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# Visual Analysis of Hurricane Data Using Joint Contour Net

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**Abstract**

*Topology provides a rigorous foundation for identifying features and transitions within data. However, computing and presenting topological features in multi-dimensional range space is still a difficult problem. The Joint Contour Net therefore is proposed as a data structure which quantizes the variation of multiple variables and presents multiple-field topology. In this paper, we apply the Joint Contour Net to real-world applications in order to present, analyse and explore features related to phenomenon. We have proposed a framework based on Joint Contour Net for iterative data exploration and knowledge discovery. The data set we investigate is from a simulation of Isabel Hurricane. We are able to demonstrate that the multi-field topological features such as rainbands, air flow and hurricane eye, as well as their relationship, can be exploited from a global topological view.*

Categories and Subject Descriptors (according to ACM CCS): Joint Contour Net [Application]: Hurricane Data—

## 1. Introduction

The Joint Contour Net (JCN) [CD13] is a data structure that approximates the Reeb space of a Piecewise-Linear (PL) multi-field function. The essence of this data structure is based on a quantization of the level sets into discrete ones. A connected component of the quantized level set in the mesh is called a quantized contour or a contour slab. Unlike topology in univariate data where the critical points are clearly defined, multi-field topological features in JCN are not obvious to define [CCDG14]. There are difficulties when interpreting the JNC structure. Therefore features related to the actual phenomenon in data domain is not trivial to interpret from JCN structure.

The previous paper [DCK*12] has shown that the Joint Contour Net can be used successfully to identify the scission point in nuclear physic data set. Whereas in this paper, we apply the Joint Contour Net to a more sophisticated domain, i.e in studying Hurricane Isabel [Com04]. Compared to the previously studied nuclear physics data set, the challenges in Hurricane Isabel come from several points: 1. it has a much larger data size that leads to large scale JCN graph and complex graph structure ; 2. it contains much higher dimensionality ; 3. it contains a larger feature space to explore.

The hurricane Isabel data set is widely used in the flow visualization community [CJR07, WPB*11, MII*08, GABJ08, MCHM10, WPB*11], where the vector fields are sufficiently studied. Among these work the hurricane data is mostly used as visual benchmark and not much data analysis is involved. In addition to vector fields, some scalar fields including temperature, pressure and precipitation, are closely related to the domain phenomenon which could uncover the hurricane formation and evolution over time [HE03]. The multivariate analysis over these fields are important and has mostly been studied in VisWeek contest 2004 [Com04].

In this paper, we would like to apply the Joint Contour Net to multi-field hurricane Isabel data. Our goal is to better understand the Joint Contour Net by investigating how its structure is related to the actual phenomenon of the domain. In order to enable exploratory analysis, we have implemented a number of interaction support as part of the visualization system. The interaction support includes different kinds of selection, brushing and filtering in the range space. The user is able to achieve information seeking mantra: overview first, zoom and filter, detail on demand [Shn96]. The contribution of this paper can be listed as:

- We have proposed a framework based on Joint Contour Net for iterative data exploration and knowledge discovery.
- We have developed a number of interaction support for Joint Contour Net, such as various kinds of selection, brushing and filtering.
- We have systematically applied our visualization framework to Hurricane Isabel data set and present topological view of hurricane structure with respect to temperature, pressure and precipitation. Some domain features

such as rainbands, hurricane eye and outflow air are also exploited.

This paper is not meant to propose any new visualization techniques. We mainly focus on developing an interactive visualization system based on JCN for multi-field data analysis. In addition, we have specified a systematic framework for iterative data exploration using our visualization framework. The rest of the paper is organized as follows : Section 2 summarizes the previous studies on hurricane data. Section 3 describes our visualization system. Section 4 describes an iterative framework for data exploration. Section 5 demonstrates the data analysis on Hurricane data set. Section 6 presents a comparison with univariate visualization. Section 7 wraps up the conclusion.

## 2. Related Work

We refer [JCRS09] for an overview of previous work on Isabel Hurricane data set. A number of useful findings related to phenomenon are presented in VisWeek contest 2004 submissions. One category of work is to utilize various glyphs combined with volume rendering to represent both vector and scalar fields. Interaction such as brushing and filtering is also utilized. The immersive visualization [GM04] approach investigated vector fields, cloud, precipitation and pressure. The vector fields of wind are rendered by volume rendering. The rest of the fields can be represented by histograms-like glyphs and text labels. The paper only discussed the system design and interaction support, but no data analysis with respect to domain phenomenon is discussed. The disadvantage of this approach is that it is not scalable to higher dimensional data in range space. The OpenGL-based glyph visualization [JB04] mainly focuses on achieving real-time interaction on high resolution data. It studies the relationship between clouds and precipitations. The clouds are rendered using particle system and wind is rendered using vector glyphs. As we can see, it is tailored for two specific data fields and is not scalable to higher dimensions. The SimVis framework [DMH04] utilizes interactive feature specification through interactive brushing in data views. Results of various brushing on different scalar fields can be combined. This work demonstrates most of the domain features compared to other submissions. The strength of this work is that it effectively explores subset of the data sets, but it is difficult to give an overview structure of the data set. The other relevant approach which is applied on hurricane data is TransGraph [GW11]. It is a graph-based representation to visualize hierarchical state transition relationships between time steps. The data volume is subdivided into blocks and blocks are further clustered. This approach is effective to track volumetric data set over time, but it is unable to track multi-field data at the same time. Overall, these techniques, though effective in visualizing certain aspects of the hurricane, were limited in their ability to show internal structural details of a particular time step incorporated with multiple dimensions.

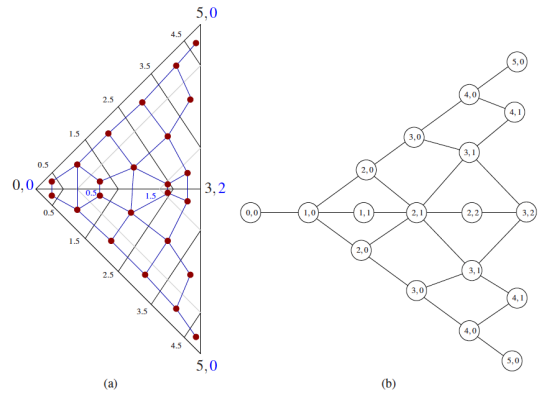


**Figure 1:** *(a) The joint contour fragments and their adjacency graph corresponding to the PL-bivariate iňĄeld deiňĄned by the values (5,0),(0,0),(5,0),(3,2) at the vertices of a mesh of two triangles. (b) Corresponding Joint Contour Net.*

The other category of work is purely focused on vector fields of hurricane data. They treat hurricane as a type of vortex and various vortex detection and tracking techniques are applied, such as anisotropic diffusion [HE03, JSZ*04], texture advection [TDT04] and other approaches in flow visualization community [CJR07, WPB*11, MII*08, GABJ08, MCHM10, WPB*11]. In these approaches, the focus is on visualization and there is not much domain-specific discovery presented and discussed.

## 3. Our Visualization System

In this section, we briefly discuss some of the fundamental set-ups for our interactive visualization system based on Joint Contour Net.

### 3.1. Joint Contour Net

The Joint Contour Net (JCN) [CD13] is a data structure that approximates the Reeb space of a Piecewise-Linear (PL) multi-field function in a d-dimensional domain. The essence of this data structure is based on quantizing the level sets into discrete ones. A connected component of the quantized level set in the mesh is called a quantized contour or a contour slab. The first step of the JCN algorithm constructs all the contour fragments corresponding to a quantization of each component field. In the second step, the joint contour fragments are computed by computing the intersections of thee contour fragments for the component fields in a cell. The third step is to construct an adjacency graph of these joint contour fragments, a node in the graph corresponds to a joint contour fragment and there is an edge between two nodes if the corresponding joint contour fragments are adjacent. Finally, the JCN is obtained by collapsing the neighbouring

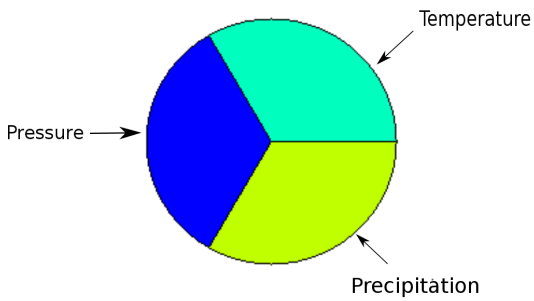


**Figure 2:** *This figure shows a glyph representing a JCN graph node in Hurricane Isabel data set. Each node is evenly divided based on the number of scalar fields. The quantity of each field is depicted by colour mapping. In the example of hurricane data set, we can incorporated temperature, pressure and precipitation fields in the glyph.*

redundant nodes with identical isovalues. In other words, each node in the JCN construction corresponds to a joint contour slab. A simple demonstration of the JCN construction algorithm is given in Figure 1. We have implemented the Joint Contour Net in version 5.8 of the Visualization Toolkit (VTK), taking advantage of VTK and integrated support for both scientific and information visualization techniques [DCK*12]. Our implementation of Joint Conout Net is able to handle data set with any number of dimensions both in domain space and range space.

### 3.2. Choice of Slab Widths

Given a multi-field function $f : \mathbb{R}^d \rightarrow \mathbb{R}^r$, the slab widths refer to a series of values $(sw_1, .., sw_r)$ which are used to uniformly quantize each field component of range space $\mathbb{R}^r$. Smaller slab width in each dimension leads to more accurate approximation of Reeb space and larger value could give an abstract view of Reeb space. In practice, the user could define slab widths based on the data distribution. Due to the fact that the data distribution in range space might vary in each time step, the user needs to change slab widths over time to have a coherent quantization. Therefore, instead of setting slab width, we offer a user option to determine the number of quantized intervals along each field.

### 3.3. Multivariate Glyphs

In JCN graph, each node represents a combination of multiple fields, namely a joint contour slab. We have introduced a pie glyph visualization to represent multiple fields for each graph node. Each glyph consists of a circle subdivided into equal sized segments, one segment per field. Each segment

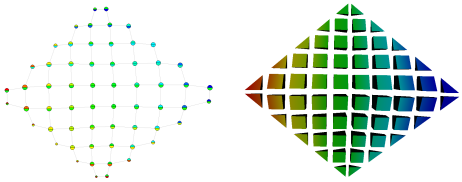

**Figure 3:** *Shown on the left is the Domain-space placement layout for Joint Contour Net on a tetrahedron domain. It positions nodes of the graph at the barycentre of the corresponding slab which is shown on the right. For demonstration, a small gap is inserted between contour slabs in geometric view.*

for a field is mapped to a colour according to its scalar value *val* which is linear interpolated between the scalar range of this field. In this paper we have utilized rainbow colour mapping. The size of a glyph is mapped to the number of fragments of its corresponding joint contour slab. When the variance of slab size becomes large, we provide a user option to apply a log scaling on the node size to ensure that small slabs are visible. Figure 2 demonstrates the layout of the glyph.

### 3.4. Graph Layout

In this paper, we have utilized Domain-space placement [DCK*12] for joint contour net layout. Domain-space placement positions nodes of the graph at the barycentre of the corresponding slab in $\mathbb{R}^d$. This placement builds a one to one mapping between graph nodes and slab geometry in domain space. The user could understand how the domain is divided and what is the relationship between the divided slabs. Figure 3 demonstrates how the graph layout works. On the left side is the JCN graph using Domain-space placement, whereas on the right side is the slab geometry where a uniform interval is placed between every two slabs for demonstration purpose. In addition to unveil the underlying global topological structures, the domain-space placement layout could also unveil the local properties by user interaction, as described in the next section.

### 3.5. Brushing and Filtering

We have provided a number of user options to enable interactive exploration in JCN visualization. With these interaction support, the user is able to perform linking and brushing between the JCN graph and slab geometry. Singular selection allows the user to select any subset of the graph node and the corresponding slab geometry is updated. Results of multiple selections are automatically merged.

We have also developed a number of pre-set selection options. For example if choosing the boundary pre-set, the user is able to see slabs touching the domain boundary. If

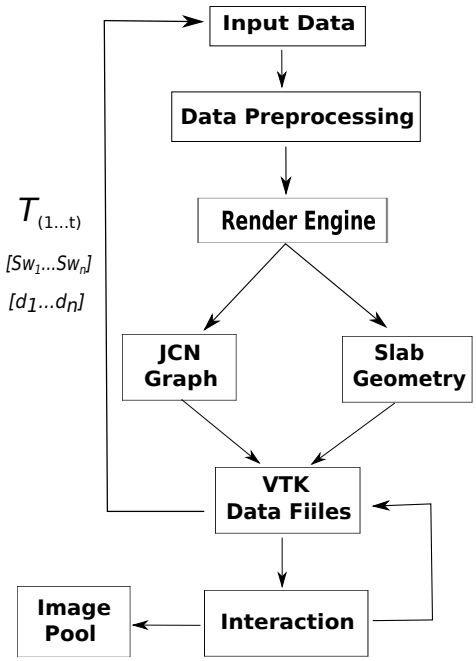


**Figure 4:** *This figure shows the iterative data analysis framework. It starts by taking the input raw data set, preprocessing it and sending to the computation engine. The computation engine then computes the JCN structure and output one graph and one contour slab geometry. The output data structures are stored in VTK data files. This process will repeat with respect to different time steps (T), slab widths (Sw) and choice of data fields (d). Once all outputs in the parameter space are generated, further interaction can be performed based on these pre-computed data files. During interaction, the user could also save some important selection to an additional VTK data files. In the end of the framework, the user could save the visualization result to the image pool.*

choosing the interior pre-set, slabs which are inside domain boundary will be displayed.

In addition to the selection, various filtering are developed, such as AND and OR filtering. The filtering is based on multiple fields in the range space. The user is able to specify the range of each field and the results of the filtering can be combined either by AND or OR function. AND operation preserves the intersection and OR preserves the union of filtered data on each field.

## 4. Iterative Data Exploration Framework

In order to systematically perform exploratory analysis of an input data set, we have specified an iterative framework, as shown in Figure 4. As discussed in Section 3, our visualization system is implemented in VTK [DCK*12]. Our JCN algorithm takes a simplicial mesh as input, and produces two outputs, (i) a graph dataset encoding the topological structure of the network, and (ii) a set of 3D polyhedra (or 2D polygons) stored as an unstructured grid, representing the slabs in domain space.

In each round of JCN computation, the user needs to specify the slab width, time step and the names of data fields. When they change any of these parameters, the computation will run over again. This process is time consuming when the user needs to work dynamically with these parameters. Therefore, in our framework, we choose to go over a specified range of the parameter space and generate the corresponding JCN outputs offline. The output data structures, including graph and slab geometry, are stored as VTK data files. When the user needs to interactively manipulate the JCN structures in any parameter setting, they could just load the corresponding pre-computed data files.

In addition, during the interaction process, if the user finds some selection or brushing to be interesting or useful, they could also save these structures as additional VTK data files. In the end of the framework pipeline, when the user is satisfied with the resulting image, they could save the image into image pool for further comparison and notation. This iterative data exploration framework has been systematically applied on Hurricane Isabel data set and the result is reported in the next section.

## 5. Case Study : Studying Hurricane Isabel

The data set we have experimented is a simulation of a hurricane from the National Centre for Atmospheric Research in the United States [Com04]. This simulation consists over 12 variables. Each of them has 48 time steps. The resolution of each data is $500 \times 500 \times 100$. Because the sheer size of the data presents a challenge for interactive exploration, therefore we have down-sampled this data set to $125(longitude) \times 125(latitude) \times 100(height)$.

We have systematically examined all of the fields and time steps in Hurricane Isabel data set, in this section we demonstrate how our JCN graph can be applied on these fields. As described in the hurricane mechanics and previous literature [FOX11, HE03], the formation of hurricane is driven by large regions of warm water on the surface of ocean. This warm region serves as a heat engine where water is evporated into air. The rising of warm, moist air creates a low-pressure zone, pulling in more moist and uprising air from nearby regions. The continued updraft is re-condensed into clouds and rain as temperature drops in higher altitude [FOX11]. During this process, regions with strong precipitation often form rainbands. Within hurricane eye, the pressure and precipitation is low.

We can present multivariate structure of temperature, pressure and precipitation in one JCN graph view. On the left of Figure 5 shows the main hurricane structure emerging

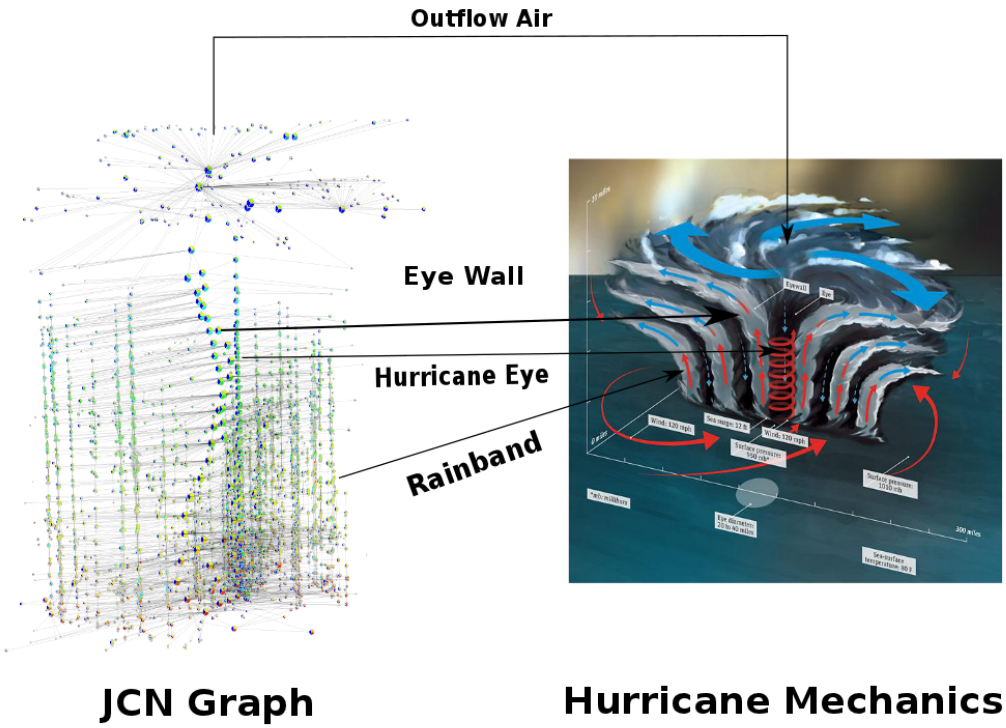


**Figure 5:** *In this figure, the Joint Contour Net is used to incorporate three fields, such as precipitation, pressure and temperature, in time step 10 of Isabel hurricane data. The following images show : A. the JCN graph of hurricane structure is presented. B. In order to demonstrate the correspondence between our JCN structure and actual hurricane mechanic, we place a demonstration graph aside as a linking to the phenomenon [FOX11].*

over the ocean in time step 10. We are able to see the internal topology of the hurricane clearly. The graph is layered from surface level to top altitude in the domain. In order to demonstrate the correspondence between the JCN structure and actual hurricane mechanic, we place a demonstration graph aside as a linking to the actual phenomenon [FOX11], as shown on the right of Figure 5. From the JCN structure we are able to make few hypotheses. A series of nodes connected vertically in the centre of the graph form the eye of the hurricane surrounded by a list of nodes with high precipitation (rainbands). The series of nodes connected as a curve surrounding the hurricane eye forms the eye wall. Air is ejected from the top of the storm at the highest altitude. This cooled, dried air sinks through the eye of the storm or else flows out and sinks in the outer bands of the storm. The outflow air forms a rotational structure.

In order to further verify the hypotheses made in Figure 5, we utilize filtering and brushing to examine the properties of each hypothesized feature. The rainband is formed in area where heavy rain happened. We can then extract the rainbands from JCN graph by preserving slabs with high precipitation. The JCN graph and its corresponding slab geometry are shown in A-C in Figure 6. From the top-down view of the rainband shown in part C of Figure 6, we can see the rainband spirals into and connects with the eyewall. This pattern matches the description from the previous literature [FOX11, HE03]. The studies of hurricane [FOX11] demonstrate that the eye of hurricane has low pressure, warm temperature and low precipitation [DMH04]. Therefore the eye structure can be obtained by the filtering based on its properties. The hurricane eye together with rainband can be presented together as shown in D-F of Figure 6. The colour is mapped to temperature field in slab geometry.

In Figure 6 we can also observe that a layer of region with high temperature can be found between ocean surface and hurricane structure. Within this region the water is evaporated into rising warm and moist air which creates a low-pressure zone. Warm water in nearby region is subsequently evaporated and sucked into the hurricane which constitutes eye wall. The uprising air spirals in the direction determined by the Coriolis effect which is a byproduct of the Earth's rotation [FOX11]. Figure 7 shows the struc-

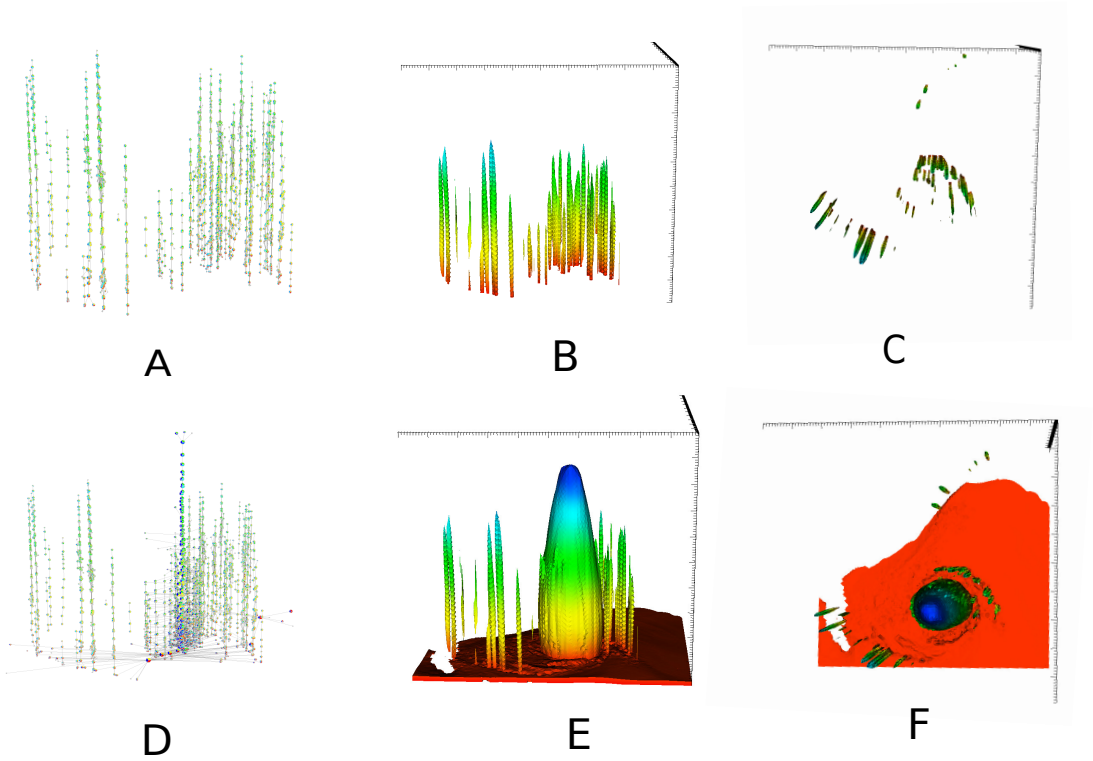


**Figure 6:** *In this figure, the Joint Contour Net is used to incorporate three fields, such as precipitation, pressure and temperature, in Isabel hurricane data. The following images show : A. JCN graph of rainbands. B. a horizontal view of domain geometry of rainbands. C. a top-down view of domain geometry of rainbands. D: Hurricane eye structure and rainband. E : a horizontal view of domain geometry. F: a top-down view of domain geometry .*

ture of eye wall. This can be obtained by brushing the surrounding slabs closely around the hurricane eye. As the altitude increases the temperature drops and evaporated water is condensed into clouds and rain. On the top altitude of the domain, cooled and dried air is ejected as shown in Figure 8. This outflow air is obtained by preserving the lowest temperature region. Figure 9 shows the hurricane core structure with rainbands in different time steps. We are able to see as the hurricane moves toward the land, the intensity of rainfall drops. This also implies that the intensity of the hurricane declines when it landfalls.

As we can see, utilizing Joint Contour Net could offer a global topological view incorporating multiple fields. This could not be done by traditional visualization, such as volume rendering. This global structure offers an overview of the data characteristics. Based on this overview, the user could utilize various interaction support to further examine each subset of the feature space. By looking at the glyph of each individual graph node, we can further capture the scalar range of each presented feature. This could be used as guideline for further brushing.

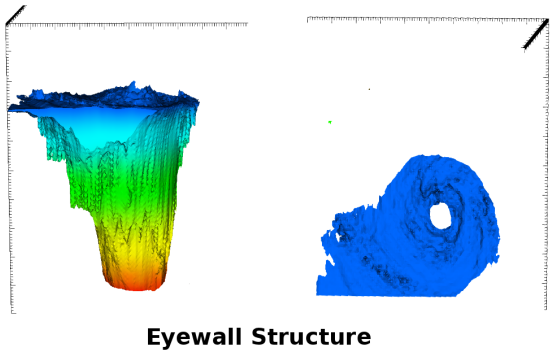


**Figure 7:** *This figure shows two different view angles of geometry of eyewall. This structure is obtained by selecting spiral patterns surrounding hurricane eye demonstrated in Figure 5.*

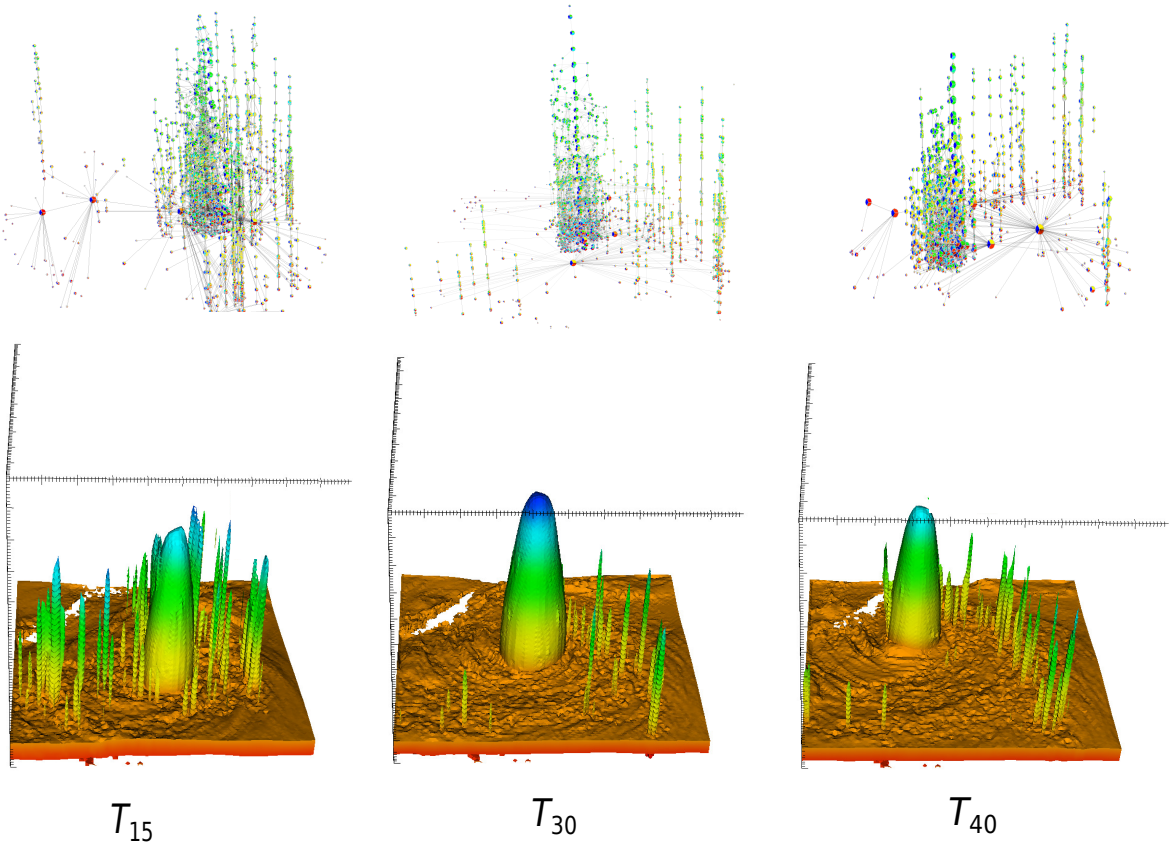


**Figure 9:** *This figure shows the JCN graph and corresponding slab geometry with relatively low pressure, warm temperature and high precipitation in time steps 15, 30 and 40. This captures the hurricane core structure with rainbands as well as the warm area between hurricane core and sea surface. We are able to see how the hurricane evolves along time.*

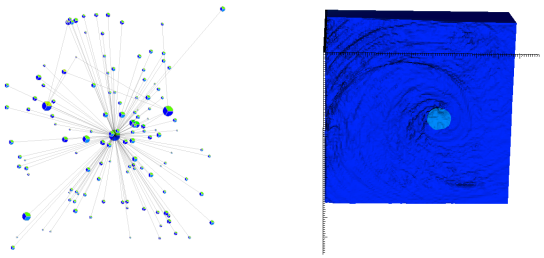

**Figure 8:** *This figure shows outflow air which is ejected from the top of the storm at the highest altitude. On the left is the JCN graph nodes with low temperature, low precipitation and positioned in high altitude. On the right is the corresponding slab geometry. For demonstration purposes, both graph and geometry are rotated 90 degrees anti-clockwise around x-axis of the domain.*

## 6. Comparison

The advantage of JCN lies in its capability of capturing multi-field topological structure of the data set. Compared to single field visualization, it reveals more features and present relationship between various fields. Figure 10 shows the univariate contour slabs of each individual field, namely temperature, pressure and precipitation. The domain-space displacement layout is applied on these contour slabs. We can observe that each of the fields depicts only a subset of the feature space. From the temperature field, the outward and inward flow structure can be observed. But the hurricane eye and eye wall cannot be distinguished. From the pressure field, we could see a list of nodes connected vertically inside the graph depicting the low pressure area within the hurricane eye. But the outward air flow structure is missing. From the precipitation field, we could observe the spread of rainfalls, but other hurricane structures cannot be presented. When we incorporate all these three fields together in Joint Contour Net, we are able to obtain a complete picture of do-

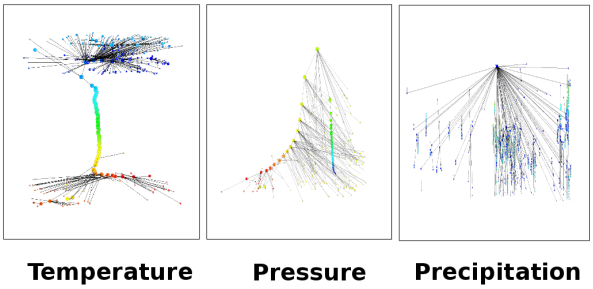


**Figure 10:** *This figure shows the JCN graph of each field. We could easily observe that they only depict a subset of the domain features respectively, but they could not depict all of the features described in Figure 5.*

main features. It provides a global topological view in multi-field data. Based on such an overview, the user is able to further examine each subset of the feature space with the help of interaction support.

## 7. Conclusion and Future Work

In this paper we have developed an interactive visualization system based on Joint Contour Net. In addition, an iterative framework for data exploration is proposed. We have applied our system and framework in Isabel Hurricane data and examined topology in three major fields, namely precipitation, pressure and temperature. The results demonstrate the topological structure of the hurricane and identify few multi-field phenomena. In the future, we would like to apply our technique on more real-world data sets in order to better understand multi-field topological structure.

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