ETH zürich

Center for Climate Systems Modeling

C2SM Annual Report

2022

C2SM Center for Climate Systems Modeling

The Center for Climate Systems Modeling (C2SM) is an extradepartmental science and technology center of ETH Zurich and a joint initiative between ETH Zurich, MeteoSwiss, Empa, and WSL with the main objective to improve the understanding of the climate system and to strengthen the predictive skill of atmospheric models on time scales from days to millennia. The center was established as a competence center of ETH in 2008. It was accredited as a center of the school board in December 2020 hereby gaining a long-term perspective to pursue its goals. This document highlights the main achievements in 2022.

The C2SM Steering Committee, September 2023

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About C2SM

Rationale

There is probably no other societal challenge than climate change that is more deeply intertwined with the technological, economical, and human aspects of society and the natural environment around us. Addressing climate change requires a profound knowledge of these intertwined systems, all of which rests on the understanding of the Earth system and our ability to project its future. This knowledge is needed to address urgent societally relevant questions, such as how can we determine with greater certainty the carbon budget associated with the 1.5 or 2°C warming targets of the Paris agreement, how can we better project the changes in extreme precipitation events, or how can we improve our ability to assess the impact of climate change on ecosystems? Without such an understanding, the Paris target remains a loose goal. Thus, while the climate change problem cannot be solved by climate and weather sciences alone, it remains a key task of this community to provide the best scientific basis for climate change mitigation and adaptation across a wide spectrum of impacted fields.

To provide this scientific basis, numerical simulation has become one of the most important pillars in weather and climate science. Atmospheric models running on modern high performance computing (HPC) systems are large simulation infrastructures with millions of lines of code. Developing and maintaining such a simulation infrastructure goes significantly beyond the capability of individual research groups and institutions. Providing such a simulation infrastructure to its member institutions was the key rationale for the foundation of C2SM in 2008 and has been the cornerstone of its existence ever since. C2SM has substantially contributed to the rise and growing together of the atmospheric modelling community in the Zurich area, enabling it to become one of the leading research communities worldwide. The rationale for a coordinated science and technology platform extends further as individual groups are similarly challenged with the development and application of models, the handling and analysis of large data sets, with the training of researchers in coding and code & data management, and in the areas of education and outreach. In addition, the intertwined nature of the climate change problem requires a concerted and multidisciplinary approach extending from the fundamental aspects of atmospheric and climate science to the study of impacts across a wide range of areas. All this can be achieved by building and supporting a community brought together and supported by a central hub.

Vision

We solve tomorrow's challenges in the analysis and modelling of weather and climate.

Mission

Our overarching objective is to bring the weather, climate, climate impact, computational, and related communities in the Zurich area together in order to improve their ability to analyse, model, and predict multi-scale and multi-component interactions within the Earth System. To this end, our mission is to empower this community by acting

- as a collaborative platform for innovation,
- as a provider of scientific and technical support,
- as an organiser of technical training, and
- as a vehicle for public outreach.

We focus on the development and application of complex models of weather, climate, and the Earth system, including its atmospheric composition. We provide a simulation and data analysis infrastructure for these models and the science that emanates from them. We connect to related disciplines at ETH and beyond to exponentiate research outcomes and to bridge disciplines in the area of climate change impacts, adaptation, and mitigation.

Strategic foci

For the 2021 through 2025 period, C2SM focuses its work on four strategic areas:

(i) Working closely together with the Swiss National Supercomputer Centre (CSCS) and computer scientists at ETH and C2SM's member institutions, as well as international partners, C2SM develops and applies the next generation modelling paradigms in weather and climate. Through this endeavour, not only will the weather and climate models be readied for the next generation of supercomputers, but also will their resolutions be enabled to increase to unprecedented levels.

(ii) C2SM applies and further develops the developed ultrahigh-resolution models considering the interactions between atmospheric dynamics and the other components of the Earth system, such as land surface, ocean, and atmospheric composition.

(iii) In collaboration with MeteoSwiss, C2SM takes the lead in the development of the next generation modelling and data system required to provide the highest quality climate change information for Switzerland to the Swiss people and authorities.

(iv) C2SM works together with experts in the areas of impact and risk modelling to foster the seamless integration of climate impact sciences into weather and climate models.

Activities

Networking

C2SM acts as a network by bringing the scientific community together and creating cross-disciplinary and -institutional synergies through a number of initiatives and processes:

- the initialisation of joint projects through workshops
- creating networking opportunities by organising community-wide scientific seminars and technical workshops
- improved flow of information by publishing a four-monthly C2SM newsletter.

Research coordination

High priority for joint projects during the 2021-2025 period are given to the development of the next generation ICON model within the open ETH project EXCLAIM, which aims at refactoring the model to make it ready for emerging hardware achitectures and to permit high-resolution modelling on the global scale (page 10). Another strategic focus, in collaboration with MeteoSwiss, is the planning for and production of the next generation climate change scenarios to be published in the middle of the 2020s (page 9).

Support for research activities

C2SM maintains, improves, and provides to the center's community a hierarchy of state-of-the-art weather, climate, and climate-related models. In particular, the center is responsible for maintaining the regional climate model COSMO, and maintaining and refining the Earth System Model ICON. This includes providing the associated modules, e.g., for aerosols, atmospheric composition, (biogeo)chemistry, oceans, land surfaces, and clouds.
C2SM also prepares, quality-controls, and disseminates key national and international data sets such as CORDEX and CMIP data to its users who work in the areas of climate scenarios and impacts. It is envisaged to extend the services in the area of climate impacts to also directly and seamlessly integrate impact models in the evaluation chain of our climate models.
C2SM supports its ETH members in organising funding for data storage and computing nodes.

Education and training

C2SM contributes towards an improved training of PhD students through the establishment of projects across research groups, institutions, and disciplines. It trains scientists (PhD students, post docs, etc.) in the areas of data visualisation, data analysis, use and interpretation of climate data, programming, and code and data management. C2SM organises the international Swiss Climate Summer Schools jointly with the Oeschger Center for Climate Research at the University of Bern.

Outreach and events

C2SM raises public awareness related to climate and weather through various channels while focusing on linking with other relevant themes, for which climate change has implications. The primary avenues are the well-established "Klimarunde" and public outreach events such as Scientifica.

Governance

Structure, organisation, and personnel of C2SM

C2SM was established in 2008 as an ETH competence center by the funding partners ETH, MeteoSwiss, Empa, and Agroscope, and it became operational in March 2009. WSL joined the center in 2013 to enhance the collaborations and respective expertise in the area of climate change and climate change impacts. After 12 years, C2SM was transferred to become an extradepartmental center of ETH in the end of 2019. As such, it is directly associated with the school board and reports to the Vice President of Research of ETH and the directorates of its continued partner institutions MeteoSwiss, Empa, and WSL.
As of 31 December 2022, the center includes 41 members, who are professors or senior scientists at the partner institutions (see Annex for a detailed list) and form the center's Plenary.
The C2SM community includes all students, postdoctoral fellows, scientific, and technical staff from the research groups of each member and thus represents a group of over 400 people. Seven members form the Steering Committee (SC) who defines the overall strategy and oversees its implementation. The SC elects a chair and co-chair from its members. The Scientific Advisory Board (SAB) consists of recognised individuals from different Swiss and European institutions and advises and supports the center in its strategic planning (see Annex).
Operationally, the center is run by an executive director, who oversees an administrative office composed of scientific programmers, a data analyst, a project manager, a PR and communication specialist, and an administrative assistant. The scientific programmers and the data analyst are active in the four main focus areas of C2SM: High performance computing (HPC), general weather and climate modelling, climate scenarios, and climate impacts. Four working groups, composed of 6 to 10 C2SM members or researchers meet on a regular basis to discuss and propose the strategy to be developed and the tasks to be performed in each of the areas. The center also supports six software developers and postdocs through specific research projects acquired by C2SM and its members (see page 23 for more details on the current projects). The structure and organisation of C2SM is described in greater detail in the Terms of Reference, which can be downloaded from the C2SM website.

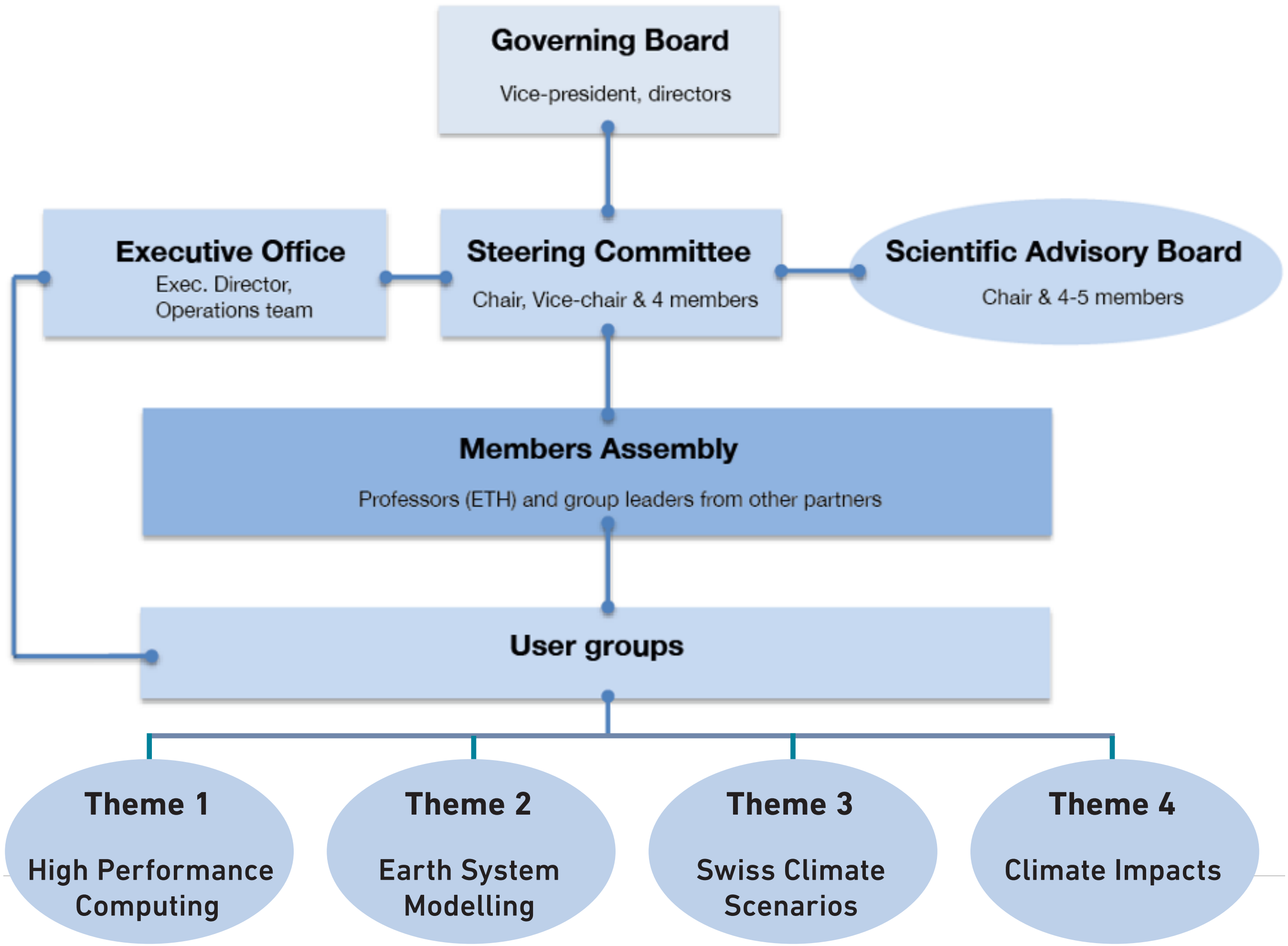
www.c2sm.ethz.ch/the-center/documents.html

Core staff

Role	Name
Executive Director	Christina Schnadt Poberaj
Project manager	Tamara Bandikova
Scientific programmer	Urs Beyerle
Administrative assistant	Rahel Buri
Scientific programmer	Michael Jähn
Scientific programmer	Jonas Jucker
Scientific programmer	Annika Lauber
Scientific programmer	Matthieu Leclair
Scientific programmer / Data analyst	Ruth Lorenz
PR and communication	Tanja Meier

As of 31 December 2022, the core staff corresponds to a total of 5.25 FTE. The administrative assistant is directly supported by the Institute for Atmospheric and Climate Science, and is only paid by C2SM to a small fraction. In addition to the core staff, project fellows and research assistants are supported through funding from different projects.

www.c2sm.ethz.ch/the-center/people.html

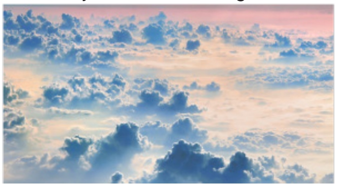


C2SM organisational structure as a science and technology platform (as of January 2021)

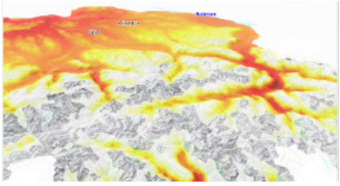
Main achievements

High Performance Computing

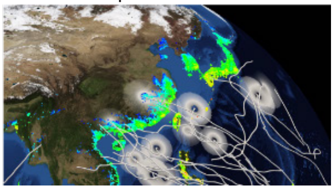
Earth System Modelling



Swiss Climate Scenarios



Climate Impacts



Support for research activities

C2SM provides services and support for research activities organised around its four major themes "High performance computing", "Earth system modelling", "Swiss climate scenarios", and "Climate impacts". This concept is built on the premise that the optimal way to support activities of research groups in the Zurich area is to work jointly on common objectives and to share resources.

C2SM provides the expertise, know-how, and infrastructure to enable and enhance the members' research portfolios and to foster synergies between the members, building upon the respective strengths of the four member institutions.

https://c2sm.ethz.ch/research.html

Highlights from the working groups

Theme 1: Development of next-generation modelling systems for weather and climate

Accelerating the ICON weather and climate model with GPU Ports

ICON (ICOsahedral Nonhydrostatic) is a weather and climate model that has been significantly optimised by porting its code to GPUs (Graphics Processing Units). Previously, the model could only be run on CPUs (Central Processing Units), but with the addition of OpenACC directives, a large part of the code can now be run on GPUs, resulting in faster simulations. Both MeteoSwiss and DWD (Deutscher Wetterdienst) have already ported a significant part of the model to GPUs, but until recently, the 2-moment cloud microphysics, the three-dimensional turbulence scheme, and the lightning potential index (LPI) were still missing. C2SM core team ported these latter routines to GPUs in 2022:

- The 2-moment cloud microphysics scheme plays a critical role in improving the representation of clouds and precipitation in weather and climate models. While the ported code has been optimised for GPUs, the runtime on GPUs is still slower than on CPUs due to the scheme's internal structure. In future work, C2SM plans to restructure the code to further optimise it for GPUs.

- The three-dimensional turbulence scheme has also been successfully ported to GPUs, resulting in a 1.5x speedup in its runtime. The scheme is particularly important for simulating the interactions between the atmosphere and the Earth's surface, which affect wind patterns, temperature, and precipitation.

- The lightning potential index is a parameterisation that predicts the lightning activity in thunderstorms. It is a requirement for the operational weather forecast of MeteoSwiss. As part of C2SM efforts, the code was modified such that it can be run on GPUs.

Overall, the GPU porting of essential schemes in ICON represents a major step forward in the development of the model. As further optimisations are made, researchers can expect even faster, higher-resolved and thus, more accurate simulations, which are critical to understanding the complex dynamics of the Earth's climate system.

Reducing software maintenance for weather and climate models through containers

Containerisation is the packaging of software code with just the operating system libraries and dependencies required to run the code to create a single executable—called a container—that runs consistently on any infrastructure. C2SM core team was able to put a GPU-capable version of COSMO 6.0 into a container. The containerised executable runs as fast as an executable directly built on the supercomputer Piz Daint at CSCS, and more importantly, the physical results are not affected by the container. This is a great success as previous attempts could not achieve correct results for COSMO inside a container. The know-how to containerise complex GPU-applications is very valuable since containers are expected to play a major role in the EXCLAIM project and the upcoming Alps system infrastructure to replace Piz Daint at CSCS.

Theme 2: Earth system modelling

Keeping the ICON model accurate: Stable RBF interpolation

The ICON weather and climate model is being optimised by running its code on GPUs. However, ensuring that the results are accurate is challenging. To validate GPU against CPU simulations, a reference run is generated from multiple CPU runs with slightly different input data. But comparing these results across different machines or compilers can fail, even for simulations run on CPUs only. The culprit is an unstable radial basis function (RBF) interpolation that maps ICON's unstructured grid to a rectangular grid. To address this issue, RBF interpolation coefficients can now be saved and loaded, enabling accurate cross-machine and cross-compiler testing of ICON.

Better visualisations with icon-vis

ICON is becoming increasingly popular for research and operational forecasting. However, visualising model output on the native ICON grid can be challenging as most common plotting routines cannot handle the unstructured grid of ICON. To address this issue, C2SM and MeteoSwiss have developed a collection of plotting routines for ICON using modern Python packages. This tool is publicly available and called "icon-vis". It is available at the **C2SM GitHub**. With "icon-vis", researchers can create more accurate and informative visualisations of ICON model output, improving the analysis and understanding of weather and climate data.

Theme 3: Developing user tailored future climate scenarios

The next generation of Swiss climate scenarios are due approximately in 2025 according to the Federal Council strategy for adaptation to climate change in Switzerland. They will again be prepared in close collaboration between Meteo Swiss, C2SM, and ETH. In 2022 the C2SM EURO-CORDEX database was updated and the additional simulation data were evaluated. The increased database does not change the main picture, and the results from the last published climate scenarios from CH2018 remain valid. This result is also supported by the work carried out by Maximilian Gorfer within his internship at MeteoSchweiz ("maternity replacement" of Ruth Lorenz). M. Gofer compared CMIP5 and CMIP6 global modelling runs in the framework of global warming levels. While substantial differences between models exist in terms of temporal characteristics, high qualitative and quantitative agreement for the global and regional response at specific warming levels exist. Therefore, research and scenario products based on CMIP5 do not lose validity.

In addition, C2SM core staff made high resolution convection resolving regional climate modelling data available for the C2SM community. This data was produced during the EUCP project by the group of Christoph Schär and partners from all over Europe. This data will complement the scenario data available from CH2018 and the updated database for Klima CH2025. Three master students are writing their theses based on this dataset. The students are looking at warm spells, elevation-dependent climate change signals and high impact precipitation events in Switzerland. They will finish their theses in spring 2023.

As part of the preparation of EURO-CORDEX simulations with a GPU version of ICON-CLM, C2SM core team has adapted a processing chain tool developed by the CLM community. It is known as the "Starter Package for ICON-CLM Experiments" (SPICE). It has been modified to run on Piz Daint, as it was previously only available on the German HPC clusters, and is now available for all C2SM members via GitHub. The necessary input data (ERAinterim and ERA5) for climate runs were downloaded directly from Deutsches Klimarechenzentrum (DKRZ) to CSCS. They range from the year 1979 onwards and are regularly synchronised with the original dataset on the DKRZ servers. After completion of the GPU ports within the ICON code for relevant components of the CLM simulations, a first evaluation run will be performed in Q1/2023.

Theme 4: Climate impacts

One of the main needs of C2SM's climate impacts community that has crystallised so far is a need for standardised, documented data sets with easy access. C2SM provides access to a number of datasets and has collected information on its **technical webpage.** We provide datasets such as **CMIP6** or **CORDEX** as downloaded from the Earth System Grid, but also some datasets that have been processed in a certain way. For instance, C2SM has taken over the CMIP6-NextGeneration (CMIP6-NG) archive from Reto Knutti's group. CMIP6-NG contains a number of variables which have been checked for physical plausibility, standardised where necessary and also regridded to a common grid. Similar efforts have been done for the re-analysis dataset MERRA-2 as an example. The originally hourly MERRA2 data is available for some variables on the same grid as CMIP6-NG as daily and monthly data.

Research coordination

C2SM and its community have contributed to the successful acquisition and subsequent implementation of several large collaborative projects addressing a range of topics, particularly in the area of high-performance computing.

PASC HAMAM

ICON-ART and ICON-HAM are essential extensions of the ICON Numerical Weather Prediction (NWP) framework, employed for simulating atmospheric composition and investigating chemistry-climate interactions. At Empa, ICON-ART is instrumental in estimating greenhouse gas emissions from atmospheric observations through a data assimilation framework. The primary aim of the HAMAM project is to augment the computational efficiency of both ART and HAM by harnessing the extensive parallelism capabilities of GPUs. Considerable advancements in 2022 included the transition of the HAM code and the Online Emissions Module (OEM) of ART to GPUs, utilising OpenACC compiler directives. This ensures compatibility with the existing OpenACC code of ICON. In HAM, significant developments included an update to a more recent version of ICON and integration with the RTE-RRTMGP radiative transfer code. For ART, key improvements encompassed redesigning its interface with ICON and the refactoring and porting of the OEM module to GPUs.

The GPU-enhanced versions of ICON-HAM and ICON-ART will facilitate simulations at unprecedented resolutions. The target application for ICON-HAM is a global climate simulation with detailed aerosol representation, fully integrated with a two-moment microphysics scheme at approximately 10 km resolution. For ICON-ART, defined by the EXLAIM project, the target application involves a year-long data assimilation run to estimate European methane emissions.

In the remainder of the project, our plan is to port additional components of ART, including sections pertaining to the gas phase chemistry, to finalise the porting and optimisation of HAM, and to prepare the production runs for the target applications

WEW-ICON

WEW-ICON, short for "Weiterentwicklungen ICON," is a collaborative research and development initiative hosted at C2SM and financially supported by MeteoSwiss. The project is dedicated to enhancing the ICON weather forecast and climate model system, specifically for applications in the Alpine region. This entails integrating high-frequency and high-density observational data. It includes assimilating high-frequency and high-density observational data. Another pivotal aspect of the project involves adapting and testing the ICON model for use on hybrid high-performance architectures and the simulation workflow.

In the current year, essential components required for operational configurations at MeteoSwiss, including radiation, various diagnostics, and a portion of the assimilation code, have been successfully ported to GPUs. The ICON-CH1 configuration, with a horizontal mesh-size of 1km, can now be run on GPUs. On the modelling front, diverse tuning and configuration adjustments for both the ICON model and assimilation processes have been experimented in view of improving forecasting accuracy in the Alpine region.

www.c2sm.ethz.ch/research/wew-cosmo.html

EXCLAIM

The interdisciplinary research initiative EXCLAIM (Extreme scale computing and data platform for cloud-resolving weather and climate modeling) aims to develop an infrastructure based on the ICON model capable of running kilometre-scale climate simulations at both regional and global scales. The simulations will cover complex phenomena such as convective cloud formation, enabling more reliable predictions of extreme weather events like heat waves, heavy rainfall, thunderstorms, and droughts.

EXCLAIM is a six-year (2021-2027) open ETH project that aims to overcome current limitations in hardware, system software, model algorithms, and data infrastructure, in order to create the weather and climate modelling infrastructure of the future. The project brings together some of the most prominent research institutes in Switzerland, including the ETH Zurich, the Swiss National Supercomputer Centre (CSCS), MeteoSwiss, the Swiss Data Science Center (SDSC), and Empa, all under the umbrella of C2SM.

Building of the EXCLAIM development team consisting of six software engineers and two postdocs has been completed in summer 2022. The team is working in close collaboration with the expert teams from MeteoSwiss and CSCS on refactoring the ICON model. Furthermore, we have initiated a productive partnership with SDSC. The EXCLAIM project has received tremendous support from C2SM, which has enabled us to make significant progress toward achieving our goals.

The primary focus of the development team was on expanding the GT4Py Python library (GridTools for Python) using a declarative approach and implementing the ICON dynamical core and microphysics in Python using GT4Py. By the end of the year, we achieved one of the significant milestones: running the first prototype of the ICON dynamical core in Python. We also made progress on ICON software reorganisation and refactoring, which enables interoperability with the implementation of the model in Python. To improve data processing capabilities, we implemented an atmospheric radiation scheme using machine learning and neural networks, which results in faster data processing. In addition, we have developed a new data compression algorithm that is currently being tested. We continue a productive collaboration with our international partners in the ICON consortium (MPI-M, DWD, KIT, DKRZ, C2SM). The contract for C2SM to become a key development partner of the ICON consortium has been finalised and is currently being signed.

https://exclaim.ethz.ch/

Education and training

C2SM organised and carried out several workshops.

COSMO ICON user workshop

In January 2022 C2SM organised the COSMO ICON User Workshop (CIUW) in collaboration with MeteoSwiss and Empa. Due to Covid restrictions the workshop was held online with 13 presentations and an interactive posters-session. The talks covered a wide range of subjects, starting from informing users about pure technical developments in ICON or about latest results from inverse modelling activities at Empa. The main goal of the event is to bring together all COSMO and ICON users in an informal way and to make people aware what kind of research is done with the C2SM-supported models.

https://wiki.c2sm.ethz.ch/MODELS/COSMOCuW2022

Git workshops: beginners & advanced users

C2SM hosted two successful Git workshops - "Git for Beginners" and "Git for Advanced Users" - in June and September 2022. The former was designed to introduce version control systems and common workflows to those with little to no experience. The latter focused on advanced Git features for users with some experience.

The workshops received excellent feedback from attendees, who found them informative, practical, and well-organised. C2SM plans to offer the Git for Beginners workshop on an annual basis, and the Git for Advanced Users workshop on an annual or biennial basis, depending on demand. These workshops provide valuable opportunities for attendees to learn and improve their skills in using Git for efficient software development.

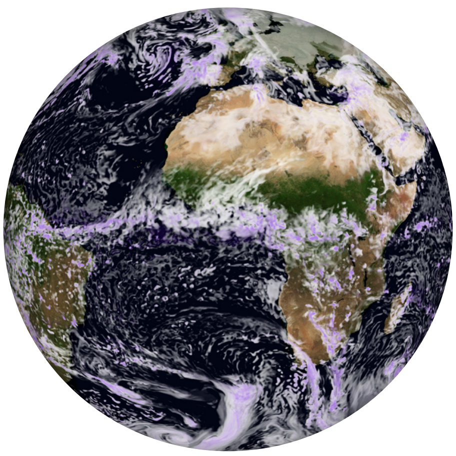
https://github.com/C2SM/git-course

Outreach and events

In 2022, C2SM organised the 9th edition of ETH-Klimarunde.

Wetterextreme im Klimawandel: Wie gut sind wir vorbereitet?

Prolonged periods of heat and drought, storms, heavy precipitation and floods - extreme weather and climate are already affecting millions of people today. Although such events have also occurred in the past, heat waves are now five times more frequent than in pre-industrial times, and 15 to 20 percent of all heavy rainfall can now be clearly attributed to climate change. Also climate models clearly show that many extreme events will become even more frequent and intense due to global warming - with drastic consequences.



In the future, even more regions of the world will be affected by advancing climate change. Extreme heat increases health risks for the population. Periods of drought will increase the risk of forest fires and threaten the the secure supply of food and water. Meanwhile, infrastructure, roads and settlements are increasingly at risk from floods and landslides.

Extreme weather events are also increasing in Switzerland. At ETH-Klimarunde we discussed what this development means for Switzerland in concrete terms. Specifically, we wanted to know how extreme events favour natural hazards and affect the energy supply. The focus was on how we can best adapt to avoid such risks.


Climate change & weather extremes


Impacts in Switzerland


Challenges for energy systems


Handling natural hazards

During the first part 22 table discussions (Tischgespräche) were held at which the participants could interact with experts from ETH, and other scientific institutions, as well as from politics directly. The questions focused on the four main topics "climate change and weather extremes", "impacts in Switzerland", "challenges for energy systems" and "handling natural hazards".

In the second part, Christina Schnadt Poberaj, Executive Director of C2SM held an introduction speech that was followed by presentations of the three keynote speakers. In the first presentation ETH Professor Sonia Seneviratne showed us the latest findings of the IPPC report in regard to weather extremes. This was followed by a presentation by Dr. Christian Schaffner, Executive Director of the Energy Science Center, who elaborated on the impact of weather extremes on the energy supply. Finally, Dr. Norbert Kräuchi pointed out the effects of weather extremes in Switzerland with his insightful presentation "Too much or too little water - extreme weather events as normality in the water castle Switzerland".

Dr. Christina Schnadt Poberaj
Exec. Director Center for Climate Systems Modeling
ETH Zurich

Prof. Sonia Seneviratne
Professor for land-climate dynamics
ETH Zurich

Dr. Christian Schaffer
Exec. Director Energy Science Center
ETH Zurich

Dr. Norbert Kräuchi
Head of landscape and water department
Canton Aargau

The event ended with a lively panel discussion with experts and representatives from science, industry and politics who all got challenged by questions from students of the Rämibühl gymnasium.

We received very positive feedback regarding the quality and the organisation of the event. We would like to thank all our volunteers and our co-organiser, the Energy Science Center, for their support in making this event a great success. Impressions of the event and a video-recording of the presentations and panel discussion can be found on our website:

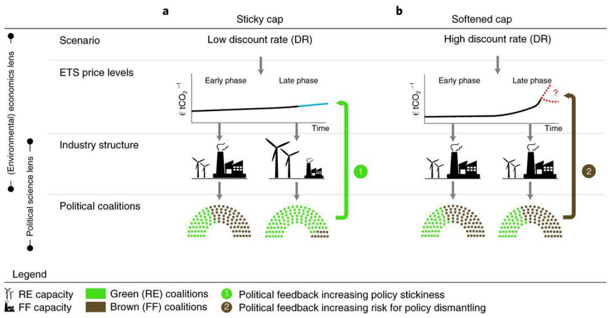
https://c2sm.ethz.ch/events/eth-klimarunde-2022.html

Scientific highlights

Paper: Safeguarding the energy transition against political backlash to carbon markets

Fig. 1: Dynamic policy feedback from allowance prices to politics.

'rom: Safeguarding the energy transition against political backlash to carbon markets

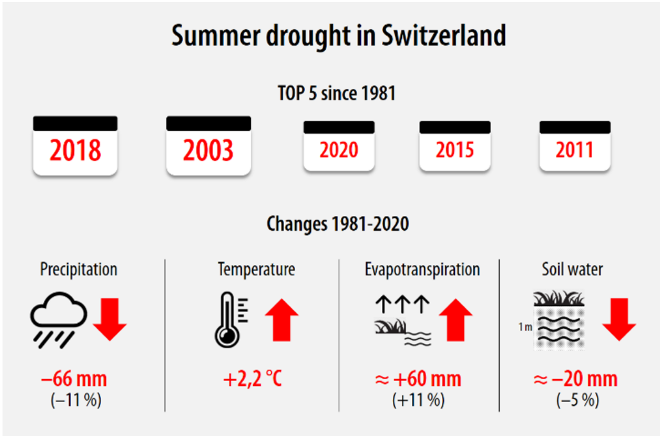


ı, In the case of a low discount rate, prices in the early phase are relatively high, inducing investment that 'greens' the industry structure early on. When the ate phase is reached, predominantly positive feedback ensures that the cap is sticky as indicated by the continuous price path in blue. **b**, The opposite ıolds for a high discount rate, where negative feedback is predominant in the late stage introducing a risk that the cap will be softened as indicated by the ıncertain price path in dashed red. Note that adjustment costs (not shown) are smoothly distributed over time in **a** and concentrated in the late phase in **b**.

Substantial renewable energy (RE) cost reductions have raised the prospect of a subsidy-free RE era of the energy transition. The envisaged policy cornerstones of this era are carbon markets, which create economic incentives for sustaining further RE deployment. However, this overlooks that exposing RE to market risks and increasing interest rates would result in substantially higher financing cost, which in turn would lead to much steeper carbon price paths. The resulting political pressure may provoke a price-depressing regulatory intervention, disrupting further RE expansion. Here we conceptualise this feedback and infer indicators for the risk of such an intervention. By quantifying these indicators for the European Union, we find that increased financing cost could double carbon prices in the long term, halve the rate of renewable capacity deployment in the next 15 years and considerably increase the profits of fossil fuel plants. This implies a substantial risk of pushback that policymakers should safeguard against.

Pahle, M., Tietjen, O., Osorio, S., Egli, F., Steffen, B., Schmidt, T. S., & Edenhofer, O. (2022). Safeguarding the energy transition against political backlash to carbon markets. Nature Energy, (available online). **https://doi.org/10.1038/s41560-022-00984-0**

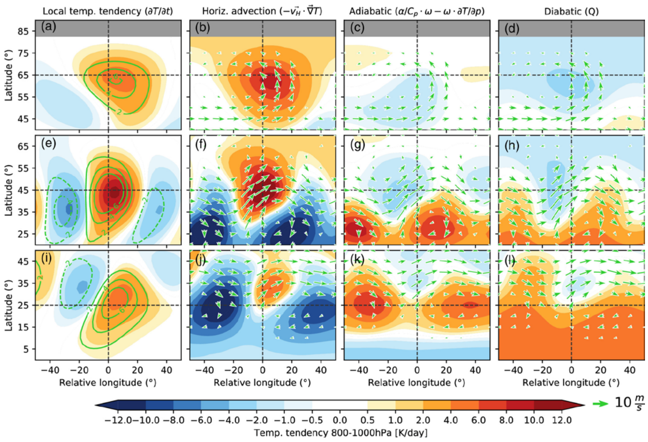
Paper: Trends and drivers of recent summer drying in Switzerland



Drought indicators, evapotranspiration and meteorological data from point observations, reanalyses and regional climate model data have been analysed to assess trends and drivers of summer drought in Switzerland in the period 1981–2020. Indicators from station observations and reanalyses (ERA5 and ERA5-Land) show a clear tendency towards drier summer half-years with a drying in most months from March to October. Both increasing evapotranspiration and a non-significant precipitation decrease are identified as important and roughly equivalent drivers. However, reanalyses show considerable differences for soil water and actual evapotranspiration, especially in drought summers. Variability and trends of the drought drivers temperature and precipitation are also investigated in the EURO-CORDEX regional climate model ensemble. Most simulations considerably underestimate the recent warming and the ensemble shows a large possible range of precipitation changes with a mean change near zero. The study highlights that the analysis of Central European summer drought evolution and its drivers remains challenging.

Scherrer, S.C., Hirschi, M., Spirig, C., Maurer, F., and Kotlarski, S. (2022). Trends and drivers of recent summer drying in Switzerland. Environ. Res. Commun., 4, 025004. **https://doi.org/10.1088/2515-7620/ac4fb9**

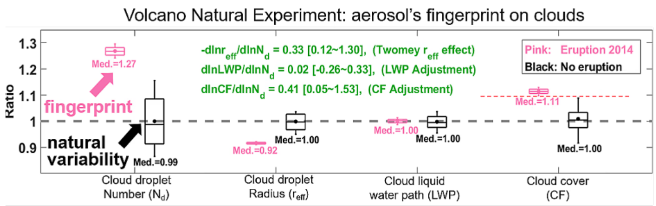
Paper: The role of atmospheric dynamics and large-scale topography in driving heatwaves



Heatwaves are weather events characterised by extreme near-surface temperature anomalies that persist for several days, and therefore lead to catastrophic impacts on natural ecosystems, agriculture, human health, and economies. Different physical processes can contribute to the temperature anomaly associated with heatwaves. Previous studies have shown that increased solar radiation and adiabatic heating associated with blocking systems and local land–atmosphere coupling are important drivers of summer heatwaves. Less is known about the fundamental role of atmospheric large-scale dynamics and topography in generating heatwaves. Here, we perform idealised model simulations where all physical parameterisations are substituted by a simple zonally symmetric temperature relaxation scheme. This allows us to characterise the dynamical processes involved in the life cycle of heatwaves occurring at different latitudes. We find that blocking plays an active role in the life cycle of high- and midlatitude heatwaves, while blocking is less relevant for low-latitude heatwaves. Rossby-wave packets are the dominant drivers for midlatitude heatwaves, with horizontal advection being the main mechanism leading to heat extremes. Heatwaves exhibit a higher persistence and frequency near the pole and Equator compared with the midlatitudes, but a higher intensity in the midlatitudes compared with higher and lower latitudes. Topography located along the midlatitude jet has the largest impact on the heatwave distribution around the planet, resulting in increased heatwave frequency upstream for moderate topographic forcing and a circumglobal increase for topographic elevations above 6 km. Identifying the most relevant processes driving heatwaves can potentially benefit the prediction and representation of extreme events in operational weather and climate forecast systems.

Jiménez-Esteve, B., and Domeisen, D.I.V. (2022). The role of atmospheric dynamics and large-scale topography in driving heatwaves, Q. J. R. Meteorol. Soc. **https://doi.org/10.1002/qj.4306**

Paper: Aerosol's fingerprint on clouds: Increases in cloud cover appear to dominate the cooling effect



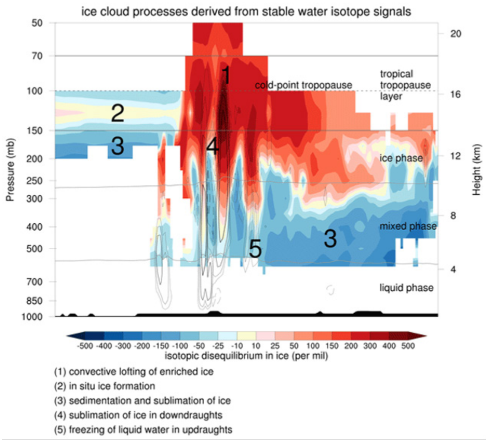
Aerosol's fingerprint on clouds remains the largest uncertainty for climate forcing since decades. The impacts derived from climate models are poorly constrained by observations because retrieving robust large-scale signals of aerosol–cloud interactions is frequently hampered by the considerable noise associated with meteorological co-variability.

To solve this, we pioneer a new novel approach to distinguish the aerosol's fingerprint in clouds from natural variability using an unprecedented effusive volcanic eruption in Iceland in 2014 as a natural experiment. This approach combines modern machine-learning data-science technique and long-term satellite remote sensing records, to generate an emulator which tells us how clouds would look like in the absence of aerosol perturbation.

Our analysis shows that aerosols from the eruption increased cloud cover by approximately 10%, and this appears to be the leading cause of climate forcing, rather than cloud brightening as previously thought. We find that volcanic aerosols do brighten clouds by reducing droplet size, but this has a notably smaller radiative impact than changes in cloud fraction.

Chen, Y., Haywood, J., Wang, Y., Malavelle, F., Jordan, G., Partridge, D., Fieldsend, J., De Leeuw, J., Schmidt, A., Cho, N., Oreopoulos, L., Platnick, S., Grosvenor, D., Field, P., and Lohmann, U. (2022). Machine learning reveals climate forcing from aerosols is dominated by increased cloud cover, Nature Geoscience. **https://doi.org/10.1038/s41561-022-00991-6**

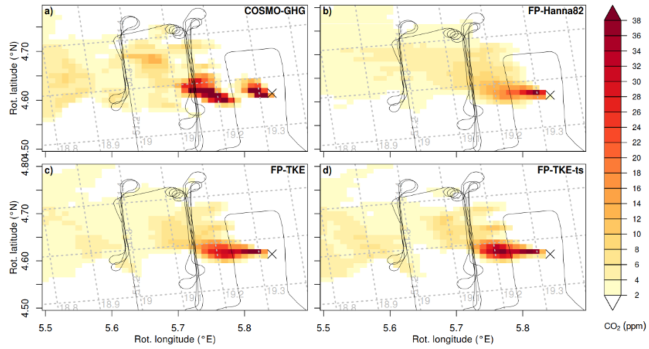
Paper: COSMO simulations of ice clouds in the West African monsoon



This study investigates the formation of ice clouds related to deep convection in the West African monsoon, using stable water isotopes as tracers of moist processes. In the convection-permitting simulations, performed with the COSMOiso model, the following five key processes related to tropical ice clouds can be distinguished based on isotope information (see figure): (1) convective lofting of enriched ice into the upper troposphere, (2) cirrus clouds that form in situ from ambient vapour under equilibrium fractionation, (3) sedimentation and sublimation of ice in the mixed-phase cloud layer, (4) sublimation of ice in convective downdraughts, and (5) the freezing of liquid water just above the 0°C isotherm in convective updraughts. This study demonstrates that isotopes are useful to disentangle the role of different processes in the West African monsoon water cycle and their impact on the tropical tropopause layer. The study has been selected as a highlight paper in ACP.

De Vries, A. J., Aemisegger, F., Pfahl, S., and Wernli, H. (2022). Stable water isotope signals in tropical ice clouds in the West African monsoon simulated with a regional convection-permitting model. Atmos. Chem. Phys., 22, 8863–8895. **https://doi.org/10.5194/acp-22-8863-2022**

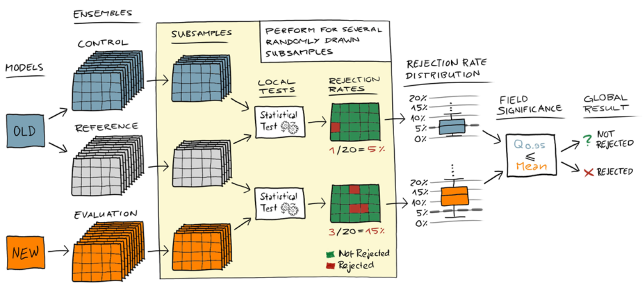
Paper: Lagrangian Particle Dispersion Models in the Grey Zone of Turbulence: Adaptations to FLEXPART-COSMO for Simulations at 1 km Grid Resolution



For the last decade, the atmospheric transport model FLEXPART-COSMO, run at 7 km horizontal resolution, formed the backbone of numerous studies on greenhouse gas emissions. However, when using higher resolution COSMO (1 km resolution) to drive FLEXPART, transport became too dispersive. This study demonstrates that a double representation of turbulent transport (partly resolved by COSMO grid-scale winds, and also parameterised as a stochastic process in FLEXPART) is responsible for additional dispersion. We suggest an alternative turbulence parameterisation for FLEXPART, which aligns the turbulent kinetic energy between COSMO and FLEXPART. The performance of FLEXPART using the new parameterisation is validated against observations of a power plant plume and long-term methane observations at a tall tower site. The new parameterisation clearly improves model performance in both cases. Future inverse modelling of Swiss greenhouse gas emissions is expected to largely benefit from these model developments.

Katharopoulos, I., Brunner, D., Emmenegger, L., Leuenberger, M., and Henne, S. (2022). Lagrangian Particle Dispersion Models in the Grey Zone of Turbulence: Adaptations to FLEXPART-COSMO for Simulations at 1 km Grid Resolution, Bound. Lay. Met. **https://doi.org/10.1007/s10546-022-00728-3c**

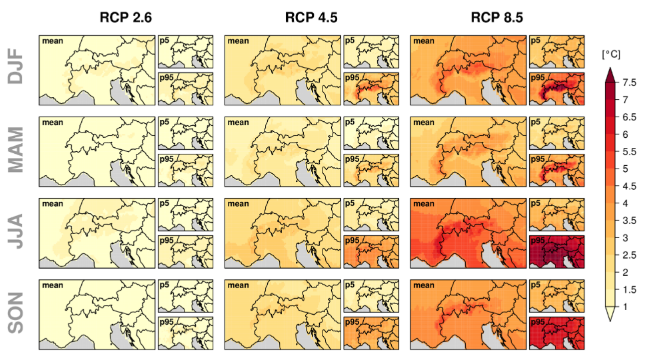
Paper: An ensemble-based statistical methodology to detect differences in weather and climate model executables



Many changes in weather and climate models are not meant to change the model behavior (i.e., code rearrangements or changes in hardware/software infrastructure). However, verifying such changes is challenged by the chaotic nature of our atmosphere, where even rounding errors can significantly impact individual simulations.
We propose a new methodology for quantifying and verifying the impacts of such changes by using ensemble simulations in combination with a statistical hypothesis test at the grid-cell level.
The methodology shows great sensitivity and can detect changes such as a tiny amount of added diffusion or the switch from double to single precision in the COSMO model. However, the test showed no differences after a major system update of Piz Daint or between the GPU and CPU versions of COSMO.
Our results suggest that short-term ensemble simulations are best suited for the methodology, making the test computationally inexpensive and thus ideal for automated testing.

Zeman, C., and Schär, C . (2022). An ensemble-based statistical methodology to detect differences in weather and climate model executables, Geosci. Model Dev., 15, 3183–3203. **https://doi.org/10.5194/gmd-15-3183-2022**

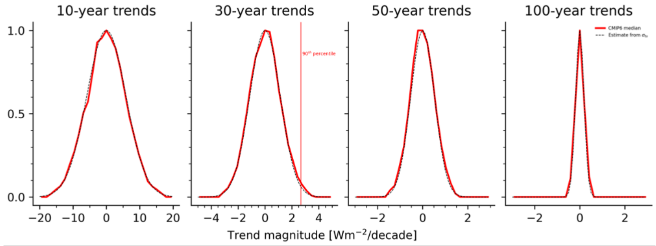
Paper: 21st Century Alpine Climate Change



A new paper published in Climate Dynamics exploits the EURO-CORDEX RCM ensemble (the same ensemble as used for CH2018) to quantify projected future climate change on an Alpine scale. Results reveal that the entire Alpine region will face a warmer climate in the course of the twenty-first century for all emission scenarios considered. Strongest warming is projected for the summer season, for regions south of the main Alpine ridge and for the high-end RCP 8.5 scenario. Depending on the season, medium to high elevations might experience an amplified warming. Model uncertainty can be considerable, but the major warming patterns are consistent across the ensemble. Among other indicators, surface snow cover will be strongly affected by the projected climatic changes and will be subject to a widespread decrease except for very high elevation settings.

Kotlarski S., Gobiet, A., Morin, S., Olefs, M., Rajczak, J., Samacoits, R. (2022). 21st Century Alpine Climate Change. Climate Dynamics. **https://doi.org/10.1007/s00382-022-06303-3**

Paper: Internal variability and decadal-scale trends of surface solar radiation



The climate science community has since long pinpointed the importance of understanding unforced climate variability for a better evaluation of climate projections. Internal variability (a.k.a. noise) arises solely from processes intrinsic to the climate system and is amplified by the non-linear interactions between them. One of the reasons for running forced simulations with many ensemble members is to test the models' response with different background states of the noise. This helps to better distinguish their response to external forcings from noise. Yet it still does not enable a direct one-to-one comparison with observations, because we cannot really simulate all components of the background state in their correct phases and amplitudes at the correct times. We take an alternative, statistical approach to gain a better understanding and quantitative estimate of the influence of internal variability on decadal-scale trends of surface solar radiation (SSR), a key energy budget variable. We performed a statistical analysis on unforced multi-century control simulations from the Coupled Models Intercomparison Project – Phase 6 (CMIP6), which do not include any natural (e.g., volcanoes) or anthropogenic (e.g., greenhouse gases and aerosols) forcings. We show that for annual mean SSR the distribution of all possible N-year trends can be analytically derived from the standard deviation of the underlying time series (σts). This results from two important properties of the annual mean SSR time series: that the distribution of all values is Gaussian and that there is no autocorrelation in time. Based on our analysis, we can estimate the probability of an unforced trend (or the unforced component contributing to a trend) for any location on the planet. The figure shows the simulated trend distribution over different N-year periods for Lindenberg, Germany. At this location, an unforced trend with a magnitude of 2.7 Wm-2/decade can be sustained over 30-years with a probability of 10% (90th percentile of the 30-year trends distribution). The magnitude of unforced trends decreases over longer time scales or when spatially averaged.

Chtirkova, B., Folini, D., Correa, L. F., and Wild, M. (2022). Internal variability of all-sky and clear-sky surface solar radiation on decadal timescales. Journal of Geophysical Research: Atmospheres, 127, e2021JD036332.
https://doi.org/10.1029/2021JD036332

Key publications of C2SM members 2022

*For all publications with more than ten authors we cite the first author together with the author(s) from the C2SM community

Bergamaschi, P., Segers, A., Brunner, D. Haussaire, J. M., Henne, S.; Ramonet, M., Arnold, T., Biermann, T., Chen, H. Conil, S. et al. (2022). High-resolution inverse modelling of European CH4 emissions using the novel FLEXPART-COSMO TM5 4DVAR inverse modelling system. Atmos. Chem. Phys. 2022, 22 (20), 13243-13268.
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https://doi.org/10.5194/gmd-15-3183-2022

Annex

Members as of 31 December 2022

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Dr. Mauro Bianco	CSS	Director of Software, EXCLAIM
Prof. David Bresch	ETH D-USYS, MeteoSwiss	Environmental Decisions
Prof. Manuela Brunner	ETH D-USYS	Hydrology and Climate Impacts
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Dr. Marco Arpagaus	MeteoSwiss	Numerical Predictions
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Dr. Oliver Fuhrer	MeteoSwiss	Numerical Prediction
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Prof. Michael Lehning	WSL	Snow and Permafrost
Dr. Gian-Kasper Plattner	WSL	Climate, Environmental ORD
Dr. Massimiliano Zappa	WSL	Hydrological Impacts
Prof. Niklaus Zimmermann	WSL	Landscape Dynamics

As of 31 December 2022

Scientific Advisory Board (SAB) members

Prof. Bjorn Stevens	MPI-Meteorology, Hamburg, DE
Dr. Karin Ammon	SCNAT, Bern, CH
Dr. Albert Klein Tank	Met Office, Exeter, UK
Prof. John Mitchell	University of Reading, Reading, UK
Dr. Jürg Füssler	INFRAS, CH

The SAB has the mandate to advise the Center on strategic matters and to provide feedback regarding the achievements, as well as the planned developments.

Within the C2SM community

Research projects related to C2SM

A number of projects were initiated within the C2SM community.

Project name	Lead PI	Funding mechanism	Duration
EXCLAIM	N. Gruber (ETH)	ETH	2021 - 2027
scCLIM	D. Bresch (ETH)	SNF	2022 - 2025
PASC HAMAM	D. Brunner (Empa)	PASC	2021 - 2023
WEW-ICON	O. Fuhrer (MeteoSwiss)	MeteoSwiss	2021 - 2026
Klimasz. Technisch	S. Kotlarski (MeteoSwiss)	MeteoSwiss	2020 - 2023
Entwicklung CH2025	S. Kotlarski (MeteoSwiss)	MeteoSwiss	2022 - 2025
OWARNA2	M. Croci-Maspoli (MeteoSwiss)	MeteoSwiss	2022 - 2024
INCA	M. Liniger (MeteoSwiss)	MeteoSwiss	2020 - 2027
Vorhersagbarkeit Trockenheit	M. Liniger (MeteoSwiss)	MeteoSwiss	2022 - 2025

Reporting period (1 January 2022 - 31 December 2022)

Budget

Saldo (CHF) 01/01/2022	436'326

Income (CHF) 01/01/2022-31/12/2022	
ETH School Board	300'000
USYS Department	147'000
Surcharges core staff	15'824
ETH members	56'000
MeteoSwiss	100'000
Empa	70'000
WSL	70'000
Third-party contributions	17'706
Total income	776'530

Expenses (CHF) 01/01/2022-31/12/2022	
Salaries core staff	721'818
Events & education	25'412
Running costs	17'743
Total expenses	752'266

Saldo (CHF) 31/12/2022	447'883

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement des Innern EDI
Bundesamt für Meteorologie und Klimatologie MeteoSchweiz

MeteoSchweiz

Empa
Materials Science and Technology

WSL

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