



Earth Virtualization Engines (EVE)

Bjorn Stevens¹, Stefan Adami^{2,3}, Tariq Ali⁴, Hartwig Anzt^{5,6}, Zafer Aslan⁷, Sabine Attinger⁸, Jaana Bäck⁹, Johanna Baehr¹⁰, Peter Bauer^{11,*}, Natacha Bernier¹², Bob Bishop¹³, Hendryk Bockelmann¹⁴, Sandrine Bony¹⁵, Veronique Bouchet¹², Guy Brasseur¹, David N. Bresch^{16,17}, Sean Breyer¹⁸, Gilbert Brunet¹², Pier Luigi Buttigieg¹⁹, Junji Cao²⁰, Christelle Castet²¹, Yafang Cheng²², Ayantika Dey Choudhury²³, Deborah Coen²⁴, Susanne Crewell²⁵, Atish Dabholkar²⁶, Qing Dai²⁷, Francisco Doblas-Reyes²⁸, Dale Durran²⁹, Ayoub El Gaidi³⁰, Charlie Ewen³¹, Eleftheria Exarchou³², Veronika Eyring^{33,34}, Florencia Falkenhoff³⁵, David Farrell³⁶, Piers M. Forster³⁷, Ariane Frassoni³⁸, Claudia Frauen¹⁴, Oliver Fuhrer¹⁷, Shahzad Gani³⁹, Edwin Gerber⁴⁰, Debra Goldfarb⁴¹, Jens Grieger⁴², Nicolas Gruber¹⁶, Wilco Hazeleger⁴³, Rolf Herken⁴⁴, Chris Hewitt¹², Torsten Hoefler¹⁶, Huang-Hsiung Hsu⁴⁵, Daniela Jacob^{46,47}, Alexandra Jahn⁴⁸, Christian Jakob⁴⁹, Thomas Jung¹⁹, Christopher Kadow¹⁴, In-Sik Kang⁵⁰, Sarah Kang^{51,1}, Karthik Kashinath⁵², Katharina Kleinen-von Königslöw¹⁰, Daniel Klocke¹, Uta Kloenne⁵³, Milan Klöwer⁵⁴, Chihiro Kodama⁵⁵, Stefan Kollet⁵⁶, Tobias Kölling¹, Jenni Kontkanen⁵⁷, Steve Kopp¹⁸, Michal Koran⁵⁸, Markku Kulmala⁹, Hanna Lappalainen⁹, Fakhria Latifi⁵⁹, Bryan Lawrence⁶⁰, June Yi Lee^{61,62}, Quentin Lejeun⁵³, Christian Lessig⁶³, Chao Li¹, Thomas Lippert⁵⁶, Jürg Luterbacher¹², Pekka Manninen⁵⁷, Jochem Marotzke¹, Satoshi Matsouoka⁶⁴, Charlotte Merchant⁶⁵, Peter Messmer⁵², Gero Michel⁶⁶, Kristel Michielsen⁵⁶, Tomoki Miyakawa⁶⁷, Jens Müller⁶⁸, Ramsha Munir⁵⁹, Sandeep Narayanasetti²³, Ousmane Ndiaye⁶⁹, Carlos Nobre⁷⁰, Achim Oberg¹⁰, Riko Oki⁷¹, Tuba Özkan-Haller⁷², Tim Palmer⁷³, Stan Posey⁵², Andreas Prein⁷⁴, Odessa Primus⁵⁸, Mike Pritchard⁵², Julie Pullen⁷⁵, Dian Putrasahan¹, Johannes Quaas⁷⁶, Krishnan Raghavan²³, Venkatachalam Ramaswamy^{65,77}, Markus Rapp³³, Florian Rauser⁷⁸, Markus Reichstein⁷⁹, Aromar Revi⁸⁰, Sonakshi Saluja^{81,82}, Masaki Satoh⁶⁷, Vera Schemann²⁵, Sebastian Schemm¹⁶, Christina Schnadt Poberaj¹⁶, Thomas Schulthess^{16,83}, Cath Senior³¹, Jagadish Shukla⁸⁴, Manmeet Singh²³, Julia Slingo^{31,*}, Adam Sobel⁸⁵, Silvina Solman^{86,87}, Jenna Spitzer⁴³, Detlef Stammer¹⁰, Philip Stier⁷³, Thomas Stocker⁸⁸, Sarah Strock⁸⁹, Hang Su²⁰, Petteri Taalas¹², John Taylor⁹⁰, Susann Tegtmeier⁹¹, Georg Teutsch⁵⁸, Adrian Tompkins²⁶, Uwe Ulbrich⁴², Pier-Luigi Vidale^{60,92}, Chien-Ming Wu⁹³, Hao Xu²⁷, Najibullah Zaki⁵⁹, Laure Zanna⁴⁰, Tianjun Zhou²⁰, and Florian Ziemann¹⁴

¹Max Planck Institute for Meteorology, Germany

²Technical University of Munich, Germany

³AI engineering GmbH, Germany

⁴University of Liverpool, United Kingdom

⁵University of Tennessee, United States

⁶Karlsruhe Institute of Technology, Germany

⁷Istanbul Aydın University, Turkey

⁸Helmholtz Centre for Environmental Research - UFZ, Germany

⁹University of Helsinki, Finland

¹⁰University of Hamburg, Germany

¹¹Destination Earth, European Centre for Medium-Range Weather Forecasts, United Kingdom

¹²World Meteorological Organization, Switzerland

¹³International Centre for Earth Simulation Foundation, Switzerland



- ¹⁴German Climate Computing Center (DKRZ), Germany
- ¹⁵LMD/IPSL, CNRS, Sorbonne University, France
- ¹⁶ETH Zurich, Switzerland
- ¹⁷Federal Office of Meteorology and Climatology (MeteoSwiss), Switzerland
- ¹⁸Esri Inc., United States
- ¹⁹Alfred Wegener Institute for Polar and Marine Research, Germany
- ²⁰Institute of Atmospheric Physics - Chinese Academy of Sciences, China
- ²¹AXA Climate, France
- ²²Max Planck Institute for Chemistry, Germany
- ²³Indian Institute of Tropical Meteorology, India
- ²⁴Yale University, United States
- ²⁵University of Cologne, Germany
- ²⁶Abdus Salam International Centre for Theoretical Physics, Italy
- ²⁷Tencent, China
- ²⁸Barcelona Supercomputing Center (BSC), Spain
- ²⁹University of Washington, United States
- ³⁰National Centre of Meteorology, United Arab Emirates
- ³¹Met Office, United Kingdom
- ³²MITIGA Solutions, Spain
- ³³German Aerospace Center, Germany
- ³⁴University of Bremen, Germany
- ³⁵Max Planck Institute for Dynamics and Self-Organization, Germany
- ³⁶Caribbean Institute for Meteorology & Hydrology, Barbados
- ³⁷University of Leeds, United Kingdom
- ³⁸Brazilian National Institute for Space Research, Brazil
- ³⁹Indian Institute of Technology Delhi, India
- ⁴⁰New York University, United States
- ⁴¹Amazon Web Services, United States
- ⁴²Freie Universität Berlin, Germany
- ⁴³Utrecht University, Netherlands
- ⁴⁴MINE Inc., United States
- ⁴⁵Research Center for Environmental Changes - Academia Sinica, Taiwan
- ⁴⁶Helmholtz-Zentrum Hereon, Germany
- ⁴⁷Climate Service Center Germany (GERICS), Germany
- ⁴⁸University of Colorado Boulder, United States
- ⁴⁹Monash University, Australia
- ⁵⁰Indian Ocean Center / Second Institute of Oceanography, India
- ⁵¹Ulsan National Institute of Science and Technology, South Korea
- ⁵²NVIDIA Corporation, United States
- ⁵³Climate Analytics, Germany
- ⁵⁴Massachusetts Institute of Technology, United States
- ⁵⁵Japan Agency For Marine-Earth Science and Technology, Japan
- ⁵⁶Forschungszentrum Jülich, Germany
- ⁵⁷CSC - IT Center for Science, Finland
- ⁵⁸Global Arena Research Institute, Czech Republic
- ⁵⁹Technical University of Darmstadt, Germany
- ⁶⁰University of Reading, United Kingdom
- ⁶¹Pusan National University, South Korea
- ⁶²IBS Center for Climate Physics, South Korea



- ⁶³Otto-von-Guericke-Universität Magdeburg, Germany
⁶⁴Riken Center for Computational Science, Japan
⁶⁵Princeton University, United States
⁶⁶AIG Reinsurance, United States
⁶⁷The University of Tokyo, Japan
⁶⁸Eberswalde University for Sustainable Development, Germany
⁶⁹National Agency for Civil Aviation and Meteorology, Senegal
⁷⁰Science Panel for the Amazon, Brazil
⁷¹Earth Observation Research Center, JAXA, Japan
⁷²Oregon State University, United States
⁷³University of Oxford, United Kingdom
⁷⁴National Center for Atmospheric Research (NCAR), United States
⁷⁵Propeller Ventures, United States
⁷⁶Leipzig University, Germany
⁷⁷National Oceanic and Atmospheric Administration (NOAA), United States
⁷⁸Federal Office for Radiation Protection, Germany
⁷⁹Max Planck Institute for Biogeochemistry, Germany
⁸⁰Indian Institute for Human Settlements, India
⁸¹Reiner Lemoine Institute, Germany
⁸²Alexander von Humboldt Foundation, Germany
⁸³Swiss National Supercomputing Centre, Switzerland
⁸⁴George Mason University, United States
⁸⁵Columbia University, United States
⁸⁶University of Buenos Aires, Argentina
⁸⁷National Scientific and Technical Research Council, Argentina
⁸⁸University of Bern, Switzerland
⁸⁹Hewlett Packard Enterprise, Switzerland
⁹⁰Commonwealth Scientific and Industrial Research Organisation, United States
⁹¹University of Saskatchewan, Australia
⁹²National Centre for Atmospheric Science, United Kingdom
⁹³National Taiwan University, Taiwan
*retired

Correspondence: Bjorn Stevens (bjorn.stevens@mpimet.mpg.de)

Abstract. To manage Earth in the Anthropocene, new tools, new institutions, and new forms of international cooperation will be required. Earth Virtualization Engines are proposed as international federation of centers of excellence to empower all people to respond to the immense and urgent challenges posed by climate change.

5 **An international federation of centers of excellence to empower all people to respond to the immense and urgent challenges posed by climate change**

Every day, more and more people are waking up to the consequences of Earth's changing climate. Changes in weather, water, and ecosystems are catching communities unprepared, and scientists by surprise. These changes are highlighting how little we know about basic questions, such as for whom the monsoon rains may falter, or even fail; or more generally, whether warming



is causing shifts in atmosphere and ocean circulations and how these may connect to more frequent and intense heatwaves, wildfires and flooding. Climate change is also exposing a fundamental injustice, whereby those least responsible are impacted the most. Efforts to know more, and plan better, are severely under-resourced, and inequitably distributed, deepening both the sense of anxiety and the injustice. This increases the disruptive potential of climate impacts for all. EVE responds to this new reality.

EVE envisions a world where everyone knows how climate and climate change affect them, and where this knowledge empowers them to act. By generating entirely new and inherently better sources of information, EVE strives to catalyze a change in the broader ecosystem of data and services to deliver a just, equitable and scientifically grounded basis for action.

EVE will be made up of international centers of excellence, each accessing outstanding computational and data handling capabilities, and each embedded within the rich and expanding landscape of climate-related data, experiences, and information. This will enable EVE to fill a data space with climate projections of much greater fidelity, with local granularity, globally. And to link these, through a digital commons, to data describing the physical, biological, chemical, and social dimensions of the Earth system. EVE's digital commons will efficiently expose data to new (e.g., generative AI, augmented reality) methods of analysis and proactive information production. This will enable stakeholders to construct and interact with their own climate scenarios. EVE's technical ambition will strengthen the capabilities of all sorts of communities to command new technologies – built on scientific excellence, transparency, and openness across disciplines – to rise to the specific challenges climate change poses for them.

EVE will add modelling capacity beyond the reach of most countries, let alone existing modelling centers. This capacity is urgently needed to improve model fidelity, to assess impacts, and to integrate observations, globally. EVE's digital commons will provide access to software and infrastructure-as-a-service that would otherwise not be available at the necessary scale, nor aligned with emerging technologies. Through a commitment to international cooperation and capacity development, EVE's centers of excellence will extend, accelerate, and further open the generation of climate information of unprecedented quality and salience to enhance climate services globally.

Each of EVE's centers of excellence will:

- apply and advance the best available science to continuously grow and refresh a data space with small ensembles of km-scale multi-decadal global climate projections, juxtaposed with larger ensembles at coarser granularity;
- establish and maintain equitable access to a space of interoperable data and software, through open and secure protocols aligned to global standards and conventions, as part of an emerging ecosystem of planetary data;
- support and encourage the innovative uses of data to generate information particularly on local climate impacts and interactively expose it to users, especially those that would not otherwise have access, and to develop standards and trust in their global use;
- cooperate with existing operational climate services and practitioners at all levels, as well as research infrastructures and programmes in the natural, information and social sciences, to amplify both their own and EVE's impact;



- include a strong component of well-tailored capacity development, outreach, and exchange, to enrich EVE’s with local knowledge, and to bridge divides to train and employ new developers and users of climate information globally.

Each EVE center of excellence will require experts to maintain and advance state-of-the-art computing and data facilities, to improve its models (physically and computationally), to support training and capacity development, and to engage with users to enlarge the public sphere of climate information. To meet these requirements, alongside EVE’s computing and data demands, will require a funding rate of about € 300 million per year per center. Three to five centers should be sufficient to fill the data space of future projections, and at the same time extend access to, and engage, communities globally in using it. Global governance is key to the creation and sustainability of EVE. This could be in the form of an international treaty, or through coordination of self-governed centers by the WMO, UNEP or other inter-governmental organizations. Independent of the governance model, EVE will be charged with maintaining consistent and open delivery of value to the widest possible user community and to support constructive innovation through scientific excellence.

By comparison with the climate-change impacts it seeks to predict, EVE is asking for a tiny investment. All the more so that it takes advantage of an enormous opportunity. And that is to confidently open the door to new worlds. Worlds where water managers in Bhutan can, with confidence and trust, interactively explore the interplay between adaptation strategies and different scenarios of global climate change. Where agriculturalists in northern India, or managers of blue-carbon mangrove stocks in Bangladesh, can anticipate the implication of Bhutan’s choices; and where climatologists working in Cape Town can investigate how it all couples back to influence weather, water and ecosystems globally. EVE will allow impact communities, who link ecological changes to patterns of weather and water, to leverage ever richer descriptions of present and past climates to scenarios for the future, to develop strategies for building resilience. EVE’s ability to bring forth such worlds will come as much from the fidelity of its new models, as from the power of its new technologies, as from its ability to equitably engage those who need its information most.

Frequently Asked Questions

Are scientists really ‘surprised’ by the changes?

Yes, but not by every change, and by different changes in different ways. To be clear, climate science has long established why Earth is warming, and has developed models that have explained its broad trends and contours. Scientists understand, in general terms, how some forms of extremes might change with warming. What’s lacking is a specific understanding of such changes, as is needed to guide adaptation. Often this is because projected changes in atmospheric and oceanic circulations and patterns of precipitation differ from one model to the next for reasons we don’t understand. While this makes it hard to form expectations, and hence be surprised, there are a growing number of cases where models do agree with one another, but observed changes behave differently, i.e., surprises. A prominent example is the persistence of La Niña conditions over the past half-century (the present El Niño notwithstanding), others include the slowdown in warming between 1998-2013, or the rapidity of arctic sea-ice decline in 2012.



What is meant by the 'expanding landscape of climate-related data and information'?

75 In addition to the reanalyses, which are often the starting point for global climate data, a great many organizations and agencies collect and disseminate climate-related data directly— from satellites, networks of ground sensors, gliders, floats, and drones, to integrative ecosystem supersites. EVE will strengthen these services by making it easier to access their data and combine them with reanalyses and to climate projections with local granularity, globally, by increasing access to open and interoperable data and software, and through the equitable distribution and use of this capacity.

80 What is meant by the phrase 'local granularity, globally'?

There is no unequivocal definition of local, but many people would associate it with the environment that they can perceive with their senses, and the space over which they typically move under their own power, if not a somewhat larger area. This defines local to be about 1 km, or perhaps between 0.1–10 km. Infrastructures are constructed, lives are lived, and impacts are felt on this scale of 'granularity'. This has been appreciated for some time, and has motivated work in climate services to 'downscale'
85 models with much reduced (100 km) granularity to finer scale. Hence the phrase 'local granularity, globally' emphasizes the importance of the km-scale for impacts, globally; for observations whose footprint is often on a local scale, globally; and for how important climate processes (ocean eddies, overflows, orographic effects, atmospheric convection) influence much larger-scales, sometimes referred to as upscaling.

Aren't there already a great number of digital twinning activities, what makes EVE different?

90 There are a handful of related activities (e.g., Destination Earth, NVIDIA's Omniverse, and the DITTO Programme of the UN Ocean Decade). EVE draws impetus from them, but is larger in scope. EVE differs also through its focus on establishing a sustainable and equitable global footing that better links to the landscape of climate-related data and information, adds interactivity at scale, and is constituted to enable global capacity building, cooperation, and co-development. Depending on local circumstances, an EVE center could, however, emerge as an outgrowth of an existing activity.

95 Isn't EVE adopting a technocratic approach that risks increasing inequity?

EVE is a technology project, and is rooted in the experience that technology, increasingly through the use of AI, can improve the quality of information while simultaneously lowering the barriers to its access. EVE is aware, however, that this requires the engagement of the users of the information (or their trusted representatives) in its production. That is why EVE places such an emphasis on capacity development and exchange in its centers of excellence, to enable co-production at the forefront of
100 technology. Ideally EVE would give every country in the world the capability to train people to develop models, AI algorithms, and tailor climate information to meet their needs. This is a tall task, and because it touches on the more difficult question of how humans and social systems interact with new sources of information, EVE also must engage research and researchers from the social and behavioral sciences.



What role will AI play in EVE’?

105 AI is one of EVE’s core technologies. It can make models more performant, and thereby fit for greater purpose. EVE distinguishes between *AI Inside*, to refer to what is done to help the models perform better, and *AI On-Top* which describes methods to increase information extraction from model output and data. EVE will greatly expand the scope of AI in every regard. EVE’s digital commons anticipates the use of generative AI to enable interactivity (AI On-Top) with large amounts of data, and this is envisioned to be a game changer.

110 Does EVE aim to replace existing modelling activities?

No. EVE is additive and complements existing activities by targeting important scales that would otherwise be out of reach, i.e., EVE’s ‘local granularity, globally’. EVE emphasizes better information provision, whereas research also targets knowledge creation, and these are symbiotic. EVE thus needs and benefits from ongoing modelling activities, for instance as coordinated by the World Climate Research Programme, but at the same time, it will also support those external research efforts through its
115 technology development, its ability to set standards, by increasing their access to frontier computing, and by providing career paths for their trainees.

Why 3-5 centers of excellence?

A smaller number of centers risks not meeting the ambitious computing requirements to fill the required data space with the required diversity in modelling approaches. Too few centers also make it more difficult to engage a sufficient breadth of
120 users, thereby limiting access to data and expertise. More centers could help EVE be more inclusive, sample more climate trajectories, and engage more users. However, given each center’s need to access a critical mass of human resources for model development, to innovatively develop and maintain infrastructure, etc., the reality of limited human and financial resources, and EVE’s novelty, having fewer centers, each with a higher profile, is advantageous.

How much power would an EVE center consume, and is this sustainable?

125 EVE’s use of high-performance computing requires substantial electricity resources. Based on practice at some of the world’s leading supercomputing facilities, it is estimated that each EVE center would need to access approximately 50 MW of power. The compute resources need not be sourced from a dedicated site but must facilitate interoperability of software and data, maintain computing co-proximate with the largest sources of data. By focusing on the development of just a few centers, and concentrating the powered delivery to access renewables and favor circular economies, for instance through productive use of
130 ‘waste’ heat, EVE will be exemplary of responsible power production and usage.



How was EVE's budget estimated?

The €300M per center per year price tag was estimated based on the current budget of international organizations whose profile overlap with parts of EVE's remit, and it anticipates a roughly equal split between funding for staff, running costs (mostly power), and investments (hardware procurements).

135 **Will EVE take away resources from existing efforts?**

EVE relies on a vibrant climate research and services community, and cannot be funded at their expense. EVE centers can be expected to employ some of the leading climate science, climate impact, climate services, and technologists world wide, but in the end this will represent a very small fraction of these workforces. Without simultaneously strengthening ongoing research activities, EVE would lose access to trained staff, would become less innovative, and would fail to adequately understand and communicate its outcomes. Without simultaneously strengthening existing climate services EVE would lose its ability to connect its data and information provision to the communities it must serve, let alone scale this globally. In this sense, EVE will only be successful if it strengthens climate science and service more broadly.

What's next?

The outcomes from the Berlin Summit for EVE will be presented and discussed at the World Climate Research Programme Open Science Conference in Kigali Africa, in October 2023. We are engaging with the WMO and the organizers of COP28 to obtain their formal support, based on which we would develop an implementation plan and governance structure.

What would happen without EVE?

Without EVE urgently needed information for adaptation and resilience building would be of inferior quality, and much less accessible to those that need it most. Some of EVE's key technologies and methodologies may be developed anyway, but more slowly and then only by, and for, the few who can afford to do so. Climate information for business, finance, and global policy, would continue to proliferate, but would lack standardization, inclusivity, and a compelling tie to the best available science. Without EVE, research laboratories would continue to explore the frontiers of computing, but with diminished access, little participation from the global South, and a reduced ability to link their findings and technologies to inform climate actions. Climate services would continue to do their best to exploit advances in the science to inform users, but would be handicapped in their efforts. The operational aspect of EVE, the co-production of regularly updated information that matches the rapid pace of innovation, would be lost. The world won't be empty-handed, but it would be left with less, and less trusted, information, leaving many less resilient. Just as profoundly, a chance to engage many more people in new, and more equitable, economies at the nexus of emerging technologies and sustainable development would have been missed.



Summit Participants

160 Many people contributed to the Berlin Summit for EVE. A discussion paper in preparation for the summit was downloaded more than 4500 times. A video presentation of EVE at the CONSTRAIN external assembly a week before the meeting was recorded and viewed more than 700 times. A forum was set up that collected extensive input from scores of people. Impulse for the working meeting was provided by a welcome from Bettina Stark-Watzinger, the German minister for research and education, Jensen Huang, founder and CEO of NVIDIA, the most valuable semiconductor company in the world, Debra
165 Roberts, Co-Chair of the IPCC Working Group II, and by many other distinguished speakers. Participants in the working aspect of the Berlin Summit sampled diverse backgrounds. Joining the many participants working in the host nation (Germany) were representatives of every continent (other than Antarctica), and more than twenty individual countries. Participants ranged from students, like Charlotte Merchant of Princeton University, who led a breakout group, to Petteri Taalas the Secretary General of the World Meteorological Organization. Many past and present leaders of the IPCC, heads of world-renowned research
170 institutes, leading figures from technology, scientists from fields as diverse as sociology, behavioral psychology, informatics, and the varied fields of climate and climate-impact science, hydrology, ecology, and finance, as well as practitioners from climate services and operational services contributed and joined as signatories.

Why *Earth System Science Data*

Fundamentally EVE is about improving the quality of and accessibility of Earth system data and doing so in ways that are just
175 and equitable. Although many journals have higher profiles, and are the more usual targets for such perspectives, none better reflect and practice the values of EVE.

Signatories

1. Bjorn Stevens, Director, Max Planck Institute for Meteorology, DE (corresponding author)
2. Stefan Adami, Technical University of Munich / AI engineering GmbH, DE
- 180 3. Tariq Ali, Professor and Pro-Vice-Chancellor for Global Engagement & Partnerships, University of Liverpool, UK
4. Hartwig Anzt, University of Tennessee / Karlsruhe Institute of Technology, US/DE
5. Zafer Aslan, Istanbul Aydın University, TR
6. Sabine Attinger, Helmholtz Centre for Environmental Research (UFZ), DE
7. Jaana Bäck, Professor, University of Helsinki, FI
- 185 8. Johanna Baehr, Professor, University of Hamburg, DE
9. Peter Bauer, (Director Destination Earth for ECMWF, retired), UK
10. Natacha Bernier, Director of Earth System Science Research and Innovation, Dept. Science and Innovation WMO
11. Bob Bishop, International Centre for Earth Simulation Foundation, CH



12. Hendryk Bockelmann, German Climate Computing Center (DKRZ), DE
- 190 13. Sandrine Bony, LMD/IPSL, CNRS, Sorbonne University, FR
14. Veronique Bouchet, World Meteorological Organization (WMO)
15. Guy Brasseur, Director Emeritus, Max Planck Institute for Meteorology, DE
16. David N. Bresch, ETH Zurich / MeteoSwiss, CH
17. Sean Breyer, ESRI Inc.
- 195 18. Gilbert Brunet, Chair of the Scientific Advisory Panel, World Meteorological Organisation (WMO)
19. Pier Luigi Buttigieg, Alfred Wegener Institute, DE
20. Junji Cao, Director General, Institute of Atmospheric Physics - Chinese Academy of Science, CN
21. Christelle Castet, AXA Climate, FR
22. Yafang Cheng, Max Planck Institute for Chemistry, DE
- 200 23. Ayantika Dey Choudhury, Indian Institute of Tropical Meteorology - Pune, IN
24. Deborah Coen, Professor of History, Yale University, US
25. Susanne Crewell, Professor, University of Cologne, DE
26. Atish Dabholkar, Director, Abdus Salam International Centre for Theoretical Physics, IT
27. Qing Dai, Tencent, SSV Carbon Neutrality Lab, CN
- 205 28. Francisco J. Doblas-Reyes, Barcelona Supercomputing Center (BSC), ES
29. Dale Durran, Professor, University of Washington, US
30. Ayoub El Gaidi, National Centre of Meteorology, Presidential Court, AE
31. Charlie Ewen, Chief Technology Officer, Met Office, UK
32. Eleftheria Exarchou, MITIGA Solutions, ES
- 210 33. Veronika Eyring, Professor of Climate Modelling, DLR Institute of Atmospheric Physics & University of Bremen, DE
34. Florencia Falkenhoff, Max Planck Institute for Dynamics and Self-Organization, DE
35. David Farrell, Principle, Caribbean Institute for Meteorology & Hydrology, BB
36. Piers Forster, Professor, University of Leeds, UK
37. Ariane Frassoni, Brazilian National Institute for Space Research, BR
- 215 38. Claudia Frauen, German Climate Computing Center (DKRZ), DE
39. Oliver Fuhrer, Federal Institute of Meteorology and Climatology, MeteoSwiss, CH
40. Shahzad Gani, Indian Institute of Technology Delhi, IN
41. Edwin Gerber, Professor, New York University, US
42. Debra Goldfarb, Amazon Web Services, US



- 220 43. Jens Grieger, Institute of Meteorology - Freie Universität Berlin, DE
44. Nicolas Gruber, Professor, ETH Zurich, CH
45. Wilco Hazeleger, Professor and Dean, Utrecht University, NE
46. Rolf Herken, MINE
47. Chris Hewitt, World Meteorological Organization (WMO)
- 225 48. Torsten Hoefler, Professor, ETH Zurich, CH
49. Huang-Hsiung Hsu, Research Center for Environmental Changes - Academia Sinica, TW
50. Daniela Jacob, Helmholtz-Zentrum Hereon, Director, Climate Service Center Germany (GERICS), DE
51. Alexandra Jahn, University of Colorado Boulder, US
52. Christian Jakob, Professor, Monash University, AU
- 230 53. Thomas Jung, Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research, DE
54. Christopher Kadow, German Climate Computing Center (DKRZ), DE
55. In-Sik Kang, Indian Ocean Center/ Second Institute of Oceanography, IN
56. Sarah Kang, Ulsan National Institute of Science and Technology, Max Planck Institute for Meteorology, KR/DE
57. Karthik Kashinath, NVIDIA, US
- 235 58. Katharina Kleinen-von Königslöw, University of Hamburg / CLICCS, DE
59. Daniel Klocke, Max Planck Institute for Meteorology, DE
60. Uta Kloenne, Climate Analytics, DE
61. Milan Klöwer, Massachusetts Institute of Technology, US
62. Chihiro Kodama, Japan Agency For Marine-Earth Science and Technology, JP
- 240 63. Stefan Kollet, Forschungszentrum Jülich GmbH, DE
64. Tobias Kölling, Max Planck Institute for Meteorology, DE
65. Jenni Kontkanen, CSC - IT Center for Science, FI
66. Steve Kopp, Esri Inc.
67. Michal Koran, Global Arena Research Institute
- 245 68. Thilo Körkel, New Ground e.K., DE
69. Markku Kulmala, Professor, University of Helsinki, FI
70. Hanna Lappalainen, University of Helsinki, FI
71. Fakhria Latifi, Technical University of Darmstadt, DE
72. Bryan Lawrence, Professor, NCAS / University of Reading, UK
- 250 73. June-Yi Lee, Professor, Pusan National University / IBS Center for Climate Physics, KR



74. Quentin Lejeune, Climate Analytics, DE
75. Christian Lessig, Otto-von-Guericke-Universität Magdeburg, DE
76. Chao Li, Max Planck Institute for Meteorology, DE
77. Thomas Lippert, Head of Jülich Supercomputing Centre, DE
- 255 78. Jürg Luterbacher, Director Science and Innovation / Chief Scientist, World Meteorological Organization (WMO)
79. Pekka Manninen, CSC - IT Center for Science, FI
80. Jochem Marotzke, Director, Max Planck Institute for Meteorology, DE
81. Satoshi Matsuoka, Head, Riken Center for Computational Science, JP
82. Charlotte Merchant, Student, Princeton University, US
- 260 83. Peter Messmer, NVIDIA, CH
84. Gero Michel, AIG Reinsurance, BS
85. Kristel Michielsen, Forschungszentrum Jülich GmbH, DE
86. Tomoki Miyakawa, Atmosphere and Ocean Research Institute - The University of Tokyo, JP
87. Samuel Morin, Météo-France - CNRS/CNRM, FR
- 265 88. Jens Müller, Eberswalde University for Sustainable Development, DE
89. Ramsha Munir, Technical University of Darmstadt, DE
90. Sandeep Narayanasetti, Indian Institute of Tropical Meteorology, Pune, IN
91. Ousmane Ndiaye, National Agency for Civil Aviation and Meteorology, SN
92. Carlos Nobre, Science Panel for the Amazon, BR
- 270 93. Achim Oberg, Professor, University of Hamburg, DE
94. Riko Oki, Director, Earth Observation Research Center, JAXA, Tsukuba, JP
95. Tuba Özkan-Haller, Professor and Dean, Oregon State University, US
96. Tim Palmer, Royal Society Research Professor of Climate Physics, University of Oxford, UK
97. Stan Posey, NVIDIA, US
- 275 98. Andreas Prein, National Center for Atmospheric Research (NCAR), US
99. Odessa Primus, Global Arena Research Institute, CZ
100. Mike Pritchard, NVIDIA / University of California - Irvine, US
101. Julie Pullen, Propeller Ventures, US
102. Dian Putrasahan, Max Planck Institute for Meteorology, DE
- 280 103. Johannes Quaas, Professor, Leipzig University, DE
104. Krishnan Raghavan, Director Indian Institute of Tropical Meteorology - Pune, IN



105. Venkatachalam Ramaswamy, Director, NOAA/ Geophysical Fluid Dynamics Laboratory - Princeton University, US
106. Markus Rapp, Director, DLR Institute of Atmospheric Physics, DE
107. Florian Rauser, Bundesamt für Strahlenschutz, DE
- 285 108. Markus Reichstein, Director, Max Planck Institute for Biogeochemistry, DE
109. Aromar Revi, Director, Indian Institute for Human Settlements, IN
110. Sonakshi Saluja, Reiner Lemoine Institute / Alexander Von Humboldt Foundation, CH
111. Masaki Satoh, Professor, Atmosphere and Ocean Research Institute, The University of Tokyo, JP
112. Vera Schemann, University of Cologne, DE
- 290 113. Sebastian Schemm, ETH Zurich, CH
114. Christina Schnadt Poberaj, Executive Director, Center for Climate Systems Modeling C2SM, ETH Zurich, CH
115. Thomas Schulthess, Professor ETH Zurich, and director, CSCS, CH
116. Catherine Senior, Met Office, UK
117. Jagadish Shukla, Professor, George Mason University, US
- 295 118. Manmeet Singh, Indian Institute of Tropical Meteorology - Pune, IN
119. Julia Slingo, (Chief Scientist of Met Office, retired), UK
120. Adam Sobel, Professor, Columbia University, US
121. Silvina Alicia Solman, University of Buenos Aires / CONICET, AR
122. Jenna Spitzer, PhD Candidate, Utrecht University, NE
- 300 123. Detlef Stammer, Professor, University of Hamburg, WCRP JSC Chair, DE
124. Philip Stier, Professor, University of Oxford, UK
125. Thomas Stocker, Professor, University of Bern (former IPCC WG1-Cochair), CH
126. Sarah Strock, Hewlett Packard Enterprise
127. Hang Su, Institute of Atmospheric Physics - Chinese Academy of Science, CN
- 305 128. Petteri Taalas, Secretary General, World Meteorological Organization (WMO)
129. John Taylor, Commonwealth Scientific and Industrial Research Organisation, AU
130. Susann Tegtmeier, Professor, University of Saskatchewan, CA
131. Georg Teutsch, Professor, UFZ - Leipzig, DE
132. Adrian Tompkins, International Centre for Theoretical Physics - Trieste, IT
- 310 133. Uwe Ulbrich, Professor, Institute of Meteorology - Freie Universität Berlin, DE
134. Pier Luigi Vidale, Professor, NCAS / University of Reading, UK
135. Chien-Ming Wu, Professor, National Taiwan University, TW



136. Hao Xu, Tencent Sustainable Social Value (SSV) / Tencent Carbon Neutral Lab Tencent, CN
137. Najibullah Zaki, Technical University of Darmstadt, DE
- 315 138. Laure Zanna, Professor, New York University, US
139. Tianjun Zhou, Professor, Institute of Atmospheric Physics - Chinese Academy of Sciences, CN
140. Florian Ziemer, German Climate Computing Center (DKRZ), DE

Author contributions. All authors: Conceptualization, Writing – review & editing, Bjorn Stevens: Supervision, Writing – original draft preparation, Methodology

320 *Competing interests.* The authors declare no competing interests.