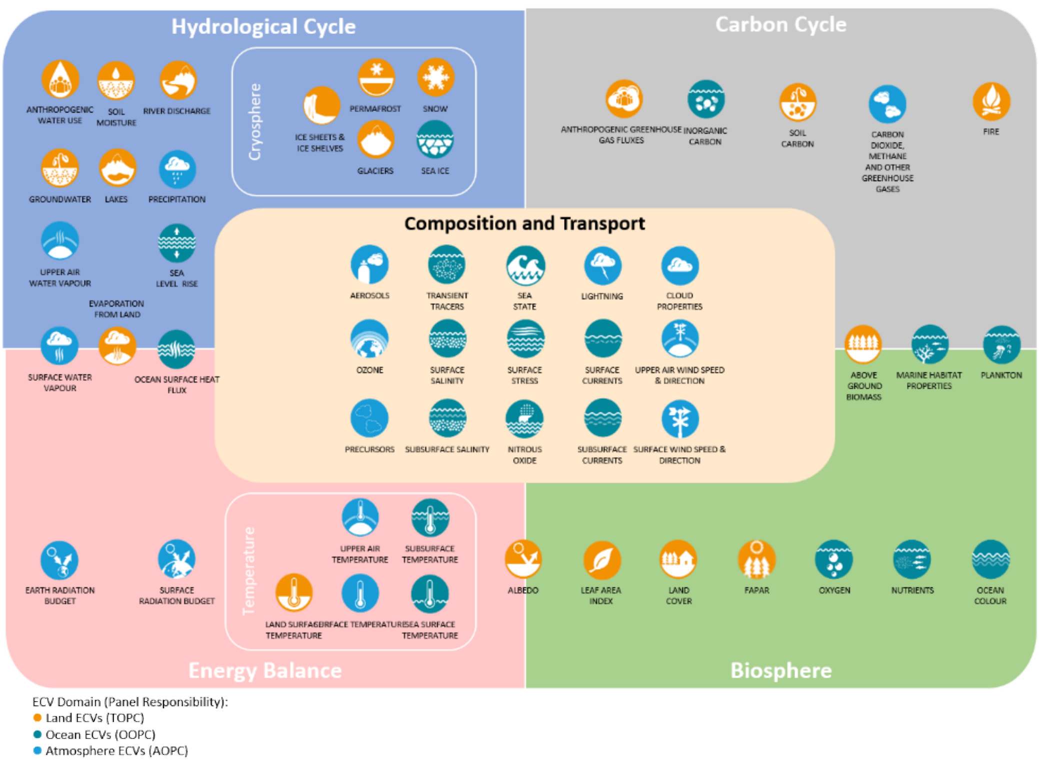

Figure 2: Schematic illustrating a simplified earth-system cycle perspective (GCOS 2021). Shown are the current ECVs as listed in the 2016 GCOS Implementation Plan (IP). Many of the transport and composition ECVs that are essential for a deeper understanding and improved modelling of the cycles and energy balance intersect with several cycles and cannot merely be assigned to a single cycle.

[9] https://gcos.wmo.int/en/essential-climate-variables/

2 Goal and Structure of the Symposium

The Earth System approach to observation and forecasting, as promoted by the current WMO Strategy 2020-2023 and the GCOS Implementation Plan, requires an integrated perspective on, and approach to, numerous disciplines in order to describe and understand the relevant Earth System processes and cycles. The programme of the Symposium (Appendix C) was structured in three half-day sessions on the Earth System cycles of carbon, energy and water, preceded by a high-level opening session in which major stakeholder representatives, i.e. the WMO, the IPCC and European Copernicus Services, reflected on the importance of the GAW and GCOS programmes. Each of the three Earth cycle sessions featured a keynote presentation, designed to give an overview of the main recent achievements of that discipline. Furthermore, the keynote speakers presented some of the generally recognised unresolved questions and reflected on the potential contribution that the Swiss programmes could envisage. The keynote addresses were followed by four invited presentations, which aimed at showcasing the Swiss achievements and indicating possible future avenues, and a perspective on how these can benefit society in specific services. Each session was concluded by a panel discussion between these national experts and moderated by the international keynote speaker with the aim to consolidate the relevant open questions and formulate recommendations for future activities of the Swiss GAW and GCOS programmes. The total of 18 oral presentations were complemented by 21 poster presentations of current GAW-CH and GCOS Switzerland activities, encompassing research work and central facilities as contributions to the global programmes. The closing panel, composed by representatives of the top-level management of major Swiss environmental institutions and moderated by Thomas Stocker, University of Bern, reviewed and consolidated the outcomes of the Symposium.

Figure 3: Official poster of the 1st Swiss National GAW/GCOS Symposium 2021.

Figure 4: Top: closing panel from left to right: Jürg Luterbacher, Janet Hering, Thomas Stocker, Brigitte Buchmann, Bertrand Calpini (with Carlo Scapozza virtually). Bottom: MeteoSwiss organisers invite the national and international speakers on location at Zentrum Paul Klee to the stage, marking the end of the event. Over 130 participants followed the livestream from home.

3 Cycle Session Summaries, Open Questions and Recommendations

Sections 3.1, 3.2, and 3.3 summarise the overviews and challenges for the Earth System cycles of carbon, energy, and water as presented by the invited international keynote speakers in three distinct sessions. These are complemented by shorter summaries of the presentations given by national experts on specific parts of each cycle. Each session was concluded by a panel discussion between the national experts and moderated by the respective international expert. These interactive moments are summarised to yield the recommendations for the way forward. Finally, the overarching recommendations are collated in Section 4.1.

3.1 Carbon Cycle

3.1.1 Keynote Address: Overview and Challenges

In his keynote talk, Han Dolman, Vrije University Amsterdam, now Royal NIOZ, Texel, comprehensively introduced the main elements of the carbon cycle, a complex system involving many different environmental compartments or spheres. Natural fluxes between these are large, but anthropogenic fluxes increasingly interfere with the natural cycle. Carbon emissions are rising, mainly due to anthropogenic activities. Only about 45% of the emitted carbon remains in the atmosphere (called the airborne fraction), the land and the oceans take up the rest. The airborne fraction remained rather constant in the recent past, which indicates that uptake by land and oceans tends to grow with rising emissions. However, scenario simulations predict that the airborne fraction may increase considerably mainly due to saturation of the oceans, especially for the high emission scenarios.

Observations of how much carbon is accumulating in the different spheres is critical, as it is insufficient to rely purely on the bottom-up estimates of carbon emissions. Science also needs to investigate climate feedbacks more thoroughly, e.g., when and how they may kick in and accelerate climate change, and climate processes, like how much carbon gets into the ocean and can be stored there on geological timescales. Uncertainties in land use and land sink fluxes could not be reduced much in the recent past. As a result, those fluxes still contribute to the largest uncertainties in the global carbon cycle. Consistent observations are a key requisite for improving the understanding of the carbon cycle, and various shortcomings in terms of adequate observations persist:

- atmospheric in-situ observations have a decent coverage but still suffer from data sparse regions;
- satellite observations of greenhouse gases are becoming increasingly available, but CO_2 and CH_4 total column inventories are temporally and spatially inadequately sampled despite the global coverage achieved with satellites;
- satellite-derived maps of biomass are not yet suited to assess biomass change;
- frequency of reporting of land use and land use change is not sufficient and is not specifically targeted towards carbon accounting;

- in the oceans, data availability varies from region to region, and data are particularly missing in the Southern hemisphere with its large ocean surfaces;
- observations in terms of the biosphere's role in the oceans is inadequate.

Han Dolman advocated a budgeting and monitoring system for supporting the compliance to international agreements. Plans exist to get such a system operational by 2025, but this is a very ambitious timeline. In terms of observations, it requires satellite and in-situ observations with unprecedented temporal and spatial resolution. Once such observations are available, the data need to be combined with newest generations of models and simulations. Han Dolman finished his presentation with four key questions to be addressed in the future: (a) should derived variables like gross primary production, net primary production or net biome exchange also become Essential Climate Variables? (b) should different requirements be defined for different applications? (c) how should novel techniques and approaches be implemented? (d) how should in-situ measurements and satellite borne observations be balanced?

3.1.2 Summaries of National Presentations

From weather to ecosystem forecasts – Opportunities for reliable carbon cycle and climate impact projections – Benjamin Stocker, ETH Zurich: Benjamin Stocker focused on the role of the terrestrial biosphere due to its strong sink for CO2 released into the atmosphere, the important interaction of the biosphere and the atmosphere, and the impact of climate change on species and ecosystems. Research capacities and infrastructure need to be developed to quantify and forecast such impacts. Benjamin Stocker suggests to develop near-term (weeks to months) ecosystem forecasts for climate impacts on multiple variables across space. Past observations, like long-term observations of atmosphere-ecosystem exchange and forest monitoring, both in-situ and by remote sensing, are key here to advance our understanding. Forecasts can be made by using data assimilation and models, which are based either on data-driven approaches or mechanistic ecosystem approaches. Models have made significant progress in the recent past and can be used for a variety of applications.

Combined O_2 and CO_2 measurements as tool for the partitioning of CO_2 emissions among the atmosphere, biosphere and ocean – Markus Leuenberger, University of Bern: Markus Leuenberger presented an observation-based approach to better understand the fate of the carbon that is emitted into the atmosphere. To do so, the long-term trends of CO_2 and oxygen O_2 recorded at the high-altitude station Jungfraujoch are used along with known carbon emission from different sources and oxidation ratios of CO_2 in the oceans, the terrestrial biosphere and of fossil fuels. His approach results in estimates of 26.3%, 29.2%, and 44.5% of the emitted carbon to be taken up by the oceans, the biosphere, and the atmosphere, respectively. Markus Leuenberger also gave a comprehensive overview of the global oxygen budget, which is important to be known when researching the carbon and the oxygen budget in concert. Overall, the O_2 content in the atmosphere is decreasing, mainly due to the combustion of fossil fuels. Markus Leuenberger also reiterated that the carbon uptake by oceans and land is expected to increase. However, with still increasing emissions, a larger fraction of the emitted carbon will accumulate in the atmosphere in the future. Finally, he briefly touched upon recent technical developments that simplify the operation of combined CO_2 and O_2 measurements; this could result in an increase in the number of such observations worldwide.

Soil carbon sequestration as negative emission technology – Where do we stand? – Jens Leifeld, Agroscope: Jens Leifeld discussed the role of soils in the carbon cycle. One key question in this respect is the carbon sequestration by soils (SCS). It is a matter of scientific debate if and how much SCS and related increase of the carbon content in soils can mitigate greenhouse gas emissions into the atmosphere. Contradictorily, several studies have shown that soils lost about 60 Pg of carbon since 1850, i.e. soils are carbon sources. Long-term monitoring activities like the National Soil Monitoring Network can help unravelling this issue. However, if soils should become accountable in carbon trading, extensive and repeated physical soil sampling and eddy covariance flux observations are required. Many different practices are currently in use to get more carbon into the soil, which need to be accompanied scientifically. Additionally, the role of lower soil layers needs to be investigated in more detail. The protection of the carbon stock in soils is important, also in the context of climate change.

Estimating emissions from ground-based and space-borne trace gas observations: Services for climate change mitigation – Dominik Brunner, Empa: Dominik Brunner talked about the estimation of carbon emissions from atmospheric observations and its policy relevance. Reliable emission inventories are required for a variety of current environmental issues, like climate change, stratospheric ozone destruction, or air quality. National agencies and authorities regularly prepare emission inventories, usually based on economic and activity data (bottom-up inventories). Estimates based on atmospheric observations (so-called top-down estimates) can complement the existing inventories as they are independent, can partly distinguish different sectors, or can detect unreported sources. To quantify emissions, (ground-based and/or airborne) atmospheric observations usually are either performed upwind and downwind of specific source areas along with subsequent analysis of the mass balance, or are combined with inverse atmospheric transport modelling. For example, the value of the observation-based emission monitoring was shown by the detection of unexpected emissions of the globally banned ozone-depleting substance CFC-11. For a couple of years already, Switzerland complements its National Inventory Report to the United Framework Convention on Climate Change with top-down estimates for selected greenhouse gases. Bottom-up and top-down comparisons are also performed on a European level. Recently, increasing focus is also given to cities and their carbon footprints.

3.1.3 Discussion, Synthesis and Suggested Way Forward

Han Dolman, as moderator, launched the discussion by asking the panelists for their most pressing observational needs to advance the knowledge and services in the near future. Responses identified that (a) existing data to understand the spatial heterogeneity of how the carbon cycle and the biosphere respond to climate change need to be used more thoroughly, (b) a more systematic combination of ground-based in-situ measurements, integrated column measurements across the whole atmosphere, vertical profiles, and satellite observations is required, (c) measurements should be expanded to data sparse regions including regions where satellites face issues like in the often cloudy tropics, (d) more data on spatially resolved ground-water information of drained organic soils and peatlands are needed, as this provides fairly good proxy information on the emissions of CO_2, CH_4, or N_2O, (e) data on the contribution of peat to vegetation fires should be collected, (f) N_2O in-situ measurement networks should be expanded. The panel restated that measurements and related services need to be fit-for-purpose, and cooperation with stakeholders, like emission inventory builders, national agencies and other (regional) authorities, but also with station operators and data providers should be intensified. The provision of policy-relevant information requires standardisation and uncertainty calculations that go beyond the current research-type approaches. Much also needs to be done in terms of improving climate projections and forecasts at various ranges.

3.2 Energy Balance

3.2.1 Keynote Address: Overview and Challenges

In her keynote presentation Karina von Schuckmann, Mercator Ocean, Toulouse, outlined how understanding of changes in the Earth's energy flows is fundamental for comprehending of the main physical processes driving climate variability and change. She demonstrated how human-caused net positive radiative forcing can be observed as accumulation of additional energy (heating) in the climate system. The keynote stated the importance of separating climate forcing and response. Both components can be better constrained by thorough and long-term observations across the whole range of ECVs. Observations of the Earth's surface energy balance have been going on for the last decades. Satellite measurements of the net radiation at the top of the atmosphere (ToA) and the rate of global ocean heat storage observations have played a central role in refining reconstructions of the Earth's energy balance. Especially the Earth's Energy Imbalance (EEI) as a single number is critical for monitoring global warming and climate change (response) to continued greenhouse gas emissions and land use changes (forcing). The EEI is the portion of the forcing that the Earth has not yet responded to, a critical metric for prospects of continued global warming and effectiveness of climate change mitigation measures. Such single indicators are important for both the scientific community, policy makers and the public since they are a good measure of the effectiveness of climate change mitigation. Climate models and global reanalyses offer a fundamental test bed to document the causal links between the observable forcing and the response components. Future observational systems need to address the substantial surface energy balance residual of 10-15 W/m^2 as well as horizontal energy transport in order to reach regional energy budget closure.

3.2.2 Summaries of National Presentations

The GAW-CH contributions to constraining aerosol radiative impacts with in-situ and remote sensing measurements – Martin Gysel-Beer, PSI: The difficulty with observing atmospheric aerosols is their high variability in space and time, combined with the number of chemical, physical and optical properties that are needed to characterise aerosols and for driving aerosol process / modeling studies. Aerosols are still responsible for the largest uncertainty in determining the effective radiative forcing, and they currently mask greenhouse gas related warming. Aerosol load trends differ around the globe with most (but not all) of Europe having a decreasing and most of Asia having an increasing trend. Aerosols are transported over intercontinental distances. Saharan dust aerosols, for instance, negatively influence German PV production, and North American wildfire events are well visible in the 25-year-long aerosol climatology of the Jungfraujoch. The GCOS and GAW programmes currently ensure the quality and traceability of a global reference network for aerosol properties through the development and calibration activity of PMOD/WRC.

Radiation balance measurements from the Surface and Space – Julian Gröbner, PMOD: The Earth's energy balance is constrained by top-down satellite-based top of atmosphere and bottom-up station-based surface energy balance estimations. PMOD/WRC played a significant role since the 1970-ies in providing high quality sensors, traceability to standards, calibration services and analyses for a better quantification of both radiation estimates. Since the magnitude of the human induced changes in radiative forcing are on the order of a few W/m^2 a cyclic calibration effort combined with a continuous refinement of the world's best standard for both the solar and thermal radiation component is needed. The best-known radiation component is the extraterrestrial solar irradiance. There is now a community consensus for a TSI value of 1361 W/m^2 during the quiet solar phase. In view of providing SI-traceable measurements of surface based solar and terrestrial radiation, an expert group has been established by the WMO to provide a framework for an eventual update of the respective radiation references and thereby reduce the current uncertainties of solar and terrestrial radiation measurements.

Aerosol-cloud interactions in orographic clouds – Observations and simulations – Ulrike Lohmann, ETH Zurich: Orographically induced precipitation is a major source for fresh water and precipitation and will increase in a warmer climate. Orographic precipitation is often initiated in mixed-phase clouds. Measurements of processes in these clouds in orographic terrain are highly demanding and require a coordinated ensemble of in-situ data for instance on a tethered balloon and obtained at high altitude research sites. RACLETS was such a campaign and took place in 2019 near Davos (Ramelli et al. 2021a, b)[10]. During the RACLETS campaign, the seeder-feeder mechanism including ice nucleation and secondary ice production in mixed phase clouds was observed. These insights have been implemented in the COSMO NWP model and improve the simulated orographic precipitation.

Satellite-based radiation and its application – Anke Duguay-Tetzlaff, MeteoSwiss: The aim of international remote sensing programs like the EUMETSAT Satellite Application Facility on Climate Monitoring is ultimately to resolve the full energy and water cycle in space and time and satisfying GCOS accuracy and stability requirements. In order to reach this goal MeteoSwiss developed a joint retrieval of the surface radiation balance (SRB) from historical Meteosat data. It retrieves all SRB components in a single step in order to keep them consistent with each other. Substantial progress was made in calibrating historical satellite data back to the 1980s, which now enables to reproduce yearly and decadal SRB anomalies of BSRN time series. The satellite community however would need more support from aerosol community to get spatially resolved aerosol series back to the 1980s as input for satellite retrievals of the SRB. Currently the Copernicus CAMS aerosol reanalysis ex-

[10] Ramelli, F., Henneberger, J., David, R. O., Lauber, A., Pasquier, J. T., Wieder, J., Bühl, J., Seifert, P., Engelmann, R., Hervo, M., and Lohmann, U.: Influence of low-level blocking and turbulence on the microphysics of a mixed-phase cloud in an inner-Alpine valley, Atmos. Chem. Phys., 21, 5151–5172, https://doi.org/10.5194/acp-21-5151-2021, 2021a.

Ramelli, F., Henneberger, J., David, R. O., Bühl, J., Radenz, M., Seifert, P., Wieder, J., Lauber, A., Pasquier, J. T., Engelmann, R., Mignani, C., Hervo, M., and Lohmann, U.: Microphysical investigation of the seeder and feeder region of an Alpine mixed-phase cloud, Atmos. Chem. Phys., 21, 6681–6706, https://doi.org/10.5194/acp-21-6681-2021, 2021b.

tends back to 2003. Many satellite climate datasets now cover the full WMO Norm period 1991-2020 and can thus be included in national climate applications.

3.2.3 Discussion, Synthesis and Suggested Way Forward

The open discussion that concluded the session was moderated by Karina von Schuckmann and reviewed advancements and remaining challenges in constraining the global scale energy cycle. Opportunities were identified in observing and evaluating changes in regional and local scale energy cycles. The discussion also focused on the major known drivers of the energy cycle such as aerosols, clouds and their impact on the surface budget, as well as on opportunities to refine the linkage between research, services and society.

The panel underscored the critical importance of data control, traceability and sound documentation for global scale measurements. Moreover, the discussion had shown the importance of regular re-evaluation of historical data sets, to increase their stability and robustness and to guarantee their usability as reference measurements. For the example of aerosols, ongoing efforts between the in-situ, the remote-sensing and the re-analysis communities should be pursued. Complementary to single ECV observation studies, joint efforts could further support the development of observing system recommendations, including the filling of measurement gaps. Good examples are the NASA NEWS (NASA Energy and Water Cycle) initiative or the efforts at ETH Zurich to combine surface- and satellite-based observations with models to estimate the Earth's energy budget for the Sixth IPCC Assessment Report (AR6).

Efforts to constrain the global scale energy balance are well underway. The overall recommendations included to continue to foster research advances on understanding the changes in the Earth's energy flows, as well as to embark upon new pathways to determining changes in the energy balance, particularly while bridging the gap between global scale and regional to local scales. Models can play a substantial role in this context. However, we know that e.g. CMIP6 model spread of the surface energy balance of 12 Wm^{-2} (shortwave) and 22 Wm^{-2} (longwave) need to be reduced beforehand. Complex measurement campaigns (but limited in time) involving regional modelers, ground-based and remote sensing observations can feed process studies that will ultimately generate new physical understanding and subsequently generate a more realistic representation of cloud physical processes in models, for instance. The Swiss GCOS and GAW-CH programmes are invited to consider supporting such campaigns.

In view of the current set of GCOS Global Climate Indicators, the panel proposed to promote the EEI as a fundamental measure for the monitoring and communication of climate change to account for missing indicators of the storage components (e.g. for land).

3.3 Water Cycle

3.3.1 Keynote Address: Overview and Challenges

Anny Cazenave, from the International Space Science Institute in Bern, started by making reference to the GCOS IP (GCOS 2016), which aims to improve the monitoring of the global climate cycles, more specifically to close the three cycles for carbon, energy, and water, as well as explaining conditions to the biosphere. Important factors influencing the water cycle are precipitation, evapotranspiration, runoff, water storage (surface waters, snowpack, soil moisture, groundwaters). These are directly linked to climate change and its variability (natural and anthropogenic forcing factors). Of particular importance are the direct human impacts on the water cycle through ground water mining, irrigation, dam building, urbanisation, deforestation and land use change. She also highlighted the following data needs and corresponding challenges:

- Precipitation is in general highly variable in time and space and is often inadequately monitored by surface rain gauge and ground-based radars networks, especially in most lesser-developed countries.
- In mountain areas and high latitudes in-situ rainfall observations are poor and snow is strongly under sampled. The detection of extremes remains a big challenge.
- Evapotranspiration cannot be directly observed, and current estimates are based on complex empirical approaches or process-based models. Satellite observations have too coarse resolutions for applications as drought assessment, water management, agricultural monitoring. Requirements to improve this coverage include high-resolution surface temperature and radiation budgets as well as improved representation of hydro-meteorological and vegetation components.
- For soil moisture, the current coarse resolution of satellite-based passive microwave sensors remains a big challenge, but the perspective of near real-time, high-resolution radar imagery from the Copernicus Sentinel-1 satellites holds great promise.
- River runoff is the most important of all hydrological variables, particularly for water management. Ungauged basins are still a large problem because of insufficient spatio-temporal resolution of the current space observation capabilities. However, the development of Surface Water and Ocean Topography (SWOT) missions will revolutionise this area by providing daily/sub-daily resolution.
- In the topic of groundwater, space gravimetry was recognised as a unique tool for monitoring large aquifers. For small aquifers, it has still too coarse a resolution and is therefore very limited in value for operational applications and decision-making.
- Cryospheric observations are still poorly represented in the global water cycle. Retrieval of cryospheric variables such as snow depth, density, rate of snowmelt, permafrost dynamics, and glacier mass change is still very challenging particularly in mountain areas.

3.3.2 Summaries of National Presentations

Observations for land water resources and drought conditions: Soil moisture and runoff – Lukas Gudmundsson, ETH Zurich: Lukas Gudmundsson presented observations for land water resources and drought connections in relation to soil moisture and runoff. He pointed out that only a small fraction of Earth surface fresh water is available for humans to use. He also showed that water and carbon cycles are related via global feedbacks showing that in globally very dry years, a certain increase in CO_2 growth is observed. There is also an urgent need to improve soil moisture networks, particularly to develop sensor technology that makes the network easier to maintain. He concluded his talk by highlighting that the current anthropogenic climate change is impacting the freshwater dynamics on global scale, and feedbacks are possible consequences at planetary scale. The water cycle observations are crucial for the long-term monitoring of the development and of observing the changes. Some new data-science methods can help to infill some missing values, but validation data is necessary.

Glacier changes and water resources in a changing climate in the water towers of the world – Francesca Pellicciotti, WSL: Francesca Pellicciotti reminded us of that millions of people depend on their water resources of glaciers. Particularly in very dry land environments, summer runoff of glaciers is the main existing water contributor and a vital source for human beings and the whole ecosystem. In addition, glaciers are currently one of the largest contributors to sea level rise. She pointed out that standardised datasets such as the RGI or the WGMS database help to validate models or to calibrate and improve models, which are becoming more and more advanced. A very important point is that new research findings should be included in the newest model generations. Finally, she concluded that long-term observations are very crucial for long-term simulations (strong support of high-altitude observations), and experimental catchments are needed to be further investigated in mountains in more detailed observation plans.

Combining approaches for improved quality and quantity of precipitation estimates in high mountain environments – Nadine Salzmann, University of Fribourg: Nadine Salzmann explained how difficult measurements in the very harsh high mountain environments are to perform. In general, the available data in high mountain areas have very low quality, and inaccuracies and uncertainties constrain the observations. She focused her talk on measurements on high altitude solid precipitation and presented the ‘Cosmic Ray Sensor’ to measure with high accuracy continuous SWE observations. This sensor reveals high observation quality and should be used together with a combination of other sensors. Improved quality and quantity of precipitation (liquid and solid) in high altitudes is a key variable to advance our understanding of rapid ongoing changes (including extremes) which often have far-reaching impacts downstream such as mass movements, droughts and other impacts.

Couple information sources nurture water quality studies and services – Damien Bouffard, Eawag: Damien Bouffard showed the important ecosystems services of lakes. He pointed out that often-conflicting uses of ecosystem services are occurring, and ecosystem services perturbed by local watershed and global climate change forces can be impacted. Today, multiscale temporal and spatial dynamics of lake ecosystem observations are urgently needed and further developed. The following problems must be solved: a) Implement standardised quality assurance for all incoming datasets, b) research limited by limited access to existing datasets and c) limited trust in models and data due to lack of reproducibility and d) limited value of our results if not used by others.

3.3.3 Discussion, Synthesis and Suggested Way Forward

A good part of the panel discussion was dedicated to scale issues showing that, as of today, even under the best conditions for remote sensing, spatial and temporal resolution of our data records is still too low to detect certain changes (e.g. groundwater). Several panelists mentioned that approaches to get better information had to consider a combination of all available measurements (e.g., in-situ measurements, remote sensing and numerical models), including the development of 'super sites' in high-alpine areas using improved data assimilation techniques. New model approaches should also try to bring the different objectives of the Symposium together by combining the carbon, energy and water cycles. A point several participants mentioned is the land evapotranspiration and land water storage, which are main variables associated with large uncertainties and controlled by various mechanisms needing improved measurement networks, also revealing that the overall topic of a better understanding of the global processes between oceans and land should be improved.

Many Symposium presentations, including of the water cycle session, underscored the Swiss contributions as being world-leading in terms of monitoring networks and sound research. Nevertheless, in many data sparse regions neither short nor long-term monitoring is available. Therefore, many presenters and participants in the discussion argued that Switzerland had a responsibility to help particularly the less developed countries to increase and improve observations, especially in data-sparse areas. Also, observing networks are completely missing at high altitudes, important areas to observe environmental changes as they often are the 'Water Towers' for very arid but heavily populated regions. It is precisely in such areas that Switzerland, with its rich experience in processes in the Alpine environment, has the potential to take a leading role in the establishment of long-term observation networks in mountainous areas of lesser-developed countries. However, working in the Global South requires an integrating view with strongly inter- and transdisciplinary work to make the investments in these countries sustainable. Reliable and trustful connections to local stakeholders are indispensable for robust capacity building and further development of the research structure within these developing countries.

4 Conclusions and Recommendations for Future Activities

4.1 General conclusions and Recommendations from the Cycle Sessions

Open and constructive discussions following the individual presentations in all three cycle sessions provided new momentum and highlighted opportunities to contribute to observing, understanding and predicting the entire Earth System, while highlighting the critical importance of each individual cycle and their interlinkages. Opportunities were identified to improve the observation and evaluation of changes in global-, regional- and local-scale cycles. The discussions also focused on the major known drivers of the cycles such as aerosols, clouds and the surface fluxes, soil carbon content and its variability, and the cryosphere component. Emphasis was laid on the need for combined O_2/CO_2 measurements, and modelling studies for specifying CO_2 monitoring systems for in-situ versus remote sensing measurements.

Moderated panel discussions at the end of each of the three cycle sessions served to condense the main messages and allowed the audience that followed the Symposium in live streaming to interact and give input. The following thoughts were offered to the Swiss GAW and GCOS programmes for consideration in their current and future implementation efforts:

Innovation and silo-breaking collaboration across cycles: Exploration of new approaches and methods should be facilitated more strongly. Also, as well as joint efforts are neede to ensure the continued development of existing observing systems, and ideally to close critical measurement gaps. Next-generation numerical weather and climate prediction models simulate an increasing number of Earth System elements and should be recognised and exploited as a natural platform for collaboration.

Approaches to constrain individual and overall fluxes and processes: Overall fluxes within the carbon, energy and water cycles should be explored individually, but also across the cycles. This will help close their balance globally by reducing sources of uncertainties, and identifying calibration and reprocessing needs. New types of uncertainties arise with the possibility of thresholds or tipping points that might be reached under further global warming. Early warning systems can only be designed on the basis of robust and long-term observations. Targeted analyses on a specific focus across all cycles, for example, on mountain areas, should be pursued. This requirement is complementary to single ECV observation studies but could be supported through GCOS or GAW.

Data maintenance and sustainability: Quality control, traceability and a sound documentation for global-, regional- and national-scale measurements are critically important and must be assured. In addition, the importance of regular re-evaluation of historical data sets is important, in order to increase their stability and robustness and guarantee their best possible consistency and compatibility.

Data integration and research: Progress towards a more comprehensive observation coverage should be sought by improving the link between the in-situ, remote sensing, modelling and reanalysis communities. Achievement of a global-scale balance for carbon, energy and water fluxes, cross validation of datasets, and the definition of observational requirements should be performed at different scales, possibly with the help of the setup and promotion of supersites. The cryosphere is notoriously under-observed at the global scale, especially in high-mountain areas.

Knowledge transfer: There is the clear need to transfer knowledge from science to society, and questions remain how to connect the full range from observations and science via climate services to climate communication. 'Climate Indicators' should play a more prominent role for creating such a dialogue, hence the recommendation to extend the current set of GCOS Global Climate Indicators. Knowledge transfer, especially to less developed countries around the globe, is a great opportunity for making the GAW and GCOS programmes more valuable at the global scale. New avenues to most efficiently transfer and export knowledge should be explored. WMO Chief Scientist Jürg Luterbacher underscored that the world can learn a lot from Switzerland.

4.2 Overarching Recommendations of the High-level Closing Panel

A final moderated panel discussion concluded the Symposium. Representatives from the top management of the major Swiss environmental institutions and the WMO summarised and consolidated the main outcomes and recommendations that emerged from the past two days. Thomas Stocker, University of Bern, moderated the discussion; the panel members were Jürg Luterbacher, Chief Scientist of the WMO, Janet Hering, Director of Eawag, Brigitte Buchmann, member of the Board of Directors of Empa, Carlo Scapozza, Head of Hydrology Division FOEN on behalf of Karine Siegwart, Vice Director of the FOEN, and Bertrand Calpini, Deputy Director of MeteoSwiss. This discussion followed five-minute summaries of the international keynote speakers on the carbon, energy and water cycles as well as the services perspective, the latter given by Vincent-Henri Peuch, Head of the CAMS and Deputy Director of the ECMWF Copernicus Services[11]. The discussion converged around the themes of tackling the inherent interdisciplinarity of the Earth System, the perpetual challenge of striving for sufficient high-quality observational data, the indisputable need for more collaboration and knowledge export and, not least, the timeliness of added-value climate services and an effective climate communication. More explicitly, the main conclusions and recommendations are summarised in the following.

Earth System Approach – an Inherent Interdisciplinarity: The panel started by acknowledging the impressive quality and range of results that were achieved in the framework of the GAW-CH and GCOS Switzerland programmes. The panel considered the joining of forces by the programmes as timely and appropriate for this outreach and planning effort. The choice to look at the Earth System as a whole, adds the challenge of interdisciplinarity to the challenges of each individual discipline. On one side, this calls for a wealth of complementary data necessary to describe, understand and predict the Earth System. On the other hand, the need to proceed in a coordinated and targeted manner requires the diverse scientific communities to find ways to strengthen their communication and collaboration. Next to the need to integrating the main Earth System components for a more complete picture, the requirement of geographical coverage of the entire planet adds an additional formidable task. This cannot be tackled within the boundaries of a single country. Additional efforts on education and training, along with a systematic know-how transfer are key.

[11] https://www.copernicus.eu/en/copernicus-services

More Data Needed: Given their monitoring nature, data are at the heart of the GAW and GCOS programmes. There was a clear consensus that the amount of data available at present is partly insufficient and has to increase. Brigitte Buchmann emphasised the importance of having reliable, comparable, long-term measurements to describe cycles and close budgets. Thomas Stocker underscored the need for comparability at the continental and global scales, as well as consistency over many decades. This requirement places high demands on the quality of the measurements and raises the question of optimal task sharing between research and operational institutions. Bertrand Calpini committed to one of the core mandates of MeteoSwiss as a data provider and stressed that his institution has to include additional key variables in its portfolio such as soil moisture and snow water equivalent, to mention but a few. Carlo Scapozza mentioned the transfer of measured hydrologic data via the MeteoSwiss data infrastructure as an exemplary model for inter-institutional collaboration and data integration across distinct parts of the earth system. He also pointed out the necessity of harmonisation and standardisation of hydrological and meteorological data. Janet Hering, on the other hand, recalled that some of the most important time series in the context of global warming were produced by universities. She added that the open data movement is an optimal vehicle to make data widely available, and encourage many to contribute and promote the formulation of consensus statements. In this context Bertrand Calpini made mention of OSCAR/Surface[12], an effort led by Switzerland to support global data exchange. It consists of a web-based platform operated by Switzerland on behalf of WMO to support the documentation of observing capabilities in the framework of the WMO Integrated Global Observing System WIGOS. In the same context, Jürg Luterbacher presented the WMO's recent GBON[13] effort to encourage improved data coverage around the globe, where many data sparse areas still exist.

Closer Collaboration and Know-How Transfer: One major barrier for closer collaboration, Janet Hering said, is the limited time available to each individual scientist. She welcomed the initiative to seek efficiencies in bringing the programmes together as to facilitate the necessary interaction and collaboration. The need for close collaboration between research and operational institutions is quite evident and has been a key focus of GAW-CH and GCOS Switzerland for many years. In fact, numerous innovative measurement approaches were developed and tested over the years, some of which were presented at the Symposium, some were later transitioned into operational activities. Another large area of collaboration can be promoted in the field of combining in-situ and remote sensing observations. The practical impossibility of ever producing sufficient in-situ observations calls for deriving information on essential variables where they are not directly observed. This requires close collaboration with the modelling and data assimilation communities in all disciplines studying the Earth System. As mentioned before, the, capacity building through collaborating with countries in data sparse areas will help to improve close the Earth System cycles at the global and regional scales. Jürg Luterbacher commended the unique way of how interdisciplinary collaboration is promoted in Switzerland, and encouraged institutions to continue the knowledge transfer to less developed WMO members.

Sustainability through Large-scale Added Value Services: The sustainability of the activities promoted by the GAW and GCOS programmes is of prime importance and concern. Jürg

[12] https://oscar.wmo.int/surface/

[13] https://community.wmo.int/gbon

Luterbacher underlined the importance of communicating the benefits of research, systematic observation and forecasts to society. The ECMWF Copernicus Services have done this in an impressive manner. Vincent-Henri Peuch presented the Climate Change and Atmospheric Monitoring Services C3S[14] and CAMS[15], respectively. For example, in the matter of only a few years the C3S has become a reference portal for climate information, predominantly for delivering reanalysis data sets - a fact that points out the importance of data assimilation. For CAMS the modelling system has been extended to include the chemical composition of the atmosphere, with the potential to provide air quality information at a global and regional scale, an important source of information for the WHO. Collaboration with the GAW programme shows promise for further improvements. A Top-down greenhouse-gas emission estimation capability will be developed in the newly started second phase of Copernicus and will be a major element in the European Commission's strategy to mitigate global warming and reduce fossil fuel emissions. Vincent-Henri Peuch expressed his strong wish for Switzerland to join Copernicus, not least because of the innovative contributions of several Swiss institutions to the development of the top-down emission estimation methodology over the last decade. Bertrand Calpini replied that from a scientific and operational perspective there is a very significant interest for Switzerland to become part of Copernicus, sooner rather than later, but that the political way needed to be paved.

As there are only few places on the globe that are as closely monitored as Switzerland, Thomas Stocker concluded the panel discussion with the question if Switzerland had something to offer with respect to increasing and improving the monitoring at the global level. Jürg Luterbacher replied that Switzerland has indeed a lot to offer. He listed the positive spirit and intellectual capacity behind all the research done in GAW-CH and GCOS Switzerland, the solution-oriented collaboration, the pragmatism in seeking and exploiting synergies, the exemplary data stewardship, exchange and integration, as well as the interdisciplinary approach. WMO is strongly driven by the research to services component, and bases its collaborations with stakeholders on interactions of mutual benefit, and he encouraged the two Swiss programmes to embrace these principles. The world can learn a whole lot from Switzerland, Jürg Luterbacher concluded, and the country is a role model of how research can be fueling the advances of GAW and GCOS also on the global scale.

[14] https://www.copernicus.eu/en/copernicus-services/climate-change

[15] https://www.copernicus.eu/en/copernicus-services/atmosphere

Abbreviations

AR6	IPCC Sixth Assessment Report
BSRN	Baseline Surface Radiation Network
C3S	Copernicus Climate Change Service
CAMS	Copernicus Atmospheric Monitoring Service
CFC	Chlorofluorocarbon
CMIP	Coupled Model Intercomparison Project
COSMO	Consortium for Small-scale Modelling
Eawag	Swiss Federal Institute of Aquatic Science and Technology
ECMWF	European Centre for Medium-Range Weather Forecasting
ECV	Essential Climate Variable
EEI	Earth Energy Imbalance
Empa	Swiss Federal Laboratories for Material Science and Technology
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FOEN	Federal Office for the Environment
GAW	Global Atmosphere Watch
GAW-CH	Swiss implementation of the GAW programme
GBON	Global Basic Observing Network
GCOS	Global Climate Observing System
GCOS Switzerland	Swiss implementation of the GCOS programme
IPCC	International Panel on Climate Change
NASA NEWS	NASA Energy and Water Cycle
NIOZ	Royal Netherlands Institute for Sea Research
NWP	Numerical Weather Prediction

OSCAR	Observating Systems Capability Analysis and Review Tool
PMOD/WRC	Physikalisch-meteorologisches Observatorium Davos, World Radiation Center
RACLETS	Project, Role of Aerosols and Clouds Enhanced by Topography on Snow
RGI	Randolph Glacier Inventory
SCS	Soil organic carbon sequestration
SRB	Surface Radiation Balance
SWE	Snow Water Equivalent
SWOT	Surface Water and ocean Topography
ToA	Top of the Atmosphere
WHO	World Health Organization
WGMS	World Glacier Monitoring Service
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization

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Acknowledgements

Foremost, we would like to express our thanks to the Scientific Programme Committee of the Symposium for their work with the Swiss GAW/GCOS programmes both in the lead-up to and during the conference, and whose expertise provided most of the scientific content of the White Paper. We sincerely thank the contributing scientists for their reviews, especially Thomas Stocker and Bertrand Calpini for providing insightful comments to the final manuscript.

We are grateful to all the speakers for their substantial contributions to the Symposium, in particular for the international keynote speakers for giving excellent overviews and facilitating the panel discussions. We extend a special thank you to the Swiss Academy of Sciences (SCNAT) for their financial support, as well as to the Zentrum Paul Klee in Bern for being professional hosts. We thank Loïc Rickenmann, Alicia Pache, and Anna Schmid for assisting their MeteoSwiss colleagues in planning the Symposium. Last but not least, we would like to express our gratitude to the Swiss GAW/GCOS communities, whose active engagement on the virtual platform made the Symposium a fruitful event; an important step towards promoting innovative and collaborative approaches to researching Earth System Science in Switzerland.

Appendices

A Partner Institutions

Table 1: Partner Institutions of the GAW-CH and GCOS Switzerland programmes.

Institution
Agroscope
École polytechnique fédérale de Lausanne EPFL
ETH Zurich
Federal Department of Foreign Affairs FDFA
Federal Institute of Metrology METAS
Federal Office for Agriculture FOAG
Federal Office of Meteorology and Climatology MeteoSwiss
Federal Office of Topography swisstopo
Federal Statistical Office FSO
Istituto Ricerche Solari Locarno IRSOL
Meteodat GmbH
Paul Scherrer Institute PSI
Physical Meteorological Observatory in Davos/World Radiation Center (PMOD/WRC)
ProClim
Scuola Universitaria Professionale della Svizzera Italiana SUPSI
State Secretariat for Education, Research and Innovation SERI
Swiss Academy of Sciences SCNAT
Swiss Agency for Development and Cooperation SDC
Swiss Federal Institute for Forest, Snow and Landscape Research WSL
Swiss Federal Institute of Aquatic Science and Technology Eawag
Swiss Federal Laboratories for Materials Science and Technology Empa
University of Basel

University of Bern
University of Fribourg
University of Geneva
University of Zurich
WSL Institute for Snow and Avalanche Research SLF

B Central Facilities Supported by GAW-CH and GCOS Switzerland

Table 2: Central Facilities supported by the GAW-CH and GCOS Switzerland programmes.

Central Facility	Short Description	Institution
Euro-Climhist[16]	Historical climate database for Switzerland and Europe	University of Bern
GEBA[17]	Global Energy Balance Archive	ETH Zurich
QA/SA Switzerland[18]	Quality Assurance/Scientific Activity Centre for CO, CO2, CH4, O3	Empa, Dübendorf
WCC-Empa[19]	World Calibration Center for CO, CO2, CH4, O3 Empa	Empa, Dübendorf
WGMS[20]	World Glacier Meteorological Service	University of Zurich
WRC-IRS[21]	Infrared radiometry section	PMOD, Davos
WRC-SRS[22]	Solar radiometry section	PMOD, Davos
WRC-WCCUV[23]	World Calibration Center for UV radiation	PMOD, Davos
WRC-WORCC[24]	World Optical Depth Research and Calibration Center	PMOD, Davos

[16] https://www.euroclimhist.unibe.ch/

[17] https://geba.ethz.ch/

[18] https://www.empa.ch/web/s503/qa-sac-switzerland

[19] https://www.empa.ch/web/s503/wcc-empa

[20] https://wgms.ch/

[21] https://www.pmodwrc.ch/weltstrahlungszentrum/irs/

[22] https://www.pmodwrc.ch/weltstrahlungszentrum/srs/

[23] https://www.pmodwrc.ch/weltstrahlungszentrum/wcc-uv/

[24] https://www.pmodwrc.ch/weltstrahlungszentrum/worcc/

C Symposium Programme

Day 1 – Monday, 13th September 2021

9:00		Log-in & virtual welcome
10:00	Opening Session	**Welcome address: Meteoswiss** Betrand Calpini, MeteoSwiss Deputy Director
	10:05	**Welcome address: GAW and GCOS International Programmes** Oksana Tarasova, Head of GAW – WMO Han Dolman, Chairman GCOS Steering Committee – WMO
	10:15	**Information** regarding the structure and agenda of the symposium
	10:20	**Keynote address: WMO perspective** Jürg Luterbacher, WMO Director of Science & Innovation
	10:35	**Keynote address: IPCC perspective** Sonia Seneviratne, Coordinating lead author of the AR6
	11:05	**Keynote address: ECMWF perspective** Vincent-Henri Peuch, Deputy Director of the Copernicus Department at ECMWF
11:45		Lunch break
10:00	Carbon Cycle	**Keynote address: Overview and challenges** Han Dolman, Vrije University Amsterdam
	13:30	**From weather to ecosystem forecasts - Opportunities for reliable carbon cycle and climate impact projections** Benjamin Stocker, ETH Zurich
	13:50	**Combined O_2 and CO_2 measurements as tool for the partitioning of CO_2 emissions among the atmosphere, biosphere and ocean** Markus Leuenberger, University of Bern
	14:10	Short break
	14:20	**Soil carbon sequestration as net emission technology – Where do we stand?** Jens Leifeld, Agroscope

	14:40	**Estimating emissions from ground-based and space-borne trace gas observations: Services for climate change mitigation** Dominik Brunner, Empa
	15:00	**Meet the speakers on gather.town**
	15:20	**Synthesis discussion and main findings** Discussion moderated by Han Dolman
	15:45	**Poster pitches**
16:00		**Virtual poster session & open-end apéro on gather.town**
17:30		End of day 1

Day 2 – Tuesday, 14th September 2021

9:00	Energy Balance	**Keynote address: Overview and challenges** Karina von Schuckmann, Mercator Océan – France
	9:30	**The GAW-CH contributions to constraining aerosol radiative impacts with in-situ and remote sensing measurements** Martin Gysel-Beer, PSI
	9:50	**Radiation balance measurements from the Surface and Space** Julian Gröbner, PMOD
	10:10	Short break
	10:20	**Aerosol-cloud interactions in orographic clouds – Observations and simulations** Ulrike Lohmann, ETH Zurich
	10:40	**Satellite-based radiation and its application** Anke Duguay-Tetzlaff, MeteoSwiss
	11:00	**Meet the speakers on gather.town**
	11:20	**Synthesis discussion and main findings** Discussion moderated by Karina von Schuckmann
	11:45	**Poster pitches**
12:00		Lunch break
13:00		**Virtual poster session on gather.town**
10:00	Water Cycle	**Keynote address: Overview and challenges** Anny Cazenave, ISSI
	14:10	**Observations for land water resources and drought conditions: Soil moisture and runoff** Lukas Gudmundsson, ETH Zurich

14:30		**Glacier changes and water resources in a changing climate in the water towers of the world** Francesca Pellicciotti, WSL
14:50		Short break
15:00		**Combining approaches for improved quality and quantity of precipitation estimates in high mountains environments** Nadine Salzmann, University of Fribourg
15:20		**Coupled information sources nurture water quality studies and services** Damien Bouffard, Eawag
15:40		**Meet the speakers on gather.town**
16:00		**Synthesis discussion and main findings** Discussion moderated by Anny Cazenave
16:00	**Recap**	**Recap of the main points of the symposium** Han Dolman, Karina von Schuckmann, Anny Cazenave, Vincent-Henri Peuch
16:45	**Closing Part**	**Synthesis discussion panel with introductory remarks from Thomas Stocker** Brigitte Buchmann – Empa, Bertrand Calpini – MeteoSwiss, Janet Hering – Eawag, Jürg Luterbacher – WMO, Karine Siegwart – FOEN
		Closing of the symposium Bertrand Calpini, MeteoSwiss Deputy Director
17:35		End of day 2

Day 1 – Poster pitches, 15:45

M1	GCOS	**POC21 Harnessing the Power Of Crowdsourcing to tackle 21st century mountain observation challenges** Reik Leiterer, MountaiNow
M2	GCOS	**Absolute validation of a balloon-borne spectrometer for the upper atmosphere** Simone Brunamonti, Empa
M3	GCOS	**Archiving and publication of sunspot drawings of the Specola Solare Ticinese** Renzo Ramelli, ASST
M4	GCOS	**Hundred years of Swiss glacier changes from historical terrestrial images** Erik Mannerfelt, ETH Zurich
M5	GCOS	**Extending the calibration traceability of longwave radiation time-series in MeteoSwiss and BSRN Archives** Stephan Nyeki, PMOD/WRC

M6	GAW	**Employment of novel tools for the continuous characterization of the carbonaceous fraction in ambient aerosol** Alejandro Keller, FHNW Windisch
M7	GAW	**Development, Validation and Implementation of a GRUAN-Worthy Plug-and-Play Balloon Borne Hygrometer** Frank Wienhold, ETH Zurich
M8	GAW	**FWCC Empa Switzerland** Chritsoph Zellweger, Empa
M9	GAW	**QA/SAC Empa Switzerland** Martin Steinbacher, Empa
M10	GAW	**FTIR measurements at the Jungfraujoch** Emmanuel Mahieu, GIRPAS, University of Liège

Day 2 – Poster pitches, 11:45

T1	GCOS	**Long Swiss Meteorological Series** Stefan Brönnimann, University of Bern
T2	GCOS	**Operational Monitoring of the Rain Rate by Ground-based Microwave Radiometry in Switzerland** Wenyue Wang, University of Bern
T3	GCOS	**'Fractional snow cover time series (1981 – 2021) – a novel data set from space to support climate studies in Switzerland'** Helga Weber, University of Bern
T4	GCOS	**Permafrost monitoring by reprocessing and repeating historical geophysical measurement** Christian Hauck, University of Fribourg
T5	GCOS	**Swiss glacier lake inventory that is about to be published from the AlpineWELLS project** Daniel Odermatt, Eawag
T6	GAW	**Development and application of a novel polar imaging nephelometer and complementing the aerosol measurement program at Payerne towards a new supersite of the ACTRIS research infrastructure** Benjamin Brem, PSI
T7	GAW	**Monitoring of Ice Cloud Forming Aerosols at the Jungfraujoch: Automation of HINC for Continuous INP Monitoring** Jie Chen, ETH Zurich
T8	GAW	**Investigating the future evolution of the ozone layer above Switzerland (INFO3RS)** Luca Egli, PMOD/WRC
T9	GAW	**WORCC – World Optical Depth Research and Calibration Center** Stelios Kazadzis, PMOD/WRC
T10	GAW	**WCC UV PMOD/WRC** Julian Gröbner, PMOD/WRC
T11	GAW	**Aerosol monitoring at the Jungfraujoch** Martin Gysel-Beer, PSI

D List of Participants

Table 3: List of Participants.

Participants		**Institution**
International Speakers		
Cazenave	Anny	ISSI
Dolman	Han	GCOS; VU Amsterdam, NIOZ
Luterbacher	Jürg	WMO
Peuch	Vincent-Henri	ECMWF
Tarasova	Oksana	GAW; WMO
von Schuckmann	Karina	Mercator Océan
National Speakers		
Bouffard	Damien	Eawag
Brunner	Dominik	Empa
Duguay-Tetzlaff	Anke	MeteoSwiss
Gröbner	Julian	ETH Zurich
Gudmundsson	Lukas	ETH Zurich
Gysel-Beer	Martin	PSI
Leifeld	Jens	Agroscope
Leuenberger	Markus	University of Bern
Lohmann	Ulrike	ETH Zurich
Pellicciotti	Francesca	WSL
Salzmann	Nadine	WSL/SLF
Stocker	Benjamin	ETH Zurich
Closing Panel		
Buchmann	Brigitte	Empa
Calpini	Betrand	MeteoSwiss
Hering	Janet	Eawag
Scapozza	Carlo	Federal Office for the Environment
Stocker	Thomas	University of Bern
MeteoSwiss Organisers		
Durmus	Seda	MeteoSwiss
Fontana	Fabio	MeteoSwiss

Klausen	Jörg	MeteoSwiss
Rickenmann	Loïc	MeteoSwiss
Rossa	Andrea	MeteoSwiss
Stalder	Michelle	MeteoSwiss
Werner	Isabelle	MeteoSwiss
Scientific Programme Committee		
Gröbner	Julian	ETH Zurich
Hölzle	Martin	University of Fribourg
Joos	Fortunat	University of Bern
Seneviratne	Sonia	ETH Zurich
Steinbacher	Martin	Empa
Stöckli	Reto	MeteoSwiss
Wild	Martin	ETH Zurich
Virtual Participants		
Adler	Silke	ZAMG
Adler	Carolina	Mountain Research Initiative & GEO Mountains
Aichinger-Rosenberger	Matthias	ETH Zurich
Andres	Hanspeter	Federal Institute of Metrology METAS
Arpagaus	Marco	MeteoSwiss
Bartold	Maciej	Institute of Geodesy and Cartography
Bauder	Andreas	VAW, ETH Zurich
Bernasconi	Ugo	City of Lugano
Bessenbacher	Verena	ETH Zürich
Beutel	Jan	Universität Innsbruck
Bircher-Adrot	Simone	MeteoSwiss
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Brem	Benjamin	PSI
Brönnimann	Stefan	OCCR/GIUB, University of Bern
Brunamonti	Simone	Empa
Bühlmann	Tobias	METAS
Bukowiecki	Nicolas	Universität Basel
Burgstall	Annkatrin	MeteoSwiss
Burri	Susanne	ETH Zurich
Chen	Jie	ETH Zurich
Collaud Coen	Martine	MeteoSwiss
Conen	Franz	University of Basel
Croci-Maspoli	Mischa	MeteoSwiss
Dätwyler	Christoph	University of Bern
de Morsier	Guy	MeteoSwiss
Dehecq	Amaury	ETH Zurich

Dongre	Prateek Kumar	Cardiff University
Egli	Luca	PMOD/WRC
Emmenegger	Lukas	Swiss Federal Laboratories for Materials Science and Technology
Eugster	Werner	ETH Zurich
Fisler	Joël	MeteoSwiss
Franziskakis	Florian	Group on Earth Observations Secretariat
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Hirschi	Martin	ETH Zurich
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Hodel	Elias	VAW, ETH Zurich
Hou	Shengyi	University of Bern
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Manu	Tom	Eawag
Marano	Gina	ETH Zurich
Martin	Belen	WMO

Martín Míguez	Belén	WMO
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Nowak	Nora	PSI
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Rothacher	Markus	ETH Zurich
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Stürzl	Franziska	MeteoSwiss
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