Vector Graphics-Based Geospatial Contour Maps: A Web-Native Interactive Approach for Modern Geospatial Data Science Applications

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Abstract

Visualizing scalar fields (e.g., temperature, precipitation etc.) on the web is often done via pre-rendered raster tiles. While simple to serve and fast to access, rasters limit interactivity (feature picking, dynamic styling) and typically require heavy pre-generation pipelines. Raster tiles remain the dominant method for web-based scalar field visualization, but they are storage-heavy and inflexible, often requiring thousands of pre-generated images and limiting dynamic exploration. We present a lightweight method to render fully interactive, vector-based contour maps for gridded scalar data in standard web mapping stacks. The approach computes isolines/isobands on demand from gridded fields, converts the contours to GeoJSON, and renders them as interactive vector layers without any pre-tiled rasters. This enables hover/click inspection, dynamic filtering, level toggling, and restyling entirely client-side. For large scenes, the same GeoJSON can optionally be streamed as vector tiles, but this is not required. Our method is particularly advantageous for environmental modeling workflows, where large gridded outputs from atmospheric transport or climate simulations must be explored interactively. By eliminating pre-rendered rasters and enabling dynamic contour generation, our method supports rapid, web-native visualization of model outputs such as pollutant dispersion or climate variables, improving interpretability and reducing operational overhead. This approach enhances the interpretability of complex environmental model outputs, enabling faster hypothesis testing, model–observation comparison, and data-driven insight generation across domains such as climate analysis, pollutant dispersion, and ecosystem monitoring. By improving accessibility and interactivity, it supports transparent, reproducible science and facilitates the translation of modeling results into decision-making and policy contexts.

Keywords— *Vector contour visualization, Interactive geospatial mapping, Isoline and isoband extraction, Cartographic interactivity, Vector graphics for geospatial data*

1 Introduction

Web mapping for atmospheric and geospatial data has long relied on raster tiles (WMS/XYZ). Rasters are easy to cache but are inherently static: they fix symbology at render time, do not expose feature attributes for inspection, and make dynamic interactions such as level filtering or on-the-fly thresholding cumbersome. Moreover, raster pre-rendering pipelines often produce thousands of static files and can require gigabytes of storage. By contrast, vector representations, built from simple geometrical primitives such as points, lines, curves, and polygons, expose semantics and enable web-native interactivity (hover, click, queryRenderedFeatures) with GPU-accelerated rendering in modern engines such as MapLibre GL JS and stacks that integrate it (e.g., Plotly maps) (MapLibre (2025), Plotly (2025)). This emphasis on open, interoperable visualization workflows aligns with current trends in environmental data science toward transparent, reproducible, and FAIR-aligned research infrastructures (Wilkinson et al., 2016; Hollaway et al., 2022; Arkin et al., 2023). These developments highlight the growing importance of open-source methods that integrate data science practices into environmental modeling and analysis pipelines.

GeoJSON (RFC 7946) is the de-facto standard for exchanging such vector features on the web, using WGS-84 (EPSG:4326) longitude/latitude coordinates. The Mapbox Vector Tile (MVT) format provides a compact, tiled encoding for very large datasets but is optional for many use cases. We adopt GeoJSON for simplicity and portability, while discussing optional vector tiling for scale-up (Butler et al. (2016a), Mapbox (2016)).

For generating contours from gridded fields, we leverage mature contouring algorithms implemented in ContourPy/Matplotlib (e.g., 2005/2014 algorithms) and the classic marching squares approach for isolines/isobands. We then convert the resulting contours to GeoJSON using geojsoncontour, preserving level attributes and supporting both lines and filled bands (Developers (2025), Romgens (2025), Maple (2003a)).

As an applied case we target the FLEXPART BC gridded products available through ATMO-ACCESS, where we provide model results which complement atmospheric observation by visualizing source regions of the black carbon aerosol (ATMO-ACCESS (2021b), ATMO-ACCESS (2022)).

Unlike prior web-contouring approaches such as d3-contour, our method directly integrates with established scientific Python workflows (xarray, Matplotlib, ContourPy) and outputs standards-compliant GeoJSON layers. This allows seamless embedding into existing data portals while retaining scientific precision.

For environmental modeling applications, where outputs often consist of high-resolution scalar fields from atmospheric or climate simulations, the ability to visualize results interactively is critical for decision-making and scientific insight. Our vector-based contour pipeline addresses this need by providing a standards-compliant, lightweight alternative to raster tiles, enabling dynamic styling, level filtering, and semantic feature queries directly in the browser—capabilities that significantly enhance the usability of environmental model data. Beyond computational efficiency, the proposed workflow directly benefits environmental science applications. By enabling interactive inspection of modeled fields, scientists can more rapidly evaluate atmospheric transport pathways, compare model outputs with observations, and identify emission source regions. Such interpretability accelerates hypothesis testing in dispersion studies and facilitates the integration of model products into decision-support and policy contexts where transparency and accessibility are critical.

Contributions

- A simple, reproducible pipeline to render interactive contours from gridded fields with no pre-generated rasters.
- A reference implementation (Python) that emits GeoJSON contours and visualizes them in Plotly/MapLibre (Plotly (2025)) or Shiny/Leaflet/MapLibre (Posit (2025)).
- A case study integrating FLEXPART BC products from ATMO-ACCESS to create a new visualization of source regions and modelled black carbon concentration for different observational sites. The data is delivered on a 3 hourly basis over a 10 years period for over 20 measurement stations. In addition it is necessary to view the products for different region of interest, which could be local within 100 kilometers, global or with an arctic focus. This results in a large number of plots as they are created for every region, time step and emission source (ATMO-ACCESS (2022), ATMO-ACCESS (2021a), ATMO-ACCESS (2021b)).

2 Related Work

2.1 Isocontouring and Algorithmic Foundations

Isoline generation on structured grids is a well-studied topic, dating back to the marching squares and marching cubes algorithms proposed by Lorensen and Cline (1987). Subsequent refinements, such as the Asymptotic Decider (Nielson and Hamann, 1991) and Flying Edges (Schroeder et al., 2017), address ambiguities and scalability for high-resolution scalar fields. More recently, the SurfaceNets algorithm has been revisited for high-performance discrete isocontouring on modern hardware (Schroeder et al., 2024). These works establish efficient contour extraction frameworks, upon which our approach builds by focusing not on the underlying algorithms but on their integration into *web-native, interoperable visualization workflows*. A recent comprehensive survey of isocontouring methods further consolidates these developments and highlights the need for flexible, interoperable representations that our approach directly addresses (Zhou et al., 2024).

2.2 Raster versus Vector Paradigms in Web Geovisualization

Traditional environmental web maps typically rely on pre-rendered raster tiles (e.g., WMS/XYZ), which constrain interactivity, symbology, and data exploration. Studies such as Zhang et al. (2020) have systematically compared raster and vector tile paradigms, showing that vector-based approaches enable richer interactions and dynamic styling at comparable performance costs. However, these systems still depend on pre-tiled data pipelines and often lack semantic queryability. Our work extends this by generating vector contours (*GeoJSON*) on demand, merging the benefits of semantic interactivity with lightweight data transmission.

2.3 Topology-Preserving Simplification and Cartographic Generalization

Vector-based representation introduces challenges in geometry simplification and topology preservation. Foundational line simplification algorithms such as Douglas–Peucker (Douglas and Peucker, 1973) and Visvalingam–Whyatt (Visvalingam and Whyatt, 1993) remain influential, yet naïve application may yield self-intersecting polygons or invalid geometries. Topology-preserving simplification methods, such as those discussed by Stojanović and Stojanović (2013) and implemented in geospatial libraries like PostGIS's *ST_SimplifyPreserveTopology* (PostGIS Development Team, 2023), mitigate these issues. We integrate these considerations into a browser-rendered environment, maintaining geometric validity while enabling smooth interaction and minimal payloads.

2.4 In-Browser Contouring and Visualization Libraries

Client-side contouring libraries such as *d3-contour* (D3js, 2011) demonstrate real-time polygon extraction in the browser using the marching squares algorithm, yet they are largely decoupled from scientific data analysis pipelines. Our workflow bridges this gap by combining Python's scientific stack (*xarray*, *ContourPy*, *Matplotlib*) with web standards like *GeoJSON*, thereby ensuring both reproducibility and semantic interoperability. This aligns with trends toward end-to-end open-source geospatial workflows and complements existing frameworks like MapLibre and Plotly that support GPU-accelerated rendering and feature querying in the browser.

2.5 Interactive Environmental Data Portals and Decision Support

Recent research in environmental data visualization emphasizes interactivity and reproducibility. For example, the Interactive Catchment Explorer (*ICE*) (Rodgers et al., 2020) illustrates how web-based visualization can enhance environmental analysis but still relies on predefined data visualizations rather than dynamic rendering. Other frameworks in environmental modeling advocate for lightweight, reusable interfaces that connect data science workflows to policy or public outreach tools (van Beek et al., 2023; Hsu et al., 2021). Our approach operationalizes these principles by delivering a generalizable, standards-compliant visualization pipeline applicable to diverse environmental datasets.

2.6 Applications in Atmospheric and Environmental Modeling

The FLEXPART Lagrangian particle dispersion model is widely used for simulating atmospheric transport and source–receptor relationships of aerosols and trace gases (Stohl et al., 2005; Pisso and et al., 2019). Black carbon (BC), a short-lived climate forcer, has been studied extensively for its role in Arctic climate feedbacks and transboundary pollution (Wang and et al., 2019; Zanatta and et al., 2025). The datasets from the ATMO-ACCESS and ACTRIS infrastructures embody these challenges by producing dense, gridded scalar fields requiring flexible visualization methods. Our case study builds on these efforts by introducing an interactive contour visualization framework that reduces storage (from $\sim$7500 raster files to a single 100–500 kB *GeoJSON*) and enhances interpretability through web-based interactivity.

2.7 Bridging the Gap

Across these strands of literature, a methodological gap becomes clear. While contouring algorithms and web mapping technologies have advanced independently, few works have connected high-performance scientific contour generation with open web standards and browser-based interactivity. Existing visualization portals often remain limited to static rasters or closed frameworks, and client-side examples lack the rigor of scientific data integration. Our contribution closes this gap by unifying these domains through a reproducible, vector-based pipeline that integrates Python-based scientific workflows with standard web mapping engines, achieving dynamic, interactive environmental visualization without heavy server-side infrastructure. A comparison of different approaches is summarized in Table 1. Our approach also complements emerging work on open environmental data infrastructures and web-based visualization platforms designed to improve scientific transparency and model validation (Lowndes et al., 2017; Stevens et al., 2024; Hollaway et al., 2022). Such efforts collectively advance the integration of open data science tools into environmental modeling workflows, a direction this study explicitly

Table 1: Comparison of approaches for web-based contour visualization

Approach	**Interactivity**	**Scalability**	**Compliance**	**Complexity**	**Use Case**
Raster tiles (WMS/XYZ)	Very limited (fixed symbology, no feature attributes)	High (pre-tiled, CDN caching)	PNG/JPEG tiles (not semantic)	Medium (requires pre-render pipeline & storage)	Static maps, legacy data portals
Client-side contouring (d3-contour)	Moderate (hover/click, dynamic styling)	Limited (browser computation scales poorly with large grids)	Custom SVG/Canvas (no geospatial standard)	Low–Medium (JavaScript only)	Exploratory browser-based visualizations
Vector contour pipeline (this work)	High (hover, click, query, dynamic styling, level toggling, time stepping)	Flexible (GeoJSON for moderate, MVT/PMTiles for large)	Full compliance with GeoJSON (RFC 7946), optional MVT/PMTiles	Medium (Python workflow with ContourPy/-Matplotlib, GeoJSON export)	Interactive dashboards, web-native geospatial applications

supports.

3 Methodology

The proposed workflow transforms gridded scalar fields into fully interactive, vector-based contour maps suitable for web deployment. We begin with a scalar field $Z(\lambda, \phi)$ defined on a rectilinear longitude–latitude grid, or any grid convertible to geographic coordinates. Input fields are read using *xarray* from NetCDF/CF datasets, ensuring compliance with the WGS 84 (EPSG:4326) coordinate reference system for interoperability across web platforms. When source data are provided in alternative coordinate systems, reprojection is performed via *Cartopy* and *pyproj*, guaranteeing consistency with the GeoJSON standard (RFC 7946) (xarray Developers, 2025; Butler et al., 2016b; Cartopy Developers, 2025).

Given a user-defined set of contour levels $\{c_k\}$, isolines and filled isobands are extracted using the *ContourPy* backend through *Matplotlib*. The algorithm applies the marching-squares principle to detect scalar-field level crossings along grid-cell edges, interpolating between sample points to construct continuous contour lines and closed polygons (ContourPy Developers, 2025; Maple, 2003b). Adjacent level pairs $[c_k, c_{k+1}]$ define filled regions representing intervals of the scalar field. The resulting *QuadContourSet* structure provides a robust in-memory representation of isolines and isobands, including metadata such as contour level, color mapping, and connectivity.

To produce web-native vector outputs, these contours are converted into Geo-

JSON using the *geojsoncontour* package (Romgens, 2025). The function *contourf_to_geojson* traverses each polygonal ring in the *QuadContourSet*, serializing it into a *FeatureCollection* compliant with RFC 7946. Each feature carries a *Polygon* or *MultiPolygon* geometry with associated properties describing the contour level, range boundaries, and optional styling parameters (e.g., fill color and opacity). Coordinate precision is configurable (typically six decimal digits), balancing geometric fidelity and file size. This conversion provides a semantic, standards-based vector encoding that can be rendered directly by modern mapping engines such as MapLibre GL JS and Leaflet without any rasterization or preprocessing.

The GeoJSON features generated through this process preserve both spatial topology and semantic metadata, enabling advanced web interactivity. Once rendered, users can query feature attributes, adjust contour-level visibility, restyle fills dynamically, or animate temporal sequences of GeoJSON layers entirely client-side. This vectorization pipeline therefore bridges high-performance scientific Python workflows with open, browser-native geospatial technologies, eliminating the need for pre-rendered raster tiles and enabling scalable, interactive visualization of environmental model data.

For integration with interactive dashboards, we support two web rendering paths. In the first, *Plotly* is used to overlay the GeoJSON contours on a *MapLibre*-based basemap (*go.Scattermap* or *go.Choroplethmap*), providing hover and click callbacks through GPU-accelerated WebGL rendering (Plotly Technologies Inc., 2025). Alternatively, in *Shiny* for Python, the contours are added as a *GeoJSONLayer* using *ipyleaflet*, with reactive bindings allowing level filtering and time-stepping functionality (Posit Software Inc., 2025). In both cases, the result is a lightweight, interactive, and fully reproducible visualization that can be embedded in environmental data portals or decision-support systems.

Overall, the proposed vectorization framework constitutes a compact, standards-compliant method for transforming scientific contour visualizations into portable geospatial vector layers. By leveraging established open-source Python libraries and interoperable web standards, it provides a reproducible bridge between environmental data analysis and interactive visualization, substantially reducing storage and bandwidth requirements while enhancing interpretability and accessibility.

4 Implementation

In the Appendix we provide compact Python source code for a minimal reproducible reference implementation that (i) reads a gridded field, (ii) generates contours, (iii) converts to GeoJSON, and (iv) renders interactively with Plotly (MapLibre). The library dependencies for our reference implementation are: xarray, numpy, matplotlib, contourpy (via Matplotlib), geojsoncontour, plotly, and optionally geopandas/shapely for simplification (xarray Developers (2025), Developers (2025), Romgens (2025), Plotly (2025)).

5 Case study: FLEXPART BC products

We applied the method to gridded FLEXPART products for BC available through the ATMO-ACCESS virtual access services. Products include map-gridded arrays (e.g., footprints, sectoral contributions) in NetCDF, ideal for generating isolines and isobands across selected concentration steps (ATMO-ACCESS (2022)). Previously, the pre-rendered approach has stored approximately 7500 pre-rendered GIF-files. With our new interactive vector-based graphics approach, such pre-rendering is no longer necessary as the user can interactively select the parameters and have the plot rendered on the fly, taking less than 1 second per rendering. Compared to the raster pipeline (7500 pre-rendered GIFs, requiring several hundred megabytes of storage), the vector workflow transmits a single GeoJSON of 100–500 KB per scene, drastically reducing storage and bandwidth requirements.

To quantitatively evaluate the performance and efficiency of the proposed approach, we compared key metrics of the legacy raster-based workflow against the new vector contour pipeline. Table 2 summarizes the improvements in storage footprint, rendering speed, and interactivity.

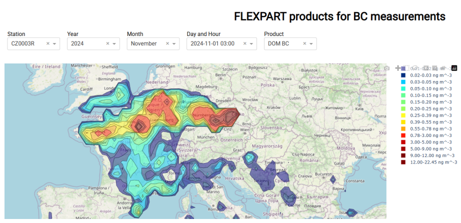
Table 2: Quantitative performance evaluation comparing the traditional raster workflow with the proposed vector-based GeoJSON workflow.

Metric	**Raster workflow**	**Vector** (this work)	**Benefit**
Storage per scene	10–20 MB	0.1–0.5 MB	≈97–99% reduction
Files per dataset	∼7,500 images	1 GeoJSON	≈99.98% reduction
Network payload per update	5–10 MB	0.1–0.5 MB	20–100× smaller
Rendering time	pre-rendered (offline)	$<$ 1 s per scene	on-demand (near real-time)
Interactivity	static (no querying)	hover/click, dynamic styling, level toggle	+ new interaction modes

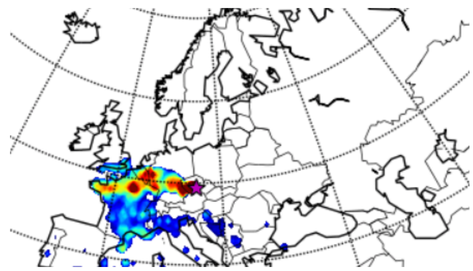
The results demonstrate reductions in storage and bandwidth of up to two orders of magnitude, while simultaneously enabling real-time interaction and dynamic styling directly in the browser.

We selected a Black Carbon (BC) field (e.g., total BC contribution) for a given site and time, defined 15 contour levels spanning the data range, and produced both isolines and isobands. The resulting GeoJSON layers were rendered in Plotly (MapLibre) with hover templates exposing level and value ranges. An example of the resulting vector-based contour plot is shown in Figure 1a, while Figure 1b illustrates the corresponding raster-based plot for comparison. Additional examples of our new vector-based and the original raster-based plots are presented in Figures 1c and Figure 1d, respectively.

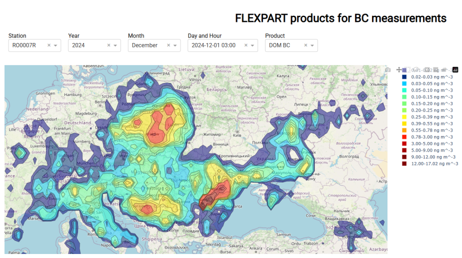
Interactivity. Users can (i) toggle line/band layers, (ii) query level values by hovering/clicking, (iii) adjust level sets on the fly (server recomputation only), and (iv) animate over time by swapping GeoJSON sources tied to a time slider in Plotly or Shiny. Because features are vectors, styling changes are instantaneous without server re-rendering.



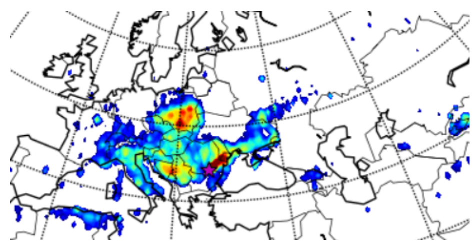
(a) Vector-based contour plot (site A).



(b) Raster-based contour plot (site A).



(c) Vector-based contour plot (site B).



(d) Raster-based contour plot (site B).

Figure 1: Comparison of vector-based and raster-based contour visualizations for two case study sites.

6 Discussion

The proposed approach offers several advantages over traditional raster-based visualization workflows. First and foremost, it eliminates the need for pre-generated raster tiles. By computing contours on demand and transmitting them as GeoJSON vectors, the method decouples styling from rendering. This means that changes in color schemes, line thickness, or level selection can be applied instantly on the client side without triggering a new rendering pipeline. Such flexibility is particularly valuable in exploratory analysis, where users often need to adjust visualization parameters interactively.

Another key benefit lies in the richness of interactivity. Because the contours are represented as vector features, they retain semantic attributes such as contour level and associated metadata. This enables intuitive interactions like hover tooltips, click-based queries, and dynamic filtering, all of which are natively supported by modern web-mapping engines such as MapLibre GL JS and Leaflet. These capabilities transform static maps into interactive analytical tools, allowing users to explore spatial patterns in a more engaging and informative way.

The approach is also grounded in open standards, which ensures interoperability and long-term maintainability. GeoJSON, as defined by RFC 7946, serves as the primary exchange format, while optional extensions such as Mapbox Vector Tiles (MVT) or PMTiles can be introduced for large-scale deployments. This standards-based design makes the solution portable across different platforms, including Plotly dashboards, Shiny applications, and custom web clients, without requiring specialized server infrastructure.

Despite these strengths, the method is not without limitations. Filled contours, for example, introduce topological complexity in the form of nested polygons and holes. When applying geometry simplification to reduce payload size, care must be taken to preserve topology and avoid self-intersections. Projection handling is another consideration: while GeoJSON mandates WGS-84 coordinates, rendering engines may apply different projections, which can lead to distortions at high latitudes. Finally, scalability remains a challenge for global datasets or dense contour levels. In such cases, strategies like adaptive simplification, reducing the number of contour levels, or adopting vector tiling become essential to maintain performance. Mitigation strategies could include topology-preserving simplification algorithms (e.g., via Shapely), adaptive level selection to minimize polygon density, and projection-aware pre-processing to reduce distortion at high latitudes.

From an environmental science perspective, the vector-based contour visualization significantly improves how researchers and policymakers interpret complex model outputs. For example, interactive exploration of FLEXPART BC fields allows rapid identification of potential source regions or transport events, which previously required generating and reviewing thousands of static plots. The ability to query, restyle, and filter data interactively thus supports model validation workflows and strengthens the connection between scientific modeling and actionable environmental insights. Preliminary feedback from environmental scientists using the FLEXPART BC interface indicated improved interpretability and reduced workflow time compared to static rasters. These outcomes resonate with ongoing discussions in the environmental data science community about bridging computational methods, scientific interpretation, and decision-support (Hollaway et al., 2022; Arkin et al., 2023; Wilkinson et al., 2016). By providing an openly available, interoperable workflow, the approach operationalizes these principles and contributes to the broader movement toward transparent, FAIR, and reproducible environmental research.

Looking ahead, several extensions could further enhance the utility of this approach. Time-series animation is a natural next step, enabling users to explore temporal dynamics by smoothly transitioning between contour states. Another promising direction is on-the-fly contour generation in the browser using WebAssembly bindings to libraries like ContourPy, which would reduce server load and latency. Additionally, hybrid visualization techniques that combine contours with heatmaps or uncertainty bands could provide richer insights for noisy or sparse datasets. Another promising extension is progressive refinement: initial coarse contour layers are rendered first, then incrementally refined as bandwidth permits, or even refined as the user changes zoom-level, aligning with modern progressive web mapping practices.

7 Conclusion

We introduced a simple, standards-based workflow to render interactive, vector contour maps for gridded scalar fields entirely in the browser, using GeoJSON and MapLibre in Plotly or Shiny. The approach preserves interactivity (hover/click, dynamic styling), minimizes server complexity (no raster pipelines), and scales with optional simplification and vector tiling when needed. Our FLEXPART BC case study illustrates how ATMO-ACCESS products can be explored in new, user-driven ways, reducing bandwidth and operational overhead while improving insight. Although the FLEXPART black carbon (BC) use case demonstrates the method in an atmospheric modeling context, the proposed visualization framework is designed as a generalizable paradigm for interactive environmental data visualization. Any gridded scalar field—such as temperature, soil moisture, hydrological fluxes, air pollutant concentrations, or biodiversity indicators—can be rendered through the same vector-contour pipeline. By integrating established scientific Python libraries (`xarray`, `ContourPy`, `Matplotlib`) with open web standards (GeoJSON, MapLibre GL JS), the workflow enables FAIR-aligned, reproducible, and web-native visualization applicable across environmental disciplines, bridging scientific modeling outputs with interactive data exploration and decision-support interfaces (Stevens et al., 2024; Lowndes et al., 2017). This generality supports cross-domain applications in climate analysis, hydrology, and ecosystem monitoring, bridging scientific modeling outputs with interactive data exploration and decision-support interfaces.

In environmental science and policy contexts, the method supports rapid exploration and validation of geospatial model results, accelerating the interpretation of environmental change processes and strengthening the bridge between quantitative modeling and evidence-based environmental management.

8 Statements and declarations

The author declares no competing interests.

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Data and code availability

This work aligns with the FAIR (Findable, Accessible, Interoperable, Reusable) principles through open and reproducible methodological design, and is not tied to any specific datasets. The visualization technique, code, and workflow are openly shared and fully documented, ensuring transparency and reusability. The demonstration use-case (FLEXPART BC) relies on openly accessible model outputs from the ATMO-ACCESS data portal, while the accompanying source code provides a complete, reproducible reference implementation. Together, these elements enable others to reproduce, adapt, and extend the method across different data sources and contexts in a FAIR-compliant manner.

The complete source code implementing the interactive vector-contour mapping workflow, including scripts for GeoJSON generation and Plotly/MapLibre rendering, is openly available at `https://git.nilu.no/asan/vector-contour-maps`. An archived, versioned release corresponding to this manuscript is preserved on Zenodo under the DOI: 10.5281/zenodo.17405398. This ensures long-term accessibility and supports reproducibility in line with FAIR principles.

References

Arkin, A. P., Wilkinson, D. J., Chang, H., Clark, M. P., Jackson, C., Lawlor, P., Thornton, P., and Hsu, A. (2023). Environmental data science as an emerging discipline: Towards open, integrative, and reproducible environmental research. *Environmental Data Science*, 2:e25.

ATMO-ACCESS (2021a). Atmo-access - sustainable access to atmospheric research facilities. `https://www.atmo-access.eu/`. Accessed: 2025-09-01.

ATMO-ACCESS (2021b). Solutions for sustainable access to atmospheric research facilities. `https://cordis.europa.eu/project/id/101008004`. Accessed: 2025-09-01.

ATMO-ACCESS (2022). Flexpart data portal. `https://flexpart-request.nilu.no/data-access`. Accessed: 2025-09-01.

Butler, H., Daly, M., Doyle, A., Gillies, S., Hagen, S., and Schaub, T. (2016a). The geojson format. RFC 7946. GeoJSON standard for geospatial data exchange.

Butler, H., Daly, M., Doyle, A., Gillies, S., Hagen, S., and Schaub, T. (2016b). The geojson format. Technical Report RFC 7946, Internet Engineering Task Force (IETF). GeoJSON standard for geospatial data exchange.

Cartopy Developers (2025). *Cartopy: A Cartographic Python Library with Matplotlib Support*. Cartopy CRS Projection Documentation.

ContourPy Developers (2025). *ContourPy: Python Library for Calculating Contours of 2D Quadrilateral Grids*. Contour generation algorithms used in Matplotlib.

D3js (2011). D3 contour.

Developers, C. (2025). Contourpy: Python library for calculating contours of 2d quadrilateral grids. Contour generation algorithms used in Matplotlib.

Douglas, D. H. and Peucker, T. K. (1973). Algorithms for the reduction of the number of points required to represent a digitized line or its caricature. *The Canadian Cartographer*, 10(2):112–122.

Hollaway, M. J., Evans, B. J., Maskell, G. A., Oliver, S., Atkinson, M., Williams, M., Sanderson, M. G., Allen, J., Dacre, H., and Young, P. J. (2022). Fair and open environmental data for modelling and decision support. *Environmental Data Science*, 1:e10.

Hsu, A., Xie, Y., Boucher, T., Lesk, C., and de Sherbinin, A. (2021). Advancing environmental data for decision-making: Integrating visualization, accessibility, and public engagement. *Environmental Research Letters*, 16(11):115005.

Lorensen, W. E. and Cline, H. E. (1987). Marching cubes: A high resolution 3d surface construction algorithm. *ACM SIGGRAPH Computer Graphics*, 21(4):163–169.

Lowndes, J. S. S., Best, B. D., Scarborough, C., Afflerbach, J. C., Frazier, M. R., O'Hara, C. C., Jiang, N., and Halpern, B. S. (2017). Our path to better science in less time using open data science tools. *Nature Ecology & Evolution*, 1(6):0160.

Mapbox (2016). Mapbox vector tile specification. Specification for tiled vector data.

Maple, C. (2003a). Geometric design and space planning using the marching squares and marching cube algorithms. *International Conference on Geometric Modeling and Graphics, 2003. Proceedings. pp. 90-95.*

Maple, C. (2003b). Geometric design and space planning using the marching squares and marching cubes algorithms. In *Proceedings of the International Conference on Geometric Modeling and Graphics*, pages 90–95.

MapLibre (2025). Geojsonsource - maplibre gl js. MapLibre GL JS documentation for GeoJSON sources.

Nielson, G. M. and Hamann, B. (1991). The asymptotic decider: Resolving the ambiguity in marching cubes. In *Proceedings of Visualization '91*, pages 83–91.

Pisso, I. and et al. (2019). The lagrangian particle dispersion model flexpart version 10.4. *Geoscientific Model Development*, 12:4955–4997.

Plotly (2025). Maplibre migration in python. Plotly migration from Mapbox to MapLibre for map rendering.

Plotly Technologies Inc. (2025). *MapLibre Migration in Python: Plotly Maps Documentation*. Plotly migration from Mapbox to MapLibre for map rendering.

Posit (2025). Map (ipyleaflet) – shiny for python. Interactive maps in Shiny for Python using ipyleaflet.

Posit Software Inc. (2025). *Map (ipyleaflet) – Shiny for Python: Interactive Maps Documentation*. Interactive maps in Shiny for Python using ipyleaflet.

PostGIS Development Team (2023). *ST_SimplifyPreserveTopology — PostGIS Documentation*. Available at: `https://postgis.net/docs/ST_SimplifyPreserveTopology.html`.

Rodgers, C., Morris, D., Gadd, H., and Ball, M. (2020). Interactive catchment explorer (ice): A web-based interactive data visualization framework. *Water*, 12(4):1045.

Romgens, B. (2025). geojsoncontour: Convert matplotlib contour plots to geojson. Python module for converting contour plots to GeoJSON.

Schroeder, W., Ahrens, J., and Martin, K. (2017). The flying edges: A high-performance scalable isocontouring algorithm. *IEEE Transactions on Visualization and Computer Graphics*, 23(1):931–940.

Schroeder, W., Ahrens, J., and Martin, K. (2024). A high-performance surfacenets discrete isocontouring algorithm. *arXiv preprint arXiv:2403.01582*.

Stevens, R., Duffy, C., Allen, J., and Gray, S. (2024). Web-based interactive environmental visualization and model validation platforms. *Environmental Modelling & Software*, 170:106951.

Stohl, A., Forster, C., Frank, A., Seibert, P., and Wotawa, G. (2005). Technical note: The lagrangian particle dispersion model flexpart version 6.2. *Atmospheric Chemistry and Physics*, 5:2461–2474.

Stojanović, R. and Stojanović, N. (2013). A topology-preserving line simplification algorithm. In *ICT Innovations 2013*, pages 45–54.

van Beek, L. P. H., Wanders, N., Bierkens, M. F. P., and Sutanudjaja, E. H. (2023). Open environmental data infrastructure for global hydrological modeling and decision support. *Environmental Modelling & Software*, 164:105696.

Visvalingam, M. and Whyatt, J. D. (1993). Line generalisation by repeated elimination of points. *The Cartographic Journal*, 30(1):46–51.

Wang, Q. and et al. (2019). Black carbon aging and transport in the arctic: Implications for climate. *Atmospheric Chemistry and Physics*, 19:10389–10409.

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J., da Silva Santos, L. B., Bourne, P. E., et al. (2016). The fair guiding principles for scientific data management and stewardship. *Scientific Data*, 3:160018.

xarray Developers (2025). Xarray n-d labeled arrays and datasets in python. `https://docs.xarray.dev/en/stable/generated/xarray.open_dataset.html`. Accessed: 2025-09-01.

Zanatta, M. and et al. (2025). Long-term observations of black carbon in the arctic: Trends and source contributions. *Atmospheric Chemistry and Physics*. in press.

Zhang, X., Li, Y., Wu, Q., and Zhao, X. (2020). Performance testing on vector vs. raster map tiles — a comparative study. *ISPRS International Journal of Geo-Information*, 9(3):163.

Zhou, L., Zhao, X., and Gao, Y. (2024). A comprehensive survey of isocontouring methods: Applications and techniques. *Algorithms*, 17(4):142–165.