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.

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)).

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. (2016), 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 (2003)).

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.

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 (2021a), ATMO-ACCESS (2021b)).

2 Related Work

Isoline generation on regular grids is commonly implemented via marching squares and variants; modern Python stacks expose these through ContourPy (used by Matplotlib) with high-performance serial and multithreaded backends. In the browser, d3-contour also applies marching squares on raster inputs to produce polygons (Maple (2003), Developers (2025), D3js (2011)).

On the rendering side, MapLibre GL JS supports GeoJSON sources natively (tiling on the fly with geojson-vt under the hood), while Plotly has migrated its mapping traces from Mapbox to MapLibre, exposing map subplots (Scattermap, Choroplethmap, etc.) with WebGL2 acceleration and globe/projection support. Shiny (R and Python) integrates well with Leaflet and ipyleaflet for interactive GeoJSON layers (MapLibre (2025), Plotly (2025), Posit (2025)).

For large-scale deployments, pre-tiled vector formats such as MVT (served as .mvt or packed into MBTiles/PMTiles) allow efficient panning/zooming with minimal bandwidth and latency. We treat these as optional extensions when contour complexity and extent demand it (Mapbox (2016), Protomaps (2025)).

A comparison of different approaches is summarized in Table 1.

3 Methodology

The essential idea of our new method is to use matplotlib to plot a filled contour and then extract and encode this contour plot as polygons using GeoJSON, which can be plotted on interactive maps.

3.1 Data model and coordinate handling

We assume a gridded scalar field $Z(\lambda, \phi)$ on a rectilinear lon/lat grid (or any grid convertible to lon/lat). We read fields with xarray (netCDF/CF) and ensure WGS-84 coordinates for GeoJSON output per RFC 7946. If source data are

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

in another CRS, we convert via Cartopy/pyproj (xarray Developers (2025), Butler et al. (2016), Cartopy (2025)).

3.2 Contour extraction

Given a set of contour levels $\{c_k\}$, we compute isolines and/or isobands using ContourPy (via Matplotlib), which provides robust algorithms and masked-array support. For isobands, adjacent level pairs define filled polygons. We apply linear interpolation along cell edges following the marching-squares principle (Developers (2025), Maple (2003)).

3.3 GeoJSON conversion

We convert Matplotlib contour objects to GeoJSON using geojsoncontour (contour to geojson / contourf to geojson). Resulting features carry properties such as level, fill, and stroke, following common styling conventions. Output conforms to RFC 7946 (FeatureCollection of LineString/Polygon geometries) (Romgens (2025), Butler et al. (2016)).

3.4 Rendering on the web

We support two integration paths:

Plotly (MapLibre): Use Plotly's MapLibre-based map traces (e.g., go.Scattermap for isolines or go.Choroplethmap for filled polygons) and set layout.map basemap styles. These traces provide hover/click callbacks and GPU acceleration (Plotly (2025)).

Shiny (Python) with ipyleaflet: Add the GeoJSON as a GeoJSON layer and attach tooltips/popups; Shiny wiring enables reactive level selection and time stepping (Posit (2025)).

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.

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 1, while Figure 2 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 3 and Figure 4, 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.

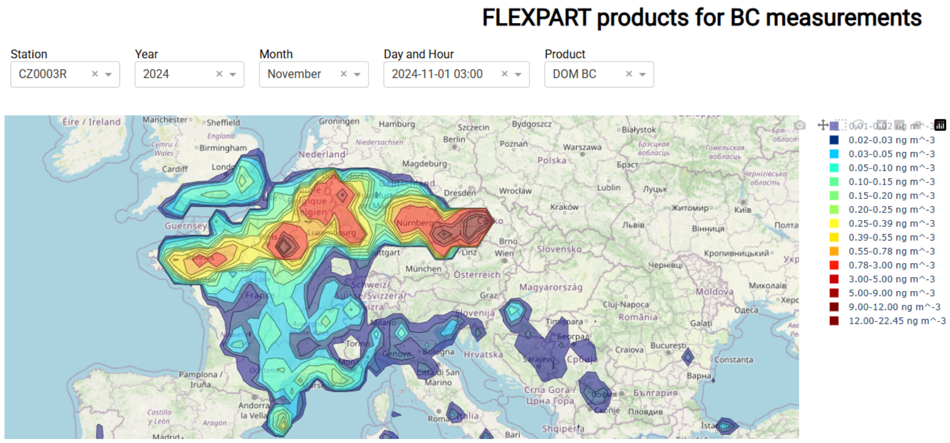

Figure 1: An example of our vector-based contour plot for the FLEXPART BC source contribution field.

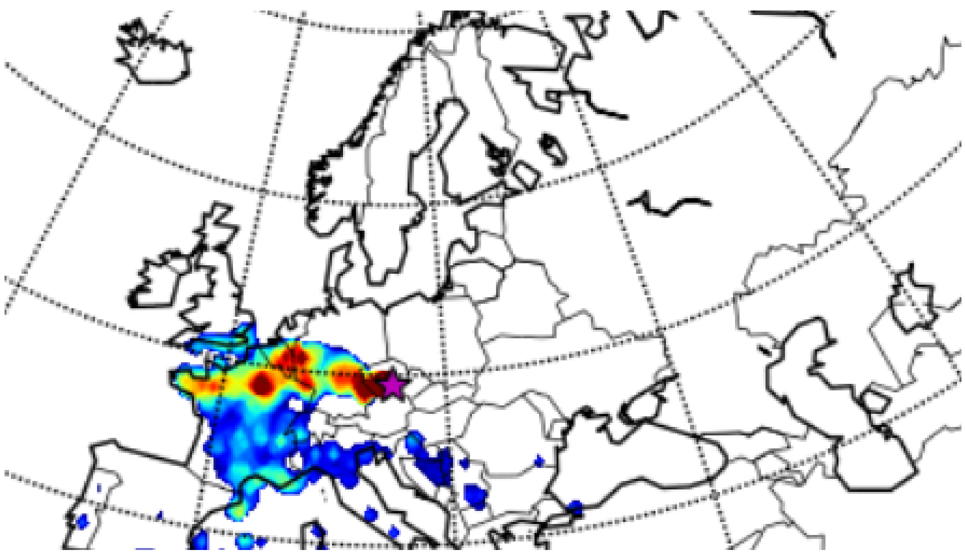

Figure 2: The original raster based contour plot for comparison with Figure 1

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

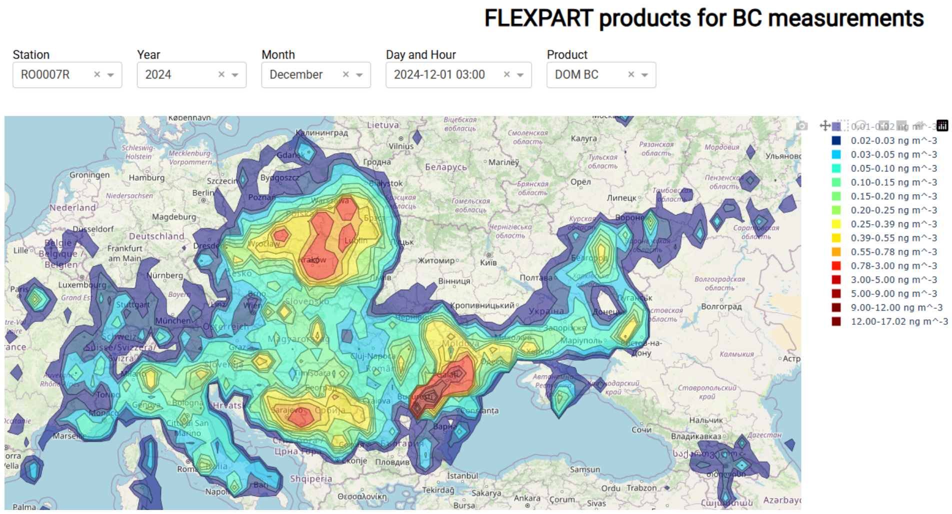

Figure 3: Another example of our vector-based contour plot for the FLEXPART BC source contribution plot

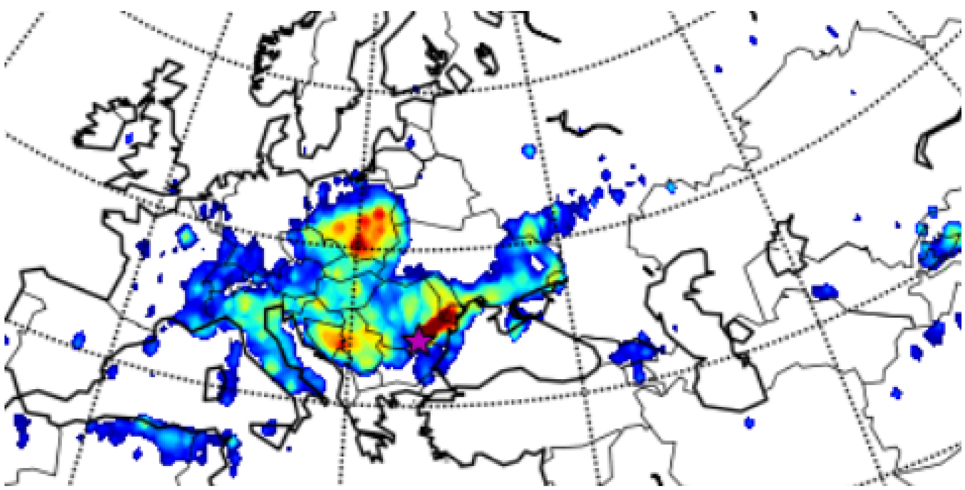

Figure 4: The original raster based contour plot for comparison with Figure 3

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.

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.

8 Statements and declarations

The author declares no competing interests.

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.1 Source code

We include a simple code example to demonstrate the new method. The following minimal reproducible implementation demonstrates the pipeline. The example reads a NetCDF file, generates contours, converts to GeoJSON, and renders them interactively.

```python
import plotly.express as px
import xarray as xr
import matplotlib
import matplotlib.pyplot as plt
import geojsoncontour
import cartopy.crs as ccrs
import cartopy.feature as cfeature
import pandas as pd
import geopandas as gpd
import json

def plot(file_path):
    ds = xr.open_dataset(file_path)
    df = ds[["dom_BC"]].to_dataframe() # Here we assume that "
    dom_BC" is the variable to be plotted
    df = df[["dom_BC"]].reset_index()
    df = df[df.dom_BC > 0.001]
    dom_BC = df.dom_BC.values
```

```python
    target_values = ds.dom_BC.values
    max_val = float(dom_BC.max())
    levels = [0.01, 0.02, 0.03, 0.05, 0.10, 0.15, 0.20, 0.25, 0.39, 0.55, 0.78, 3.00, 5.00, 9.00, 12.00, max_val]

    proj = ccrs.PlateCarree()

    fig_matplotlib, ax = plt.subplots(figsize=(10, 10), subplot_kw=dict(projection=proj))

    # Set the plot extent
    ax.set_extent([ds.longitude.min(), ds.longitude.max(), ds.latitude.min(), ds.latitude.max()])

    # Add map features
    ax.add_feature(cfeature.LAND, facecolor='lightgray')
    ax.add_feature(cfeature.COASTLINE, linewidth=0.5)
    ax.add_feature(cfeature.BORDERS, linewidth=0.5)

    # Add the latitude and longitude grid
    gl = ax.gridlines(crs=ccrs.PlateCarree(), draw_labels=True, linewidth=1, color='gray', alpha=0.5, linestyle='--')
    gl.top_labels = False
    gl.right_labels = False
    gl.xlabel_style = {'size': 12, 'color': 'gray'}
    gl.ylabel_style = {'size': 12, 'color': 'gray'}

    cf = ax.contourf(ds.longitude, ds.latitude, target_values, cmap='jet', levels=levels) # jet

    col = "dom_BC"

    fig = px.density_map(
        df,
        lat="latitude",
        lon="longitude",
        z=col,
        hover_data={
            "latitude": True,
            "longitude": True,
            col: True,
        },
        center=dict(lat=48.85, lon=2.35),
        zoom=4,
        radius=30,
        opacity=0.0, # hide this plot, as we are only interested in the traced and filled contour added below as fig2
        map_style="open-street-map",
```

```
        color_continuous_scale="Jet", # Note! This color scale does not get applied to the trace below. The trace gets the colorscale set in ax.contourf above which we modiy with cmap dict below
    )
    _ = fig.update_layout(coloraxis_showscale=False)
    _ = fig.update_layout(coloraxis_colorbar_y=0.2)

    geojson = geojsoncontour.contourf_to_geojson(
        contourf=cf,
        ndigits=6,
        unit='ng m^-3'
    )
    geojson_obj = json.loads(geojson)
    gdf = gpd.GeoDataFrame.from_features(geojson_obj)
    gdf["fill-opacity"] = gdf.apply(lambda x: 0.6, axis=1)
    gdf = gdf.loc[~gdf.geometry.is_empty]

    cmap = dict()
    cmap['0.01-0.02 ng m^-3'] = '#000080'
    cmap['0.02-0.03 ng m^-3'] = '#002F80'
    cmap['0.03-0.05 ng m^-3'] = '#00CAFF'
    cmap['0.05-0.10 ng m^-3'] = '#26FFD1'
    cmap['0.10-0.15 ng m^-3'] = '#62FF95'
    cmap['0.15-0.20 ng m^-3'] = '#7DFD78'
    cmap['0.20-0.25 ng m^-3'] = '#9CFF5B'
    cmap['0.25-0.39 ng m^-3'] = '#FFFB26'
    cmap['0.39-0.55 ng m^-3'] = '#FFE600'
    cmap['0.55-0.78 ng m^-3'] = '#FFA80D'
    cmap['0.78-3.00 ng m^-3'] = "#FF1C00"
    cmap['3.00-5.00 ng m^-3'] = "#C80000"
    cmap['5.00-9.00 ng m^-3'] = '#A20100'
    cmap['9.00-12.00 ng m^-3'] = '#7C0200'
    cmap[f"12.00-{max_val:.2f} ng m^-3"] = '#800000'

    for k,v in cmap.items():
        gdf.loc[gdf['title'] == k, 'fill'] = v

    fig2 = px.choropleth_map(
        gdf,
        geojson=gdf.geometry,
        locations=gdf.index,
        color="title",
        color_discrete_map=cmap,
        opacity=.5
    )
    fig.add_traces(fig2.data)
    fig.update_layout(height=1000, width=1600, margin={"r":0,"t":0,"l":0,"b":0})
```

```
    fig.show()
```

.2 Data availability

Only publicly available data were used in the research. The method works with any similarly structured data as demonstrated by the source code.