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Temporal Visualization of Boundary-based Geo-information Using Radial Projection

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Abstract

*This work is concerned with a design study by an interdisciplinary team on visualizing a 10-year record of seasonal and inter-annual changes in frontal position (advance/retreat) of nearly 200 marine terminating glaciers in Greenland. Whilst the spatiotemporal nature of the raw data presents a challenge to develop a compact and intuitive visual design, the focus on coastal boundaries provides an opportunity for dimensional reduction. In this paper, we report the user-centered design process carried out by the team, and present several visual encoding schemes that have met the requirements including compactness, intuitiveness, and ability to depict temporal changes and spatial relations. In particular, we designed a family of radial visualization, where radial lines correspond to different coastal locations, and nested rings represent the evolution of the temporal dimension from inner to outer circles. We developed an algorithm for mapping glacier terminus positions from Cartesian coordinates to angular coordinates. Instead of a naive uniform mapping, the algorithm maintains consistent spatial perception of the visually-sensitive geographical references between their Cartesian and angular coordinates, and distributes other termini positions between primary locations based on coastal distance. This work has provided a useful solution to address the problem of inaccuracy in change evaluation based on pixel-based visualization [BPC*10].*

1. Introduction

Because field-based glaciological research is a costly and very challenging undertaking, satellite remote sensing represents an ideal tool for scientists to study the ice masses around the world with the aim of understanding their behavior especially in the light of a changing climate, and being able to predict their future contribution to sea level rise.

One interesting focus is the recent advance and retreat of *calving glaciers* in Greenland. Also known as tidewater glaciers, they transport ice and snow from the inland ice sheet seawards. Glaciologists are especially concerned about their behavior through time as these outlets contribute directly to sea level rise by releasing icebergs into the ocean, in a process referred to as 'calving'.

The advances and retreats of calving glaciers are commonly visualized using time series plots as shown in Figure 1(a). However, such a visualization does not convey spatial relation among the glaciers and can become much cluttered when the number of glaciers increases.

When a large spatial coverage of many glaciers is desirable, one approach is to use circular glyphs with varying colors or sizes to depict the measured advances and retreats at different locations, as shown in Figure 1(b). Scientists normally juxtapose several such visualizations to aid the evaluation of temporal changes of the levels of advances and retreats. The drawbacks of this approach include the limited variation in both color and size, and the difficulty to locate the same or nearly glaciers in visualizations corresponding to different temporal steps. Hence it is very hard to visualize temporal changes. In addition, as a recent study [BPC*10] indicated, the performance of human observers is noticeably poor when evaluating and comparing changes based on colors in pixel-based visualization.

In this work, we conducted a design study to address a major visualization difficulty encountered by a team of glaciologists, who needed to gain an insight into a 10-year record of termini positions of 199 tidewater outlet glaciers around the Greenland ice sheet, resolving both their seasonal and inter-annual fluctuations. The requirements for a visualization to convey both spatial and temporal changes effectively make the traditional visual designs such as those in Figure 1 inappropriate. During the study, the interdisciplinary team identified that the location of calving glaciers around a coastal

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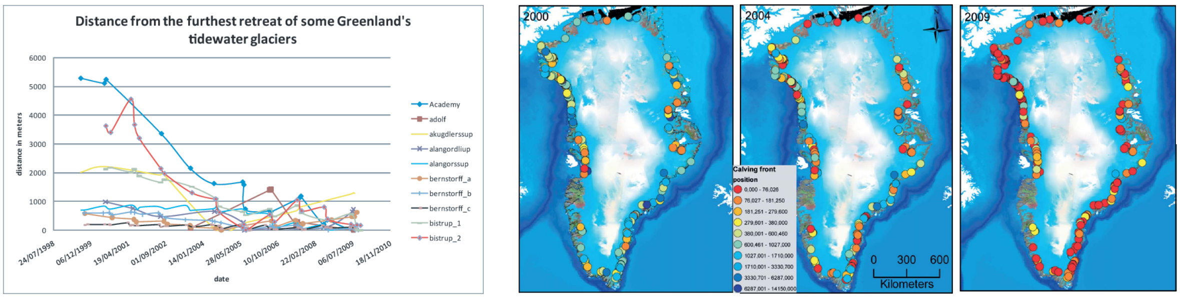


(a) time series visualization (b) color-coded frontal movement

Figure 1: Two classic visualizations in geography: (a) plotting the relative frontal positions of 10 calving glaciers as time series, (b) using color-coding glyphs to represent different scales of relative frontal positions, and visualizing temporal changes by juxtapositions (the background color of figure (b) represent sea surface temperature, the glyphs legends goes from red for the furthest retreat to blue for the most advanced position).

boundary could potentially provide an opportunity for dimension reduction. We decided to adopt radial visualization as the principal visual design, and explore a number of options of visual mapping. We evaluated these options based on a number of criteria, such as compactness, intuitiveness, and effectiveness in conveying temporal changes and spatial relations. We developed a novel algorithm for spatial mapping from Cartesian coordinates to angular coordinates, while maintaining consistent visual cues of primary spatial references in terms of orientation and neighborhood distance to facilitate effective visual search.

2. Related Work

Much research has been carried out in geo-visualization [DMK05], which takes advantage of its links with cartography, image analysis, information visualization and geographical information systems (GIS) [MK01]. Thematic map [SMKH05] is perhaps the most effective way to visualize geographical data, and the basic rules of semiology [Ber83] applies to support the readability [Kea96]. A novel type of quantitative thematic map was introduce by Speckman *et al.* [SV10] with Necklace Maps. There are many geo-visualization systems, such as Quantum GIS, GRASS GIS, ArcGis, and ERDAS. However, the support they provide for visualizing time-varying geo-information is limited.

Times series visualization is commonly used in geo-visualization, with the aid of a variety of graphs, such as sequence charts, point charts, bar charts, line graphs, and circle graphs [Har00]. Havre *et al.* developed the Themeriver plot [HHWN02] for visualizing time-varying multi-attributes data and Javed *et al.* [JME10] evaluated the Horizons graph for multiple time series dataset introduced by Saito *et al.* [SMY*].

Hägerstrand [H70̈] was the first to propose, in the field of geography with his space-time cube, the use of the third dimension to visualize temporal information; later Kapler and Wright [KW04] and Thakur and Hanson [TH10] proposed other possible designs. An extensive review of space/time visualization can be found in Andrienko *et al.* [AAG03].

Nowell *et al.* conducted an important study on change blindness in information visualization [NHT01], highlighting the difficulties in time-varying data visualization by juxtaposing a sequence of visualizations of different time steps. Borgo *et al.* conducted a detailed study on the impact of different tasks in visualizing time-varying data [BPC*10].

Radial visualization has been widely used for time-varying data, for example, spiral graph [WAM01], spiraClock [DH02], perspective wall [MRC91], axes-based visualization [TAS04], and concentric circles technique [DDF*00]. Radial visualization has also been used extensively for non-temporary data. Draper *et al.* conducted a comparative study on radial visualization [DLR09].

3. Application and Dataset

The Greenland ice sheet is the world's second largest body of ice after Antarctica, storing an equivalent of about 7m of sea level rise if the entire ice sheet was lost by melting [IPCC07]. In the past decade, large scale changes have been reported in many areas of the Greenland ice sheet [RK06, SW07]; concentrated at its margins, especially where marine terminating outlet glaciers are located [PAVE09, HJF*08]. The mass loss has nearly doubled between the early 1990's and early 2000's [TFK*06], mainly attributed to a widespread and synchronous frontal retreat and an accompanying dynamic thinning of tidewater glaciers [LMdLH06, TAF*03]. Since the dynamic component contributed about 50% to the recent increase in overall mass loss [vdBBE*09], further understanding of the nature, distribution, and controls on dynamic change is essential for predicting Greenland's future sea-level contribution.

In order to address this crucial question, glaciologists produced the record of calving front positions for Greenland outlet glaciers described above. Several studies analyzing the evolution of tidewater glacier calving fronts around Greenland have been carried out [JHA*08, MJ08]. However, those studies have either been spatially (e.g., [LMdLH06]) or temporally coarse [MJ08]. This dataset compiling, much more complete both temporally and spatially has created a need of an effective means for visualizing the record, such that the visualization can convey both temporal changes and spatial relationships in both global and local contexts, while facilitating efficient visual search for individual calving glaciers spatially and temporally. The visualization techniques available to the glaciologists then were shown in Figure 1, which were found inadequate to address the spatial complexity, resolution, and coverage of the dataset.

The difficulties were identified in a previous interdisciplinary project [BPC*10] on pixel-based visualization where temporal sequences of satellite imagery were considered as a special case of temporal pixel-based visualization. The project involved three empirical studies on the impact of task demands and block resolution on the effectiveness of pixel-based visualization, and the stimuli used (i.e., a sequence of temperature maps) represent an abstraction of typical visualization needs of glaciologists. The finding of the project indicated that evaluating and comparing changes in different temporal period is a much more difficult task than comparing scalar values after the original values have been visually mapped to color space. The performance of human observers was poor in terms of both accuracy and response time. The possible reasons included higher cognitive load and higher demand for working memory. This suggested that the visualization shown in Figure 1(b) is not adequate for the required scientific tasks to be performed by the glaciologists.

This problem provides the motivation for this work. The project team consists of three glaciologists, two computer scientists and one PhD student jointed funded by the computer science and geography departments. Taking the advantage of being based in the same campus and having established collaboration through the previous project, the team conducted the design study together by employing a user-centered design process. The team worked together on the requirements and carried out evaluation of various design options, and co-authored this paper.

3.1. Dataset

The dataset used in this study was compiled by the team of glaciologists, based on sequences of Landsat satellite images, freely available from the United States Geological Survey (USGS). The optical Landsat satellite images have a spatial resolution of 20m and are frequently affected by cloud coverage. One image covers about a 180 km section of coastline, where the total length of Greenland's coastline is about 44,000 km. On average, three to five images per glacier per year were processed to sufficiently cover the changes during the entire melt season (May to September) when most of the iceberg calving events occur. The calving front positions are manually digitized from the satellite imagery for the time period 1999-2009. In a second step, the distances between the terminus positions are measured automatically on a profile along the center flow line of each calving glacier relative to the position of the furthest retreat. This last step resulted in the dataset to be analyzed, which is composed of 199 irregularly spaced time series of glacier terminus positions distributed around the Greenland coastline.

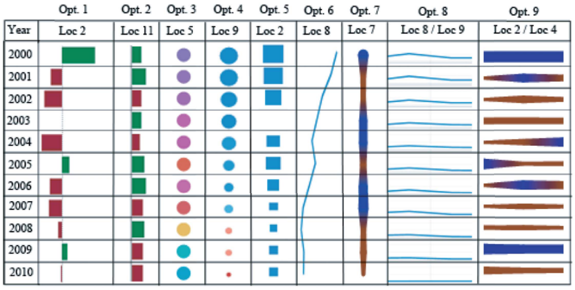


Figure 2: Nine design options presented in the evaluation. Participants were asked to score [0-5] against 7 criteria. (Visualizations generated using Tableux [Tab11].)

4. Visual Design

As the interdisciplinary team has worked together for nearly two years, the visualization scientists have a fairly good general understanding about the scientific activities of the glaciologists in the team, including their research goals and methodologies, and means of visualization. This enables us to focus on the visual design task to address the needs for visualizing the dataset described in the previous section. We adopted a user-centered design approach [MMP09, MWS*10, JBMC10, GTS10], using a focused group meeting to gather requirements, participatory design exercise in several brainstorm meetings and a questionnaire for evaluating design options. In addition, there were many discussions taking place in group meetings, PhD project meetings as well as informal communications among members of the team. In the visualization literature, such an approach has yielded many successful visual designs for specific applications (e.g., [MMP09, MWS*10, JBMC10, GTS10]).

4.1. Design Principles and Assessment Criteria

The user requirements gathered determine our design principles and assessment criteria. The design principles include the followings. (a) The visual design must convey effectively scalar changes in both temporal and spatial dimensions, while in spatial dimension, the focus is placed on the neighboring glaciers along the coastal boundary. (b) The visual design must be able to accommodate about 10-20 temporal steps and about 150-250 spatial locations. Of course, scalability in both temporal and spatial dimensions is welcome. (c) The visual design must serve the purposes of overview and detailed investigation of individual glaciers can be carried out using traditional time series visualization as in Figure 1(a). (d) The visual design must support effective visual search for a number of neighboring glaciers at a specific time step, and a specific glacier over several time steps.

We established 7 main criteria for evaluation: (i) How compact is the visual design in the spatial or temporal dimension? (ii) How many *scalar values* can be represented? How easy can one determine a value from its visual mapping? (iii) Can one easily differentiate a positive value (for advance) from a negative value (for retreat)? (iv) How easy can one compare scalar quantities among neighbors? (v) How easy can one compare scalar quantities along a time line? (vi) How easy can one spot and quantify changes between regions? (vii) How easy can one compare relative changes over time and among neighbors?

4.2. Design Process

We used several brainstorm meetings to develop our designs. We identified the fact that the study of calving glaciers focuses on the coastal boundary of Greenland. The boundary is a 1D object in 2D space, and can potentially offer dimension reduction. We considered to use nested boundary lines to represent different time steps, but found that the geometry, represented by a polyline with 3647 vertices, was too irregular and it was difficult to avoid overlapping between nested boundaries especially when there are many fjords. We also considered to use a simplified polygon or ellipse, but found that it is difficult to maintain a consistent perception of the time lines due to distorted projection. An abstract radial projection can make better use of space while offering a consistent perception along the temporal direction. This dimension reduction method can also be applied to other insular areas (e.g., Antarctica). Once we decided on radial projection, we shifted our attention to come out with different design options to address the 7 criteria discussed in Section 4.1.

We proposed nine different plots as prompts for design evaluation and discussion. Each plot used a specific semiotic to represent the information. We agreed with the glaciologists to use the conventional representation of time one the y-axis, and the termini on the x-axis for the evaluation. The key visual elements of the nine plots are shown in Figure 2, while the complete plots used in the design evaluation are given in the supplement material. As illustrated in Figure 2, these plots captured various design options, such as visual coding (color, size, offset, length, height, thickness), glyph geometry (square, circle, line, bar), connectivity and value interpolation (horizontal, vertical), and categorization (advance, retreat). As this evaluation is not a formal user study, we did not generate all possible combinations, as too many options could easily causing confusion in the evaluation. We used discussion session after the evaluation to identify the preferred design components in these nine prompts.

As illustrated in Figure 2, the first two options are *bar plots*. They are often used in environmental studies to show temperature evolution throughout time. We used a horizontal orientation as there is less vertical space than horizontal direction. *Opt 1* shows a plot that makes use of both sides of the 0 axis, and the values are color-coded (red negative, green positive). *Opt 2* displays absolute values of the distance from the reference point and the values are color-coded in the same way as *Opt 1*.

The next three options are *glyph plots*, showing different visual attributes in terms of varying color or size. *Opt 3* maps values to colors by applying the choropleth technique to same-sized circle glyphs. The technique is commonly used in geo-visualization as shown in Figure 1(b). *Opt 4* maps values to both sizes and colors with redundancy for visual error detection. *Opt 5* maps values to sizes only. This technique is also commonly used in geo-visualization when punctual data is to be displayed.

The last four are types of line graphs in different orientation. Such a representation is the most common way to depict a time series. *Opt 6* shows a time series plot with y as the time axis. This facilitates the connectivity and interpolation of values along the time line. *Opt 7* shows a streamgraph with the same orientation, and it maps absolute values to different thickness and color-codes positive and negative values for easy identification of advance and retreat events. *Opt 8* is similar to *Opt 6* but in horizontal orientation. This facilitates the connectivity in space and interpolation of values between neighbors. *Opt 9* is a horizontal version of *Opt 7*, supporting spatial connectivity and interpolation.

4.3. Evaluation of Design Options

We have organized an evaluation meeting for the design options. Each visual design was analyzed, discussed and criticized based on the 7 criteria in Section 4.1. Five attendees were given an evaluation questionnaire showing the 9 design options and assessment criteria. The full version of the questionnaire used is given in the supplement materials. Each attendee provided a score, from 0 (unsatisfactory) to 5 (fully satisfactory), for the proposed design options.

4.4. Design Decision

We gathered and analyzed the results of the evaluation questionnaires. Any score below 3 was considered as unsatisfied. In Table 1, we indicate those design options receiving an average score of 3 or above with a cross. We summarize the number of criteria met by each design in the rightmost column. The initial scores reflect heavily personal preferences. During a follow-on discussion session, five attendees explained their reasoning behind their scores, and the team soon reached some consensus. We decided to exclude any visual design that met fewer than 3 criteria, and focused our implementation on those which met a high number of criteria. *Opt 3* and *Opt 4* were considered as the weakest, be-

design options	glyph	color	size	connect	+/- class	i	ii	iii	iv	v	vi	vii	sum
Opt 1: +/- hor-bar plot	bar	yes	length	no	yes	x	x	x	x				4
Opt 2: abs hor-bar plot	bar	yes	length	no	yes	x		x	x			x	4
Opt 3: col-var glyph	circle	yes	no	no	no			x					1
Opt 4: col/size-var glyph	circle	yes	area	no	no								0
Opt 5: size-var glyph	square	no	area	no	no	x	x		x				3
Opt 6: time-on-y line plot	line	no	offset	time	no	x						x	2
Opt 7: verti streamgraph	line	yes	thickness	time	yes			x	x	x	x	x	5
Opt 8: time-on-x line plot	line	no	offset	space	no	x	x		x		x	x	5
Opt 9: horiz streamgraph	line	yes	thickness	space	yes		x	x	x	x	x		5

Table 1: Summary of the scores of the evaluation questionnaires. Columns 2-6 are visual attributes of each design option illustrated in Figure reffig:spreadSheet. In columns 7-13, a cross indicates an average score of 3 or above, for each of the 7 criteria. Last column is the total number of criteria met by each design option.

cause they had limited bandwidth for distinguishing scalar values, did not differentiate positives/negatives values, and could not depict continuing changes over time. *Opt 6* showed some strength for representing scalar values, but many found it was not straightforward enough when making comparisons, distinguishing between positives and negatives values, and consuming too much space horizontally. Three designs matched most of the criteria: (i) *Opt 8*, time-on-x line plot, with a weakness in change detection and in differentiating between positive and negative values; (ii) *Opt 9*, horizontal streamgraph, with a weakness in depicting scalar quantities and change detection over time; (iii) *Opt 7*, vertical streamgraph, with a weakness in depicting scalar quantities and detecting changes between neighbors.

To finalize our design, we combined the above design options with the radial layout. We cut out the northernmost part of plot to provide labels for the time-axis in terms of years. Each ring of the radial graph would represent a year. Within this radial layout we designed two different visualizations (see Figure 5) based on the above three winning design options, *Opt 7*, *Opt 8*, and *Opt 9*.

Greenland is commonly classified by glaciologists into 4 (northeast, northwest, southeast, southwest) or 5 regions (based on climate, ocean current influences). In order to support the data analysis process, we assigned a different color to each region and added a colored dot for each glacier around the outermost ring. Dots are colored according to the region they belong to and provide additional information about the zone membership of each tidewater ice body, and act as live link to the corresponding glacier names (see Figure 5). Figure 6 shows an example of our final design, it represents a 4 zones visualization of the 199 glaciers. A scale bar at the lower right corner of the window shows the range and color scale used in the visualization while a small "pie chart" at the lower left corner shows how many regions (and therefore colors) are depicted in the current visualization. Cardinal point references are also explicitly visualized to maintain and verify geographical consistency.

5. Spatial Mapping

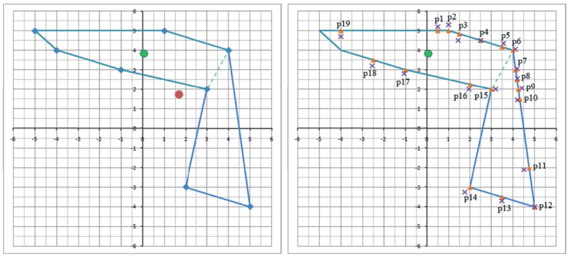
The fact that all calving glaciers are located around a coastal boundary enables us to utilize radial visualization, where the 2D Cartesian coordinates of each glacier is mapped to a 1D angular coordinate. This facilitates the reduction of one spatial dimension, allowing the use of the freed dimension to represent time. In this case, we use radial coordinates to represent different time steps as nested rings.

The overall algorithm for the spatial mapping has to address a number of issues. While we focus on the dataset of Greenland, we would like to make the algorithm as generic as possible to accommodate other possible geographies. Firstly, the algorithm needs to determine the center of a radial projection. Secondly, the algorithm needs to determine how Cartesian coordinates are mapped to angular coordinates, while ensuring the natural ordering of the termini along the coastal boundary. Thirdly, the algorithm needs to address possible cluttering problems. In the following subsections, we describe each algorithmic step, comparing naive methods with more sophisticated methods.

5.1. Center of Radial Projection

Let $B = \{b_1, b_2, \ldots, b_m\}$ be a set of ordered vertices representing a coastal boundary. Here we assume B to be a *simple* polygon (i.e., closed and no self-intersection). In the case when the imagery data shows only a partial coastal line, one can complete the polygon with the image edges where the inland is cropped. To facilitate any radial mapping, one must establish a *center of radial projection*, c, that must be inside B.

The standard formula for computing the centroid of a polygon, also known as the *center of gravity (or center of mass)*, cannot be applied naively, because it only guarantees that the centroid is within any convex polygon but not for all concave polygons. Such scenarios may not occur often, and in fact our application does not have the risk of an external center. However, it is desirable to ensure the robustness of



(a) centroid (b) snapping

Figure 3: a) Center of radial projection based on the largest convex polygon inside B (in green); b) snapping of all the termini points (shown as crosses) onto B.

the mapping algorithm by ensuring an interior centre for the radial projection. We safely assumed our polygon to be concave but not self-intersecting, and adopted the area cutting method of [Kho10], which finds a subset of B that represents the largest convex polygon inside a concave B. We compute the centroid of the convex subset as the centre of radial projection. Figure 3a shows such an example, where the red dot indicates the centroid of the original concave polygon, while the green dot is the centroid of the largest convex subset.

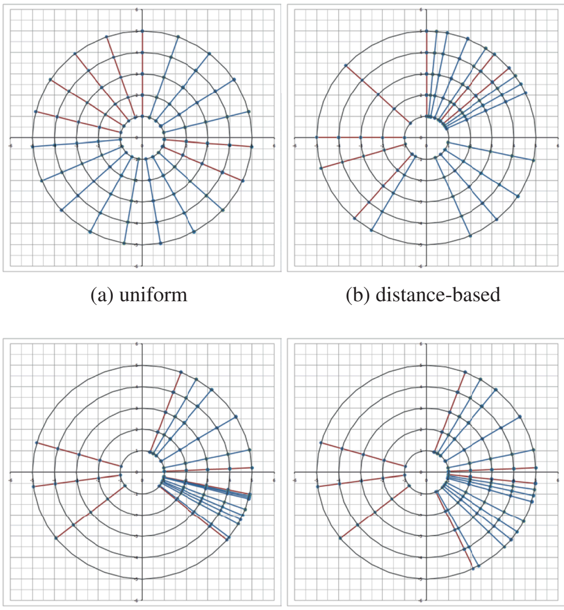
5.2. Ordering Glacier Termini

Each glacier has a fixed reference point, called *terminus*, g, against which the calving frontal position is measured. An *advance* is the distance to g when the ice front goes beyond g seaward. A *retreat* is a distance to g when the ice front retreats behind r in the opposite direction. Consider a dataset with n calving glaciers. We have n termini, $G = \{g_1, g_2, \ldots, g_n\}$, in Cartesian coordinates.

These points in G are normally either on an edge of B or very close to one, but are sometimes unordered. It is thus relatively trivial to determine the order of these points by first snapping them onto B and then comparing them while traversing along the polygonal edges of B. Snapping falls into the classical problem for finding the nearest edge for a given point. As this needs to be computed only once, a naive algorithm ($O(nm)$) is usable in practice. A more efficient algorithm is to pre-partition the space according to bisectional lines at each $b_i \in B$, resulting in a tessellation similar to, but not the same as, Delaunay triangulation based on B. We can use a binary space partitioning (BSP) tree [FKN80] for organizing these bisectional lines to support the search algorithm in $O(n \log m)$. In our case $n = 199$, $m = 3647$.

Note that the centre of radial projection discussed in 5.1 is not used in the snapping operation, as a projection based on the center would change the natural order of points along the coastal line. Figure 3b illustrates the process of snapping and ordering.

In the following discussion, we assume that $P = \{p_1, p_2, \ldots, p_n\}$ to be a set of ordered points on B, and there is a one-to-one mapping between P and G.



(a) uniform (b) distance-based

(c) with key references (d) relaxation

Figure 4: Spatial mapping algorithm: a) uniform distribution of P loses visual cues; b) distance-based distribution does not help orientation visual cue; c) fixing key references may cause cluttering; d) relaxing angular coordinates produces a radial projection with both distance and orientation cues .

From P, we compute the distance between neighbouring points, i.e., $d_i = dist(p_i, p_{i+1})$, for $i = 1, 2, \ldots, n-1$, and $d_n = dist(p_n, p_1)$. The *dist* function measures the traversal distance along the connecting edge or edges between the two neighbouring points, rather than the direct Euclidean distance between them. For example, in Figure 3b, the traversal distance between p_{18} and p_{19} involves three edges.

5.3. Radial Projection

Given a centre of radial projection c and an ordered set of n points P, one can easily map P uniformly onto n polar angles, providing a simple radial visualization with necessary spatial information. Figure 4a shows such a uniform mapping. While such a geometrical layout facilitates visual clarity and good space utilization, it loses a number of visual cues that are important to glaciologists in performing their visual search. One visual cue is the *distribution of termini*, which are rarely evenly located on the coastal lines and often form groups along segments of the coastal line. Another visual cue is the *relative orientation of termini*. When inspecting imagery data or discussing their work, glaciologists maintain such a sense of orientation, e.g., p_a is at the north of Greenland, or let us move from p_a clockwise to p_b at the southeast. Unfortunately, the uniform distribution of P in Figure 4a spoils both visual cues.

One alternative is to distribute P according to the distance, d_i, between neighbouring points in P (see Section 5.2). However, the orientation cue is still lost as in Figure 4b that shows such a distribution.

We found that once glaciologists have established the centre of a region, they normally use a number of key termini as the main references of orientation, and mentally organize the rest of points based on these key references. One approach is to require users to specify these key points. When there are observable clusters, one can divided P into several disjoint subsets, $P_1, P_2, \ldots, P_k$. An alternative is to select key points automatically based on geographical significance, especially when the clusters are not easily observable. For example, we may consider that the points closest to the four cardinal axial directions, $\pm x, \pm y$, are geographically significant and make them as the reference points. One could place these reference points on the four cardinal axes and distribute other points between the key references according to the order of set P. However, sometimes, the closest point may not be close enough to facilitate a nature correspondence between its original Cartesian coordinates and its radial projection, and placing such a point on an axis would confuse the visual cue instead helping.

In this work, we chose two key references for each axial direction. For example, for north $+x$, we chose one key reference on the left (i.e., the closest point in the northwest quadrant), and one on the right (i.e., the closest point in the northeast quadrant). We assign their own actual polar angles to themselves. We then distribute the rest of the points according to the order in P and the distance between neighbouring points. Figure 4c illustrates the application of this radial mapping, where red lines are the key references. Note that if there is only one point in a quadrant, such as p_{19} in Figure 3b, it is the closest to both nearby axes. Maintaining its own polar angle offers a consistent mapping.

However, as there are a large number of termini in the southeast quadrant, the radial lines are cluttered. To address this problem, we allow the mapping to be relaxed in two ways. (i) We set a minimal angle between radial lines. (ii) We allow the two reference lines to be moved towards the axial directions when there is a clutter. This is algorithmically achieved by reducing the angle between each reference line and the corresponding axis by half. Such a relaxing process can be done iteratively. Figure 4d illustrate this approach.

A more efficient relaxing algorithm, which avoids iteration, is to involve three steps of the data points to be relaxed. Without losing generality, we consider only the northeast quadrant. Let $A = \{a_1, a_2, \ldots, a_r\}$ be the r mapped angular coordinates in any clockwise order. Thus a_1 is the nearest to the $+y$ axis, and a_r is the nearest to the $+x$ axis. We can add $a_0 = 90$ and $a_{r+1}) = 0$ to the ends of the list A respectively.

Let τ be the minimal angular gap allowed between any pair of angles (a_i, a_{i+1}). This value depends on the type of visual design. Some visual designs, such as glyph-based required more gap space, others, such as horizontal plots (e.g., line plots) require little gap space.

First we determine if it is necessary to adjust a_1 and a_r based on the following conditions:

$$a_0 - a_1 \geq 0.5\tau \qquad and \qquad a_r - a_{r+1} \geq 0.5\tau \tag{1}$$

$$(r-1)\tau \leq (a_1 - a_r) \tag{2}$$

If any of these conditions is not met, we try to adjust a_1 and a_r. If the conditions still cannot be met after adjustment, we have to terminate the algorithm and modify the requirement τ. In the case that $(r-1)\tau = (a_1 - a_r)$ after adjustment, we simply distribute $a_i, i = 2, 3, \ldots, r-1$ evenly between a_1 and a_r with a uniform gap τ.

Otherwise, we start the second step by scanning the gaps between $(a_i, a_{i+1}), i = 1, 2, \ldots, r-1$. We compute $\delta = a_i - a_{i+1} - \tau$. We then sum up all positive and negative δ_i separately as Δ^+ and Δ^-. If $\Delta^- = 0$, no relaxing is necessary. Otherwise, we invoke the third step.

In the third step, we compute the ratio of reduction for all positive gaps as

$$\eta = (\Delta^+ - (a_1 - a_r) + (r-1)\tau))/\Delta^+$$

We then visit each δ_i. If $\delta_i < 0$, we make $a_{i+1} = a_i - \tau$ to ensure the minimal gap between (a_i, a_{a+1}). If $\delta_i > 0$ we reduce the gap by the amount of $\eta\delta_i$. In other words, we make $a_{i+1} = a_i - (1-t)\delta_i - \tau$.

This second relaxing algorithm was used to produce all the results in the following section.

6. Results and Discussion

Figure 6 and Figure 5 show the most representative results of our work. In our final design we closely followed the suggestion of glaciologists to plot advance/retreat values rather than the raw data, which can be counter intuitive and difficult to interpret. As demonstrated by these figures, we have made two contributions. Firstly our algorithm successfully transforms the terminus positions from their original positions to their projected positions along the circle, while maintaining the natural order of the termini along the coastline, and necessary visual cues for rapid visual search. Two types of visual cues, key reference points for clusters and distance between neighbors, were found helpful. As it can be seen in the center of Figure 6, the glaciers are originally very unequally distributed around Greenland. The relaxation algorithm has successfully optimized the use of space by stretching distances in crowded area.

Secondly our new visual design was built through a close

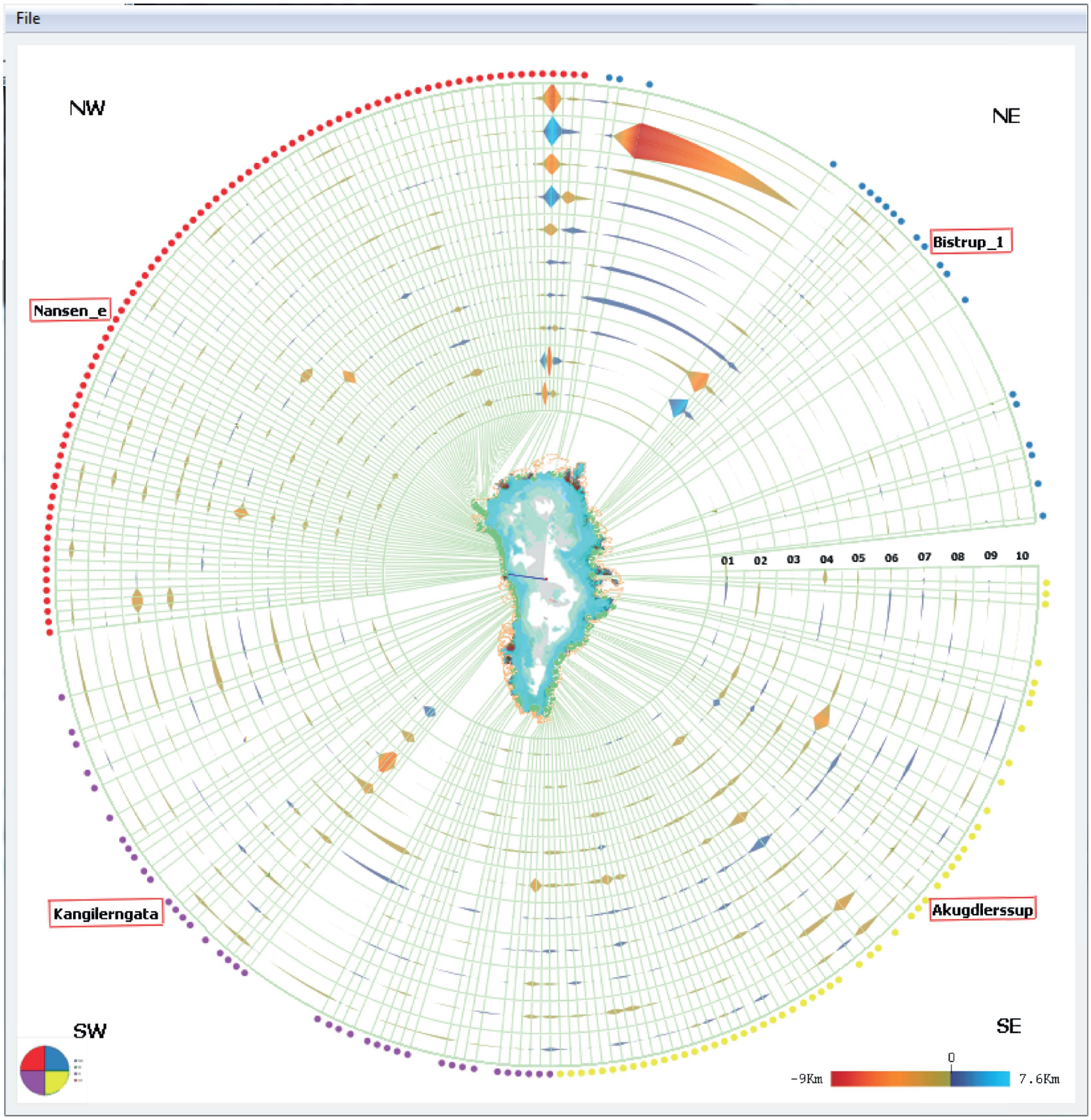
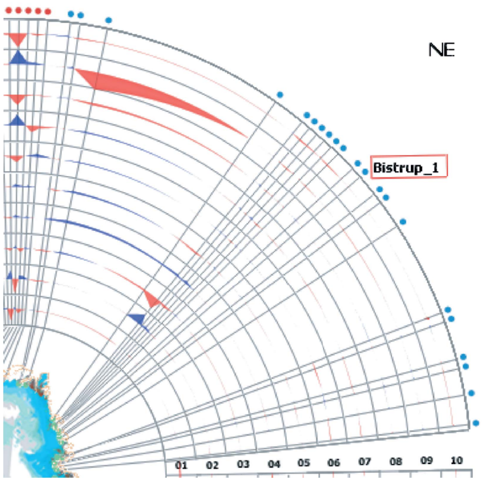
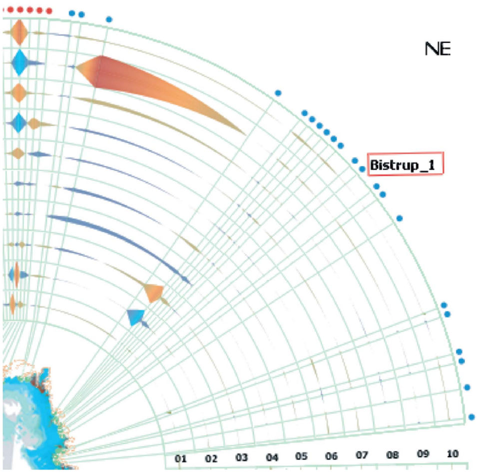


Figure 6: Radial design example. Area plot of the relative frontal positions of 199 calving glaciers over 10 years (rings). The background image of Greenland is a false color mosaic of Landsat images.

collaboration with domain experts using a user-centered approach reported in Section 4. We noticed that for visualizing the calving fronts dataset, several criteria were weighted more heavily than others. (a) Categorization of negative and positive values in terms of a diverging color map is very useful for quick visual search for advance and retreat events (Figure 6). We thus designed our final colormap with a discontinuous banding at value 0. (b) Offset- and thickness-based coding are much preferred over color-coding in visual mapping, and the continuous interpolation of values temporally or spatially is also preferred. Our final designs bring together the advantages *Opt 8* and *Opt 9*. Figure 5a shows one of our final designs where blue is used to represent positive values (advance) and red negative (retreat), while the amplitude of each peak represents the absolute value (amplitude of the phenomena). Figure 5b shows a closeup of another design (Figure 6), where a red-to-dark-yellow color map is used to represent the variation of negative values,



(a) area plot



(b) tube plot

Figure 5: Radial designs close up. Relative frontal positions of calving glaciers: a) area style plot; b) tube style plot.

and a dark-blue-to-cyan color map for the variation of positive values. The amplitude of the streamtube represents the absolute value (amplitude of the phenomena). A third design was proposed, which depicted absolute values using a pixel based representation. However even with a carefully-designed color scale, the method was proved to be prone to similar mistakes as reported in [BPC*10].

In this paper, we showed the results of an automatic algorithm that partitions the visualization into quadrants. This approach suited this application dataset. There is an alternative visualization with five clusters of termini, where the key reference termini were manually specified by one of the domain expert.

Before the visualization was completed, the domain experts relied on simple graphs as shown in Figure 1(a) to analyze the dataset. They plotted the average trend of all 199 calving glaciers, and sometimes selectively had a look at a few specific glaciers. After the visualization was made available to the domain experts, the very first use was to facilitate error detection in the data processing software. After a quick glance of the visualization, a domain expert immediately spotted a few anomalies, suggesting numerical errors in the data. The second use is that the domain experts can have an overview of all glaciers in a single visualization. The visualization clearly highlighted high magnitude glacier events, such as catastrophic breakup of floating glacier tongues and therefore large short-lived retreat rates. This enabled them to compare glaciers in regions, and relate them to the overall trend.

To quote one of the glaciologists *"It is already clear that this graph is highly supportive to studies of glacier behavior in Greenland, showing important patterns of retreat around the ice sheet with exceptional variations in some places"*.

7. Conclusion and future work

This work has presented a new approach for displaying a 10 years record of seasonal and inter-annual changes in frontal position of 199 marine terminating glaciers. We adopted a user-centered design process by involving the domain experts throughout the process, supported by evaluation meetings. Our radial visualization method successfully enables plotting a sizable dataset with 199 time series, while maintain the relative geographical information and visual cues for the frequently performed visual search tasks, essential for a good interpretation of the data. The generalized characteristics of our algorithm make it applicable to similar geo-information datasets, where the data points are located on or near a boundary. This design allows the glaciologists to obtain an overall view of the data both spatially and temporally, which was not possible before. This allows the glaciologists to make hypotheses more effectively about the controls and drivers of the actual marine terminating glacier behavior.

Although this form of visualization already represents a great improvement of this dataset visualization, it could potentially be improved by adding more attribute information (e.g., temperature) in the visualization. The interdisciplinary team is working on such visualization by evaluating new design options for such multi-attribute visualization.

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