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Interactive physical data cubes: A novel perspective for exploring Earth system dynamics

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Abstract. Earth system datasets continue to expand in size and complexity, making it increasingly difficult for non-experts to explore satellite observations and model outputs. We argue that new avenues for data exploration are needed to lower this barrier. Here we present the first interactive, touch-enabled physical data cube that allows users to explore any Earth system dataset intuitively across space, time, and variables. Exhibiting the physical data cube at a major conference showed that users could easily explore and identify patterns in atmospheric and land-surface data through direct physical interaction, demonstrating the system's potential for scientific discovery, education and public engagement.

1 Introduction

Monitoring, modeling, and forecasting the Earth system rely on an ever-growing stream of spatially and temporally resolved data—from satellite observations to model outputs (Ustin and Middleton, 2021; Bauer et al., 2021). Such Earth system data are getting increasingly larger, higher-dimensional and complex. Many of these data, in particular outputs of Earth system models and regional to global Earth observation products, are based on regular grids in space and time. Higher dimensions of these arrays may correspond to multiple variables or model ensemble versions. Such data are increasingly stored as so called analysis-ready-data-cubes (ARDCs), i.e., data organized along spatial, temporal, and thematically gridded dimensions (Nativi et al., 2017; Giuliani et al., 2019; Mahecha et al., 2020; Montero et al., 2025). Paired with cloud-native file formats, they enable efficient querying of large spatiotemporal datasets.

However, as Earth system datasets grow in size and dimensionality, scientific analysis, data processing and visualization become more challenging (Sudmanns et al., 2020; Vance et al., 2024). Capable visualization tools for exploring large Earth system datasets are crucial for scientists to still be able to easily access and intuitively understand the data (Ware, 2013). To address these challenges, we previously developed Lexcube.org[1], a web-based visualization tool for data cubes (see Figure 1; Söchting et al., 2023), and Lexcube for Jupyter Notebooks, an open-source Python package[2], that allows intuitive exploration of data cubes as part of scientific workflows (Söchting et al., 2025). These developments enabled users to interact with their data

[1]https://www.lexcube.org
[2]https://github.com/msoechting/lexcube

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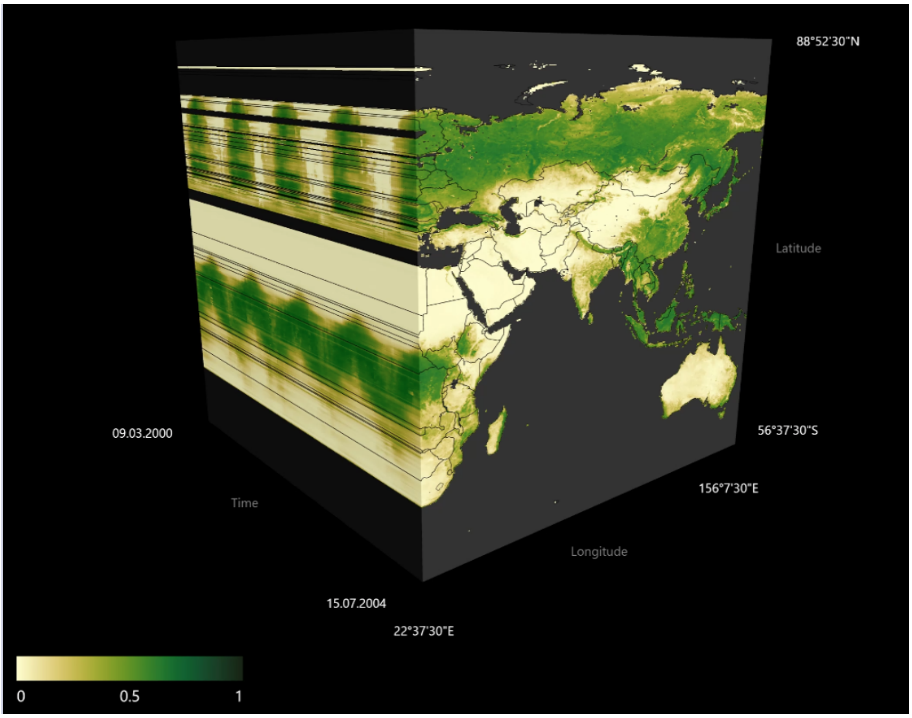

Figure 1. Visualization of a spatiotemporal remote sensing record of a vegetation greenness indicator (kNDVI; Camps-Valls et al., 2021) from MODIS using our previously developed web-based data cube viewer Lexcube.org (Söchting et al., 2023).

visualized as three-dimensional cubes in a virtual environment, where the side faces display dynamically changing Hovmöller diagrams (Hovmöller, 1949) to reveal spatiotemporal patterns. This setup enables rapid assessment of data quality and structure, making spatial or temporal gaps, anomalies, and artifacts immediately visible. Key insights, such as the presence of unexpected patterns, can thus be identified early in the analytic workflows or be effectively communicated to students or the general public.

However, limited to regular computer displays, such visualization tools can offer only a two-dimensional interface for what is fundamentally three-dimensional data, constraining spatiotemporal reasoning and intuitive understanding. While interactive physical installations featuring Earth observation data and model outputs exist, e.g., in NASA's Earth Information Center[3] (Washington D.C., USA) or ESA's Φ-Experience[4] (Frascati, Italy), they are typically serving curated data subsets and presented either on physical (interactive) globes or two-dimensional surfaces, not effectively communicating spatiotemporal dynamics beyond simple animations. This is why we propose the first interactive touch-enabled physical data cube that correctly expresses the intrinsic dimensions of Earth system data cubes. The cube allows users to explore any gridded ARDC stored in a cloud-native data format and intuitively investigate spatiotemporal patterns, effectively physicalizing Earth system data cubes (Jansen

[3]https://science.nasa.gov/science-research/earth-science/nasas-new-exhibit-showcases-our-home-planet-and-climate/
[4]https://www.esa.int/About_Us/Earth_observation_multimedia_centre

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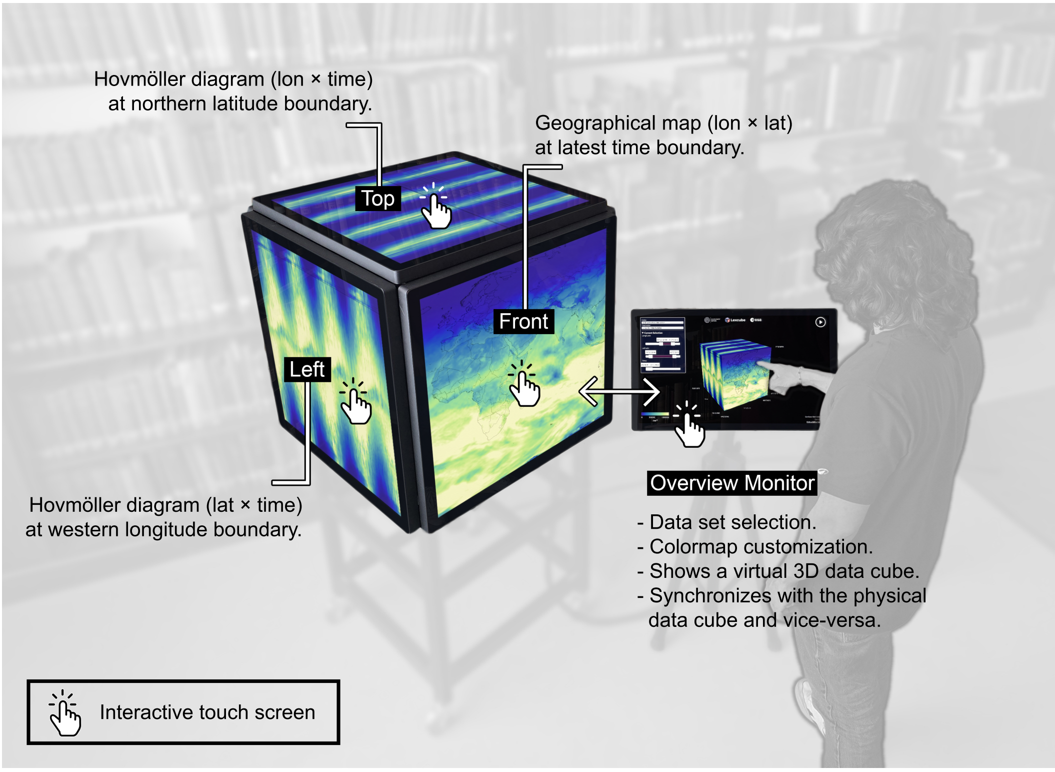

Figure 2. Conceptual overview of the interactive physical data cube. As the user modifies the selection, the front side of the cube shows a geographical map at the latest time boundary, the left side shows a Hovmöller diagram (lat x time) at the western longitude boundary and the top side shows a Hovmöller diagram (lon x time) at the northern latitude boundary. Not depicted: the back side shows a geographical map at the oldest time boundary and the right side shows a Hovmöller diagram (lat x time) at the eastern longitude boundary. The bottom side is left out for easier construction. The separate overview monitor shows a virtual 3D data cube which is synchronized in every interaction with the physical data cube. All surfaces are touch-enabled, allowing pan and pinch touch gestures to modify the selection. Visualized variable: Surface Net Solar Radiation from the ERA5 reanalysis (Hersbach et al., 2020), via the Earth System Data Cube v3.0.2 (Mahecha et al., 2020). Overlaid: Natural Earth administrative region boundaries.

et al., 2015; Jofre et al., 2016)—enabling a broader accessibility and encouraging collaboration compared to screen-based visualizations.

2 Concept & Realization

The interactive physical data cube has five square touch-enabled screens, representing five of the six sides of the virtual data cube (see Figure 2). The bottom side is left out for easier construction and improved air circulation. To guide users and allow advanced operations, there is a separate overview monitor mounted on a tripod stand. It shows a virtual 3D data cube, which is synchronized to the physical data cube, to give an overview in an interface similar to our previously developed software

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Figure 3. The interactive physical data cube as exhibited at the ESA Living Planet Symposium in June 2025 in Vienna, Austria. a), c), d), e): Visitors interacting with the interactive physical data cube. b): Inauguration ceremony with Diego Fernàndez Prieto (Head of the Research and Development Section, ESRIN, ESA), Simonetta Cheli (Director of Earth Observation Programmes and Head of ESRIN, ESA), Anca Anghelea (Open Science Platforms Engineer, coordinating the project DeepESDL funding this work, ESA), Miguel Mahecha (co-author), Maximilian Söchting (co-author), from left to right. Photo credit b): ESA/J.Mai.

at Lexcube.org. The monitor also shows meta data and the currently selected cube boundaries to help users understand what each cube side is currently visualizing. Furthermore, it is also possible to switch the currently visible dataset, make a precise data selection with sliders, play an animation through any dimension as well as adjust the colormap. See also the attached supplementary video file for a video demonstration of the physical data cube and its possible interactions.

On the software side, the interactive data cube uses existing software components from our previous work on Lexcube.org. Inside of the physical data cube, there is a single PC connected to all six screens. The PC is running a single Lexcube visualization server as well as multiple Lexcube visualization clients, one for each screen. All five clients synchronize in regards to any interaction or selection being made, achieving the effect of an interactive data cube as all five screens show the same virtual data cube from different angles. To automatically restore this setup whenever the PC is booted, an auxiliary Python script starts all software components and arranges them on the multiple displays correctly, making the interactive physical cube "plug-and-play" with just a single power cable. The server component pre-processes all ingested datasets into tiles ahead of time. These tiles contain 2D slices of the original data, indexed in all three dimensions, and are available at different levels-of-detail to connected clients. For demonstration purposes, five different Earth system data cubes with over 200 parameters

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in total from various domains and data sources are accessible. This includes spectral indices from Sentinel-2 as well as data products from the ESA Climate Change Initiative (ESA CCI), the ERA5 and CAMS EAC4 reanalyses by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020; Inness et al., 2019), the Global Land Evaporation Amsterdam Model (GLEAM) (Miralles et al., 2011) and FLUXCOM (Jung et al., 2019) - partially aggregated via the Earth System Data Cube (Mahecha et al., 2020) dataset. In practice, any gridded ARDC stored in a cloud-native data format such as Zarr[5] can be ingested into the system, as long as there is enough disk space in the magnitude of the original dataset size for the saved tiles. See the prior work on Lexcube.org on more details on tiling and the pre-processing algorithm (Söchting et al., 2023). For all applicable parameters that have multiple years of data, anomalies, i.e., deviations from the mean seasonal cycle, can also be visualized instead of absolute values.

We exhibited the interactive data cube at the Living Planet Symposium 2025 conference held by the European Space Agency (ESA) in Vienna, Austria, during 23–27 June 2025 (see Figure 3). The cube was accessible in a central location in the exhibition space during the whole conference. While we personally interacted with approximately 150 attendees at the cube over the week, many more used it on their own without further guidance. Overall, the feedback was very positive and participants noted that the physical data cube makes the concept of a spatiotemporal data cube immediately clear. With accessible examples such as precipitation and air temperature, the side faces of the cube - effectively interactive Hovmöller diagrams - were generally easily understood, allowing users to then explore typically less widely known Earth surface dynamics such as land-surface energy fluxes and soil moisture dynamics. Next to the increased understanding, users also remarked that the interaction with the cube and the data presented to be very intuitive. This is most likely because the three-dimensional data is presented as such in the real world instead of being projected onto a two-dimensional computer screen. Users particularly tested the fast interaction and responsiveness of the system. Notably, one user discovered a new spatiotemporal pattern in ECMWF aerosol data they had already worked with for years. Furthermore, users enjoyed the playful, social experience of having various large Earth system datasets accessible and explorable in physical space while discussing visible patterns with colleagues.

3 Conclusions & Outlook

We conclude that the interactive physical data cube is an effective tool for exploring and visualizing Earth observation data and model outputs for scientific analysis and scientific communication. The data cube intuitively conveys to scientists, students and the broader public how spatiotemporal Earth system data in particular appears and behaves. We see great potential for using the interactive data cube in education, as interactive visualizations have been shown to increase engagement (Cervenec et al., 2022). While we have not yet systematically evaluated the physical data cube for teaching, we anticipate high value particularly in secondary education, where geography instruction still often emphasizes static, atlas-style content and neglects temporal dynamics. Yet, understanding seasonality, trends, and variability is essential for grasping the dynamic nature of the Earth system. Having discussed phenomenons visible and explorable in a physical exhibit allows for deeper engagement and a playful learning environment. Furthermore, the data cube can be exhibited at outreach events or in natural science museums,

[5]https://zarr.dev

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offering an accessible and playful way of exploring and interacting with Earth system data without any technical knowledge required. For scientists, the physical cube allows to inspect spatiotemporal patterns even more intuitively than previously possible with digital-only tools, enabling a deeper understanding of existing data sets they might already know and use in their research.

While digital data exploration tools such as Lexcube.org are inherently more accessible than physical cubes requiring construction resources or physical access, physicalizing Earth observation data and model outputs offers significant potential for scientific communication and education. We estimate that physicalizations and tools for intuitively exploring such data sets without technical knowledge will be highly relevant in the future as the amount of available data grows exponentially, e.g., with the Digital Twin initiatives. As the societal importance of Earth system datasets increases and informs policy decisions, such tools can transparently and effectively communicate the underlying observed or modeled Earth data, e.g., global climate projections, to the general public. We believe that making petabyte-scale data easily available through physical visualizations will be crucial in scientific knowledge gain and science communication. We see further applications across disciplines in Earth sciences dealing with high-resolution, three-dimensional, simulated or recorded data, with possibilities of extending the physicalization to more dimensions beyond spatiotemporal data such as pressure, frequency or height/depth.

Video supplement. A video demonstration of the interactive physical data cube is attached as a supplementary video file.

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Competing interests. The authors declare no competing interests.

Disclaimer. Samsung Galaxy AI (One UI 8.0) has been used to extend the library background of Figure 2. Claude Sonnet 4.5 has been used to improve the language in parts of the text, however all intellectual work and writing has been performed by the authors. After using the tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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