ETH zürich

Center for Climate Systems Modeling

C2SM Annual Report 2023

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, WSL, and Eawag 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 2023.

The C2SM Steering Committee, May 2024

Visualisation front page:
ICON aquaplanet simulations: low cloud cover at 80 km, 50 km, and 5 km resolutions.
Courtesy: Praveen Pothapakula, EXCLAIM project

Content

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 advances 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 research to provide and/or simplify access to climate model, (re-)analysis, and observational data and to give advice in how to optimally use these data.

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 and other initiatives
- 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

During the 2021-2025 period, high priority for joint projects 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 Klima CH2025 to be published in the end of 2025 (page 9). C2SM also supports and is involved in the ETH domain initiative SPEED2ZERO, which aims at generating scientific insights and developing scenarios, action plans, and a toolbox to enable a sustainable transformation to a net zero greenhouse gas (GHG) and biodiversity-positive Switzerland (page 15).

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 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 maintains the regional climate model COSMO.

C2SM prepares, quality-controls, and disseminates key national and international data sets such as CORDEX and CMIP, as well as (re-)analysis, and specific observational data to its users who work in the areas of climate scenarios and impacts.

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 and postdoctoral researchers through the establishment of projects across research groups, institutions, and disciplines. It trains scientists (PhD students, postdocs, etc.) in the areas of data visualisation, data analysis, use and interpretation of climate data, programming, and code and data management including the use of versioning systems. 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 avenue is the well-established annual one-day event "Klimarunde". C2SM also regularly participates in ETH's National Future day in November each year.

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.

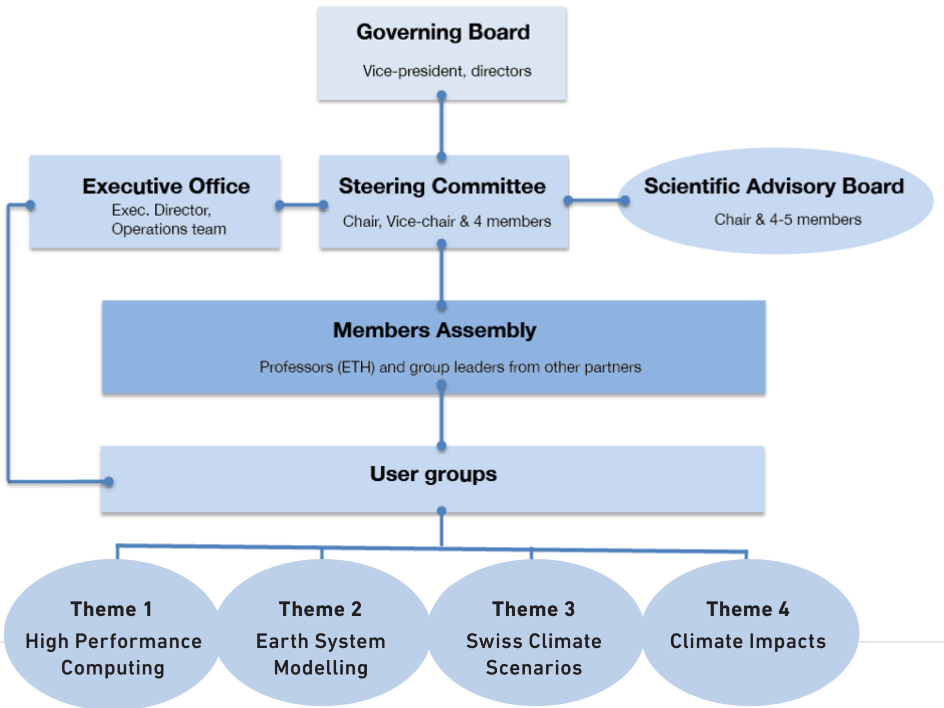
Eawag joins C2SM in 2023

In 2023, Eawag joined C2SM on a trial basis for a year. The collaboration agreed upon is in the area of climate change impacts on Swiss water bodies, which require usage of climate modelling and other data, which C2SM provides.

As of 31 December 2023, the center includes 40 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 of scientific programmers, a project manager, a PR and communication specialist, and an administrative assistant. The scientific programmers 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, consisting 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 by the scientific programmers in each of the areas. The center also supports several software developers and postdocs through specific research projects acquired by C2SM and its members (see page 14 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



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

Core staff

List of people

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

Crosscountry-skiing excursion with the C2SM core team, 2023

As of 31 December 2023, the core staff corresponds to a total of 5.25 FTE. The administrative assistant is directly supported by the ETH-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

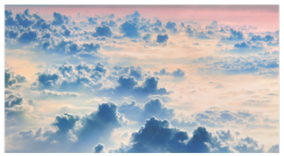
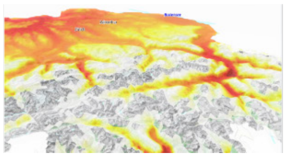
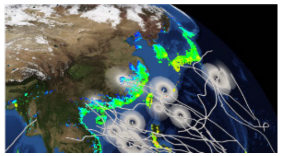
Main achievements

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

GPU port of the three-dimensional turbulence scheme

To speed up the weather and climate model ICON, its code is being ported to GPUs (graphics processing units) in a joint and ongoing endeavour between the National Supercomputing Centre CSCS, MeteoSwiss, Deutscher Wetterdienst (DWD), and C2SM. A significant part of the model had already been ported in previous years. One of the missing features included the three-dimensional turbulence scheme. This scheme was ported to GPUs by C2SM. By this means, the scheme's runtime could be accelerated by a factor of 1.5.

Speed up of two-moment microphysics scheme in ICON

C2SM core staff successfully adapted the two-moment cloud microphysics scheme from Seifert & Beheng (2006) for GPUs, significantly reducing computation time. This scheme, offering a more accurate representation of microphysical processes than the widely used one-moment scheme, was previously too computationally expensive for most applications.

The scheme is available in an implicit and an explicit mode, where the explicit scheme is computationally more efficient and the implicit scheme is potentially more accurate. After a first, unsuccessful GPU port of the implicit scheme in terms of speedup, the port of the explicit scheme resulted to be 4 times faster than its CPU version. Importantly, the overall GPU runtime of the explicit scheme is only 16% slower than the one-moment scheme.

Eventually, the implicit scheme was also improved, allowing the microphysics calculations to run 2 times faster on GPUs than the CPU version. However, the accelerated version is currently available for testing only, as considerable effort is still required to integrate it into the official version of ICON model. Users are encouraged to evaluate the suitability of the explicit scheme for their research.

Finalising the GPU port of hailcast for ICON

The GPU-accelerated variant of the hailcast model, a diagnostic to estimate expected hailsize, has been integrated into ICON from the COSMO model, thanks to a dedicated effort during a master's thesis supervised by MeteoSwiss. Significant progress towards a correct and fully GPU-capable diagnostic was made during that thesis. The remaining issues, which included refining the reset intervals and fixing a bug to ensure successful testing, were addressed by C2SM core staff. It is worth noting that the comprehensive and functional hailcast module is firmly planned to be deployed for operational use by MeteoSwiss in the near future.

Theme 2: Earth system modelling

Processing Chain: a ready-to-use workflow tool for weather and climate simulations

Processing Chain is a Python tool used for running COSMO and ICON workflows including preparing input data and post-processing, which was enhanced by C2SM to support global simulations with the ICON-ART model. However, this and previous enhancements led to increased code complexity, prompting a restructuring to improve clarity and accessibility. The refactoring carried out in 2023 by C2SM core staff aimed to simplify onboarding for new users and enable easier integration of new options. The updated version 3.0 features a user-friendly interface and potential as a workflow tool for climate simulations and applications within the openETH project **EXCLAIM**, among others. In addition, to optimise performance, asynchronous job submissions were implemented to enable parallel execution of tasks. Efforts are now also underway to revise the documentation for improved usability and transition for existing users.

COSMO-CLM²

COSMO-CLM², the coupled version of the COSMO-CLM (Climate Limited-area Modelling) regional climate model and the **NCAR CESM** Community Land Model (CLM) through the OASIS coupler, was ported to COSMO-6 and CLM-5. A major effort was required to compile CLM on Piz Daint. For this, the CLM-OASIS interface had to be completely rewritten, while the COSMO side was already implemented and waiting for testing. The resulting COSMO-CLM² model fully leverages Piz Daint's power: On each node, the COSMO part uses one CPU and the GPU device, while CLM uses the remaining 11 CPUs. The workflow tool of Christoph Schär's group dedicated to long-term COSMO simulations, **DECREMENT**, has been adapted to enable long-term simulations including pre- and post-processing and restarts.

Theme 3: Developing user tailored future climate scenarios

Regional climate modelling with ICON-CLM in EURO-CORDEX setup

One of the use cases of the **EXCLAIM** project are regional climate model (RCM) simulations over Europe using the GPU version of **ICON-CLM.** In this context, CLM stands for Climate Limited-area Modelling. These simulations will also contribute to the Klima CH2025 project. A first 10-year test simulation (driven by ERA5 data, constant aerosol climatology) with a subsequent evaluation analysis against observational data was performed. Before a full evaluation and historical run can take place, the CLM community will provide a novel setup using transient aerosol datasets, specifically the MACv2-SP dataset, together with a standardised ICON version used by all participating groups. The aerosol data have been made available at CSCS. In addition, certain components of the ICON code had to undergo GPU porting. This includes the reading-in of time-varying sea-surface temperature and sea-ice, adapting the upper boundary nudging mechanism and implementing the reading-in process for the transient aerosol data to be compatible with GPU architecture. The latter is still being worked on, while the first two ports have already been completed by the C2SM programmers.

Klima CH2025

Three Master students wrote their master theses within the Klima CH2025 project, supervised jointly by the group of Christoph Schär, Meteo Swiss, and C2SM. They evaluated convection permitting climate model simulation data, which were downloaded by C2SM in the period 2022 - 2023. The data is a multi-model ensemble of convection permitting regional climate model simulations produced during the EUCP project by Christoph Schär's group and partners from all over Europe. One of the goals was to assess the suitability of the data for Klima CH2025. Model simulations are available as time slices of ~10 years, i.e., evaluation (2000-2009), historical (1996-2005), and two slices for RCP8.5, 2041-2050 and 2090-2099.

So far, available (and checked) variables are hourly precipitation and temperature, and daily precipitation, temperature, maximum and minimum temperature. The dataset is available at CSCS and at IAC and documented on the C2SM user landing page (**CORDEX-FPSCONV data**).

Klima CH2025 was officially kicked-off in March 2023. The way forward to deal with the underestimation of recent temperature trends by climate model scenario simulations has been discussed and worked upon. In addition, C2SM work for Klima CH2025 involves work around data infrastructure (Working Group 4, lead by Felix Maurer MCH and Ruth Lorenz C2SM). For better reproducability and traceability, Working Group 4 worked on recommended code management practices for Klima CH2025.

Theme 4: Climate impacts

New member from the impacts community

Eawag is a new member institution of C2SM (cf. page 7). They are primarily involved in the impacts working group. A first meeting was carried out in January 2023 to get to know each other and to find out how C2SM could be most helpful to support climate-related research at Eawag. In fact, the needs are similar to others in the impacts community. Hence, standardised datasets, availability of climate data at single grid points or over well-defined areas such as Switzerland or hydrological Switzerland will be a key deliverable. One main outcome of the meeting was the realisation that many scientists in the impacts community are not used to work with climate model and observational data. The decision to add a "Climate model and climate data workshop" to the course portfolio of C2SM is a direct outcome of this meeting. This workshop was held in December 2023 for the first time (see page 20).

Data from Climate Data Store

On the dataset side,, C2SM core staff downloaded Copernicus European Regional ReAnalysis (CERRA) and CERRA-Land data from Climate Data Store (**cds.climate.copernicus.eu**). This data is a high-resolution (5x5km) regional reanalysis covering all of Europe and provides spatially and temporally consistent historical reconstructions of meteorological variables in the atmosphere and at the surface. The data was downloaded with a time resolution of 3 hours and then processed to daily and monthly values. A first set of variables to be downloaded was defined together with the groups of Manuela Brunner, Reto Knutti, and Sonia Seneviratne.

In addition, daily data and monthly aggregates from ERA5 and ERA5-Land, i.e., means, sums, maximum, and minima depending on the variable, were downloaded from CDS. For ERA5, a list of variables were processed for WSL (**ERA5 variables processed for WSL**). In addition to aggregating to daily values, variable names and units were changed to be as in CMIP data. Some variables not present in ERA5, but CMIP were calculated in a postprocessing step. More details on the datasets can be found on the **C2SM user landing page**.

Coupling seasonal forecast data with CLIMADA

Together with the Weather and Climate Risk Group, C2SM worked on downloading seasonal forecast data provided by DWD from the Copernicus **Climate Data Store** to couple them with the **natural hazard model CLIMADA**. CLIMADA assesses the impact of natural hazards such as heat waves. Two heat indices were calculated globally, i.e., daily mean temperature as used by MeteoSwiss for their heat warnings and a "heat index adjusted" that is adjusted between different temperature thresholds to provide a more accurate index in the tropics. To calculate these indices, 2 metre temperature and 2 metre dewpoint temperature were downloaded from the DWD seasonal forecast system. In addition, anomalies had to be computed as the seasonal forecast data is not bias-corrected. For this purpose, data were downloaded for four months into the seasonal forecasts for the full hindcast period (1993-2016) for starting months January to September. To feed the data into CLIMADA, hazard intensity and frequency then needed to be calculated based on these indices. The work was concluded successfully resulting in a wealth of new knowledge around seasonal forecast data and their integration into CLIMADA.

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 including high-performance computing, Swiss climate change scenarios, impact reseach, and sustainable energy transition.

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, that is capable of running kilometre-scale climate simulations at regional and global scales. EXCLAIM is a six-year (2021-2027) open ETH Zurich project, which brings together ETH Zurich, CSCS, MeteoSwiss, the Swiss Data Science Centre (SDSC) and Empa, all under the umbrella of C2SM.

In 2023, significant progress has been made in software development. The dynamical core of the climate model has been fully developed using the Python library GT4Py and has passed all verification tests, ensuring its reliability and accuracy in simulations. In addition, model components such as microphysics and tracer advection have been successfully ported to GT4Py and initial verification tests have been completed. The migration of the model infrastructure to Python is ongoing, as this is a key step in making the climate model compatible with the Python framework. The implementation of the dynamical core in GT4Py has proven to be on par with the standard OpenACC protocol in terms of performance. Optimisation work has started to further improve the efficiency and speed of the model. In preparation for the transition from the supercomputer Piz Daint to the Alps infrastructure at CSCS, ICON has been successfully deployed and is running on Grace-Hopper compute nodes.

In addition to software development, EXCLAIM is actively building a user platform to facilitate high-resolution simulations, handle large data sets, and manage data pre- and post-processing. Workflow tools such as **AiiDa** are being further developed and adapted for climate simulations.

In parallel with software development, EXCLAIM runs customised configurations of ICON for scientific endeavours. The 10 km and 5 km resolution aquaplanet simulations and the 12 km resolution regional climate simulations have successfully passed all initial validation and verification tests. Preparations for the global aquaplanet simulation at 1.25 km horizontal resolution have started. Furthermore, the model configuration for the TEAMx experiments, one of the EXCLAIM use cases, has been finalised. The research group of Prof. R.J. Wills joined EXCLAIM to run their use case based on prescribed SST at 5 km horizontal resolution globally.

For regional climate simulations in Europe, EXCLAIM uses the GPU-accelerated version of ICON-CLM. The first 10-year test simulation driven by ERA5 data has been conducted, with further evaluation planned using transient aerosol datasets. C2SM core team has successfully ported certain components of the ICON code to GPUs, including adaptations for reading time-varying sea surface temperature and sea ice, as well as upper-boundary nudging. Porting the transient aerosol data compatibility is ongoing and will eventually enable GPU runs of the official ICON-CLM setup.

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 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.

This year's consolidation and optimisation efforts have been ongoing for the ICON model running on GPUs using OpenACC compiler directives. The performance is now sufficient for the ICON-CH1-EPS, ICON-CH2-EPS, and KENDA-CH1 configurations. The ICON-CH1-EPS, covering the Alpine domain at 1km horizontal mesh-size can run with the required time-to-solution on eight A100 Nvidia GPUs on the Alps infrastructure at CSCS.

On the modelling side, the new configurations including the new multi-layer snow scheme have been further developed and rigorously tested. Work has also been ongoing on the simulation's workflow aspects. In particular, prototypes for a novel Python-based tool for post-processing ICON fields and for the utilisation of the field database "FDB," developed at ECMWF, have been successfully finalised.

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

PASC HAMAM

ICON-ART and ICON-HAM are essential extensions of the ICON framework, employed for simulating atmospheric composition, investigating chemistry-climate interactions, and estimating greenhouse gas emissions from atmospheric observations by inverse modelling. 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.

For HAM, the main achievement in 2023 was the completion of the porting to GPU utilising OpenACC compiler directives. A first global simulation was successfully performed with this new ICON-HAM code at 10 km resolution over a short integration duration. This demonstrated the feasibility of global climate simulations at unprecedented high resolution with detailed aerosol representation. Longer simulations will soon be set up, in the context of the EU CleanCloud project for investigating the role of aerosols in tropical cyclones.

For ART, the Online Emission Module (OEM), widely used in atmospheric inverse modelling, has been successfully ported to GPUs. The GPU-enabled code was integrated into the master branch of ICON's KIT repository and is to be included in the open-source release of ICON. An automatic test suite based on the Buildbot continuous integration framework has also been created for the ported ART components. Moreover, a year-long data assimilation run to estimate European methane emissions from in-situ and satellite observations is currently being prepared as a contribution to the ETH EXCLAIM project.

Based on a successful presentation of the HAMAM project at the PASC review meeting in January 2024, a project extension by one year was granted until June 2025. In the remainder of the project, the feasibility of the porting of HAM and ART components through the Gt4Py framework of EXCLAIM will be demonstrated, an improved parallelisation strategy for the transport of many (O(100)) tracers will be implemented, and additional ART components will be ported with a focus on modules required for gas-phase chemistry and inverse modelling.

scClim

The scClim project (Seamless coupling of kilometre-resolution weather predictions and climate simulations with hail impact assessments for multiple sectors) aims to build a seamless model chain from thunderstorm

observations and simulations to the analysis and quantification of hail impacts in Switzerland, under both current and future climate conditions. Structured in five strongly interacting subprojects, scClim utilises high-resolution weather and climate simulations, hail-track analysis from radar data, and process-based probabilistic quantifications of hail risk and impacts on agriculture, buildings and cars.

scClim is a four-year (2022-2025) research project funded by SNF Sinergia that addresses the challenges of modelling the complex small-scale events of thunderstorms and hail, and modelling their impacts for different sectors, with the crucial involvement of and collaboration with stakeholders. The project comprises leading institutes of weather and climate research in Switzerland, including ETH Zurich, the University of Bern, and Agroscope, as well as various stakeholders such as MeteoSwiss and industrial partners.

The collaboration between the subprojects resulted in the development of the initial prototype of an online hail impact assessment platform. The prototype provides comprehensive information about observed and forecasted hail events, including their impacts on buildings and agriculture. Continuous engagement and co-design with stakeholders ensured the relevance of the platform's content. Extensive testing and the feedback gathered will inform the development of the second version of the prototype, scheduled for testing in summer 2024.

Further research of the different subprojects included climate simulations (using the weather and climate model COSMO) for present-day and future conditions, and detailed case studies of extreme hail events in Switzerland, including the development of a hail cell tracking algorithm. Results indicate an increase in hail day frequency in certain regions under future climate scenarios. Furthermore, the reconstruction of past hail

days between 1950 to 2022 using statistical models showed a strong positive trend in yearly hail days in Switzerland. A hail detection algorithm based on radar data was implemented and explored for its potential for hail detection and warning applications. As for hail impacts, a framework for modelling hail damage footprints in agriculture was developed, considering factors such as spatial resolution and crop distribution. Finally, radar-based hail intensity measures and derived impact functions for building and car damages were investigated, addressing uncertainties in hail damage predictions. Here, crowdsourced hail size reports were explored as a potential data source for improving hail damage modelling.

SPEED2ZERO

The joint initiative SPEED2ZERO (Sustainable Pathways of Environmental and Energy Development towards Net Zero Switzerland) aims at contributing to halving greenhouse gas emissions by 2030. To this end, the joint initiative brings together three main disciplines – energy, biodiversity, and climate – and various institutions of the ETH Domain – ETH Zurich, WLS, EPFL, Eawag, EPFL, PSI, Empa, and SDSC.

Through the close and continuous involvement of stakeholders from the private and public sector during the project, new knowledge will help decision-makers and policymakers to achieve the net-zero greenhouse gas targets. The project is supported by the ETH Board and will run from 2023 to 2025.

The activities carried out 2023 are first steps towards positioning the consortium both internally within the partner institutions and externally towards various stakeholders. First, initial scenarios were developed that consider climate extremes, energy system planning, and biodiversity conservation. Second, the integration and linking of models from the various disciplines started in order to analyse the interdisciplinary scenarios and achieve comprehensive results. Third, data was collected and coordinated with ongoing work on the Swiss Climate Scenarios CH2025 (ETH Zurich, C2SM and MeteoSwiss).

In terms of knowledge and technology transfer, a stakeholder workshop was held to discuss different outreach formats, such as interactive platforms for communication of results, a website to debunk myths, and the publication of factsheets.

As the research groups are generating data, integrating models, and expanding simulation platforms, more substantial results, and societal impacts consistent with the project proposal are expected by the end of the second year.

https://speed2zero.ethz.ch/en/

Klima CH2025

Klima CH2025 is a joint project of MeteoSwiss, ETH Zurich and C2SM and further partners. It aims at extending and building upon the CH2018 scenarios to create an updated set of Swiss climate change scenarios providing information to Swiss policymakers in accordance with the National Adapation

Strategy of Switzerland to be updated after 2025. Specifically, it is planned to seamlessly connect information on past, present, and future climate change in Switzerland in this new edition of Swiss climate change scenarios. The scenarios are developed under the umbrella of the National Center for Climate Services (NCCS).

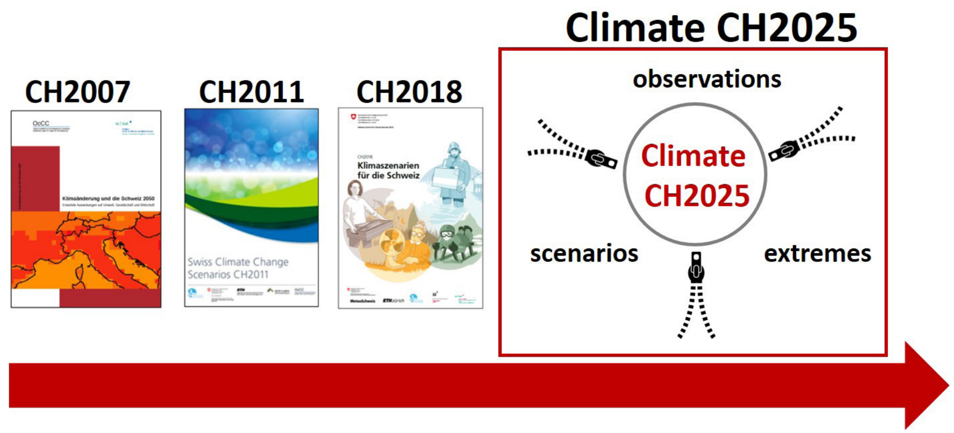
Klima CH2025's activities over 2023 saw a joint meeting between MeteoSchweiz and ETH Zurich (C2SM) take place in January 2023, setting out priorities for the project. These priorities were taken forward as part of the project's official Kick Off meeting in March 2023, involving advisory and collaborative partners.

Milestones were set to quarterly Steering Group meetings held in January, June and September 2023.

Year 1 of the Project was largely devoted to devising the scientific content and context for the Scientific Report and in making key decisions about how to best bring models and observations together. In addition, from April 2023 onwards a communication plan was created, along with monthly team calls to communicate progress.

The developments of the year 2023 provided a good basis for making progress into the main project phase in 2024 and 2025.

https://www.meteoschweiz.admin.ch/ueber-uns/forschung-und-zusammenarbeit/projekte/2023/klima-ch2025.html



Swiss climate change scenarios are regularly updated. Courtesy: MeteoSwiss

Education and training

C2SM organised and carried out several technical trainings in 2023.

COSMO ICON user workshop

In January 2023, C2SM organised the COSMO-ICON User Workshop (CIUW) in collaboration with MeteoSwiss and 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. The event took place at Empa in Dübendorf. The presentations covered a wide range of subjects, ranging from informing users about pure technical GPU developments in ICON to latest results from inverse modelling activities at Empa. The majority of the time was devoted to poster presentations with ample time for discussions. This interactive format was very much appreciated and will be resumed at the next event in 2024.

Python courses 2023

In January and February 2023, C2SM's and Scientific IT Services' (SIS) popular Python workshops took place again. The introductory course, carried out in four half days on 18&19 and 25&26 January 2023, introduced the participants to the basic language features and data types in Python The second course, a two-day workshop on 16-17 February 2023, focused on the visualisation in the Python programming language. Both workshops were fully booked and again very well received by the C2SM community. Based on the popularity and the very positive feedback from the attendees, the workshops will be carried out again in the beginning of 2024.

Workshop on scientific visualisation in Python 2023

Git workshops: beginners & advanced

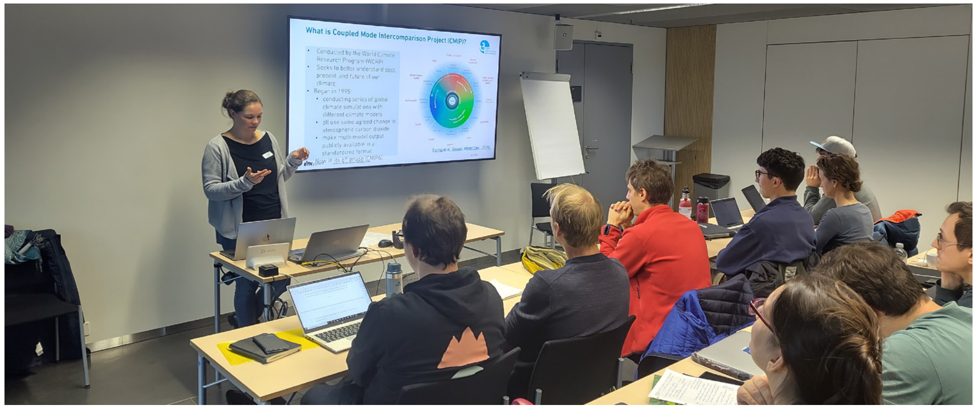
C2SM hosted two successful Git workshops - "Git for Beginners" and "Git for Advanced Users" - in April and September 2023. The former was designed to introduce version control systems and common workflows to those with little to no experience. The latter focused on advanced Git features for users with some experience. The workshops received excellent feedback from attendees, who found them informative, practical, and well-organised. C2SM continues to offer both workshops on an annual basis, as they provide valuable opportunities for attendees to learn and improve their skills in using Git for efficient software development.
https://github.com/C2SM/git-course

Climate models and data workshop

On 6 December 2023, 30 C2SM members from the impacts community met at Eawag in Dübendorf for the first „Climate Model and Climate Data Workshop". In this workshop, C2SM core team gave an introduction to the concept and functionality of climate models. After this introductory overview, various technical aspects were explored including input parameters, the types of output generated, and other considerations such as uncertainties, biases, and model independence. Various observational and reanalysis products were discussed. Furthermore, the process of accessing climate model and observational data at C2SM and other sources was explained.

The workshop also included a brief hands-on session on how to use climate data. The most common data format NetCDF was explained, as well as how to read this into Python and R. Finally, examples for simple calculations using the Climate Data Operators were given.

Based on the very positive feedback received from the participants, it was decided to repeat the workshop in 2024.



Climate models and data workshop 2023

Swiss Climate Summer School 2023

Climate-Water-Energy-Food Nexus

Since 2002, the Swiss climate research community has been committed to sustained education of young researchers in its field, and to ensure a long-term investment in the future generation of young competitive climate researchers. The Swiss Climate Summer School is jointly organised by C2SM, and the Oeschger Centre for Climate Change Research (OCCR) based at the University of Bern on an annual basis.

In 2023, the 21st Swiss Climate Summer School took place at Monte Verità in Ascona, Switzerland, from 3 - 8 September 2023 and focused on the topic of the "Climate-Water-Energy-Food-Nexus". In this highly interdisciplinary school aimed at early stage researchers, the topic of climate change was bridged with sustainable development goals strongly focusing on social, economic, and humanity aspects.

68 participants were offered a comprehensive program that included 12 keynotes lectures given by high-profile national and international lecturers, four workshops, poster sessions, and a concluding round table.

The program included the following lectures:

- Introduction to the Climate-Energy-Water-Food Nexus, Prof. Karin Ingold, U Bern, CH
- A changing climate: How it is modelled, and what are the implications for water, energy and food systems, Prof. Sonia Seneviratne, ETH Zurich, CH
- Water systems and climate: Major trade-offs between water-using sectors across borders and value of coordinated action, Dr. Annukka Lipponen, FI

- Local land use decisions and their global impact, Prof. Rachael Garrett, U Cambridge, UK
- Climate change, extreme weather events, and implications for agricultural and food systems, Prof. Robert Finger, ETH Zurich, CH
- Can fixing dinner fix the planet? Prof. Jessica Fanzo, Columbia University, USA
- Panarchy – Towards transformational resilience, Prof. David N. Bresch, ETH Zurich, CH
- Better safe than sorry about the nexus: The precautionary principle and its impact on the nexus approach, Prof. Claus Beisbart, U Bern, CH
- Low carbon energy innovation: drivers and potentials, Prof. Tobias Schmidt, ETH Zurich, CH
- Climate policies for net-zero GHG-emissions on a domestic and international level, Prof. Ralph Winkler, U Bern, CH
- Linking the nexus approach with exploring co-benefits of SDGs, Prof. Anders Branth Pedersen, Aarhus University, DK

Speakers as well as participants fed back very positively about the contents of the educational program, the motivation, enthusiasm and atmosphere during the discussions after the lectures and at the poster sessions. Certainly, the beauty and sublime aura of Monte Verita with its view of Lake Maggiore also contributed to the overall atmosphere.

Throughout the week, participants showcased their research through scientific posters, which covered a broad range of topics from climate (change), food livelihood, agricultural economics, political and social sciences, humanities, and more. Five poster sessions provided a broad opportunity for the early stage researchers to discuss and obtain feedback on their work from both peers and lecturers, of which ample use was made in lively discussions in the poster hall.

A highlight of the week and a well-deserved break from the scientific programme was the excursion to Monte di Lego, with a detour to the free-floating Cardada viewing platform. The hike led the motivated group up to the summit and then down to Brione through slightly autumnal woodland and repeatedly beautiful viewpoints of the lake over the typical stony ground of the Ticino with many natural steps. The conference dinner in the evening took place in a good-humoured mood in the form of an outdoor barbecue on the railing of Monte Verità.

The week was concluded by three round tables in a fish bowl format. The participants voted on the topics, which were chosen to be water distribution, farming systems under climate change, and how to become a multiplier. This format allowed the attendees to freely express their opinions on these topics and bring in the gained knowledge from the week's program. The statements of the discussion clearly showed that the areas of water, energy, food and climate are closely interlinked and hig hly complex.

To conclude, the school provided the young scientists with a broad spectrum of diverse expertise for their further journey and kick-started or expanded their network to jointly tackle future challenges regarding the Nexus.

https://c2sm.ethz.ch/education/summer-school-2023.html

Outreach and events

In 2023, C2SM organised the 10th edition of ETH-Klimarunde in collaboration with the Energy Science Center (ESC), and the Master Fine Arts of the Zurich University of the Arts (ZHdK).

ETH-Klimarunde 2023

Climate change: From knowledge to action

Periods of extreme heat and drought, devastating forest fires and floods, melting glaciers and ice masses on the polar caps - the consequences of global warming are omnipresent and impressively noticeable. Climate change can no longer be ignored and is now attracting global attention across the political spectrum. The issue has reached the center of society. But despite growing recognition of the reports of the Intergovernmental Panel on Climate Change, global youth for more climate protection and several calls from thousands of scientists, sufficient measures have still not been taken to effectively contain the crisis.

What will it take for politicians, society and individuals - all of us - to bridge the gap between awareness and action? What lessons can we learn from energy transitions of the past to tackle the challenge of climate change? And how can neuroscience help us to think long-term and solution-oriented and to switch from passive to active mode?

The ETH-Klimarunde took place on the 31st of October 2024. In the first part of the event, the visitors engaged in direct dialogue with over 30 climate science experts during the "Tischgespräche" table rounds, centred around the following questions:

Impressions from Tischgespräche Klimarunde 2023, (photo credit Klimarunde Tom Kawara)

- What is the state of knowledge on climate change?
- How does climate change affect Switzerland, and what solutions are available?
- What are the scopes of action and opportunities in science, politics, and economics?
- How can we communicate scientific facts to society?

In the second part of the event, ETH professors and invited guest speakers presented their view on climate change risks, what can be learnt from past energy transitions for the current one, and how we get into action concerning climate change. A special highlight were three keynote lectures:

- Prof. Manuela Brunner explained how we can deal with future climate risks such as wildfires, floods and droughts.
- Prof. Tobias Schmidt showed how previous energy transitions were mastered by societies. He then pointed out which political measures are necessary to accelerate and succesfully transform our current energy system.
- Prof. Maren Urner, guest speaker from Germany, explained why despite awareness it is so challenging for many people to become active concerning climate change. One of her main recommendations was for scientists to talk about solutions rather than problems as talking about problems creates new problems, while speaking about solutions will reate solutions.

More impressions, a full video recording of the presentations and discussions in Audimax, as well as all slides and table round discussion posters can be found at the C2SM website.

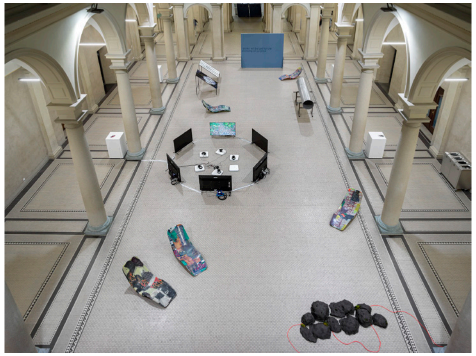
https://c2sm.ethz.ch/events/eth-klimarunde-2023.html

Maren Urner

Audimax, ETH Zurich

For the 10[th] anniversary of Klimarunde, C2SM partnered with Zurich University of the Arts (ZHdK) to present climate change from a unique perspective through the art exhibition "Of Each Absence." This collaboration between science and art provided a distinctive opportunity to make climate change feel more immediate and personal, thereby encouraging action. The art works were created especially for this occasion by students of the Master's program and were showcased in the main hall during Klimarunde and two consecutive days.

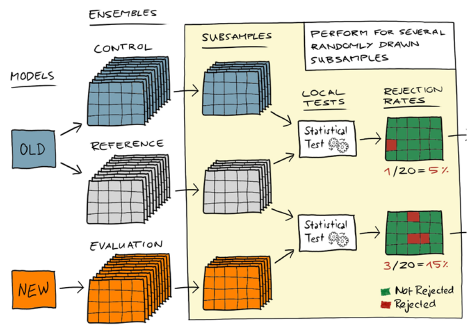
https://c2sm.ethz.ch/events/eth-klimarunde-2023/fotos-kunstausstellung.html



ZHdK artists ZHdK artists (left to right): Judith Welter (curator), Yue Wu, Francisca Patrocínio, Massimiliano Rossetto, Martin Anderegggen, Arthur Heck, Samantha Zaugg, Aleyna Günay, Stefan Schellinger, Nicola Genovese (production coordinator), photo credit: Cédric Mussano

Scientific highlights

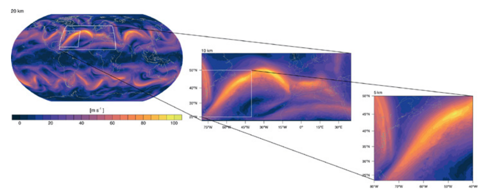
Paper: Application of the pseudo-global warming approach in a kilometer-resolution climate simulation of the tropics



Tropical clouds are an important component of the climate system as they can either amplify or dampen human-induced climate change. However, predicting how clouds will change in a warming climate is challenging due to their small-scale nature. We perform high-resolution atmospheric climate simulations over the tropical Atlantic to study what we can learn about tropical clouds from this relatively novel type of models. We validate the simulation under current climate conditions and find a good representation of tropical clouds in comparison to coarser climate models. In particular, the high-resolution simulation does not suffer from the double intertropical convergence zone (ITCZ) problem commonly present in global climate models. We then study how tropical clouds will change in a warming climate and find differences between our high-resolution simulation and coarser climate simulations. The tropical overturning (Hadley) circulation weakens in both model types, but the narrowing of the ITCZ (known as the deep-tropics squeeze) is not so pronounced in the high-resolution simulation, likely due to the absence of a double ITCZ bias.

Heim, C., Leutwyler, D., & Schär, C., (2023). Application of the pseudo-global warming approach in a kilometer-resolution climate simulation of the tropics. J. Geophys. Res. Atmos., 128, e2022JD037958 https://doi.org/10.1029/2022JD037958

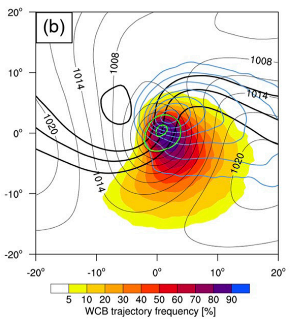
Paper: Toward Eliminating the Decades-Old "Too Zonal and Too Equatorward" Storm-Track Bias in Climate Models



Most people in the mid-latitudes will experience climate change through changes in their daily weather. Much of the daily weather variability is determined by the propagation of extratropical low pressure systems. The direction of propagation of these systems dictates regional precipitation patterns, and an accurate representation of the track is important to reduce uncertainties in future projections. However, climate models simulate tracks that are too zonal (i.e., east–west), too close to the equator and too weak. Using an idealised simulation, this study shows that individual tracks will propagate more poleward, intensification rates will increase and the tracks become less zonal at storm-resolving model resolution, helping to reduce this well-known circulation bias in climate models.

Schemm, S. (2023). Toward eliminating the decades-old "too zonal and too equatorward" storm-track bias in climate models. Journal of Advances in Modeling Earth Systems, 15, e2022MS003482
https://doi.org/10.1029/2022MS003482

Paper: Warm Conveyor Belts in Present-Day and Future Climate Simulations



This two-part study is the first that explicitly identified warm conveyor belts, based on trajectory calculations, in global climate simulations. Warm conveyor belts are moist ascending airstreams in extratropical cyclones that lead to intense precipitation and strongly influence Rossby wave dynamics. Thanks to the cooperation with colleagues from Reto Knutti's group, 3-dimensional wind fields at 6-hourly resolution were available from 50 years of CESM1 simulations both for the present-day and future climate (under the RCP8.5 scenario) to calculate the trajectories. The first part shows that WCBs are represented reasonably well in CESM1 in terms of location and occurrence frequency compared to ERA-Interim. In a future climate, important changes are found in the characteristics of WCBs. The increase in inflow moisture (up to 30% in certain regions and seasons) leads to (i) an increase in WCB-related precipitation, (ii) a strong increase in diabatic heating in the mid-troposphere, and (iii) a higher outflow level, which favours WCBs more strongly interacting with the upper-level Rossby waveguide. Part 2 the considers the effect of this increasing WCB intensity in the future climate on the associated cyclones and shows that WCB-related PV production will be even more important for explosive cyclone intensification than in the present-day climate.

Joos, H., M. Sprenger, H. Binder, U. Beyerle, and H. Wernli (2023). Warm conveyor belts in present-day and future climate simulations – Part 1: Climatology and impacts, Weather Clim. Dynam., 4, 133-155
https://doi.org/10.5194/wcd-4-133-2023

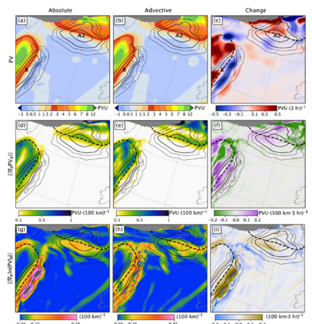
Binder, H., H. Joos, M. Sprenger, and H. Wernli (2023). Warm conveyor belts in present-day and future climate simulations – Part 2: Role of potential vorticity production for cyclone intensification, Weather Clim. Dynam., 4, 19-37
https://doi.org/10.5194/wcd-4-19-2023

Paper: The Pseudo-Global-Warming (PGW) Approach: Methodology, Software Package PGW4ERA5 v1.1, Validation and Sensitivity Analyses

The term "pseudo-global warming" (PGW) refers to a simulation strategy in regional climate modelling. The strategy consists of directly imposing large-scale changes in the climate system on a control regional climate simulation (usually representing current conditions) by modifying the boundary conditions. This differs from the traditional dynamic downscaling technique where output from a global climate model (GCM) is used to drive regional climate models (RCMs). The PGW climate changes are usually derived from a transient global climate model (GCM) simulation. The PGW approach offers several benefits, such as lowering computational requirements, flexibility in the simulation design, and avoiding biases from global climate models. However, implementing a PGW simulation is non-trivial, and care must be taken not to deteriorate the physics of the regional climate model when modifying the boundary conditions. To simplify the preparation of PGW simulations, we present a detailed description of the methodology and provide the companion software PGW4ERA5 facilitating the preparation of PGW simulations. In describing the methodology, particular attention is devoted to the adjustment of the pressure and geopotential fields. Such an adjustment is required when ensuring consistency between thermodynamical (temperature and humidity) changes on the one hand and dynamical changes on the other hand. It is demonstrated that this adjustment is important in the extratropics and highly essential in tropical and subtropical regions. We show that climate projections of PGW simulations prepared using the presented methodology are closely comparable to traditional dynamic downscaling for most climatological variables.

Brogli, R., Heim, C., Mensch, J., Sørland, S. L., and Schär, C. (2023). The pseudo-global-warming (PGW) approach: methodology, software package PGW4ERA5 v1.1, validation, and sensitivity analyses, Geosci. Model Dev., 16, 907–926
https://doi.org/10.5194/gmd-16-907-2023

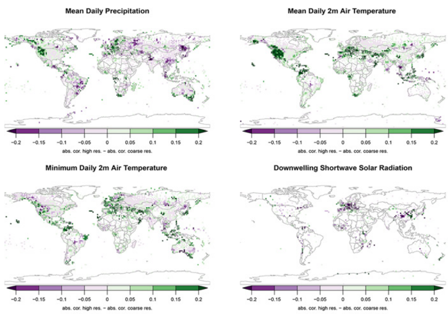
Paper: Jet Stream Dynamics from a Potential Vorticity Gradient Perspective: The Method and its Application to a Kilometre-Scale Simulation



The influence of adiabatic and diabatic processes on the midlatitude circulation is a formidable research question, especially considering their projected changes under global warming. This study presents the prospects, merits, and caveats of a potential vorticity (PV) gradient perspective as a means to disentangle the contributions of adiabatic and diabatic processes affecting the midlatitude circulation. Theoretical considerations reassess the link between the PV gradient and the jet stream. They reveal that the maximum isentropic PV gradient is consistently located on the stratospheric side of the jet, whereas the gradient of is shifted to the tropospheric side but, in general, is better aligned with the jet axis. The stratospheric shift of the PV gradient results from variations in stability across the tropopause, whereas the tropospheric shift of the gradient results from variations in vorticity. Regions of high PV gradient may serve as a proxy for the curvature of the wind field in the case of sufficiently small variations in stability. Otherwise, they depict variations in both wind and thermal stratification along tropopause-intersecting isentropic surfaces. Lagrangian "PV gradient thinking" is demonstrated in two case studies of jet streak evolution in a simulation with 1.1 km grid spacing performed with the graphics-processing-unit-enabled numerical weather prediction model Consortium for Small-Scale Modelling featuring on-line air parcel trajectories. Dry deformation drives the Lagrangian evolution of the PV gradient in the first case, whereas there is a pronounced influence of diabatic modification in the second case. The Lagrangian PV gradient perspective presented offers fresh insight into adiabatic and diabatic processes underlying the midlatitude circulation variability and change.

Bukenberger, M., Rüdisühli, S. & Schemm, S. (2023). Jet stream dynamics from a potential vorticity gradient perspective: The method and its application to a kilometre-scale simulation. Quarterly Journal of the Royal Meteorological Society, 149(755, 2409–2432
https://doi.org/10.1002/qj.4513

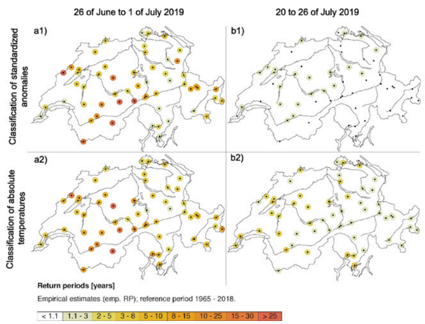
Paper: Daily 1 KM Meteorological Forcing Data for Climate Impact Studies



Many impacts of climate change happen at high spatio-temporal resolutions that are not covered by current global climate datasets. Here we present CHELSA-W5E5, a climate forcing dataset at daily temporal resolution and 30 arcsec spatial resolution for air temperatures, precipitation rates, and downwelling shortwave solar radiation. This dataset is a spatially downscaled version of the 0.5 W5E5 dataset using the CHELSA V2 topographic downscaling algorithm. The downscaling generally increases the accuracy of climate data by decreasing the bias and increasing the correlation with measurements from meteorological stations. The topographically downscaled climate data compares well with a dynamical downscaling using a regional climate model, as time series from both sources are similarly well correlated to station observations. This is remarkable given the lower computational cost of the CHELSA V2 algorithm compared to WRF and similar models. The dataset can be downloaded using the ISIMIP data portal:
https://doi.org/10.48364/ISIMIP.836809.3

Karger, D.N., Lange, S., Hari, C., Reyer, C.O.P., Conrad, O., Zimmermann, N.E., Frieler, K. (2023). CHELSA-W5E5: Daily 1 km meteorological forcing data for climate impact studies. Earth System Science Data.
https://doi.org/10.5194/essd-15-2445-2023

Paper: On the Statistical Distribution of Temperature and the Classification of Extreme Events Considering Season and Climate Change – an Application in Switzerland



With the increased occurrence of hot spells in recent years, there is growing interest in quantifying the recurrence of extreme temperature events. However, pronounced temperature anomalies occur all year round, and a reliable classification in terms of the time of occurrence in the year is needed. We present a novel approach to classifying daily air temperatures that take into account the seasonal cycle and climate change. We model the distribution of the daily Swiss temperatures using the skewed generalised error distribution with four time-varying parameters, thereby accounting for non-Gaussianity in daily air temperature, while the climatic trend is modeled linearly with smoothed northern hemisphere temperature as an explanatory variable. The approach is suitable to classify historical and current extreme temperatures with respect to the temperature range expected at the time of the event and offers new possibilities to analyse daily air temperature.

Gubler, S., Fukutome, S., and Scherrer, S.C. (2023). On the statistical distribution of temperature and the classification of extreme events considering season and climate change – an application in Switzerland. Theor. Appl. Climatol., 153, 1273–129
doi.org/10.1007/s00704-023-04530-0

Paper: Detection and attribution of an anomaly in terrestrial photosynthesis in Europe during the COVID-19 lockdown

Carbon dioxide (CO_2) uptake by plant photosynthesis, referred to as gross primary production (GPP) at the ecosystem level, is sensitive to environmental factors, including pollutant exposure, pollutant uptake, and changes in the scattering of solar shortwave irradiance (SWin) – the energy source for photosynthesis. The 2020 spring lockdown due to COVID-19 resulted in improved air quality and atmospheric transparency, providing a unique opportunity to assess the impact of air pollutants on terrestrial ecosystemfunctioning. However, detecting these effects can be challenging as GPP is influenced by other meteorological drivers and management practices. Based on data collected from 44 European ecosystem-scale CO_2 flux monitoring stations, we observed significant changes in spring GPP at 34 sites during 2020 compared to 2015–2019. Among these, 14 sites showed an increase in GPP associated with higher SWin, 10 sites had lower GPP linked to atmospheric and soil dryness, and seven sites were subjected to management practices. The remaining three sites exhibited varying dynamics, with one experiencing colder and rainier weather resulting in lower GPP, and two showing higher GPP associated with earlier spring melts. Analysis using the regional atmospheric chemical transport model (LOTOS-EUROS) indicated that the ozone (O_3) concentration remained relatively unchanged at the research sites, making it unlikely that O_3 exposure was the dominant factor driving the primary production anomaly. In contrast, SWin increased by 9.4 % at 36 sites, suggesting enhanced GPP possibly due to reduced aerosol optical depth and cloudiness. Our findings indicate that air pollution and cloudiness may weaken the terrestrial carbon sink by up to 16 %. Accurate and continuous ground-based observations are crucial for detecting and attributing subtle changes in terrestrial ecosystem functioning in response to environmental and anthropogenic drivers.

Tang ACI, Buchmann N et al. (2023). Detection and attribution of an anomaly in terrestrial photosynthesis in Europe during the COVID-19 lockdown, Science of The Total Environment, Volume 903,2023, 166149, ISSN 0048-9697
doi.org/10.1016/j.scitotenv.2023.166149

Paper: Extracting flowering phenology from grassland species mixtures using time-lapse cameras

Understanding the impacts of climate change on plant phenology is crucial for predicting ecosystem responses. However, accurately tracking the flowering phenology of individual plant species in grassland species mixtures is challenging, hindering our ability to study the impacts of biotic and abiotic factors on plant reproduction and plant-pollinator interactions. Here, we present a workflow for extracting flowering phenology from grassland species mixtures using near-surface time-lapse cameras. We used 89 image series acquired in plots with known species composition at the Jena trait-based experiment (Germany) to develop random forest classifiers, which were used to classify images and compute time series of flower cover for each species. The high temporal

resolution of time-lapse cameras allowed to select images in proper light conditions, and to extract vegetation indices and texture metrics to improve discrimination among flowering species. The random forest classifiers showed a high accuracy in predicting the cover of Leucanthemum vulgare, Ranunculus acris, and Knautia arvensis flowers, whereas graminoid flowers were harder to predict due to their green-to-brownish colours. The proposed workflow can be applied in climate change studies, ecosystem functioning, plant external pagecommunity ecologycall_made, and biodiversity change research, including the investigation of effects of species richness on individual species' flowering phenology. Our method could be a valuable tool for understanding the impacts of climate change on plant reproduction and ecosystem dynamics.

Andrea D, Bachofen C, Dalponte M, Klaus V H, Buchmann N (2023). Extracting flowering phenology from grassland species mixtures using time-lapse cameras, Remote Sensing of Environment,Volume 298, 2023, 113835, ISSN 0034-4257
https://doi.org/10.1016/j.rse.2023.113835

Key publications of C2SM members

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

Andrea D., C. Bachofen, M. Dalponte, V.H. Klaus, and N. Buchmann (2023): Extracting flowering phenology from grassland species mixtures using time-lapse cameras, Remote Sensing of Environment,Volume 298, 2023, 113835, ISSN 0034-4257
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https://doi.org/10.5194/acp-23-2699-2023

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Annex

As of 31 December 2023

Steering Committee members (7)

Prof. Reto Knutti, Chairman	ETH D-USYS	Climate Physics
Dr. Dominik Brunner	Empa	Atmospheric Modelling
Prof. Manuela Brunner	ETH D-USYS	Hydrology and Climate Impacts
Dr. Mischa Croci-Maspoli	MeteoSwiss	Climate Change, Climate Services
Prof. Nicolas Gruber	ETH D-USYS	Environmental Physics
Dr. Gian-Kasper Plattner	WSL	Climate, Environmental ORD
Prof. Sonia Seneviratne	ETH D-USYS	Land-Climate Dynamics

Regular members (40)

Prof. Reto Knutti	ETH D-USYS	Climate Physics
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
Prof. Nina Buchmann	ETH D-USYS	Grassland Sciences
Prof. Harald Bugmann	ETH D-USYS	Forest Ecology
Prof. Paolo Burlando	ETH D-BAUG	Hydrology and Water Resources
Prof. Nuria Casacuberta Arola	ETH D-USYS	Physical Oceanography
Prof. Tom Crowther	ETH D-USYS	Integrative Biology
Dr. Anurag Dipankar	ETH D-USYS	Director of Science, EXCLAIM
Prof. Daniel Farinotti	ETH D-BAUG, WSL	Glaciology
Prof. Nicolas Gruber	ETH D-USYS	Environmental Physics
Prof. Ulrike Lohmann	ETH D-USYS	Atmospheric Physics
Prof. Nicolai Meinshausen	ETH D-MATH	Statistics
Prof. Anthony Patt	ETH D-USYS	Human-Environment System
Prof. Christoph Schär	ETH D-USYS	Climate and Water Cycle
Prof. Sebastian Schemm	ETH D-USYS	Circulation of the Atmosphere
Prof. Tobias Schmidt	ETH D-GESS	Energy and Technology Policy
Prof. Thomas Schulthess	ETH D-PHYS	Theoretical Physics
Prof. Sonia Seneviratne	ETH D-USYS	Land-Climate Dynamics
Prof. Heather Stoll	ETH D-ERDW	Climate Geology
Prof. Heini Wernli	ETH D-USYS	Atmospheric Dynamics
Prof. Martin Wild	ETH D-USYS	Climate and Radiation
Prof. Lenny Winkel	ETH D-USYS	Environmental Geochemistry
Dr. Dominik Brunner	Empa	Atmospheric Modelling
Dr. Lukas Emmenegger	Empa	Air Pollution/Environmental Technology
Prof. Christof Appenzeller	MeteoSwiss	Analysis and Forecasting
Dr. Marco Arpagaus	MeteoSwiss	Numerical Predictions
Dr. Mischa Croci-Maspoli	MeteoSwiss	Climate Change, Climate Services
Dr. Oliver Fuhrer	MeteoSwiss	Numerical Prediction
Dr. Sven Kotlarski	MeteoSwiss	Climate Evolution
Dr. Xavier Lapillonne	MeteoSwiss	Computing
Dr. Mark Liniger	MeteoSwiss	Climate Prediction
Dr. Carlos Osuna	MeteoSwiss	Computing
Dr. Cornelia Schwierz	MeteoSwiss	Climate Monitoring
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
Dr. Martin Schmid	Eawag	Surface Water

As of 31 December 2023

Scientific Advisory Board (SAB) members

Prof. Bjorn Stevens	MPI-Meteorology, Hamburg, DE
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
SPEED2ZERO	R. Knutti (ETH)	ETH	2023 - 2025
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	2021 - 2023
Entwicklung CH2025	S. Kotlarski (MeteoSwiss)	MeteoSwiss	2022 - 2025
OWARNA2	M. Croci-Maspoli (MeteoSwiss)	MeteoSwiss	2022 - 2024
INCA	M. Liniger (MeteoSwiss)	MeteoSwiss	2020 - 2027
Machine Learning	M. Liniger (MeteoSwiss)	MeteoSwiss	2020 - 2023
Vorhersagbarkeit Trockenheit	M. Liniger (MeteoSwiss)	MeteoSwiss	2022 - 2025

Reporting period (1 January 2023 - 31 December 2023)

Budget

Saldo (CHF) 01/01/2023	**447'883**

Income (CHF) 01/01/2023-31/12/2023	
ETH School Board	300'000
USYS Department	147'000
Surcharges core staff	28'712
ETH members	52'000
MeteoSwiss	100'000
Empa	70'000
WSL	50'000
Eawag	40'000
Third-party contributions	10'000
Total income	817'712

Expenses (CHF) 01/01/2023-31/12/2023	
Salaries core staff	751'720
Events	47'513
Operational costs	48'463
Contribution to SPEED2ZERO	10'000
Total expenses	857'696

Saldo (CHF) 31/12/2023	**407'899**

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