Workshop on Visualisation in Environmental Sciences (EnvirVis) (2016)
A. Middel and K. Rink and D. Zeckzer (Editors) *Short Papers*

Strategic Initiatives for Flow Visualization in Environmental Sciences

Roxana Bujack[1] and Ariane Middel[2]

[1]Technical University Kaiserslautern, Germany
[2]Arizona State University, USA

Abstract

Flow plays a big role in the environmental sciences, but there are major differences between theoretically available and practically applied visualization techniques. This paper surveys various techniques in computational and environmental flow visualization, identifies challenges, and suggests strategic initiatives on how to bridge the gap.

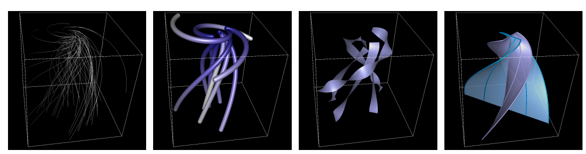
1. Introduction

Flow plays an important role in environmental sciences, because many of the Earth's physical and biological processes involve movement. 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. In this paper, we investigate the differences between these two theoretically closely related fields, point out potential reasons for the gap, and suggest solutions to bridge it.

2. Flow Visualization

Flow visualization is the science of making flow fields visible [HJ05]. It is older than scientific computing [SL00, Mer12], but the use of computers has leveraged it into a new era, on which we will focus. Openly available programs, like ParaView [AGL*05] or VisIt [CBW*12], provide many flow visualization techniques. Even though there are overlaps, they can be structured into the following categories.

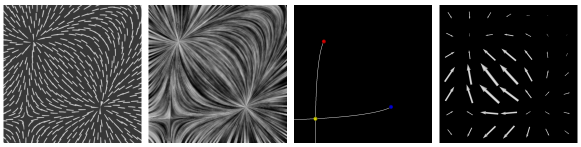
Geometric Techniques. Some of the most popular flow visualization techniques fall into the category of geometric techniques, Fig. 1. Here, geometric objects such as curves, surfaces, and volumes, are built from seeding and advecting massless particles to represent the behavior of the underling flow [MLP*09]. The basic curves that form the foundation of the geometric objects are stream, path, streak, and time lines [BS85]. Instead of visualizing the flow simply as lines, the curves can be colored and illuminated [ZSH96] and drawn in the shape of tubes or ribbons to encode additional information, e.g. rotation, divergence, or velocity [USM96]. Concatenation of the basic lines seeded along a starting curve results in stream surfaces [Hul92], path, time, or streak surfaces [MLZ09, KGJ09]. Emphasis on divergence is well provided by flow polygons [SVL91] or flow volumes [MBC93], which copy experimental smoke advection.



(a) Ill. str. lines. (b) Str. tubes. (c) Str. ribbons. (d) Str. surfaces.

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

Texture-Based Techniques. Dense and texture-based techniques are very popular for the visualization of 2D flow fields [LHD*04, EGL*06, NW13]. They cover the whole domain densely by transforming a texture 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 first such method introduced was spot noise [VW91], where a set of spots are placed on the domain and smeared in flow direction, Fig. 2a. Line integral convolution (LIC) [CL93] is a similar technique, Fig. 2b. 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. Follow up research generalizes these fundamental techniques to better encode orientation [WG97], a variety of input textures [KB96], surfaces [FC95], 3D flow fields [IG97], time-varying flow data [SK97], and more efficient calculation [SH95]. Still, the main application remains to be 2D steady flow because of the induced clutter of a dense visualization technique.



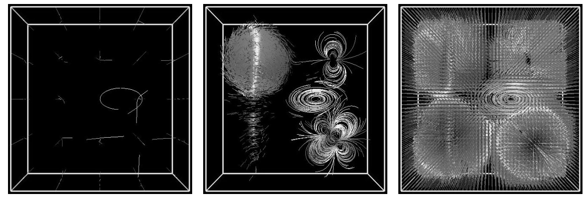
(a) Spot noise. (b) LIC. (c) Topology. (d) Glyphs.

Figure 2: Different techniques applied to an example 2D flow field with a source, a saddle, and a sink.

Topology-Based Techniques. Vector field topology [HH89] separates the domain into areas in which all flow parcels have the same origin and destination, Fig. 2c. The topological skeleton consists of critical points (the positions that have zero velocity) and separatrices (their one-dimensional invariant manifolds) [PVH*03, LHZP07]. The different flow patterns of vector field critical points can be categorized into saddles, sinks, sources, and vortices by the eigenvalues of their Jacobian [PC87]. It has become an important component of flow visualization, because it contains the important features of a vector field in a highly compressed representation [HH89]. Extensions have been made to the detection of higher order critical points [SHK*97], separation and attachment lines [KHL99], closed streamlines [WS01], 3D vector fields [WTS*05], and Galilean invariance [BHJ16]. It is also a means for flow field decomposition, simplification [TSH00], and design [The02]. Currently, the main challenge lies in generalizing flow topology to time varying data [PPF*11].

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 [PVH*03, EGL*06]. This selection process can be imposed to all the techniques mentioned earlier. Specific detectors have been taylored to identify the most typical flow features, like vortices [Rot00], the elements of the flow topology [LHZP07], or shockwaves [WXWH13]. For more general purposes, vector field pattern detection algorithms [Ebl06, Sch11, BHSH15, WSW16] allow the extraction of user defined features.

Further Techniques. There are other flow visualization techniques that can be considered as their own category, such as partition-based techniques [SJWS08], illustrative techniques [BCP*12], visualization based on glyphs [PPVWS95, WPL96], Fig. 2d, or visualization of derived scalar quantities (e.g. velocity magnitude, vorticity, finite-time Ljapunov exponent, [HY00]).



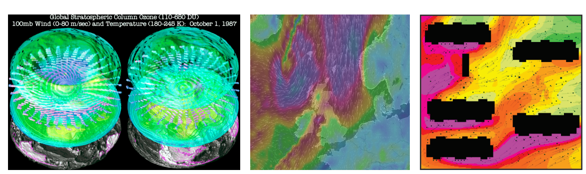
(a) Not enough. (b) Feature based. (c) Too many.

Figure 3: Feature based seeding of streamlines in regions of vortical behavior (b) vs equidistant seeding (a), (c).

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 three categories: (1) atmospheric science; (2) ecology; and (3) geosciences. The following paragraphs review examples of applications in each category that involve time and space dependent movement data appropriate for flow visualization.

Atmospheric Science. Predominant atmospheric variables that pertain to flow are air and water, usually retrieved through CFD simulations. Windyty [win16] 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. 4b. At a smaller spatial scale, [LPA11] 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. [VHB10] illustrated microscale wind flow as color-coded contours of velocity magnitude in four horizontal planes, while [MHB*14] displayed CFD modeling results for wind using arrows on a heat map, Fig. 4c. Another study investigated the impact of vertical wind shear on the predictability of tropical cyclones visualizing wind as arrows [ZT13]. Air quality assessment is another application area for flow visualization, as it is concerned with pollutant dispersion through wind. In [GZCL11], 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 [PMD*10, JS10, DBW*10].



(a) Image courtesy of L. Treinish [Tre93]. (b) Wind forecasting [win16]. (c) Wind in ENVI-met [MHB*14].

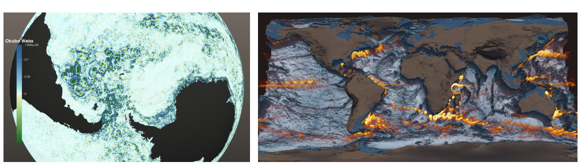
Figure 4: Wind direction and velocity mapping applications.

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 [BTB*11]. 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 [ESP*10, SBvLP*11].

Geosciences. Ocean flow simulation and analysis are crucial for assessing environmental hazards, such as oil spills and sea trash. Previous research has predominantly used color-coding [MM98, Ain99, WPS*16] and iso-lines [Sch02] to visualize ocean flow, Fig. 5. 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 [GSH*15]. A recent study presented Open Geosys, a tool to visualize geothermal energy and groundwater using streamlines and arrow glyphs [KBB*12]. Flow visualization has also been used to illustrate glacier retreat [Kau12] and volcanoes [SYM14].

4. Bridging the Gap

Our literature review suggests that environmental scientists generally use basic flow visualization techniques; atmospheric data are mapped as color-coded derived scalar fields or arrows, Fig. 4a and Fig. 4c, 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, feature based approaches, or topology are hardly used. We see the following reasons for this gap.



(a) Okubo Weiss. (b) Kinetic energy.

Figure 5: Ocean visualization by color coding of derived scalar fields. Images courtesy of F. Samsel, M. Petersen, G. Abram with MPAS-Ocean, COSIM, LANL [WPS*16].

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 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 [KMS*08].

In our opinion, the demand for sparsity in comparative environmental visualization could be well satisfied by using 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, like 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. In the future it can be bridged if flow visualization investigates views in which the immediate flow may play a subordinate role and the environmental sciences consider feature-based and topological methods.

Ackknowledgements

This research was partly funded by the German Research Foundation (DFG) as part of the the IRTG 2057 "Physical Modeling for Virtual Manufacturing Systems and Processes".

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