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Seascape corridors : modeling routes to connect communities across the Caribbean Sea

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Citation

Slayton, E. R. (2018, September 12). *Seascape corridors : modeling routes to connect communities across the Caribbean Sea*. Sidestone Press, Leiden. Retrieved from <https://hdl.handle.net/1887/66437>

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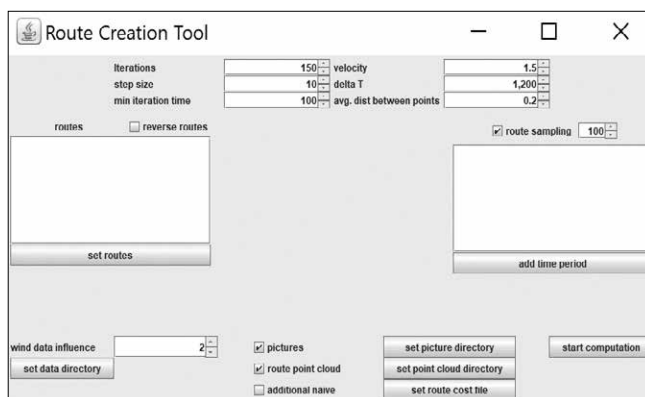
Issue Date: 2018-09-12

Modeling Reciprocal Voyages

This research seeks to explore how reciprocal voyages may have influenced inter-island mobility networks in the Caribbean, which requires consideration of multiple factors. First, these modeled pathways are based on environmental factors and constraints, such as current and wind. Second, routes are influenced through the origin and termination points, which are tied to the archaeological record and, as a result, past inter-island networks. Setting known sites as origin and termination points not only makes the routes directed but also ties these routes to real inter-island interactions. Third, the model sets a canoe speed for the vessel. Canoe speed was based on experimental and experiential canoeing voyages and set at three knots (Bérard *et al.* 2011, 2016). Routes returned by the model are thus not entirely dependent on environmental data alone, and are shaped through the speed of the canoe and the path's destination.

Landscape least-cost pathway analysis discussed in the last chapter is primarily based on static values and is not easily adapted to modeling sea routes because least-cost pathway sea-based models deal with moving or changing surfaces and needs. The model presented in this study expands on the traditional platforms to discuss movement over currents. I worked with Jan Hildenbrand and Jan Athenstädt from the University of Konstanz to build an isochrone model capable of dealing with current velocities (Athenstädt forthcoming; Hildenbrand 2015). Isochrone modeling refers to the process of suggesting the duration and layout of routes between two locations based on calculating the distance covered over several time segments (time fronts) toward the destination point. This isochrone tool was coded in Java and has an easy-to-

Figure 15: The model user interface into which the parameters are placed. The values present for each setting reflect the automated values present when the program is opened.



use user interface (Hildenbrand 2015; see Figure 15). The program uses a grid system of environmental data – namely wind and current. The underlying calculations used in these methods can calculate velocity and drift, unlike land-based cost surface analyses (Higawara 1989; Hildenbrand 2015). However, this model does operate on the same basic principles as other least-cost pathway models, as a time cost is calculated.

4.1 The Influence of Current and Wind

The most important environmental factors contributing to patterns of movement through the Caribbean Sea are current and wind. Current has the strongest effect on the direction of each modeled canoe voyage due to the impact it has on the vessel in the water. Current is a constant force that prevents any vessel from remaining stationary (*sensu* Bérard *et al.* 2011; Bérard personal communication 2014). The current continually pushes vessels in various directions. This push can either aid or disadvantage a canoe crew's journey, depending on the direction they wish to travel (*i.e.* with or against the current). Current influences the ability of peoples to connect with one another (*e.g.*, Callaghan 2001, 2003; Davies and Bickler 2015). Strong ocean currents could have prevented or promoted movement between certain communities connected through current flow and changing navigation strategies that may have influenced community links. These strong currents may have influenced the construction of seasonal strategies, depending on the location of the travel corridor.

It is also possible that the repetitive push of currents could affect the construction of a mental map. Previous research in cognitive science (Tolman 1948; Tolman *et al.* 1946), anthropology or archaeology (Kirby 2009; Tilley 1994), geography (Lowenthal 1961; Richards 1974), and the constructing of urban environments (Lynch 1960) supports the influence of continued pathway use on the development of mental navigation maps (for additional discussion on mental maps, see Chapter 2). Mental maps may have been used by Amerindian communities, as indicated through relationships between archaeological finds on islands in the Caribbean and the position of modeled canoe routes. Current movement can also direct least-cost routes, and by extension any canoe crews that might have followed them, towards certain areas increasing the likelihood that those movement corridors would be remembered and included in a wayfinding map of the region. Several hypothetical canoe routes constructed for this work suggest a link between site placement and least-cost canoe pathways, indicating some affiliation between trajectory and memory.

The time periods discussed in this study, beginning around 2000 BC in the Archaic Age and ending in AD 1600 during the early colonial period, fall after the large sea level rise that obscured the many small islands between the Greater Antilles and mainland South America (Cooper and Peros 2010). Currents encountered by Amerindians after this sea rise period can be comparable to currents recorded in the modern era (Callaghan 2001). Current flow has remained relatively level over the past one thousand years due to the consistency of the bathymetry (*i.e.* topography) of the sea floor. Sea levels have not yet risen to heights that would preclude the use of modern currents as the base for the model's cost-surface (Callaghan 2001: 309). Thus, for this study I have assumed that modern observations of current can be used to represent prehistoric sea conditions.

I took data on sea currents from the National Oceanic Atmospheric Administration (NOAA) and the AmSeas3D project. The AmSeas3D project collects data on surface currents around the Caribbean region. AmSeas3D data is spread over the Caribbean in 0.033 grids, or roughly 3.7 km separation between collected data points. This is a relatively high resolution for seascape-based cost surfaces, which have ranged from 5 degrees (roughly 550 km) to 0.25 degrees (roughly 27 km) in other works (Davies and Bickler 2015; Irwin *et al.* 1991; see Chapter 3 Table 1). AmSeas3D data include longitude, latitude, eastward velocity, northward velocity, and time-specific coordinates in the region. The two velocity readings can be used to calculate velocity vectors for current movement. Current data was collected in three-hour intervals. This allows multiple samplings of current data over the course of a day and a year. Linear interpretation is used to interpolate the force and direction of the current when calculating steps along the isochrone route for modeled pathways that launched inside these three-hour intervals (Hildenbrand 2015: 26). The AmSeas3D project has collected data from 2010 to the present and this study uses data collected from 2011 to 2014. It is difficult to exactly replicate cost values that were reflective of the real conditions faced by early seafarers without using modern records. In the future, it may even be possible to use data generated to reflect past currents directly, and to evaluate whether these data differed significantly from modern data.

Current can also affect route layout, or the trajectory of individual hypothesized canoe pathways generate by the isochrone tool. Estimating the length and trajectory of a journey partly depends on counteracting the side, front, or back push of the current on the vessel. This includes the influence of drift, or the current's impact on the canoe when at rest. Drift affects any canoe in a resting position at sea and the continual push of the current ensures that even when paddlers are at rest the vessels are in motion. Furthermore, paddlers cannot stay still, as ceasing to paddle means risking capsizing.

Experimental voyages conducted by Benoit Bérard and the Karisko project detail the difficulty of canoes staying upright in strong currents (Bérard *et al.* 2016). Karisko is a Martinique association that organizes experiential canoe voyages. Many of Karisko's routes were designed to take advantage of the current's push on the vessel, which had a significant effect on the drift of the vessel towards the destination point (Bérard *et al.* 2016; Bérard personal communication 2015). The current's push, which encourages a trend toward curved trajectories, is reflected in the routes modeled here. The current's influence on both the experiential and the modeled routes suggests that canoe travel corridors were in part constructed around current flow.

Wind also influenced canoe movement. Wind patterning has also remained consistent enough to use modern data for this type of model (Indruszewski and Barton 2008; Murray 1987). Wind data was taken from the Global Forecast System (GFS)² produced by the National Center for Environmental Prediction. The GFS has a resolution of 0.28 degrees, or roughly 28 km, grid cell size. This is coarser than for the AmSeas3D data set. As wind is not as heavily weighted within the model and is also interpolated alongside the current data, I assume a resolution for the wind data essentially equal to that of current. Like the AmSeas3D data set, the GFS data is also collected in three-hour intervals.

2 Data from the Global Forecast System (GFS) was accessed through: <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forecast-system-gfs>.

Wind plays a role in the minute-by-minute ease of travel of a voyage. Wind not only affects surface currents but provides an additional force working with or against a vessel, as it helps to shape surface currents, wave height, and drag on the vessel and the canoe crew (Bérard *et al.* 2011, 2016; Billard *et al.* 2009). Wind also affects wave height, which impacts a canoeer's ability to paddle. High winds can result in tall waves. Tall waves slow down the canoe as they make it difficult for canoeers to connect their paddles with the water in a uniform pattern. I personally encountered this problem when working with the Karisko project for three short experiential canoe voyages. I often found it difficult to push the blade of my paddle into the water to help push the canoe forward. This led me to strain my arms and an acceleration of physical exhaustion. Unfortunately, without complete access to a hydrodynamic (Bérard *et al.* 2011) model, it was not possible to directly calculate the influence of wave height and direction on the vessel.

In some cases, wind can signal the arrival of storms, which would have likely influenced a crew's decision to go out to sea. We were not able to account for storms in our model due to the inconsistency and high variability of storms within the underlying wind dataset. The snapshot nature of the current and wind data collected also made it difficult to pinpoint consistency of current or wind flow through the Lesser Antilles. In the future, it may be possible to see storm activity in abnormal pathway results by checking routes with atypical time costs against recorded weather events. Using all available environmental data, it is possible to represent an accurate approximation of optimal canoeing practices. Simulating possible least-cost paths at multiple points can suggest certain times when routes were more difficult or costly than those faced by real-world canoeers, who may have chosen to either not set out or to paddle to shore under such conditions.

These environmental constraints are combined into one surface, on which current and wind information is georeferenced to longitude and latitude coordinates. In general, a map projection affects the consideration of origin and termination points, with affixed longitude and latitude, that are placed within a grid that fits earth's surface. The map projection, or the association of environmental data with the grid, is spaced evenly when the data is collected near the equator, where degrees of longitude and latitude are relatively equivalent (Conolly and Lake 2006). As grid surfaces move further away from the equator, the shape or projection of grid cells shifts to accommodate the underlying sphere of the earth. Plotting the shortest direct path between two points, without influence from environmental data, on a Mercator projection returns a curved and not a straight line (Hildenbrand 2015: 7). Hagiwara (1989) relied on great circle calculations, used to determine the distance between two points on a sphere (Gade 2010), to ensure that the calculation of a path reflected a straight path over long distances. However, because of the Caribbean's position near the equator, which minimizes distortion due to the earth's shape, a Euclidian distance measure was used. Here, the Euclidean distance measure refers to a calculation of straight-line distances (Deza and Deza 2009). Hildenbrand's (2015) tool better fits a Euclidean distance measure as it uses a smaller step size that represents changes in canoe headings dictated by hypothetical Amerindian mental maps.

As stated earlier, because canoes of this region did not operate on sail power until after the arrival of Europeans, wind may not have had as great an effect on canoe

voyages as it had on the European sailing vessels. As a result, current would have had a relatively much greater effect on Amerindian paddled canoes. Therefore, I decided to weight current more heavily than wind. The projected wind and current data can be added together and given different weights within the tool (see Figure 15). This allows the cost surface used as the base for modeled canoe routes to reflect the percentage of influence each environmental factor had on the canoe.

Hildenbrand's tool allows for the current and wind cost surfaces to be updated at multiple stages along the isochrone route. The cost surfaces used here reflect the reality of current and tidal change over a 24-hour period. For this research, data was sampled every 3 hours to reflect the collection rates of the NOAA AmSeas3D project. However, this sampling rate can be changed to reflect whatever environmental data is used. This is because the resolution of this change is controlled by the time step, iteration settings, and route sampling settings of the model (see Figure 15). The model can also interpolate cost surfaces reflecting the change in current between current and wind datasets.

4.2 Adding a Human Element

The distances between islands in the Caribbean suggest that canoers could manage around time constraints for voyages, such as when crews became too tired. Tactics to counter these constraints include island hopping and paddling in shifts, as Callaghan and Bray (2007) have suggested. Stopover areas, where a crew could land along a coastline and rest, represent a way for crews to recharge mid-voyage. Stopover areas can be identified from pathways that go past other islands between the origin and termination points. These islands indicate the probable rest points in the journey. Whether voyagers needed to rest can be connected with the distance or time cost of a route and the position of an island.

To determine which modeled routes fit more closely to reality, I evaluated the influence that crew capability, or a canoer's physical ability, would have on the success of trips depending on a voyage's length. Determining crew capability requires a consideration of caloric (energy) loss involved in canoeing. A small number of studies have delved into the effects of canoeing on the human body. Sports medicine researchers, including García-Pallarés and Izquierdo (2011), Shephard (1987), and Tesch *et al.* (1976), have run tests on the performance of professional and semi-professional canoers. This research shows that the stress on the body from canoeing is like other sports, for example rowing or running (García-Pallarés and Izquierdo 2011; Shephard 1987; Tesch *et al.* 1976). This indicates that general considerations for how long people can canoe may be taken from similar calculations for modern day rowing or paddling studies.

Horvath and Finney (1969) conducted a short study on the capability of paddlers in a double-hulled canoe off the coast of Hawaii. Their tests found rowers could constantly paddle for eight hours and, when the canoe achieved an average speed of 3.16 knots (or 5.85232 km) per hour, an average of 369 calories were expended per canoer per hour, or roughly 2960 calories were consumed by an individual for one eight-hour voyage when the seas were fairly calm (Horvath and Finney 1969: 271). The total energy expenditure for all individuals must fall "below 35 percent of the maximum oxygen uptake" for the crew to maintain that speed. Roughly, this means that crews cannot always travel at maximum speed or they would not be able to paddle

over longer periods. However, the challenge of paddling on the open sea often led to a fluctuation in these energy expenditure levels among the canoers. Energy expenditure is dependent on sea conditions, such as current and wind speeds, as well as individual responsibility or activity during a specific period (Horvath and Finney 1969).

More recent experiential canoe voyages conducted by the Karisko project (Bérard *et al.* 2016) found that even canoers who received only a few hours of training could maintain enough energy to successfully complete at least six hours of voyaging on semi-rough seas (Bérard *et al.* 2016; Bérard personal communication 2014). According to Bérard, it is possible to have a journey last up to 12 hours under typical conditions. These voyages, however, result in heavy fatigue after the eight-hour mark. This is consistent with Horvath and Finney's (1969) findings that suggest fatigue may set in before the eight-hour mark.

In 2014 as part of my work with the Karisko project I ran heart rate monitor measurements during a two-hour canoe excursion. I had two paddlers (paddler 1 and paddler 2) out of a 23-person crew wear heart rate monitors³ as we crossed the Fort De France Bay in Martinique (see Figure 16). The weather conditions during this canoe run were considered 'normal' for the area, *i.e.* calm seas (Bérard personal communication 2014). Paddlers 1 and 2 showed an average heart rate of 89 BMP when moving at a speed of 2 knots or 3.8 km/hr. These paddlers were physically fit middle-age individuals, who exercised daily and regularly trained in a canoe with the Karisko team. The number of calories burned was calculated by taking the average weight of the canoers and applying the Wahoo Fitness App's calorie equation:

$$\text{CalorieBurnRate} = \frac{\text{abs}((0.6309 \times \text{newHeartRate}) + (0.09036 \times \text{weightInPounds}) + (0.0217 \times \text{userAge}) - 55.0969)}{4.184}$$

It is also possible to assess the theoretical capability of canoers by determining the ability of people to paddle an average distance per hour while expending a set level of energy. As there is no way to currently calculate the energy cost faced by canoers within the isochrone tool, these considerations of human capability and voyage length must be included after the routes are generated.

Due to the inclusion of several channels that surpassed normal distance covered by modern experimental voyages in the following case studies, a new way of determining the maximum length of a canoe voyage was considered. Pre-Columbian voyages modeled in this work often exceeded the six-hour voyage average and 12-hour limit discussed by Bérard (Bérard *et al.* 2016; Bérard personal communication 2014), as well as the eight-hour voyage set by Horvath and Finney (1969). Perhaps, as suggested by Callaghan (2001), these timetables could be extended by canoers taking shifts. There are various arguments for taking shifts in canoes, or calculating an overall 'safety' level for being near an island and the ability to take rest breaks on a beach (Callaghan 2001; Torres and Rodríguez Ramos 2008). Callaghan and Bray (2007) discuss the possibility of utilizing shifts of eight hours when calculating drift voyages, when canoes are not

3 Wahoo Fitness App and Ticker X heart rate monitors.

directed towards a termination point, from South America to the Greater Antilles. For these voyages four paddlers out of a crew of eight would paddle while the others rested. The shifts where canoers would paddle or rest likely changed between voyages, including the duration and timing of breaks. As any break in paddling can lead to capsizing the canoe (Bérard personal communication 2015), the ‘working’ paddlers would be required to paddle constantly. Likely, the canoeing in shifts theorized in sea-based least-cost pathway models reflect the reality of early voyages. However, there is limited ethnographic information on the use of canoes in the region and there is no information on the process of taking shifts. Therefore, the use of a shift system by canoers must be based on estimations when modeling least-cost routes, in this and other studies. These hypotheses about shift changes are typically calculated after the model has run, comparing route length with theorized size of the canoes crew (*e.g.*, Callaghan 2001).

It is possible that a voyage could exceed 12 hours due to time requirements of crossing some of the larger channels between islands in the Lesser Antilles. The speed of the

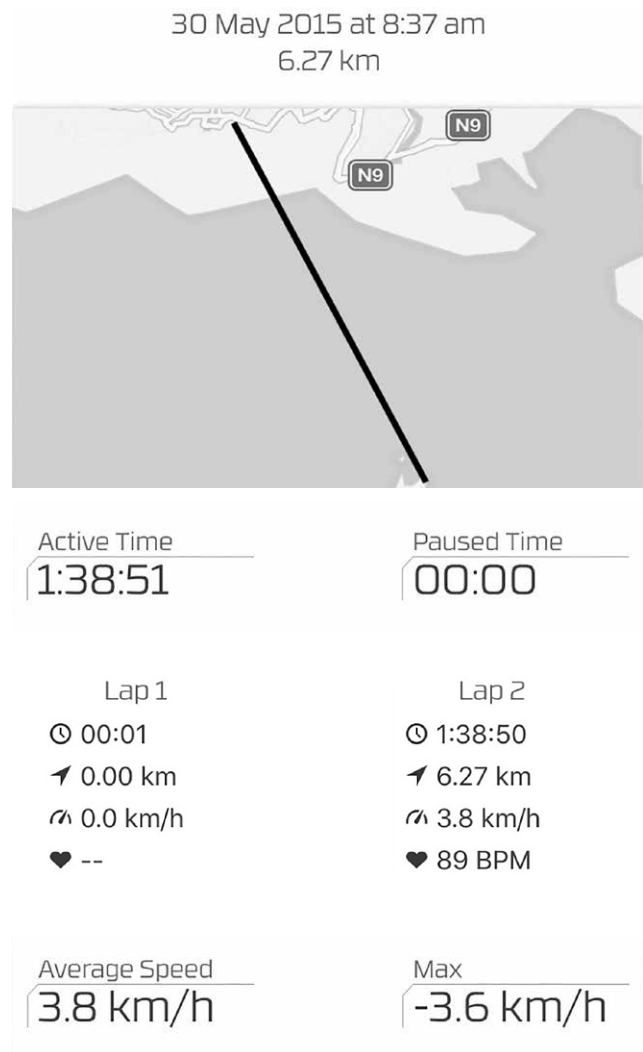


Figure 16: Route map of canoe heart monitor test run by author in bay of Fort De France, Martinique, from Pointe Du Bout to Fort Saint Louis, using the app Wahoo Fitness.

crew could fluctuate depending on the total length of the voyage. In these cases, one could consider adjusting for slower speed after the 8-hour mark to take into account a fatigued crew. With a 12-hour voyage, it is likely that a combination of eight hours of traveling at three knots and four hours of traveling at two knots could together represent a possible average speed. This corresponds to a hypothetical maximum distance across the Anegada Passage of roughly 59 km total distance when adjusting for a fatigued crew, and 66 km for a crew that theoretically manages to paddle at full speed for the entire 12 hours using the equation:

$$(\text{MaximumCanoeSpeed} \times \text{TimePaddled}) + (\text{MinimumCanoeSpeed} \times \text{TimePaddled})$$

Or

$$(5.56\text{km/hr} \times \text{TimePaddled}) + (3.7\text{km/hr} \times \text{TimePaddled})$$

Though these calculations can provide a baseline (*e.g.*, Horvath and Finney 1969), it is likely that many trips between islands involved longer distances and paddling times. These distances could take longer when working against the current or in poor weather. In this regard, it may be feasible to consider that crews took staggered or shorter breaks to extend their paddling capabilities. In this sense, no true maximum time of a voyage can be established. Pathways that pass by island coastlines should be assessed for their potential as rest areas that could extend the length of canoe voyages between islands.

By evaluating where routes passed by islands and the difficulty in completing the entire route, it may be possible to identify where stopover points along least-cost routes may have been desired or necessary, and thus possibly used as waypoints by Amerindian crews. For this work, I have discounted optimal routes that have higher route times than others, particularly those that exceed the average route time by over 15 hours. This process is done after the canoe routes have been modeled using the isochrone tool, detailed later in this chapter. By assessing the trajectory and the time costs of routes, it may be possible to determine if a crew of average size, between one and 30 people (Davies 1595; Fitzpatrick 2013; Hulme and Whitehead 1992; Peck 2002), would have been capable of making a journey if the crew was able to work in shifts (*e.g.*, Callaghan 2001).

4.3 Evaluating Currents

At my request for additional ways to evaluate seasonal trends, Jan Christoph Athenstädt from the University of Konstanz developed a program to assess the strength of the current at any given point in the region (Athenstädt forthcoming). Like the isochrone route tool discussed below, the current tool evaluates current data collected by NOAA's AmSeas3D project. The current tool details the direction and force of the current at three-hour intervals from the years 2010 to 2016. This is like the method of sampling for the route-cost tool used in this work. This ensures any evaluation run through the online interface will match the environmental factors influencing the route-cost tool.

Using the current tool, I produced a series of graphs that plot the strength of the current against the time it occurs (Athenstädt forthcoming). Each graph is accompanied by a color wheel that ties color to direction to visualize the analysis. In these graphs, colored dots correspond to the direction the current was heading at every data col-

lection time. The ‘standard direction’ of the current for the northern Lesser Antilles is due north, which is represented by grey in the color wheel. Movement away from the standard direction “to port,” or counter-clockwise, is indicated by a red dot (Athenstädt forthcoming). A green dot refers to “starboard” movement or a clockwise shift away from the standard direction. Current averages are measured to determine if trends in the data were periodic. A quadratic function was fitted to all modeled points, using interval length of one to 30 days, or eight to 240 data points (Athenstädt forthcoming). A linear regression was then run in all intervals averaging the r^2 . The average of these r^2 values should “be significantly lower if there is a periodicity” (Athenstädt forthcoming).

The current tool returns graphs with current values displayed by year in three-month intervals. Time is plotted on the X axis while current strength is plotted on the Y axis (Athenstädt forthcoming). Each interval is accompanied by a direction-wheel alongside longitude and latitude information for the point surveyed. I wanted to evaluate how time connected to current-force data averaged out over the year to compare these values seasonally. This would make seasonal trends apparent. As the tool also allows time information from these data points to be averaged, seasonal variability can be checked by using the current tool to create a running average for two period types, 15 and 30 days. The force of current is determined by averaging the strength of all data points within these time frames. Current direction was calculated by separately averaging the northerly and easterly vector component (Athenstädt forthcoming). These averages are represented in several bands corresponding to a year. The graphs created through this tool assess and visualize how currents fluctuated annually.

These current values can indicate what times of year should be evaluated using Hildenbrand’s isochrone tool. Depending on the consistency of current velocity over several years, comparing the force and direction on current at several points within the case study could indicate those regions that were accessible throughout an annual canoeing cycle. This assessment ensures a more targeted approach to uncovering canoe travel corridors can be taken with the isochrone model.

4.4 Isochrone Modeling

As stated above, isochrone modeling is a method used to calculate the optimal path between two points by linking a series of time fronts. These time fronts, which show-case movement from one point over the same period in all directions, can be linked to form a continuous route. The isochrone method, as first proposed by Richard W. James (James 1957), creates a sequence of time fronts in which each new time front is based on how far an object can move from a start point in the repeated period. In this sense, it approaches a ship’s movements as a “discrete optimization problem” (Hagiwara 1989: 17; see Figure 18). Vessel movement is charted in sections rather than as a continuous path, as shown by continuous optimization routes (see Figure 17). However, the isochrone method itself was not adaptable for computerization. This led Hagiwara to improve the method so it could be used for computational analysis. Hagiwara (1989) dubbed this the ‘modified isochrone method’. Hagiwara (Hagiwara 1989: iii), working on ship routing logistics, developed the modified isochrone method as a weather routing tool that provided accurate information on a “(sub) optimum ocean-crossing route” to captains of small wind and motor-powered vessels.

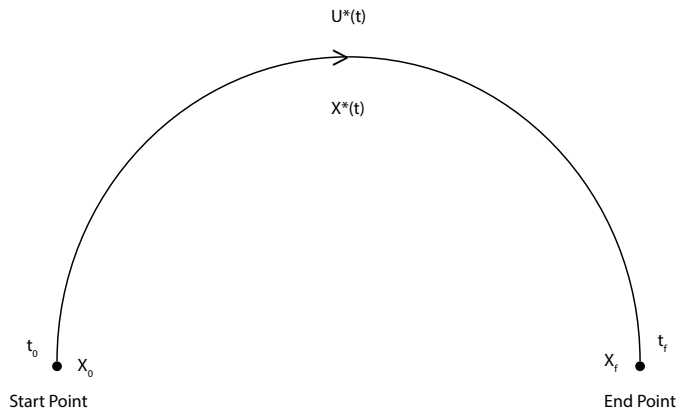


Figure 17 The formulation of ship routing as a continuous optimization problem (above figure modified from Hagiwara 1989: Figure 2.1; see Appendix A). In this method "a ship's position vector is: $X = [\phi \ \lambda]^T$, where ϕ : latitude, λ : longitude. A ship's control vector is: $U = [[\theta \ n]]^T$, where θ : ship's heading, n : number of propeller revolutions" (Hagiwara 1989: 12).

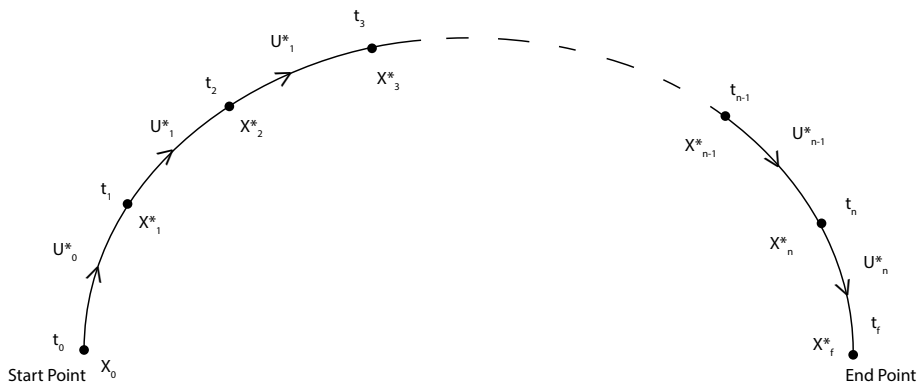


Figure 18: Formulation of ship routing as a discrete optimization problem (Modified example of a formulation for ship routing as a discrete optimization problem as seen in Hagiwara 1989: Figure 2.2; see Appendix A).

Hagiwara's (1989) modified isochrone method involves creating new iterations of isochrones from each point along the journey (see Figure 19). At the start, a series of rays is produced from the origin point. Within these rays the furthest point that can be reached by Euclidean distance standards is selected as the next point from which to model an isochrone ray. These next generation points are linked to create a time front showing the farthest possible movement from the origin point during a set time in every direction (Hagiwara 1989; see Figures 19 and 20, Appendix A). This process of creating rays and then determining new points is repeated for every time front until all possible outcomes have been explored (Hagiwara 1989; Hildenbrand 2015). These time steps create an image of continuous movement of a vessel over designated periods. While a canoe's speed during these time steps remains constant, the resulting velocity of the boat does not, as it is a combination of current velocity with the vessel's velocity.

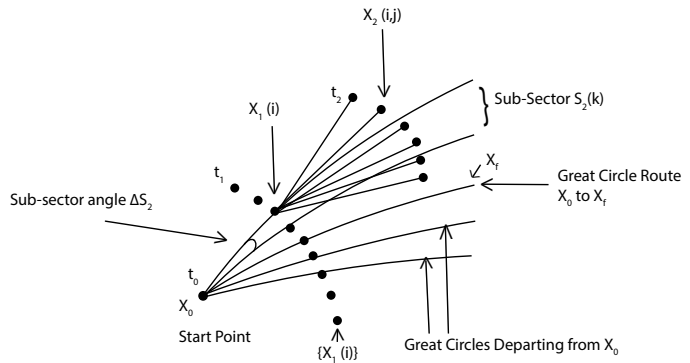


Figure 19: Modified from Hagiwara (1989) figure 2.3, Calculation of isochrone $\{X_2(k)\}$ at time t_2 .

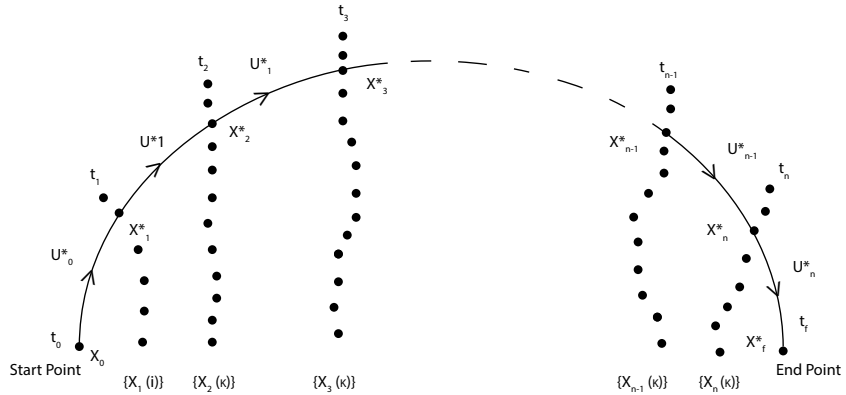


Figure 20: Modified from Hagiwara (1989) figure 2.4, showing the determination of minimum time cost fronts for routes by tracing points within the modeled isochrones.

Much like least-cost pathway analysis, the choices of joining time fronts in Hildenbrand's isochrone tool are governed by locally optimal decision-making strategies (Hildenbrand 2015). Here, 'locally optimal' refers to the tool making decisions about which direction to travel by comparing the cost of traveling in every direction from a central point and choosing the fastest heading (Bell and Lock 2000). All calculations in the model are made from one grid cell to the next (*e.g.*, Bell and Lock 2000; Conolly and Lake 2006; Wheatley and Gillings 2002), or one step between one isochrone ring (Hildenbrand 2015), or time front ring, and the next. As the routes are determined in time fronts, the evaluation of movement across the region is determined through the combination of many lengths of route. In this way, these models simulate how virtual routes mimic canoers re-evaluating their vessel's position and heading several times throughout a voyage.

In this model routes adjust position to take better advantage of changing currents (Hildenbrand 2015). Approaching sea voyages as steps also allows the model to more accurately update the underlying current and wind cost surface to reflect changing environmental factors. Updating environmental factors and taking voyages in segments is consistent with other sea-based route modeling methods (*e.g.*, Davies and Bickler 2015; Montenegro *et al.* 2016). Using time steps, pathways can reorient or change heading direction during a voyage to take advantage of optimal currents. In some ways, the possible human choices made by navigators to make use of better currents is reflected.

Though this method mimics real-world navigation techniques of re-evaluating direction, the resolution of time fronts may constrain the ability of routes to change heading independent of the isochrone steps. The area covered by isochrone steps inhibits voyages differently depending on the distance between the origin and termination points. This may be a larger issue for routes modeled between neighboring islands separated by small channels. However, the distances covered by many of the routes generated for this work minimize the smoothing of the cost surface to match isochrone steps. As some of these routes cover over 30 km, they provide many opportunities to have multiple isochrone steps. Furthermore, the distance between isochrone steps can be altered within the model, allowing for a finer resolution when necessary.

When determining what kind of model to use to calculate the true cost in movement between two points for this study, it was essential to choose a method that factored in the cost surface on which hypothetical canoes moved. Depending on their heading, canoes could travel various distances from the origin point to work with or against the underlying environment cost surface. The tool makes cost calculations based on friction surfaces derived from wind and current patterns. To counteract the current's direction and velocity to not be taken off course, crews sometimes had to move against the current in order to maintain course towards the termination point (Hildenbrand 2015; see Figures 21 and 22).

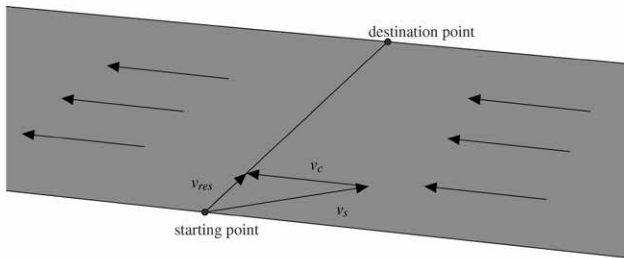


Figure 21: The direction of movement through current, where v_s is the direction of movement against the current, v_c , with the resulting direction of v_{res} (Hildenbrand 2015: Figure 2.1).

$$|\vec{v}_{res}| = \frac{\vec{c} \times \overline{p_1 p_2}}{p_1 p_2} \pm \sqrt{|\vec{v}|^2 - |\vec{c}|^2 + \frac{(\vec{c} \times \overline{p_1 p_2})^2}{|p_1 p_2|^2}}$$

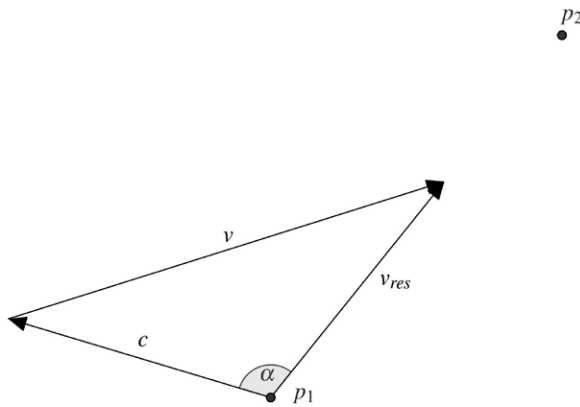


Figure 22: The equation used to determine the resulting velocity, where v = velocity of the canoe, C = current velocity, p_1 = the start point and p_2 = the end point (Hildenbrand 2015: Figure 2.2).

The resulting pathway can be considered the vector sum of the velocity and direction of the current and the velocity and direction of the canoe (Hildenbrand 2015; see Figure 22). For the tool's settings, it was assumed that the speed of the canoe is an equivalent influence or force value to the underlying environmental factors (Hildenbrand 2015). These routes confirm that Euclidean distance methods rarely capture the true restrictions met by travelers when crossing the distance between two points. Moving with or against currents can affect the distance achieved between isochrones in much the same way moving up and down a slope affects the difficulty of traveling over a raster-based cost surface (Bell and Lock 2000). To work with the current, canoers moving from site A to site B and then back from site B to A likely followed different routes. Including these factors enables the model to evaluate anisotropic movement between island sites.

Sectors, the area of the cost surface evaluated, are created for each time front to reduce the model's runtimes. These sectors are set so that from the central point time fronts are built in over a set degree from the node. The creation and positioning of sectors along isochrones is dynamic (Hagiwara 1989; Hildenbrand 2015; see Appendix A). The average distance between sectors is set as "greater than the iteration of ΔT times the speed," with ΔT being the time step (Hildenbrand 2015: 7). To create a default sector size d_p at the point farthest from the departure point d_{cmax} the angle separating every sector ω is calculated as (Hildenbrand 2015: 8):

$$\omega = 2 \times \arctan\left(\frac{d_p}{2 \times d_{cmax}}\right)$$

To increase the route tool's precision, smaller steps were created between each newly modeled isochrone point (Hildenbrand 2015). As each new route segment would be generated in the same sector consecutively they would then resemble straight lines. In addition to the modifications made to the isochrone method for this computer model, island placement needed to be evaluated. Sometimes there is an island located between the origin and termination points that could block the execution of a route. These islands needed to be clipped out of the underlying environmental surface to prevent modeled least-cost routes running through an island (*e.g.*, Altes 2011; Slayton 2013). The shape of smaller islands was difficult to clip and in some cases resulted in pathways running through the coastline of an island. However, the partial failure of the island clip did not influence the majority of the hypothetical routes returned by the isochrone tool.

The need to clip islands creates an issue within traditional isochrone methods, as there were restrictions with modeling towards a termination point on the opposite side of an island being approached. Island placement is not addressed in Hagiwara's (1989: 32) isochrone method, which has a fixed number of rays constructed per isochrone. To respond to this issue, Hildenbrand's tool "takes the angle between the right neighbor, the current point on the isochrone and the left neighbor, and constructs rays with a global constant step size so that the maximum number of rays fit in between the two neighbors" (Hildenbrand 2015: 10). To construct these additional rays moving around coastlines the angle β between the right neighbor and the left neighbor of the central point is calculated, or angle $\beta = \angle P_{rm} P_c P_{ln}$, where P_{rm} is the right neighbor, P_{ln} is the left neighbor, and P_c is the central point (Hildenbrand 2015: 10). The number of rays nr_c can be calculated from the global constant step and the quotient of (Hildenbrand 2015):

$$np_c = \left\lfloor \frac{\beta}{\gamma} \right\rfloor$$

The rays are constructed in a way that angle between and the last ray is equal to the angle and the first ray (Hildenbrand 2015; Figure 23):

$$\alpha_r = \alpha_l = \frac{\beta - \left\lfloor \frac{\beta}{\gamma} \right\rfloor \times \gamma}{2}$$

To calculate the angle β of the model offsets angles α_s and α_e for the end and beginning of the isochrone paths (Hildenbrand 2015). These steps help to generate isochrone routes that can hypothesize pathways doubling back on themselves to reach sites on the opposite side of an island. Removing the islands from the cost surface enabled these neighbor-aware ray-constructed isochrone routes to travel around instead of through islands. This process allows for routes to pass around islands in a realistic manner.

The model is also capable of distinguishing loops, or sections of the pathway that turn back on themselves within routes and eliminating them (Hildenbrand 2015). This allows for a more accurate display of possible route locations. It also removes incorrect time cost as it prevents the addition of an extended route segment to a time front.

For the tool to function the following parameters need to be set:

- “
- the start angle α_s , the direction in which the first rays are always constructed
 - the end angle α_e , the direction in which the last rays are constructed
 - the step size γ , the angle between two rays
 - the average point distance d_p , the sector size or the preferred distance between two points on the isochrone
 - the iteration time ΔT , the time, which is added between each iteration or each isochrone
 - the mini-iteration time t_{\min} , the time for each mini-step in the computation of the new isochrone
 - the departure point p_0
 - the maximum number of iterations n , the algorithm must terminate somehow, one way is to limit the number of isochrones.
 - the constant speed v , the propelling velocity of the vessel.”

(Hildenbrand 2015: 8-9).

Once these cost surfaces are combined and the parameters set, the model can begin to calculate pathways. Pathways are represented as a ‘line’ on a map of the Caribbean and a series of x and y coordinates (see Figures 26 and 27). Both outputs are tied to the positions on the isochrone time fronts connected with the optimal route. In cases where the whole route is not displayed on the provided map, the x and y coordinates are uploaded into ArcGIS 10.2 and turned into polylines using the point-to-line tool as a part of the conversion tool kit (ESRI 2013).

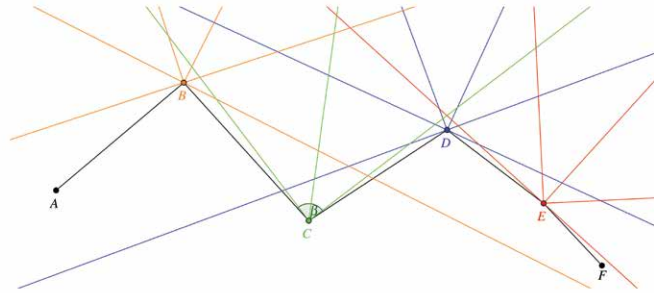


Figure 23: New neighbor ray construction with step size 45° (Hildenbrand 2015: Figure 2.6).

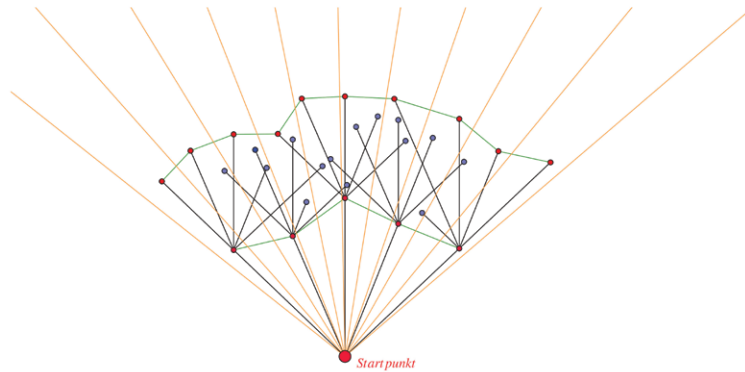


Figure 24: “Example for the modified isochrone method. The red points are on a (green) isochrone. The orange lines bind the sectors. The blue points are filtered out as they are not the farthest away from the departure point in their sector” (Hildenbrand 2015: Figure 2.3).

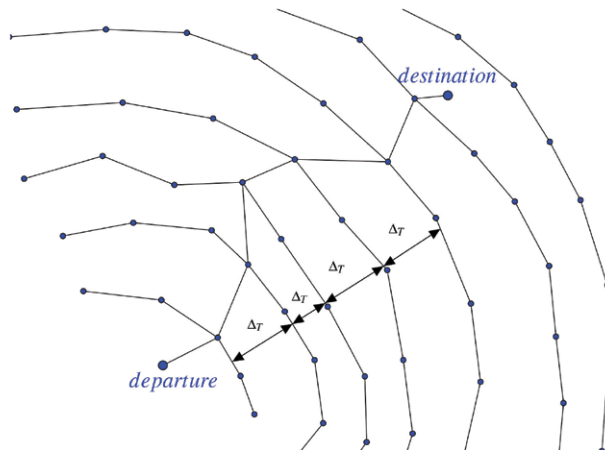


Figure 25: “The (modified) isochrone method, with the time fronts (=isochrones) seconds apart” (Hildenbrand 2015: Figure 1.1).

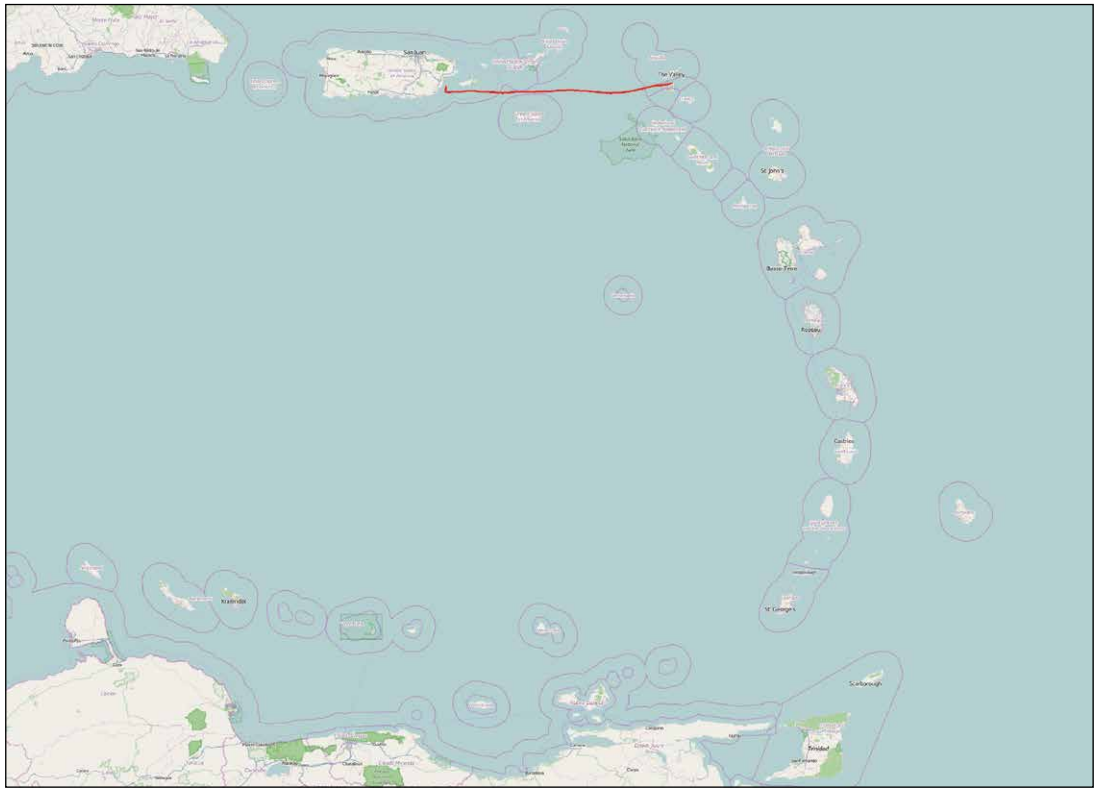


Figure 26: Example of line representing a hypothetical canoe route generated by the isochrone model route tool from Dominican Republic to Puerto Rico (0-1_2012-04-01T03_00).

-63.217	17.633	-65.748	18.069	2012-04-01T00:00	isochrone	160948.669	44.7079636
-63.153	18.175	-65.748	18.069	2012-04-01T00:00	isochrone	168225.045	46.7291792
-63.115	18.171	-65.748	18.069	2012-04-01T00:00	isochrone	170920.997	47.4780546
-63.06	18.105	-65.748	18.069	2012-04-01T00:00	isochrone	176158.659	48.9329608
-64.759	17.783	-65.748	18.069	2012-04-01T00:00	isochrone	66126.2064	18.3683907

Figure 27: Example of CSV file depicting X and Y coordinates for the Origin point, X and Y coordinates for the termination point, the day and time the canoe was 'launched' by the model, isochrone, the time cost of the voyage in seconds, and the time cost of the voyage in hours.

The location and layout of these routes can then be compared to the time cost data returned by the tool. The time cost data is returned as a CSV (comma separated value) file at the end of the tool's run. The final cost in time (in seconds and hours) is given alongside the origin and termination points as well as the time and date when the canoe was 'launched' (see Figure 27). Time costs returned for time steps can indicate what effect the time step parameter had on the model's output. Comparing start times and route costs can expand upon how launch times may have influenced canoe voyages.

Connecting routes to the archaeological record through the inclusion of site-based origin and termination points allows for the model to represent past mobility patterns that could possibly have been tied to the exchange of materials. Directed least-cost sea-based pathways can be used to evaluate reciprocated ties between Amerindian peoples

in the Lesser Antilles from the Archaic Age to the Late Ceramic Age/early colonial period. Hildenbrand's recently developed isochrone tool, used here, stands as one effort to explore reciprocal there-and-back voyaging using computer models. Even if the resulting routes do not represent actual paths used by Amerindian seafarers, they are a close equivalent, representing a best guess of possible optimal routes. There is currently no way to confirm if these exact travel corridors were used. However, modeled routes can indicate where to look for interaction points between separate island communities, as shown in all three case studies discussed in the following chapters (see Chapters 5, 6, and 7). These interaction types include indications of areas where multiple communities may have interacted and/or canoe crews sought to rest.

