




SCIENCE

Interactive video maps: *A year in the life of Earth's CO₂*

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ABSTRACT

This article introduces interactive video maps for the web. The main component of video maps is a video stream that is *areally* georeferenced to a spatial reference system in the same way rectified raster orthoimages are georeferenced. The areal georeference allows for interactivity that goes beyond the play, pause, and stop functionality of video player software. We highlight two types of functionality, allowing the user to (1) combine the video stream layer with other raster and vector map layers and (2) adjust the projection of the map in real time. We exemplify video maps by *A Year in the Life of Earth's CO₂*, an interactive video map that visualizes the results of a high-resolution NASA computer model of global atmospheric carbon dioxide distribution. The map shows how carbon dioxide travels around the globe over the course of one year. We use a combination of WebGL, a programming interface to the hardware-accelerated graphics pipeline, and HTML5 video for adding an areally georeferenced video layer to other map layers, and for the on the fly projection of the video stream in the web browser.

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1. Introduction: georeferenced video

Cartographers have used motion film and video for a long time. For example, Thrower (1959, 1961) documents early production techniques and describes cartographic film production in the United States starting in the 1930s. Early cartographic films were produced with analogue means and did not offer interactivity. As Harrower (2004) notes, the techniques ‘remained marginalized until the mid-1980s because few cartographers had either the skill or resources to create such maps manually.’ Tobler (1970) created the first computer map animation, but digital animation was only widely adopted for mapmaking by the end of the last century when personal computers capable of producing and playing digital video became available (Campbell & Egbert, 1990; Cartwright, 2007), and academic cartographers extended the visual variables by Bertin (1967, 1983) for animated maps (DiBiase, MacEachren, Krygier, & Reeves, 1992; MacEachren, 1995). Cartographic animation is now well established, and recent textbooks (e.g. Muehlenhaus, 2013; Slocum, McMaster, Kessler, & Howard, 2009) provide practical advice for creating animated maps.

Harrower (2004) notes that video and animation are not the same. While both are commonly used to visualize temporal processes, a video consists of a stream of individual frames that are displayed in rapid sequence to create a movie, whereas an animation numerically defines the appearance of objects (size, direction,

velocity, etc.) and is decoded and rendered by the computer that displays the animation.

In the context of this article, it is important to consider the type of video georeference. We make a distinction between video with a *single-point georeference* from video with an *areal georeference*. A *single-point georeference*, as defined here, is a point localizing the video in a spatial reference system. The point is typically the camera location or a location that is visible in the video. This single position is tied to a spatial reference system, which allows for placing a point symbol, such as a play button, on an interactive map. However, the geotagged video imagery is not part of the map itself, and a video with single-point georeference is therefore only a complementary medium to a map, similar to how other media such as photographs, illustrations, or text can be georeferenced to supplement a map (Luo, Joshi, Yu, & Gallagher, 2011).

In an *areally georeferenced video*, as we define it here, each video frame is georectified. That is, each pixel is referenced to a spatial reference system. This is identical to how each pixel of a static orthoimage is rectified and georeferenced, and is required for making a video stream useful for metric geospatial analysis, visualization in combination with other georeferenced information, the conversion to other spatial reference systems, or other geospatial operations.

Areally georeferenced video or video enriched with geographic information, such as the field of view and trajectory information (Han, Cui, Kong, Qin, & Fu,

2015), has surveillance and intelligence applications (Lewis, Fotheringham, & Winstanley, 2011), and is collected by aerial vehicles or terrestrial cameras. Various geographic information systems provide specialized tools for georeferencing, visualizing, and analyzing spatial video (Han et al., 2015; Lewis et al., 2011), but real-time video georectification is computationally expensive and with limited accuracy. Because camera location and orientation constantly change over time, each frame must be georeferenced individually. Furthermore, video streams collected from airplanes, drones, or other aerial vehicles are not generally suitable for cartographic visualization, because the area covered by the video stream is often limited and following a fixed camera path.

A cartographic video visualization requires a video stream that covers a large, static area (i.e. the camera should not move). There are two typical video production scenarios used in cartography, involving either (1) the use of animation software or (2) video imagery from satellites or scientific simulation models. For the first production scenario, a cartographic animation is created using an animation software package and then rendered to video frames (e.g. a ship symbol is animated along a vector path to visualize the voyages of Christopher Columbus, and the result is stored in a series of movie frames). For the second production scenario, video imagery is collected by satellites or created by scientific simulation software. The images are then color adjusted and possibly otherwise enhanced, and finally converted to a video stream. An example output of a scientific simulation is shown in Figure 1.

Areally georeferenced video can be made available in two forms. By far the most common form is a stand-alone map video, which, when combined with sound effects and voiced-over narration, Muehlenhaus (2014) calls *film-maps*. A film-map is displayed by standard video player software with customary playback controls. However, film-maps are not interactive beyond the standard play/pause and temporal navigation commands; users cannot zoom, style, query, or interact in any other way with film-maps (Figure 1).

The second form of making areally georeferenced video available in cartography is through interactive video maps, which we introduce in this article. We illustrate interactive video maps by the example of *A Year in the Life of Earth's CO₂* (Jenny et al., 2014), a video map with an areally georeferenced video layer created by an atmospheric carbon dioxide concentration model. The map is designed to inform the general public about spatial and temporal carbon dioxide emission patterns, and to increase awareness of this important process. The map includes a video layer at different resolutions, vector layers with a graticule and international borders, legends, and voiced-over narration. It allows the user to navigate temporally using a circular slider, adjust the layer composition,

select a video resolution, adjust scale, and move the center of the map to adjust the oblique map projection.

The next paragraph introduces interactive video maps and explains how they differ from film-maps. The following sections describe the NASA carbon dioxide model software used for creating *A Year in the Life of Earth's CO₂*, the characteristics of video map layers, and how they can be projected in real time. The Conclusion section outlines areas of possible future research, and the final Software section provides information about the workflow for creating the interactive video map.

2. Interactive video maps

Interactive video maps are a recent alternative to film-maps. They have been made possible by the combination of areally georeferenced video streams and modern computer technology. We define an *interactive video map* as a map that contains at least one areally georeferenced video stream and offers interactive features. (Note: In this article we use 'video map' and 'interactive video map' as synonyms.) Interactivity is an important characteristic of video maps. An interactive video map is not a film-map, because users can, for example, manipulate the content of the video map, query information, or change its projection.

The integration of video layers with raster and vector layers requires the computational power of a graphics processing unit (GPU) and recent web technology. Two current technologies are key, namely WebGL, which is a programming interface to GPU functionality (Khronos Group, n.d.) and HTML5 video, which is a standard for streaming and displaying video data (WHATWG, 2015). However, web technology evolves at a rapid pace, and we therefore expect interactive video maps to be implemented using alternative technology in the future.

Areally georeferenced video for interactive video maps is a recent development. An example of an early attempt of a somewhat related visualization type is documented by Eugster and Nebiker (2008). They coupled a live video stream captured by an UAV (unmanned aerial vehicle) with the Google Earth digital globe. However, the video was not projected onto the globe surface, but was displayed in an overlaid window. The main reason for the sparse use of interactive video maps is probably due to the required technology (HTML5 video and WebGL), which has only recently become available in web browsers. We expect interactive video maps to become more common in the near future, as some web mapping frameworks have recently added support for areally georeferenced video (an example is Mapbox, see MacWright, 2015).

One can envision a variety of analysis and visualization functionalities on the basis of interactive video layers. This article focuses on two essential types of

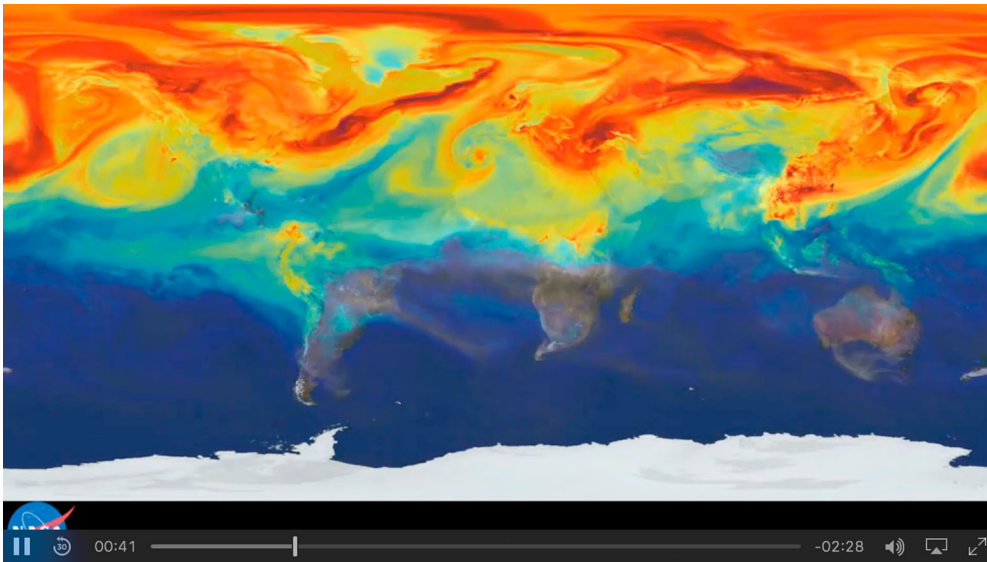


Figure 1. A still frame of a film-map with voice-over narration. The video is areally georeferenced (WGS84 and Plate Carrée projection), but is not an interactive video map, because only standard video player controls for play/pause and temporal navigation are provided. Source: <http://svs.gsfc.nasa.gov/goto?11719>.

functionality of interactive web maps: (1) the combination of video stream layers with other raster and vector map layers and (2) the projection of video layers in real time.

The combination of a video stream layer with other vector and raster layers facilitates the analysis and exploration of spatial relations by adding spatial context to a video stream, and enables the user to adapt the map to specific needs and interests.

The projection of a video layer in real time can be used to automatically adjust the map geometry to the visible map area, or to interactively adjust projection parameters, such as the center of the map (Figure 2).

3. The NASA carbon dioxide model

A Year in the Life of Earth's CO₂ shows how carbon dioxide in the atmosphere travels around the globe. As Lynch (2014a) summarizes

plumes of carbon dioxide in the simulation swirl and shift as winds disperse the greenhouse gas away from its sources. The simulation also illustrates differences in carbon dioxide levels in the northern and southern hemispheres and distinct swings in global carbon dioxide concentrations as the growth cycle of plants and trees changes with the seasons.

The carbon dioxide visualization used for *A Year in the Life of Earth's CO₂* was produced by a computer model called GEOS-5, created by scientists at NASA Goddard Space Flight Center's Global Modeling and Assimilation Office (Lynch, 2014b). The visualization is a product of a simulation called a 'Nature Run.' The Nature Run ingests real data on atmospheric conditions, the emission of greenhouse gases, and both natural and man-made particulates. The model is left

to run on its own to simulate the behavior of the atmosphere from May 2005 to June 2007 (NASA, 2013). The output of the model is limited to the year 2006, and the raw raster data are color coded and converted to a video file. The colors represent carbon dioxide concentrations between 375 (dark blue) and 395 (light purple) parts per million. White plumes represent carbon monoxide emissions (Lynch, 2014b). The video is stored and streamed to clients in the Plate Carrée projection, which has an aspect ratio of 2:1.

4. Video map layers with HTML5 video

A video map can contain one or more video layers, as well as conventional raster and vector layers. Combining a video, vector, and raster layers can add spatial context to a video. For example, in *A Year in the Life of Earth's CO₂*, vector layers with a graticule and country borders are displayed above the video layer. The user can show and hide some of the vector layers, which facilitates the analysis and exploration of spatial relations. For example, carbon dioxide plumes created by fires can be more accurately located by overlaying country borders and major hydrographic features (Figure 3). The show/hide feature could also be applied to video layers, although we do not use this feature, as it would not add useful functionality to this particular map. The user can adjust the resolution of the video, and other types of interactivity could be added to the video layer, as will be outlined in the Conclusion section.

For *A Year in the Life of Earth's CO₂*, we use the HTML5 video specification to load video data and control video playback. The video element in our HTML document element is not visible but serves as an

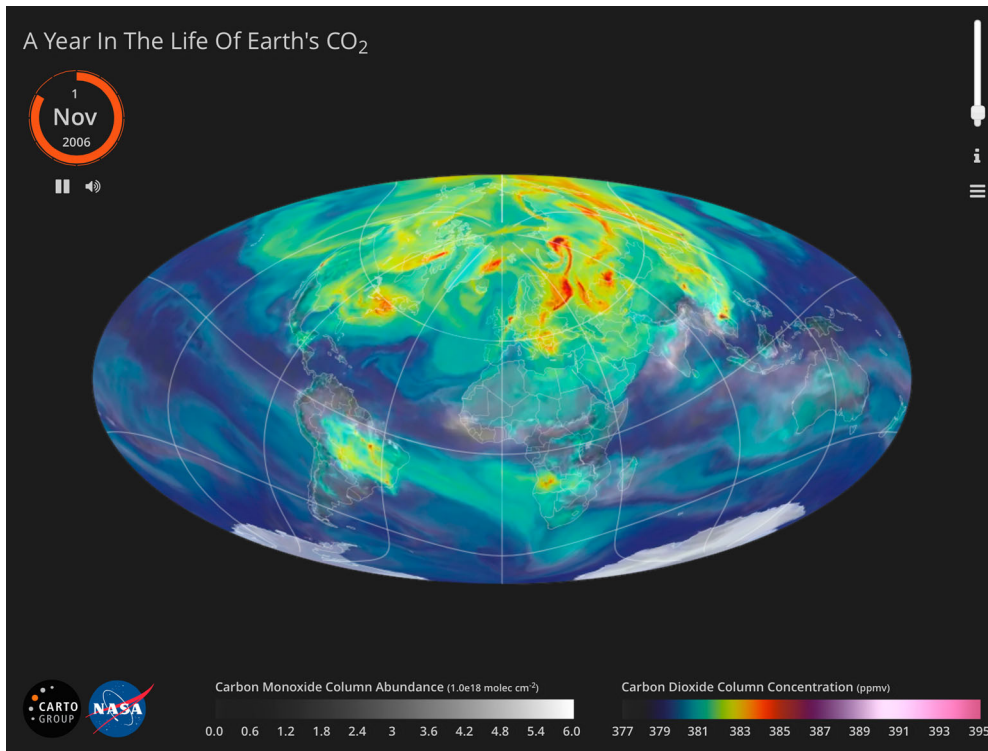


Figure 2. Screen capture of *A Year in the Life of Earth's CO₂* video map.

invisible container for streaming the data. The video stream data is uploaded to the GPU, projected with hardware-accelerated shader programs (see next section), and then displayed in an HTML5 canvas element (WHATWG, 2015). This setup differs from standard

HTML pages with video, because shader programs manipulate the video stream, and a canvas element instead of a video element displays the video stream.

The HTML5 video specification allows for a variety of video formats (such as MP4). In addition, video

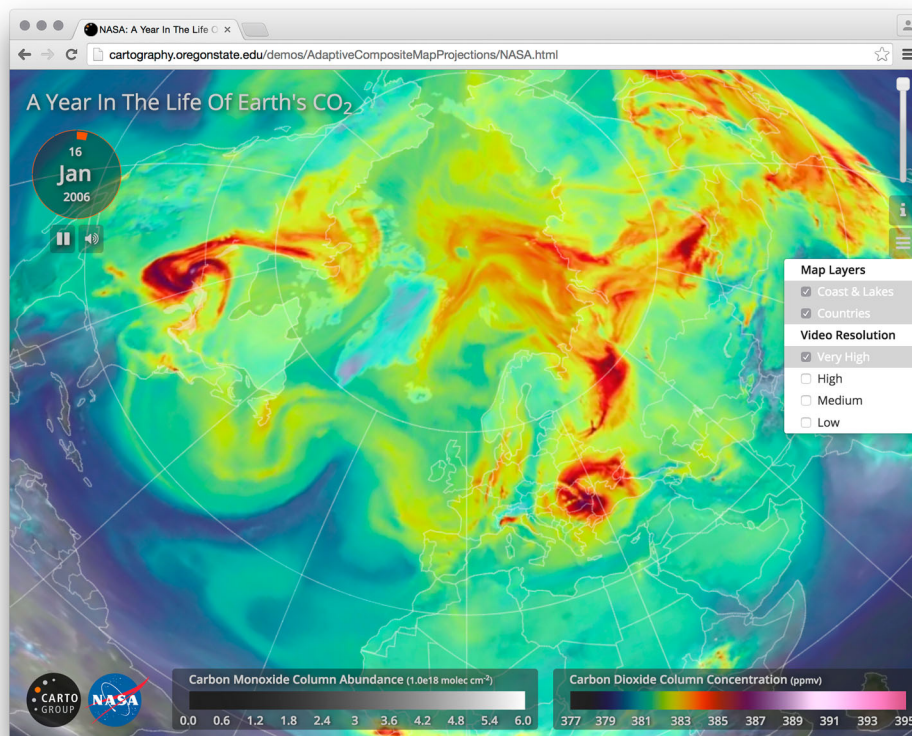


Figure 3. User elements for adjusting visibility of layers (e.g. coast and lake lines, country borders) and video resolution.

streams at different resolutions can be provided, depending on the available download speed.

Various techniques exist for rendering vector data in web browsers (Gaffuri, 2012; Lienert, Jenny, Schnabel, & Hurni, 2012). We opted for HTML5 canvas for rendering vector features. The HTML5 canvas element, which displays the movie, is overlaid by a second canvas element, which renders the other map layers using the HTML5 canvas JavaScript API (W3C, 2014). The layer geometry is loaded in vector format, projected with JavaScript, and then styled and rendered.

5. Real-time projection of georeferenced video

The real-time projection of web maps is relevant at various map scales, because it offers two main advantages: (1) the map can automatically adjust its projection to minimize distortion for the currently visible area and (2) the map center can be adjusted, either by the user or algorithmically (Jenny, 2012; Šavrič & Jenny, 2014). The projection of a video requires each movie frame to be transformed. Because a smoothly animated movie requires 25 or more frames per second, a considerable amount of raster imagery needs to be processed. The traditional CPU-based approach for projecting raster images with continuous tone colors, as described by Finn et al. (2012b), is too slow. Attempts at accelerating raster projections have been presented by various authors (Finn et al., 2012a; Tang & Feng, in press; Xie, Tang, Sun, & Chen, 2011; Zhao, Cheng, Dong, Fang, & Li, 2011), but the required technology is often not available in web browsers, geometrical accuracy is sacrificed for speed, or access to cloud computing may be needed (see Jenny, Šavrič, & Liem, 2015 for details).

An alternative approach for the real-time projection of raster images was introduced by Jenny et al. (2015). Their method uses the GPU through the WebGL API. Dedicated shader programs run on the GPU to project raster images at very high speed. The original framework by Jenny et al. (2015) works with a static raster image in the Plate Carrée projection. This image is loaded as a texture onto the GPU using the WebGL API. When the map is projected and rendered, specialized WebGL shader programs transform the texture to the current map projection and render it to an HTML5 canvas element. For *A Year in the Life of Earth's CO₂*, we extend the framework by Jenny et al. (2015) for the projection of video streams. Instead of loading individual raster images, we use an HTML5 video element to load the video stream. The video stream is linked to the HTML5 canvas element, and the video frames are accessible by the shader programs as a texture. Technical details about the combination of the HTML5 video element with WebGL are provided by Mozilla Developer Network (2015). The video stream is best streamed to the client using the Plate Carrée (or 'geographic')

projection to simplify projection algorithms. (An initial reverse projection to spherical or elliptical coordinates is not required.)

The described combination of WebGL and HTML5 video is fast enough for the real-time projection of georeferenced video streams. We achieve interactive frame rates with recent tablets and standard computers using video streams at full screen size and 25 or more frames per second. The result is a video map that can be smoothly zoomed and rotated while the video stream is playing. For example, in Figure 4, the user created an oblique projection by rotating the South Pole towards the center of the map to better visualize a georeferenced video showing the propagation of a tsunami wave through the Pacific Ocean and around Antarctica. This type of phenomenon would be difficult to visualize using a projection with a static equatorial aspect.

Additional new types of user interactions with areally georeferenced video in web browsers are conceivable that are based on transitioning projection parameters. For example, maps with panning and zooming animations could be created, projection parameters could be animated to produce maps with a rotating globular appearance, or smooth transitions between points of interest could be synchronized with the current focus of voice-over narration.

6. Conclusion

This article makes a contribution to the interactive visualization of areally georeferenced video streams by introducing the concept of interactive video maps for the web. Single-point georeference and areal georeference for video streams are defined, and video map layers based on an areally georeferenced video stream are introduced. Video map layers can be combined with traditional raster and vector layers. We use standard graphics hardware for the real-time projection of areally georeferenced video streams in web browsers. The web browser applies a cartographic projection to a video stream on the fly, allowing the user to adjust the center of a video map while the video stream is playing.

The outputs of scientific computational simulations or satellite imagery are predestined for visualization in video maps. Simulation model algorithms use georeferenced data, and the output data is therefore readily georeferenced. Video maps offer new possibilities for the exploration and visualization of temporal raster information. Scientific users as well as the general public can observe global temporal phenomena that are difficult to visualize on virtual globes or static maps with a fixed projection.

A Year in the Life of Earth's CO₂, available at <http://co2.digitalcartography.org>, is an interactive video map that visualizes the results of a high-resolution NASA computer model of global atmospheric carbon dioxide

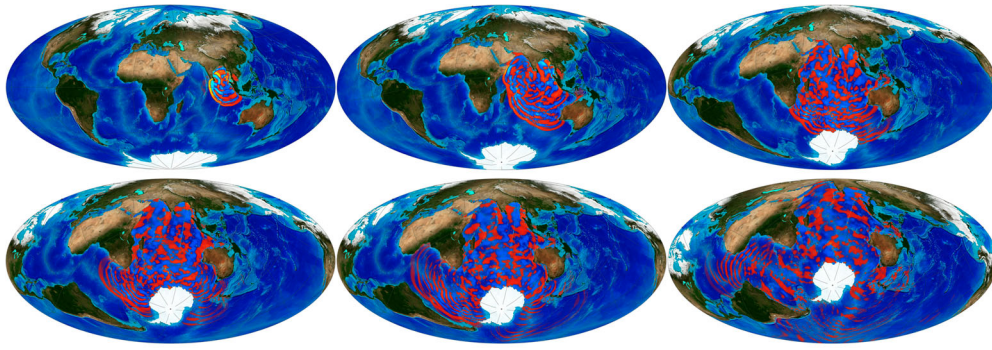


Figure 4. Still frames of a video stream transformed to an oblique projection. The user adjusts the center of the map projection while the video stream is playing. 2004 Indian Ocean tsunami model by NOAA Pacific Marine Environmental Laboratory. Video source: <http://sos.noaa.gov/Datasets/dataset.php?id=161>.

distribution. The map demonstrates that high-resolution interactive video maps are possible to create with current hardware and standard web browsers, and provides the user with new insights through its interactive capabilities.

Additional interactive functionality could be added to video maps. Future research is needed to develop new types of interactive analysis and visualization features for areally georeferenced video streams in web browsers. For example, video maps could provide functionality for reclassifying or coloring video streams, or computing areal and temporal statistic from video streams. Furthermore, our *A Year in the Life of Earth's CO₂* map uses one particular type of user interface that we assumed was appropriate for this particular map. We chose a cyclical control for indicating progress and navigating in time to emphasize the cyclical pattern of carbon dioxide emission. However, we have not ascertained this assumption; additional research is needed to better understand the suitability of alternative user interfaces for interactive video maps.

Software

The NASA GEOS-5 modeling software (NASA, 2013) simulated the behavior of the Earth's atmosphere. The model output was then converted to a narrated video stream with a 2:1 aspect ratio in the Plate Carrée map projection. The client software uses a framework for the projection of raster images in the web browser by Jenny, Šavrič and Liem (2015) that was extended for the projection of video streams. The user interface, video element, canvas, and WebGL functionality are combined with JavaScript.

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