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State of the Art in Flow Visualization in the Environmental Sciences

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Abstract Flow plays a major role in environmental sciences, because many of the Earth's physical and biological processes involve movement. Yet, there are major differences between theoretically available and practically applied visualization techniques to represent flow.

This paper surveys various techniques in computational and environmental flow visualization. Techniques from the computational flow visualization community are classified into geometric, texture-based, topology-based, and feature-based approaches. Environmental flow applications are categorized into four application domains (atmospheric science, ecology, geosciences, and urban environments). Computational and environmental visualization approaches are compared to exhibit gaps and suggest solutions on how to bridge the gap.

Outcomes from this literature review will inform the development of strategic initiatives for both future flow visualization research and flow visualization in the environmental sciences.

Keywords flow visualization · environmental visualization · state of the art

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1 Introduction

Many of the Earth's physical and biological processes are driven or influenced by movement. Flow is important for environmental water management, water allocations for humans and freshwater-dependent ecosystems, the formation of hurricanes and tsunamis, and air quality assessments, to name a few examples. In computer science, flow visualization is a well established research field that provides a variety of methods and algorithms that allow a human to see and understand the motion of water, air, or particles. Yet, a gap exists between the tools that have been proposed in flow visualization and those that have actually been applied to real world problems by domain experts in environmental sciences.

Here, we investigate the differences between these two theoretically closely related fields, point out potential reasons for this gap, and suggest solutions to bridge it.

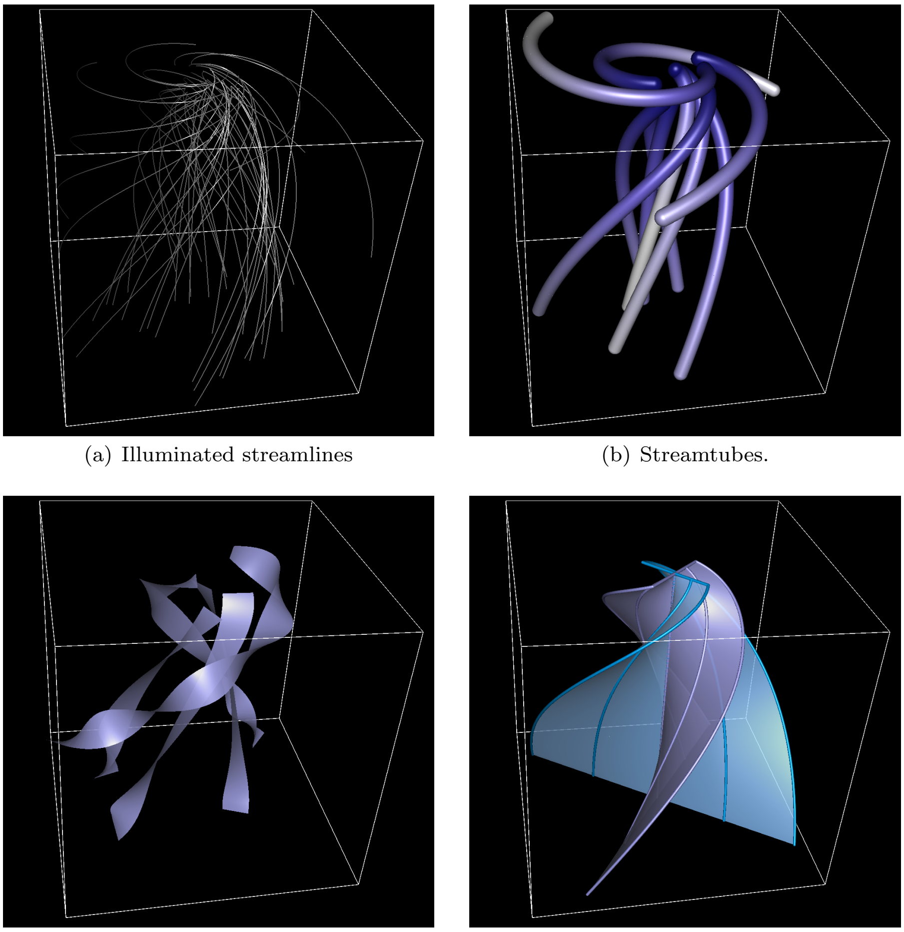
This paper is an updated version of an EnvirVIS workshop short paper on strategic initiatives in the environmental flow visualization field [13] and structured as follows: First, we review common flow visualization techniques, i.e. geometric, texture-based, topology-based, and feature-based methods. Then, we discuss flow visualization in environmental sciences, which we group into four application fields: atmospheric science, ecology, geosciences, and urban environments. Finally, we compare the visualization approaches in both research domains ans suggest solutions to bridge identified gaps.

2 Flow Visualization

Flow visualization is the science of making flow fields visible [34]. In particular, it creates images that most efficiently translate the movement of fluids into understanding of their behavior. It is older than scientific computing [89, 60], but the use of computers has leveraged it into a new era, on which we will focus. Openly available programs, like ParaView [2] or VisIt [17], provide many flow visualization techniques. Even though there are overlaps, they can be structured into the following categories.

2.1 Geometric Techniques

Some of the most popular flow visualization techniques fall into the category of geometric techniques, Fig. 1. Here, geometric objects such as curves, surfaces, and volumes, are built from seeding and advecting massless particles to represent the behavior of the underling flow [57]. The basic curves that form the foundation of the geometric objects are streamlines (the trajectories in a static field), pathlines (the trajectories in a time-dependent field), streaklines (formed by particles released at a fixed point continuously in time), and timelines (formed by particles released on a line at a fixed time) [14]. Instead of



(a) Illuminated streamlines (b) Streamtubes.

(c) Streamribbons. (d) Streamsurfaces.

Fig. 1 Different streamline-based geometric techniques applied to an example 3D flow field of swirling behavior.

visualizing the flow simply as lines, the curves can be colored and illuminated [110] and drawn in the shape of tubes or ribbons to encode additional information, e.g. rotation, divergence, or velocity [95]. Concatenation of the basic lines seeded along a starting curve results in stream surfaces [36], path, time, or streak surfaces [58,50]. Emphasis on divergence is well provided by flow polygons [83] or flow volumes [56], which copy experimental smoke advection. The main challenges using these geometric techniques are smart seeding to stress features and prevent clutter and the efficient calculation, especially in 3D unsteady fields.

2.2 Texture-Based Techniques.

Dense and texture-based techniques are very popular for the visualization of 2D flow fields [51, 23, 64]. They cover the whole domain densely by transforming an input texture, usually random noise, along the flow and are inspired by the experimental flow visualization technique where oil is applied to parts in the wind tunnel to form schlieren. The resulting output texture have small variations of color along a streamline but big changes orthogonal to the flow.

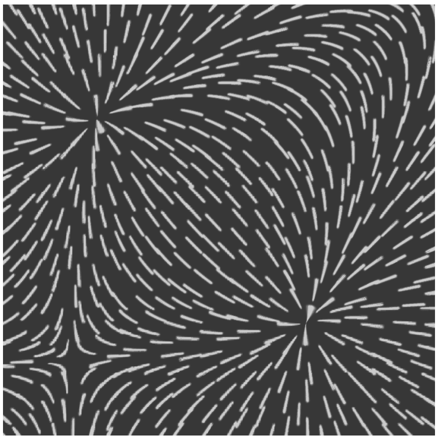
The first such method introduced was spot noise [97], where a set of spots are placed on the domain and smeared in flow direction, Fig. 2(a). Line integral convolution (LIC) [15] is a similar technique, Fig. 2(b). Instead of a finite set of spots, a dense texture is used as a starting point. The output texture is produced by a one-dimensional convolution of the input texture along the streamline passing through a pixel in forward and backward time. The success of these methods is partly based on their intuitive interpretation. Thinking of the input texture as dark and light ink sources, each flow parcel that travels though washes out some of the color and mixes it with the color it has already accumulated. While the velocity of the field can be perceived in spot noise, LIC is better suited to visualize the flow around critical points [19].

Follow up research generalizes these fundamental techniques to better encode orientation [100], a variety of input textures [47], surfaces [26], 3D flow fields [39], time-varying flow data [87], and more efficient calculation [90]. Still, the main application remains to be 2D steady flow because of the induced clutter of a dense visualization technique.

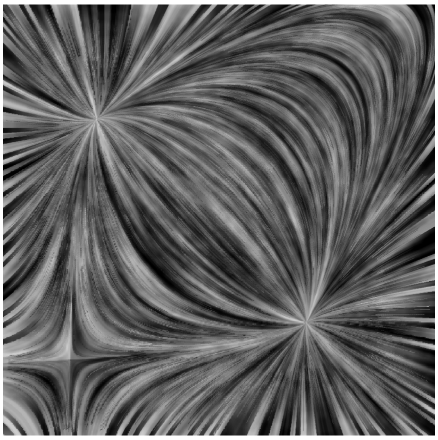
2.3 Topology-Based Techniques

Vector field topology [35] separates the domain into areas in which all flow parcels have the same origin and destination, Fig. 2(c). The topological skeleton consists of critical points (the positions that have zero velocity) and separatrices (their one-dimensional invariant manifolds) [70, 52]. The different flow patterns of vector field critical points can be categorized into saddles, sinks, sources, and vortices by the eigenvalues of their Jacobian, i.e. the velocity gradient [66]. For example, sources have two positive eigenvalues because the flow moves away from them in each direction, while saddles have one positive and one negative eigenvalue corresponding to one attracting and one repelling manifold. The separatrices can be computed by integration of forward and backward streamlines along the eigendirections of the saddle type critical points.

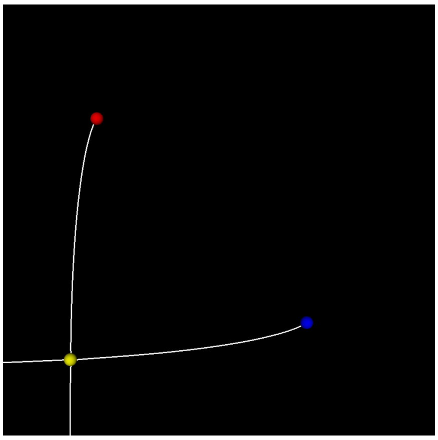
It has become an important component of flow visualization, because it contains the important features of a vector field in a highly compressed representation [35]. Extensions have been made to the detection of higher order critical points [80], separation and attachment lines [46], closed streamlines [105], 3D vector fields [101], and Galilean invariance [11]. It is also a means



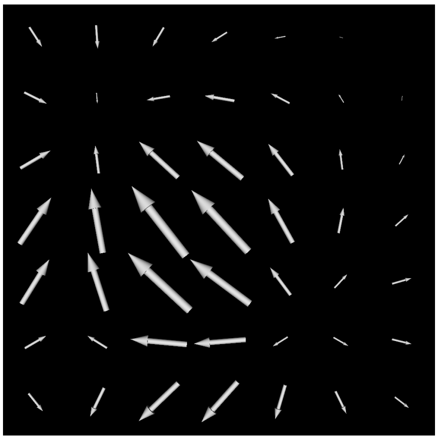
(a) Spot noise.



(b) Line integral convolution (LIC).



(c) Topology marks sink (red), source (blue) and saddle (yellow).



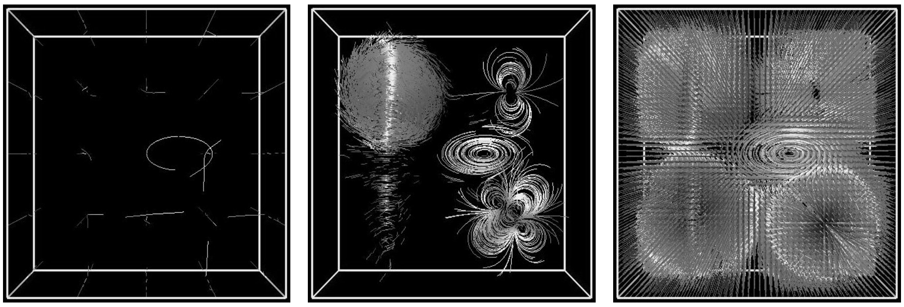
(d) Arrow glyphs.

Fig. 2 Different techniques applied to an example 2D flow field with a source, a saddle, and a sink. While the first three visualizations make sure, the critical points are not missed, the gluphs are abe to directly encode the direction of the flow.

for flow field decomposition, simplification [93], and design [91]. Currently, the main challenge lies in generalizing flow topology to time varying data [68, 10].

2.4 Feature-Based Techniques

Most flow visualization techniques produce great results when applied to 2D fields, but fail in the 3D case due to clutter, because each drawn object occludes everything located behind it, Fig. 3. Feature based techniques reduce the amount of visualization elements to the important areas of a flow field [70, 23]. This selection process can be imposed to all the techniques mentioned earlier.



(a) Equidistant low density seeding misses features between the seeds.

(b) Feature based seeding reveals the features.

(c) Equidistant high density seeding misses features due to occlusion.

Fig. 3 Comparing feature based to uniform seeding of streamlines in regions of vortical behavior demonstrates that 3D visualization is not a "Goldilocks" problem.

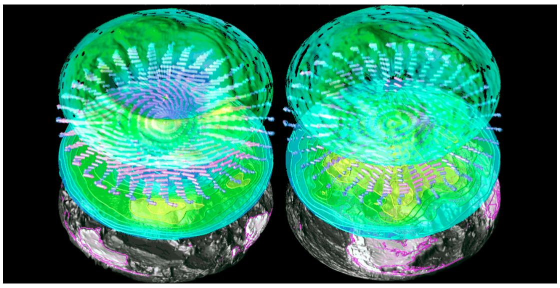
Specific detectors have been taylored to identify the most typical flow features, like vortices [74, 30], the elements of the flow topology [52], or shockwaves [108]. For more general purposes, vector field pattern detection algorithms [21, 81, 12, 99] allow the extraction of user defined features.

Vortices are probably the most studied flow feature [74, 30]. There is no generally accepted mathematical definition for a vortex, but it is mostly described as an axis around which particles move in a swirling motion. The most popular mathematical detectors are the vorticity, Q [37], Okubo-Weiss [65, 102], ∇ [18], and λ_2 [41] criteria. Recently, the development of detection criteria has moved from satisfying only Galilean invariance to objectivity, i.e. invariance w.r.t. Euclidean transformations of the reference system [31, 32, 29].

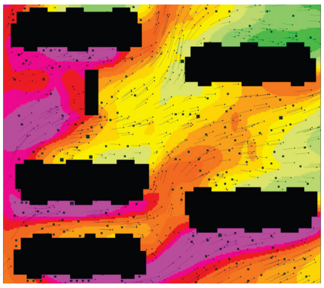
2.5 Further Techniques

There are other flow visualization techniques that can be considered as their own category, such as partition-based techniques [75], illustrative techniques [8], visualization based on glyphs [69, 106], Fig. 2(d), or visualization of derived scalar quantities (e.g. velocity magnitude, vorticity, finite-time Lyapunov exponent, [33]).

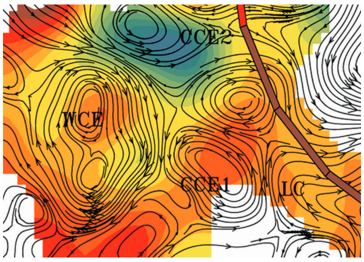
Animation is not a huge topic in flow visualization [51]. Time as a variable in the depiction is usually reserved for the different time steps in unsteady flow, which is why animation for steady flow is rare. Also, it is often considered a more concise visualization if the information over several time steps is summarized in one single steady visualization, e.g., through pathlines. Usually, animation is considered a bonus on top of a traditional visualization method, for example, on textures [55], volume rendering [56, 85], streamlines [43], line integral convolution [26, 86]. In a steady flow, it is often used to encode if the flow moves forward or backward along an otherwise ambiguous visualization element, like a line.



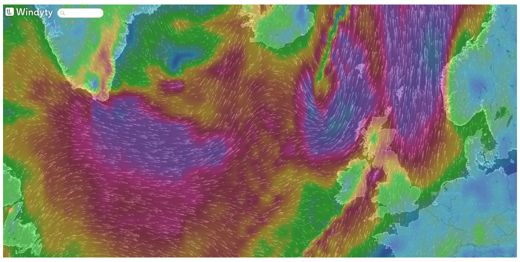
(a) Isosurfaces visualize the ozone and glyphs the wind direction over the poles. Image courtesy of L. Treinish [92].



(b) ENVI-met [61] Temperature encoded through color, flow direction through glyphs.



(c) Hurricanes visualizaed through color coding of the vertical mixing and streamlines the hirizontal wind. Image courtesy of B. Jaimes [40].



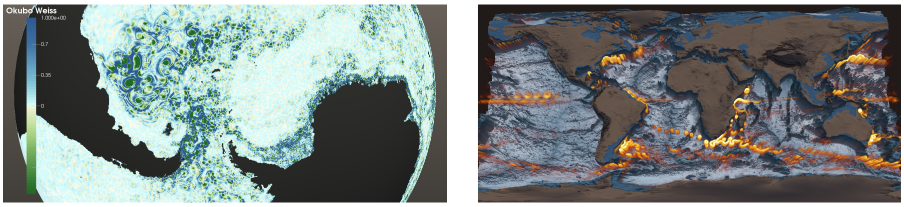
(d) Wind forecasting in Windity [1]. Temperature encoded through color, flow direction through animated spot noise

Fig. 4 Different wind direction and velocity mapping applications.

Apart from direct visualization techniques, the flow visualization community also concentrates on the reduction of clutter through smart placement of seeds and objects [94, 42, 98] and meaningful visualizations through adaption of the frame of reference [103, 7, 11, 29].

3 Environmental Flow Visualization

Environmental science is, by nature, an interdisciplinary field, combining physical, biological, and information sciences to study environmental systems. Based on our literature review, we grouped environmental research into four categories: (1) atmospheric science; (2) ecology; (3) geosciences; and (4) urban environments. The following paragraphs review examples of applications in each category that involve time and space dependent movement data appropriate for flow visualization.



(a) Color coding of the Okubo Weiss criterion on the surface indicated vortices.

(b) Volume rendering of the kinetic energy allows visualization of the flow behavior in 3D.

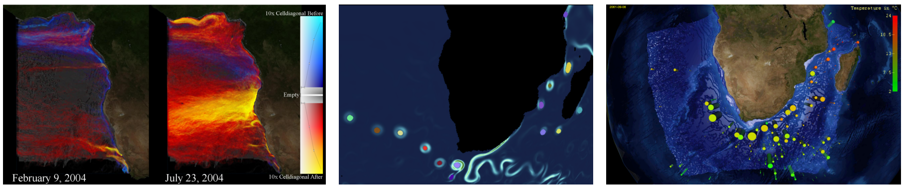
Fig. 5 Ocean visualization by color coding of derived scalar fields. Images courtesy of F. Samsel, M. Petersen, G. Abram with MPAS-Ocean, COSIM, LANL [107].

3.1 Atmospheric Science

Predominant atmospheric variables that pertain to flow are air and water, usually retrieved through CFD simulations. Windyty [1] is a web-based wind forecasting and visualization tool that maps wind direction and speed in Google Maps using a background image, color-coded by velocity, Fig. 4(d). At a smaller spatial scale, Lu and Port-Agel [54] conducted large-eddy simulations of wind farms and mapped simulated wind velocities as color-coded maps. They also provided contours of the time-averaged stream-wise velocity and turbulence intensity as color-coded isolines. Van Hoof and Blocken [96] illustrated microscale wind flow as color-coded contours of velocity magnitude in four horizontal planes, while [61] displayed CFD modeling results for wind using arrows on a heat map, Fig. 4(b). Another study investigated the impact of vertical wind shear on the predictability of tropical cyclones visualizing wind as arrows [109]. Air quality assessment is another application area for flow visualization, as it is concerned with pollutant dispersion through wind. In [28], arrows are used as velocity vectors to display air-flow in urban street canyons. Modeling and analyzing wind flow is also important to assess the impact of hurricanes and tsunamis [71, 40, 20], Figuref:jaimes1. Koutek et al. [49] combine multiple visualizations of color coding, iso-surface, glyphs, iso-bars in a web-based tool for the analysis of meteorological data.

3.2 Ecology

The predominant application of flow visualization in ecology is animal migration. In a recent review, various tracking techniques for migratory birds were presented, ranging from GPS tracking to geologgers [9]. While bird tracking techniques were diverse, the presented migration visualizations were limited to a Google Earth overlay of migration paths and a 2D view of dotted lines on a radar image. Other applications used lines on a 2D map, color-coded by bird individuals [22, 84]. Slingsby and Loon recently suggested to bin large sets of bird trajectories and visualize linked tile maps [88].



(a) Volume rendering of pathline density. Image courtesy of P. Nardini [63].

(b) Tracked vortices can be followed through color coding. Image courtesy of D. Banesh [4].

(c) Extracted eddies visually encoded as cylinders. Image courtesy of F. Raith [72].

Fig. 6 New developments in ocean visualization include pathlines, feature extraction, and tracking.

3.3 Geosciences

Ocean flow simulation and analysis are crucial for assessing environmental hazards, such as oil spills and sea trash. Previous research has predominantly used colormapping [59, 3, 107], Fig. 5. Samsel et al. [77] stress the importance of using intuitive and flexible colormaps to make use of the more automatic and subconscious channels of the observer. Iso-lines are also popular to visualize ocean data [82]. For coastal cities, flooding of urban areas was visualized using photo-realistic animations to explain impacts of sea level rise to decision-makers and the general public [27]. A recent study presented Open Geosys, a tool to visualize geothermal energy and groundwater using streamlines and arrow glyphs [48].

New directions have been followed recently. Nardini et al. [63] used task driven filtering and 3D volume rendering of streamline density to visualize the Benguela upwelling system, see Figure 6(a). Rocha et al. [73] visualize the flow direction using sparse streamlet decals to leave space for simultaneous visualization together with salinity and density.

One of the most prominent features in oceans - and probably the only one visualized in the geosciences using feature extractions - are eddies. They can either be directly visualized through color coding, volume rendering, or iso-surfacing of scalar quantities, like vorticity or the Okubo-Weiss-criterion [67, 107, 76, 6], or indirectly through extraction and placement of glyphs like cylinders [104, 72]. Banesh et al. [4, 5] not only extract but also track eddies and visualize their temporal evolution through color coding of individual eddies and an abstract graph indicating birth, death, merge, and split events, see Figure 6(b).

Flow visualization has also been used to illustrate glacier retreat [44] and volcanoes [78].

3.4 Flow in Urban Environments

Flows in the urban areas include the movement of goods and materials, but can also be concerned with invisible phenomena such as electricity. For example, Molnar and Gruchalla [62] visualize electrical power systems by producing a dense vector field from a sparse network and then applying classical flow visualization techniques. The visual analytics and information visualization communities have long investigated motorized and non-motorized vehicle flow as well as travel behavior of pedestrians [16], which is usually sparse trajectory data. Häußler et al. [38] present a visual analytic framework for the exploration of sensor data to detect, predict, and reduce pollution from traffic. Some urban flow visualizations employ simple line charts [25] or more complex line-based visualizations that use edge-bundling. Ersoy et al. [24] show immigration flow in the U.S. using a geometry-based edge bundling algorithm. Other approaches to visualize urban trajectories use Kernel density estimation (KDE), a common algorithm to generate heat maps. For example, Scheepens et al. [79] create density maps from edge KDE results for US air traffic. Spatio-temporal urban flow visualization employs space-time cubes (STC) where the x and y axes represent spatial information and the z axis encodes how the spatial information changes over time [53].

4 Bridging the Gap

Our literature review suggests that environmental scientists tend to use basic flow visualization techniques. A comprehension can be found in Table 1.

Popular	Rare	Unused
Glyphs	Spot noise	Surfaces
Color Coding	Streamlines	Volumes
Isocontours	Volume rendering	Topology
Lines	Animation	
	Feature-based techniques	

Table 1 Comprehension of the use of flow visualization techniques in the environmental sciences.

Atmospheric data are often mapped as color-coded derived scalar fields or arrows, Fig. 4(a) and Fig. 4(b), while ecologists prefer streamlines to visualize animal migration data. The gap between available flow visualization methods and their application seems to be smallest in geosciences, particularly ocean flows. In all three areas, higher visualization elements, like surfaces and volumes, or topology are hardly used. We see the following reasons for this gap.

While fluid dynamics analysts often concentrate on relatively small, contained problems, environmental scientists deal with big, complex data sets from various sources in different formats. The data sets exhibit complex boundaries, are multidimensional, or stem from observations that are too sparse for higher visualization elements. For big data problems, environmental scientists often focus on the comparison of different parameters and variables, so the flow itself is visualized sparsely to share space with other variables (e.g., rain, snow, temperature) and topographic features (e.g., rivers, administrative boundaries). Often, environmental data sets are analyzed with respect to long term correlations, longitudinal trends, or averages; instantaneous flow patterns become secondary. Environmental scientists also have to address a broader, non-expert audience that is hungry for entertainment to communicate their findings, yielding more colorful, catchy, simplified, and sometimes animated visualizations and so far, we see fewer emphasis on animation and visual analytics in flow visualization [45].

In our opinion, the demand for sparsity in comparative environmental visualization could be well satisfied by using more feature based techniques and vector field topology. Environmental scientists would benefit from implementations that connect to their data formats and can easily be incorporated into existing tools the scientists depend on. Interaction might be difficult to achieve due to the size of the datasets, but GPU-based techniques, high performance computing, and scientific computing could offer solutions.

5 Conclusion

We found that the two seemingly similar fields of flow visualization and environmental flow visualization are more different than expected. In environmental sciences, flow is almost always only visualized by basic techniques, such as arrow glyphs, streamlines, or color coding of the velocity magnitude. This gap is mainly based on the demands of environmental sciences for sparse, catchy, and simplified visualizations that run fast on big datasets and are easy to integrate into existing environments.

A change in that trend is already visible though. Since our last survey three years ago [13], we have seen a fast development toward closing this gap. Especially in ocean flow visualization, we have seen volume rendering, feature based techniques, and even feature tracking. A possible reason for this acceleration may be the current presence of sustainability and climate change in the focus of public interest, media, and politics.

Overall, we still see great potential for the two fields to learn from each other and bridging the gap from two sides. The flow visualization community could investigate views in which the immediate flow may play a subordinate role and concentrate on comparative visualization and animation. The environmental sciences on the other hand could consider to increase the use of feature-based and topological methods.

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