Earth Syst. Sci. Data, 16, 2113–2122, 2024
https://doi.org/10.5194/essd-16-2113-2024

Open Access Earth System Science Data

Earth Virtualization Engines (EVE)

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Received: 19 September 2023 – Discussion started: 22 September 2023
Revised: 11 February 2024 – Accepted: 19 February 2024 – Published: 30 April 2024

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

1 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. Earth Virtualization Engines (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. It will link these projections, 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 artificial intelligence (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 modeling capacity beyond the reach of most countries, let alone existing modeling 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, quality-control, and refresh a data space with small ensembles of kilometer-scale multidecadal 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 with global standards and conventions as part of an emerging ecosystem of planetary data;
- support and encourage innovative uses of data to generate information, particularly on local climate impacts, interactively expose them to users, especially those that would not otherwise have access, and 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 programs in the natural, information, and social sciences to amplify both their own and EVE's impact; and
- include a strong component of well-tailored capacity development, outreach, and exchange to enrich EVE 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. Meeting these requirements, alongside EVE's computing and data demands, will require a funding rate of about EUR 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 with 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 coordination of self-governed centers by existing intergovernmental organizations. Independently of the governance model, EVE will be charged with maintaining consistent and open delivery of value to the widest possible user community and supporting 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, i.e., 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 this 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 and 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 and its ability to equitably engage those who need its information most.

2 Frequently asked questions

(1) 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 is lacking is a specific understanding of such changes, which 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 do not 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 and 2013, the rapidity of

Arctic sea-ice decline in 2012, and the seemingly unprecedented 2023 global temperature jump.

(2) What is meant by the "expanding landscape of climate-related data and information"?

In addition to the reanalyses and climate projections, which provide the vast amounts of globally gridded data needed to train the most advanced weather- and climate-related AI models, a great many organizations and agencies collect and disseminate other forms of climate-related data (e.g., from satellites, networks of ground sensors, gliders, floats, and drones to integrative ecosystem super-sites) that could greatly enhance this training. EVE will demonstrate how interoperability of data and software co-proximate to the computational capacity needed for the requisite machine learning can help users extract more information, with greater salience, from their own data, thus valorizing its collection and open provision. In this way EVE will expand the landscape of climate-related data and information. By providing this capacity through its regional centers of excellence, EVE will ensure local control and the equitable distribution and use of its capacity.

(3) 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 using their own power, if not a somewhat larger area. This defines local as about 1 km or perhaps between 0.1 and 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" models with much reduced (100 km) granularity to a finer scale. Hence the phrase "local granularity, globally" emphasizes the importance of the kilometer scale for impacts, globally; for observations whose footprint is often on a local scale, globally; and for how important climate processes (ocean eddies, boundary currents, overflows and throughflows, orographic effects, and atmospheric convection) influence much larger scales, sometimes referred to as upscaling.

(4) Are there not already a great number of digital twinning activities? What makes EVE different?

There are a handful of related activities (e.g., Destination Earth, NVIDIA's Omniverse, the WCRP Digital Earths lighthouse activity, the DITTO program of the UN Ocean Decade). EVE goes beyond what was envisioned for these activities in three important ways. First, as a global effort, EVE is larger and broader in scope. Second, by locating its activities in regional centers of excellence, EVE helps ensure an equitable global footing, supports capacity development, and rewards local data provision. Third, whereas the aforementioned efforts mostly focus on twinning as a form of data provision, EVE additionally emphasizes AI integration to enable information provision. Depending on local circumstances and how existing twinning activities develop, an EVE center of excellence could, however, emerge as an outgrowth of one or more of these activities.

(5) Is EVE not adopting a technocratic approach to what is more fundamentally a question of human development?

No, quite the opposite. EVE is an exceptionally ambitious capacity development project – to access and use new technologies to understand Earth's changing climate. It is in this sense that EVE is similar to CERN, which in the years after World War II nurtured European capacity in basic science and serves as a technology accelerator to this day. Each EVE center of excellence can be seen as a local climate CERN to train, engage, and serve its stakeholders. This is not a statement of goodwill but rather the recognition that for climate information to gain trust and use and for it to best incorporate local data and knowledge, it must be organic. In this way EVE actually breaks with the current practice of training experts in the use and application of climate information produced elsewhere. By emphasizing the importance of local access to advanced technologies as part of a coordinated global network of regional centers, EVE will organically build local expertise across the span of disciplines associated with the creation and use of climate data, including the social and behavioral sciences whose insights will be essential for ensuring EVE's effective and responsible use.

(6) What role will AI play in EVE?

AI is one of EVE's core technologies. It can make models more performant and thereby fit for a greater purpose. It can also summarize and combine data to enable more salient interaction. EVE distinguishes between *AI inside*, to refer to what is done to help the models that create the training data perform better, and *AI on top*, which describes methods that learn from model output and auxiliary data. AI on top goes well beyond emulation to enable interactivity across disparate sources of data, e.g., to create new types of models and to give salience to the use of data. This is the game changer. One lesson of recent applications of generative AI is the disproportionate benefit of larger (AI) models trained on larger and more diverse data. This requires a very large computing capacity for both training and creating the training data. It means that AI, in particular AI on top, is not merely a part of EVE: it is one of the main reasons why EVE is necessary.

(7) Does EVE aim to replace existing modeling activities?

No. EVE complements and enhances these existing activities. EVE models will simulate the globe with local granularity on timescales of decades to centuries, something existing models cannot do. This will help improve more coarse-grained global models used to explore processes operating on longer timescales, which EVE models cannot simulate. The more coarse-grained models can likewise be applied more conceptually to help rationalize processes that EVE models do simulate. EVE will also enable a more consistent application of regional models on similar (decadal) timescales or yet more finely grained local models on shorter timescales to support "wide scaling" – the investigation of local change to the multitude of possible local interventions (e.g., water usage, urban planning, or energy infrastructure) – to broaden the scope of training data available at EVE centers. EVE will aid standardization and advance technologies to make all models more effective, and EVE will create professional opportunities that justify enhanced training activities and thus support centers specializing in modeling.

(8) Why three to five 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 modeling approaches. Too few centers also make it more difficult to engage a sufficient breadth of 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 and to innovatively develop and maintain infrastructure, etc., the reality of limited human and financial resources means that fewer centers, each with a higher profile, are advantageous.

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

EVE's use of high-performance computing requires substantial electricity resources. Based on the 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 computing resources need not be sourced from a dedicated site but must facilitate interoperability of software and data, maintaining computing co-proximate to 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, e.g., through productive use of "waste" heat, EVE will be an exemplar of responsible power production and usage for power-intensive applications.

(10) How was EVE's budget estimated?

The EUR 300 million per center per year price tag was estimated based on the current budget of international organizations whose profiles 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).

(11) 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 worldwide, 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. EVE's operational use of climate modeling and climate information provision can only strengthen research efforts, as it creates new economies that will draw from these efforts. Moreover, by bringing an operational culture to climate modeling and climate information provision, EVE helps compensate for well-known shortcomings (short-term focus in both career and idea development) of academic culture.

(12) How would EVE ensure data quality and accessibility?

EVE would address issues related to quality assurance, trustworthiness, etc., of data (model output and observations) in three important and novel ways. Foremost for data quality and trustworthiness is that (i) the data are used, (ii) that their creation is transparent, and (iii) that their creation and provision are responsive to those that use them – something sorely lacking in the present provision of climate data. To guard against hallucination in the use of AI-based information distillation, access to training data and the ability to revisit the creation of training data – points (ii) and (iii) – need to be ensured. Meeting these goals requires public institutions that are accountable to their users. Only this can sustain the feedback loop that makes the data provision responsive to its use. This is another motivation for creating EVE out of regional centers of excellence.

(13) 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 it would be less fit for purpose and it would lack a compelling tie to the best available science and ongoing efforts to improve standards, and becoming more inclusive would be more difficult. 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 and related communities 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 would not 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.

(14) What is next?

The World Climate Research Programme Open Science Conference in Kigali, Rwanda, organized and hosted a TownHall on EVE, and EVE's ideas were presented at national pavilions during the recent Conference of Parties in Dubai. Building on and learning from these activities, we have developed an online presence that communicates the importance of EVE and promotes activities around the world that are actively working to realize EVE's vision. Across Asia, Europe, and North America a number of projects have started which in one way or another reflect EVE's technological vision and which are being developed by the EVE community into "EVE demonstrators". The big and ongoing challenges will be to (i) to transform these projects into an internationally coordinated operational activity and (ii) to enable those presently being left out, by virtue of their lack of access to the enabling technologies, to participate in EVE, on their own terms.

3 Summit participants

Many people contributed to the Berlin summit for EVE (https://eve4climate.org, last access: 18 April 2024). 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 Roberts, co-chair of the IPCC Working Group II; and by many other distinguished speakers. Participants (https://eve4climate.org/participants, last access: 18 April 2024) in the working aspect of the Berlin summit came from diverse backgrounds. Joining the many participants working in the host nation (Germany) were representatives of every continent (other than Antarctica) and more than 20 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 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.

4 Why *Earth System Science Data*?

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

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Author contributions. All authors: conceptualization, writing – review and editing. Bjorn Stevens: supervision, writing – original draft preparation, methodology.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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Financial support. Support from the Bundesministerium für Bildung und Forschung (grant no. 01LK2202B), EC Horizon 2020 (NextGEMS, grant no. 101003470), and the JSPS Core-to-Core Program (grant no. JPJSCCA20220001) was provided.

The article processing charges for this open-access publication were covered by the Max Planck Society.

Review statement. This paper was edited by David Carlson and reviewed by two anonymous referees.