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RESEARCH

Seafaring and Modelling

Emma Slayton[1] · Katherine Jarriel[2] · Alvaro Montenegro[3] · Crystal Safadi[4] · Karl Smith[5] · Sara Zaia[6]

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Abstract
Seafaring modeling is still a developing science, and there have been many approaches taken to evaluating human sea-based mobility in the past by researchers focused on different regions and time periods. Many models utilize similar processes or data inputs, including climate models, vessel technology studies, and human capabilities. However, being able to decide on the right approach can be difficult, and often relates to the technological know-how of the researcher, access to data on which the model can be based, and a discussion of what information is necessary coming out of the research to answer the initial question posed. This paper details and compares these various methodologies to help provide a foundation for developing future models or applying existing techniques to new areas. The authors, who have used a wide array of methods in their collective research, identify different data types that form inputs for models, describe the development of models, and consider the ways in which researchers can assess the appropriateness of models and data for their research questions. The models discussed in this paper include agent-based modeling, least cost path/route optimization analysis, drift modeling, isochrone analysis, and alternative forms of mapping. This paper provides case studies from different regions and time periods for each of these models. Finally, the authors discuss the relationship between computational models and the archaeological record. We aim for this work to provide a guide to those interested in using computational seafaring models in their research and to serve as a point of comparison for the effectiveness and possible application of current methods and research in future works.

Keywords Modeling · Seafaring · Climate data · Agent based modeling

Introduction

It should come as no surprise that computationally modelling past seafaring practices is a complex process. It can be difficult for researchers to determine which methodologies are best suited to their goals, especially as new strategies are developing constantly due to the burgeoning nature of the field. As a result of the isolated nature of many newcomers, we hoped to address some basic modelling strategies, complications, and opportunities that go into the entire process of developing both research questions and methodologies targeting past human mobility on water. When discussing seafaring modelling it is important

Extended author information available on the last page of the article

to address concerns researchers face in working with and developing seafaring models, including how to determine proper environmental or humanistic inputs and how to analyze model outputs. Seafaring is very much a practice of intertwining concerns—environmental, technological, and human. Modelling these concerns is a complex process, and there are multiple ways to arrive at answers to questions around past water-based mobility. This paper aims to provide guiding waypoints along the many paths that may lead to a desired destination.

Disorientation

Beginning to model maritime spaces requires a disorientation from the tools with which many researchers are familiar. Spatial analysis tools have been primarily developed with a land-based perspective in mind and may not reflect the experiences or practices of past peoples who actively engaged with the sea. Adopting a maritime perspective requires either adapting existing spatial analysis tools (e.g., GIS being adapted to conduct isochronal analysis or model least-cost paths) or developing new tools (e.g., agent-based modelling) to answer specific research questions. Existing spatial analysis tools can render the sea surfaces as flat and undifferentiated (see Introduction in this volume for further discussion). There are several challenges to adapting traditional GIS packages to better understand the complex reality of moving across the sea. While land-based models examine directional travel relative to slope and may include hard barriers to travel, maritime models of travel must consider variables that are often more complex and dynamic.

The fluidity of the sea surface consists of currents as well as temporal fluctuations that occur at different time scales, such as tides and seasonal weather patterns. Wind is an important variable for maritime modelling, and the relationship between wind and current is still being addressed in scholarship. Different technologies have profound effects on maritime mobility. Vessel technologies relate to environmental conditions in very different ways depending on place and time period. Finally, there are different types of barriers that inform a person's decision to make a maritime voyage, such as the likelihood of storms, visibility, access to known navigational waypoints, and access to necessary knowledge and technologies, that may be difficult to incorporate in a spatial model. All these variables are interrelated, forming a complex system of concerns that the modeler must carefully consider.

Overview

This paper will walk through the different considerations that a researcher makes at each stage of the modelling process: (1) choosing inputs and model parameters, (2) choosing which model format to use, and (3) making meaning of the results of modelling relative to the archaeological record and past lived experience.

Sect. "Inputs" outlines the considerations that each modeler must make when determining what limitations to set within the model (parameters) or on what phenomena the model will base its conclusions (inputs). We also address how to evaluate input data, including the use of past and present climate data and selecting important factors from the archaeological or ethnographic record to serve as a base for the model.

Sect. "Modelling" provides an overview of select computational models that have been used in research. As many researchers have developed methodologies separately, there are many practices from which to draw inspiration within the sub-field of maritime mobility modelling. We address different types of models (e.g., isochronal and agent-based models) and the functionality of these different methods in different technological (e.g., sail vs. paddle) or functional (e.g., island hopping or island colonization) contexts.

Sect. "Outputs" discusses how to process outputs, as well as sharing data with others to encourage model comparisons and broader assessment of results. Finally, the paper concludes by looking forward to how the sea may be more broadly considered an integrated space, and how computational models might better incorporate a holistic understanding of past experience.

Inputs

Inputs consist of the data and parameters that form the basis of a computational model. Understanding and ensuring the efficacy of inputs into the model is just as, if not more, important than being able to understand the model's outputs. These inputs directly impact the functionality and flow of movement within models and can determine the level of 'reality' produced by computational results.

Using Modern Climate Data—Some Considerations

At the CAST Workshop in 2022, it was widely agreed that using modern climate data was the general standard for developing seafaring models, with the exception of researchers who were exploring paleoclimate models to address research questions such as initial colonization of the Americas (e.g., Montenegro et al. 2016) or Australia (e.g., Kealy et al. 2018; Borreggine et al. 2022). Modern climate data offers a high enough resolution to detect meaningful variation in environmental conditions, which is necessary for building models. As quality and resolution of environmental data can vary depending on the region of the world under study and is often tied to government agencies that collect data, researchers must be judicial in determining which climate data set suits their research best. Modelers should evaluate climate data to establish that the general patterns of the present are similar to those in the past before using modern climate data as a proxy for antiquity.

Moving through the following section on climate inputs, it can be helpful to think of the following questions that researchers have used modern climate data to address:

(1) What are the main drivers of wind and current patterns in the region of study, and are those conditions the same today as during the time period of the research question?
(2) Do climate proxies such as lake cores, ice cores, and speleothems indicate similar environmental conditions in the past and present?
(3) To what extent do changing sea levels affect landforms?
(4) What other geological events have affected the configuration of land and sea?
(5) Is there scholarly precedent for using modern climate data to create models of past activity in the time period in question?

Wind Data

When it comes to seafaring, wind forms the principal environmental data needed to understand maritime travel, and several studies have been conducted using wind as the primary dynamic environmental input (e.g., Indruszewski and Barton 2007; Leidwanger 2013; Alberti 2017; Jarriel 2018, 2021; Gal et al. 2021a, b; Perttola 2022). This is because (a) wind directly affects sea surface currents, so there is a strong correlation between wind and the types of currents that move boats, and (b) the dependence of sails on wind speed and direction. The combination of wind and current constitutes what constant forces are working on a boat. Wind, in particular, can affect wave height and drag on both vessel and crew (see Billard and Bérard 2009; Bérard et al. 2016; Slayton 2018, p. 66).

Incorporating wind data into maritime models requires the translation of individual data points from environmental observation stations into a contiguous cost surface raster that encompasses the entire study area. Each cell of the cost surface raster contains information about the cost of moving to and from each cell on the raster map. Some considerations for such a cost surface raster that includes wind and/or current data would be (Fig. 1):

(1) Ensuring that the raster cell size is a fine enough resolution to be meaningful for the type of voyage being modelled
(2) Ensuring that there are enough environmental data points within the study area to provide a high enough resolution for the research question
(3) Making decisions about how to sample data over time, considering the availability of data, tide cycles, seasonality, and evidence about past environmental conditions
(4) Correctly translating directionality and speed of wind wave patterns from sampled data into the cost surface raster
(5) In the event that environmental data is in raster format, translating the resolution of environmental data to match the resolution of other raster data used by the study
(6) Ensuring that the units of measurement from the sampled data match the other units of measurement of the study

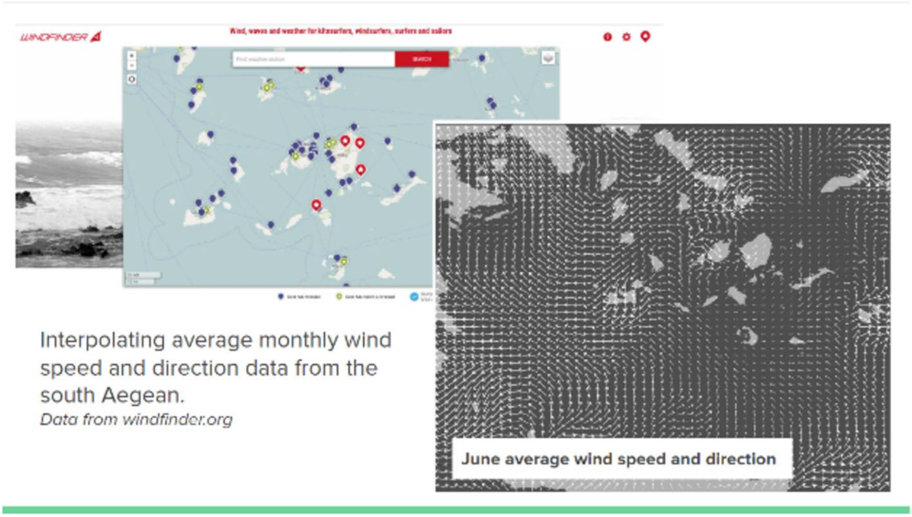

Fig. 1 Illustration of the process of downloading raw wind data from weather stations in the Aegean from windfinder.org (upper left), and then the interpolation of wind data as a regular grid in ArcGIS Pro (lower right), figure provided by Jarriel (2017)

Figure 1 is an example from Jarriel (2017, 2018) using ArcGIS. First, environmental data—in this case, wind speed and direction—were derived from observation points in the study area. Jarriel tabulated average monthly wind data from 1999 to the present. There were approximately 50 observation points for a study area of around 35,000 km^2.These data points were added to an ArcGIS shapefile, which was linked to a.csv table containing all the data for each month. Monthly data were selected because of the author's interest in the seasonality of regular maritime travel, but the sampling of data would vary depending on the research question. Jarriel then used inverse distance weighted interpolation to create two raster maps for each month, one containing speed and the other containing prevailing wind direction. These raster maps formed the inputs for subsequent path distance functions.

For visualizing environmental data, Jarriel created a fishnet mesh of regular points across the study area and combined it with the interpolated maps to produce layers that contained average wind speed and direction across the study area in a regular grid. The resulting layer can be symbolized with arrows of varying magnitudes to indicate wind speed and direction, but it is important to inverse the symbology because wind direction is measured by the direction from which it flows.

The above case study provides an example of data where observation points were translated into a vector file and then interpolated into a raster data set. However, in the event that environmental data are available in raster format, one would want to ensure that the environmental data raster's resolution matched the resolution of other data layers. For example, by resampling the environmental data to a new output cell size.

Finally, there are often mismatches in units of measurement between environmental data and other study data. For example, wind, currents, and boats may be measured in knots or meters per second. However, depending on the study question, more meaningful units of time may be hours or even days. This may necessitate recalculating a data layer to match existing data.

Water Data

Wind data alone may be sufficient for certain research questions about sailing routes, seasonal variation, and travel time. However, the inclusion of water-oriented inputs, such as bathymetric and current data, can allow researchers to develop a more-well-rounded understanding of maritime phenomena. Data from currents can often be sampled using similar strategies to those above.

For example, Safadi (2016) uses bathymetric data, wave height recordings, and wind data to create simulated wave height models for a comparative evaluation of Levantine harbour sites in the Bronze and Iron Age. In this case, the development of the model allows for comparison of the natural suitability of harbour sites for protection and shelter across the region (Safadi 2016, p. 349). Slayton (2018, 2020) combines wind data with water modelling and historical and archaeological data. Slayton argues that current would have had a greater effect on Amerindian paddled canoes than wind due to their lack of sail and low prominence in the water, and therefore weighted current data more heavily in the resulting cost surface (Slayton 2018, p. 67). Least-cost paths are assessed relative to known historical and archaeological sites and the energy expenditure of the crew to create isochrones of movement across the Caribbean seascape. This allows for the assessment of connections between islands and the "intricate interaction between social structure and the placement of canoe routes" (Slayton 2018, p. 194).

Finally, water inputs can be used to create entire seascape cost surfaces across which human mobility is modelled. Kealy et al. (2018) create a sea surface cost raster to model early modern human colonization of Sahul. They combine cost variables and bathymetric data to assess early migration routes across the entire Wallacea region. In this example, a detailed understanding of bathymetry is necessary to understand the paleogeography of Wallacea and reconstruct islands and coastlines as they would have been in the past. Davies et al. (2015) also combine bathymetric data, winds, and currents to develop a sea surface model in the Pacific Ocean. In this case, bathymetric and current data are vital for assessing the visibility of distant islands.

Seasonality

The environmental and cultural conditions for sailing could vary highly depending on the season. It is important to consider seasonal variations when creating models of ancient seafaring. However, it is also important to remember that people sailed in all seasons and in all conditions. The task of the modeler is to understand the different conditions for sailing relative to seasonal environmental changes and contextualize those within the greater temporal rhythm of cultural activities for maritime societies.

On the concept of "sailing seasons": historical evidence for certain regions and time periods indicates that there was a widely known sailing season during which the bulk of maritime activity happened, and conversely, a hazardous season where sailing ceased. This is perhaps best illustrated by the concept of *mare clausum*—or "closed sea"—in the Mediterranean during the ancient Roman Imperial period. Archaeological evidence from many time periods and regions around the world cautions modelers against assuming a proscriptive open or closed sailing season. Even when there is textual evidence of sailing seasons, maritime activities continued throughout the year. Archaeological and modelling scholarship demonstrates the range of seasonal variation in sailing in the classical Mediterranean (Beresford 2013), prehistoric Mediterranean (Jarriel 2018; Gal et al. 2023), Caribbean (Slayton 2018), South China Sea (Perttola 2022), Indo-Pacific at the Last Glacial Maximum (DiNezio and Tierney 2013), initial colonization of Australia (Montenegro et al. 2016), and prehistoric transoceanic crossings to the Americas (Montenegro et al. 2006), just to list a few.

In order to investigate the effects of seasonality on ancient maritime movement, there are a few things to consider. First, there could be a high degree of seasonal variation in the prevailing environmental conditions. When collecting environmental data, this might mean that yearly averages are not particularly meaningful. Figure 2 illustrates the difference in prevailing wind patterns between June, July, and August for the central Cycladic islands in the Aegean Sea, compared with earlier estimates of a 10 km/day average travel distance. While the 10 km/day earlier estimate was correct *on average*, the month-to-month conditions indicate a highly variable seascape (Jarriel 2017, 2018).

The scale of travel under consideration is also an important factor relative to seasonality. Shorter trips might be more opportunistic, taking advantage of daily variation in weather patterns. However, longer trips might be limited by unfavourable prevailing winds and currents, as well as more subject to storms.

The type of journey is also a consideration and is related to the scale of travel. Long-haul trading would be different than fishing, piracy/raiding, and trips to maintain social connections. These different modalities entail different risks (see Disaster, Risk, and Resilience paper in this volume) as well as different temporalities, preparation, navigation, and

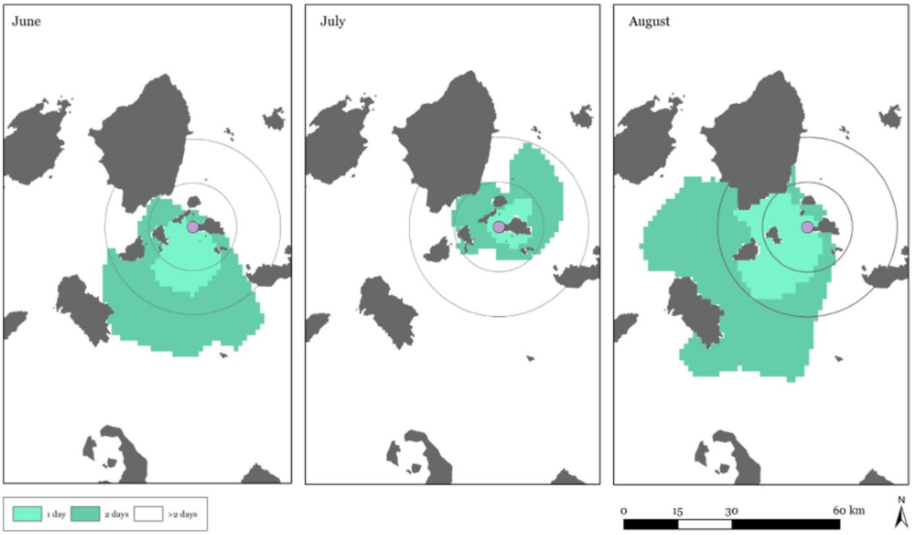

Fig. 2 Comparison of the difference ranges of travel potential centred on the island of Keros (Cyclades) for different summer months. The concentric rings represent 10 km from the central point (see Broodbank 2000), while the green coloured regions represent days of travel time. Contributed by Jarriel

specialization. Varying types of boats perform differently to prevailing environmental conditions, as well. Generally, wind-powered boats operate most favourably in a beam reach to a broad reach (90–130°), while oar-powered boats operate most favourably with the wind directly behind them (180°). Many sailboats can switch to oars, as needed. Different sailing technology means that different environmental conditions are favourable, which the modeler should account for.

Seasonal storms such as monsoons, typhoons, hurricanes, and winter storms merit special consideration. In some contexts, people might avoid sailing during the storm season, but in other contexts, storms can create advantageous conditions for maritime travel. Embarking in advance of a storm might mean being pushed by favourable winds to reach a destination more quickly. Similarly, riding the tail of a storm could result in being pulled by favourable winds. Waters may be calmer than usual following a large storm, which could create conditions for a less hazardous journey. Decisions to travel by boat in such circumstances are also dependent on culturally embedded conceptualizations of risk.

Finally, there are many aspects of maritime seasonality that relate to the seasonality of land. Especially in small-scale coastal and island communities, the resources for maritime travel are limited by land-based activities, such as the time to harvest crops. Small communities do not necessarily have the labour power to crew a ship and process the harvest at the same time. It is important to connect maritime activity to other cultural and economic activities taking place throughout the year. For example, in the Early Cycladic Period of the Aegean Sea, Jarriel (2017, Fig. 3.3) illustrates that the traditional "sailing season" during the summer months corresponds to periods of high agricultural intensity for both cereal and legumes (Fig. 3). Another example from the Early Archaic period in the northern Lesser Antillean Islands by Hofman et al. (2006, Fig. 6) shows the variety of maritime resources available throughout the year, indicating a seasonally variable maritime taskscape of resource extraction. This example itself is based off another by Kennett (2005,

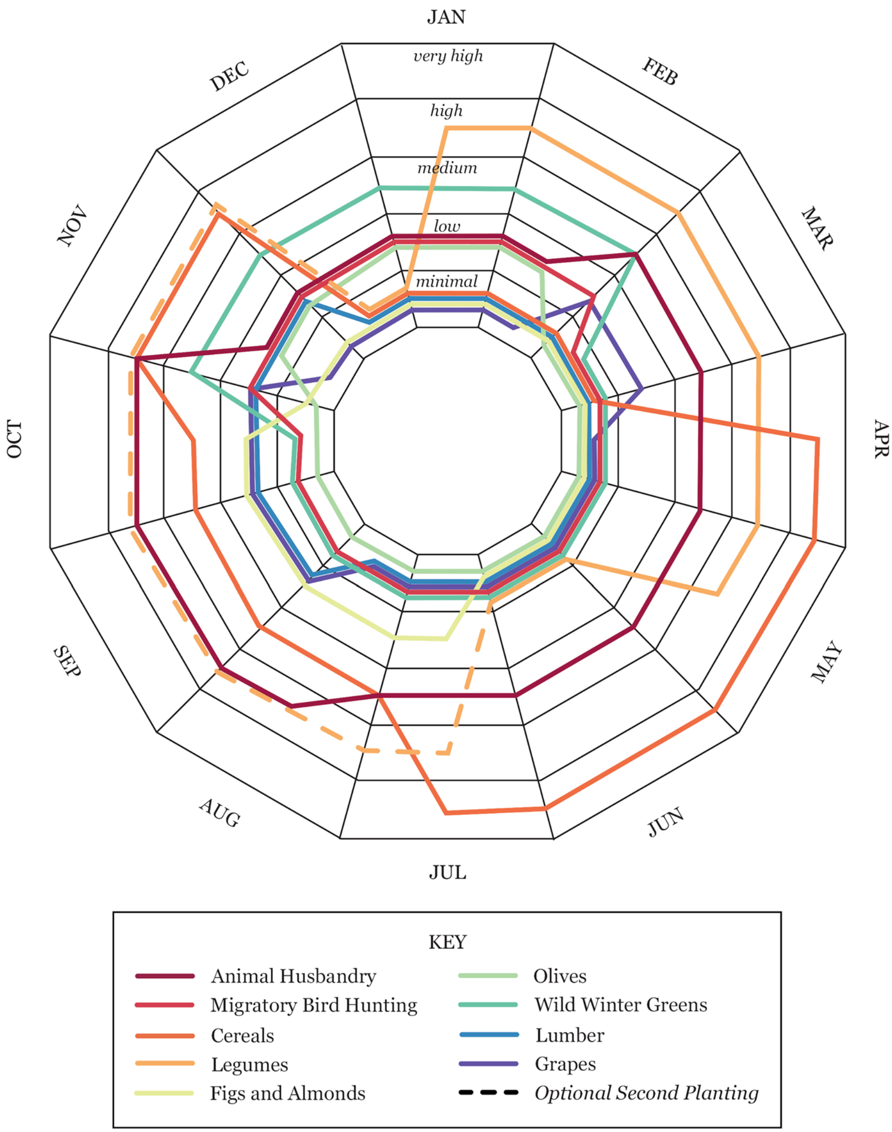

Fig. 3 This figure shows the times of year when various subsistence activities occur in the Early Bronze Age Cycladic islands (from Jarriel 2017)

Fig. 9), detailing seasonal mobility weighed against community action in the Santa Barbara Channel Islands by the Chumash. Finally, an image from a local newspaper in Yap from 1989 highlights the relationship between weather, agriculture, winds, tides, and moons, showing an integrated system that is both maritime and terrestrial, as well as cultural and environmental (Fig. 4, contributed by Jermy Uowolo).

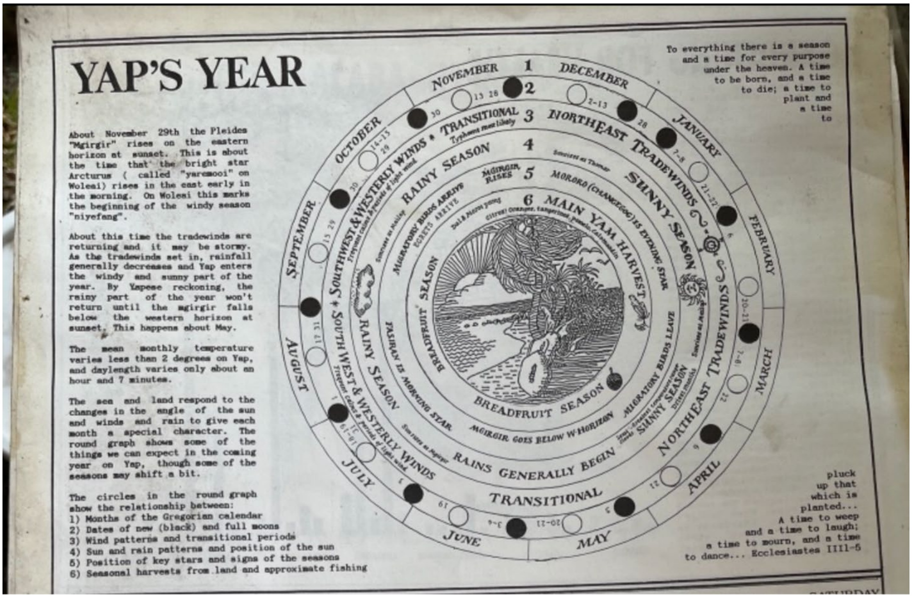

Fig. 4 This image from a Yapese newspaper shows the cyclical activities related to subsistence, weather, and sailing for the year. Unknown periodical, contributed by Jermy Uowolu

Cultural Evidence

Alongside understanding the practical inputs that govern the surface on which seafaring is modelled, it is vital to incorporate the technological toolkit used by the maritime community in question, insofar as extant evidence allows. The evaluation of past seafaring toolkits can be broken down into better understanding the evidence from (a) the archaeological record, (b) written and pictorial sources, (c) ethnographic comparanda, and (d) community-based knowledge and oral histories.

Archaeological Evidence of Boats

Direct archaeological evidence of vessels can be incorporated into a model via metrics for the boat's performance relative to prevailing environmental conditions, the amount of cargo and supplies it could carry—which would affect both performance and the duration of a voyage—and the labour required to power it. The survival of direct archaeological evidence of boats is dependent on post-depositional processes and is highly variable depending on the time and region. Direct evidence of boats may be preserved in the case of shipwrecks or other waterlogged and anaerobic environments. In some cases, boats may be preserved through burial, such as is the case with well-known Viking boat burial traditions. Other parts of the world that incorporate boats or boat-shaped burial markers include China, Japan, the Philippines (Esteban and Valientes 2019), Vietnam (Bellwood et al. 2007), and Egypt (Vanhulle 2024). Archaeological evidence includes not just the vessels themselves but also other tools in the sailing toolkit, such as paddles. It is sometimes possible to use secondary evidence to reconstruct boats, such as using the size and distribution of preserved shipwrecked cargo as well as modern underwater survey tools to recreate the shape of a boat's hull.

Written and Pictorial Evidence

Written and pictorial evidence provide indirect data that may be used to build a model, whether they account for environmental conditions, cultural decision-making, or vessel technology. In some regions and time periods, written evidence may even record routes and times of journeys (see Perttola (2022) for a discussion of modelling relative to the Seldon Map). Examining the archaeological evidence for representation of boats within their socio-temporal contexts can reveal information about seafaring technology and how it changes over time.

As an example, the prehistoric Aegean presents a case study for where some of the best evidence of what vessels were like comes from pictorial evidence due to both time depth and harsh post-depositional processes. Some of the earliest representations of boats, dating back to the Neolithic period, come from the site Korphi t'Aroniou on Naxos, where images of boats pecked into stones have been discovered. These images show very small vessels, as determined by the relative scale of the sheep/goat/animal next to the boat, which might have been used for everyday, non-specialist travel. During the Early Bronze Age, evidence comes in the form of the so-called Cycladic "frying pans," which were made from stone or earthenware and incised with geometric decorations (Broodbank 1989). Boats may be depicted in the centre. These depictions can indicate things like hull shape and oar number and orientation (which can also indicate number of crew members). They also lack any representation of sails. However, the images tend to be schematic and open to interpretation, such as whether the number of lines representing oars are reflected in reality or are artistic interpretation. Generally, these vessels are interpreted as representing Cycladic longboats, which would have engaged in regional travel and are a hallmark of Early Cycladic culture. Finally, the frescoes at Akrotiri on the island of Thera, which were preserved by the volcanic eruption during the Middle-Late Bronze Age transition, reveal a flourishing maritime culture (Warren 1979). At this point, the sail had been adopted in the Aegean sometime during the Middle Bronze Age. The frescoes indicate technological elements of boats such as rigging, hull design, oar number and orientation, number of passengers/crew, a variety of shapes and sizes of boats, cargo, evidence of other objects in the sailor's toolkit, and a depiction of the local harbour.

Looking to later visual representations of boat design, there is a distinct difference between those occurring pre- and post-invention of the printing press and or wider access to print resources. For example, historic reports of seafaring practices from both the Pacific and the Caribbean after contact with European chroniclers shows an increase in access to pictorial depictions of canoeing through either hand drawn records or wood cuts on a larger scale than has survived from the time of the sources in the Aegean mentioned above. Many cases of wood cuts found in the historic record from the sixteenth- to seventeenth-century Caribbean are modified versions of one original image with slight modifications (Slayton 2018). These images do indicate the size of the vessels, including orientation for canoers in vessels which indicate that canoers are facing the direction of travel. However, the detail of these vessels for early images provides insufficient detail for the actual shape, mode of construction, or general technical capacities for the vessels. Perhaps most interesting to note for these depictions is that they are generated concurrently alongside written records. So long as they are tied together by context, written records may complement the understanding of visual images, and vice versa, allowing the researcher to glean more detail than using one source alone.

Regardless of the time period or medium, visual and written representations of boats may provide important information about the parameters for vessel size or crew size (which can impact vessel speed), orientation of the crew (navigation capability), or general vessel shape (vessels possible interaction with the environment). Moreover, they may provide insight into how crew members interacted with vessels, such as engagement with sea-based activities or rowing direction, which, in turn, may indicate human caloric expenditure that can act as an input constraint for the model.

Cultural Knowledge

Cultural knowledge for computational modelers may include ethnography, ethnographic comparanda, oral histories, and Indigenous and local knowledge. Some of the earliest computational modelling emerged from the long tradition of ethnographic work in the Pacific. Malinowski's (1922) canonical *Argonauts of the Western Pacific* offers a prime example of how an ethnographic study, in this case of *kula* ring trade and social networks, raised ongoing questions of interest to computational modelers. Questions regarding the practical aspects of seafaring, navigation, regularity of travel, and the connections between maritime voyages and broader social structures. Oceania has a long history of computational modelling, with studies from the early 1970s—longer than any other region of maritime modelling of seafaring. Modellers studying Oceania will enjoy a robust amount of previous scholarship from which to draw; modellers from other regions may find that examples of modelling, and especially the relationship between modelling and ethnography, to be more uneven.

Cultural knowledge is most often useful for modelling as complementary lines of evidence, rather than direct inputs of data. For example, ethnographic comparanda may help broadly constrain parameters, such as in Jarriel (2018) where the estimate for how far people would be willing to travel on a daily basis was bounded by ethnographic comparanda from multiple modern and pre-modern ethnographic sources from both the study region and of cultural groups with similar technology. Cultural knowledge may also help validate the results of models. Slayton (2018) referenced work interviewing local fishermen on the island of Grenada to learn more about the continuation of navigational techniques as a guide for determining any boundaries of assessment for modelling short-hop pathways around the island.

Finally, cultural knowledge may provide valuable insights into the human elements of crewing a vessel, boat-building techniques, and navigational practices, including various methods of navigation, as well as how navigation is embedded in broader cultural practices. During the CAST Workshop in 2022, navigators Larry Raigetal and Alson Kelen shared immense knowledge of the decision-making that goes into voyaging that would be impossible to infer from archaeological or environmental evidence. The past and the present are different contexts, even within the same location, and the knowledge held by practitioners may offer helpful guidelines on what is possible, as well as expanding the variables that go into voyaging beyond the limited record of the past.

One of the exciting possibilities of cultural knowledge is that it offers researchers an opportunity to build models based on cultural conceptions of space and place, while also addressing navigation practices. This also allows the incorporation of models into the broader cultural systems that surround seafaring. To date, there are few examples of ethnographic data being directly integrated into models. Gustas and Supernant (2017) incorporated cultural variables such as inland waters, protected waters, and visibility to create least-cost paths for Late Pleistocene and Holocene canoeing in the Pacific Northwest. The ethnographic data were based on descendant communities of Coast Tsimshian, Haida, and Tlingit peoples in the region. CAST members (and authors in this special issue) Genz and Jarriel are currently collaborating to develop an agent-based model that incorporates ethnographic work completed by graduate students at the University of Hawai‘i at Hilo (see Tamagyongfal et al. 2024). This model will compare a traditional agent-based model, in which the agent assesses its course according to pre-defined time intervals, with the *etak* model of navigation utilized by Yapese navigators to mentally divide a journey into stages based on environmental observations.

A major limitation of incorporating ethnographic comparanda is the time commitment required by researchers to develop meaningful, trust-based relationships with communities. (Though not impossible, as evidenced by the work of Bérard and colleagues on experimental voyaging with local communities in the Caribbean (Bérard et al. 2016; Bérard and Biar 2021). To this end, interdisciplinary partnerships between ethnographers and modelers provide a solution of mutual benefit. As in the case of Genz and Jarriel, the Hawai‘i-based ethnographic modelling team and the Purdue-based agent-based modelling team (all of whom are students), are working to iteratively inform each other's research. As is a recurring theme of computational modelling, the key to success is cross-disciplinary, cross-institutional collaboration.

Community-Driven Research

Island and coastal communities are among those most affected by modern climate change. Moreover, remote maritime communities in the present day may depend on global supply chains which were disrupted during the COVID-19 pandemic. Computational modelling may help answer community-driven questions to promote resilience among locations experiencing precarity. This is described in more detail in the Introduction as well as in the Disaster, Risk, and Resilience paper in this special issue. It is imperative that modellers maintain open dialogue with practitioners, community members, policy makers, and other stakeholders when addressing questions that affect living communities. Moreover, we advocate for an ethical orientation to research that prioritizes studies *for* people over studies *of* them.

Experimental Archaeology

In addition to inputs that relate to climate data or weather and knowledge of humanistic practice, modelers also have to consider the technological impact of seafaring toolkits on the ability of vessels to move, as well as the ways in which people actively interact with this technology. While this is partially addressed through the study of ethnographic data and the archaeological record, another way to discern past practice is to do our best to recreate it. Experimental archaeology can help us to pinpoint specific metrics of seafaring, both in the seafaring toolkit and voyaging's effect on the human body, in ways that general ethnography or archaeological data cannot.

At the outset of experimental reconstruction, researchers often use ethnographic, historic, and archaeological data to assign quantitative metrics to how a vessel handles and its speed (e.g., Hudson et al. 1978; Narmo 2010; Bérard 2012; Bischoff et al. 2014; Van de Noort et al. 2014; Staples and Blue 2019; Osipowicz et al. 2022; Irwin et al. 2023). Some archaeologists have gone so far as to scientifically test the physical constraints of vessels through 3D modelling or wind tunnel testing (e.g., Berard 2012). While the entire specimens of physical boats are often lost to time, experiments, sometimes done with changes to a vessel's shape (e.g., using planking to build up the sides of vessels), can help to explore what possible dimensions lead to vessel constraints that paddlers or rowers might have faced. The differences in vessel construction and use can showcase wide-ranging results in how modelled vessels may be influenced by varying environmental effects. Modelling may highlight how differing costs and environmental conditions—such as wave height or current direction against a prow—may be advantageous or disadvantageous to different types of vessels. Examples exploring different vessel constructions in modelling occur in scholarship both as early as Callaghan (2001) and as recently as Fauvelle and Montenegro (2024), both of which discuss the impacts of hull type on potential vessel speed and thus different model outputs. Fauvelle and Montenegro (2024), particularly, focus on variables learned from experimental reconstructions such as paddling speed and boat velocity to determine model results, as well as the shape and roughness of the hull of vessels. This not only allows for testing variations of travel corridors for one vessel type, but many, enabling researchers to determine what was perhaps possible during different periods when specific forms of sea craft were in use. In many ways this is a novel parameter that can be directly tied to elements learned from experimental approaches.

Beyond recreating seafaring toolkits to test their dynamics in the water or function on the sea, researchers have also sailed experimental boats on voyages to assess the effects voyaging has on the body. An early example comes from Hovarth and Finney (1969), where they addressed caloric expenditure and general exhaustion of a crew traveling in a traditional style vessel around the coast of Hawaiʻi. This paddling experiment was mirrored in a small way by Slayton (2018), who also considered caloric expenditures by testing heart rates of active canoers paddling off the coast of the Caribbean. In both cases, these were one-off tests without repetition, making them only informative and not fully actionable within a modelling context.

Instead, looking to general efforts of voyaging recreation to assess crew physical mobility, social interaction within the vessel, and the path of the route may be more directly relatable to modelling efforts. Bérard (2012) not only detailed canoe construction, but he also has done work with local groups in the Caribbean to canoe around various islands on multiple voyages to observe crew cohesion and capability, as well as the general path of the canoe. Other archaeologists have taken similar steps to test voyaging in varying contexts, all of which provide a glimpse into specific practices of different regions and time periods (see above references to past seafaring reconstructions and voyaging). These efforts may inform models on how reliable it is for crews to manage long distances, interact with the change in weather patterns or tidal forces, navigation practices for novices, and the general perseverance of some crews—all factors that could be input into a model.

However, despite the assistance that experimental methods can offer computational modelling, modellers should not overly rely on modern reconstruction of past practice. For example, the physical standards set by modern canoers, as addressed in the example of Hovarth and Finney (1969), may not directly reflect past capabilities. This extends to modern recreations of seafaring toolkits, which also rely on an approximation of past construction techniques and cannot act as 'perfect' recreations (Cherry and Leppard 2015).

Furthermore, not all experimental efforts are held to the same standards or have the goal of perfectly recreating past practice. (The infamous Kon-Tiki expedition by Thor Heyerdahl is a widely known example of an experimental voyage that perpetuated false information about Oceanian navigation and culture for decades). Modelers must recognize possible adjustments needed during modelling, data processing, and analysis. For necessary rigor, it is important to use experimental reconstruction cautiously and in a way that is grounded in evidence of past phenomena.

The Human Body

Useful representations of seafaring need to account in some manner for the effects of voyaging on the human body. It is not surprising that the impact of seafarers' physiological requirements on simulated trips has been considered since the very initial efforts in the field. This has usually been done via expressions describing decreased probability of survival over time (e.g., Levison et al. 1973) or by adoption of maximum trip duration values based on expectancy of survival at sea (e.g., Irwin et al. 1990; Montenegro et al. 2006). Both strategies, while useful and defendable, can be understood as another way in which the impacts of trip length can be evaluated, being unable to identify differences related to physiology between trips with the same duration. Neither are they useful in evaluating impacts less drastic than death.

Estimates of hypothermia risk during trips undertaken by the early colonizers of Polynesia and the relationship between body size and thermoregulation efficiency have been proposed as an explanation for the significantly larger body size of present-day Polynesians compared to their source populations further to the west (Houghton 1991). This effort made use of average trip duration, trajectory, air temperature and speed values and was not based on simulated voyages. This earlier effort pointed to the feasibility and value of quantitative descriptions of the influence of physiology on the voyaging process and recent modelling applications have been developed in that direction.

Hölzchen et al. (2021, 2022) investigate potential ocean crossings by hominids using an agent model that links time of survival on water to a depletion of a set energy reserve. The rate of depletion is based on a basal metabolic rate and can also be influenced (increased) by different physical activities (swimming, paddling and rowing) with distinct time-independent energy consumption rates. In the case of swimmers, a temperature-dependent thermoregulation energy consumption rate is also included as well as a representation of death due to hypothermia depended on water temperature and period of immersion. While Hölzchen et al. (2021, 2022) adopt a much more complete representation of physiological processes, these are—like in previous models—still only used by the authors as a way to estimate survival at sea. A different approach was taken by Montenegro et al. (2023), who used simulated vessel trajectories, hourly air temperature and wind speed values, quantitative estimates of basal metabolic rates and of net body heat loss to estimate the energy needed for thermoregulation during trips from Tahiti to New Zealand and Tahiti to Hawai'i. In what is possibly a first for the field, the incorporation of physiology in the simulations was not aimed at determining survival but at describing differences in energetic demands between the two trips.

Although recognized and considered early on, the representation of processes related to the effects of trips on seafarer bodies have not accompanied the development seen in the modelling of other aspects of voyaging, such as vessel performance. Much progress can still be made. Some of it will require better observations of how the human body responds to the peculiar conditions faced by ocean travellers, but quantitative representations of important physiological processes that could be readily added to simulations exist (see Sørensen 2009 for an example). An exciting possibility would be the inclusion of physiological demands on the in-trip navigational decisions being made by the crew.

Modelling

Once a research question has been set, a region identified for review, and environmental and humanistic inputs decided on, it is time to conduct your analysis based on the constraints or possibilities of your chosen method. There are many different methods to choose from when conducting computational seafaring modelling, each with their own positives and limitations. As there are a variety of tools that can be used to run each of these different methodologies, the description of each method provided below focuses more on the major tenants of the process rather than specific instructions.

Geographic Information Systems

Geographical Information Systems (GIS) can be defined as a set of spatial digital tools for managing, manipulating, and analysing information. Data are spatially referenced according to geographical coordinates represented in a Cartesian space defined by x and y axes (and sometimes a z axis for elevation, and even a time variable t) (Aldenderfer and Maschner 1996; Chapman 2006; Dell'Unto and Landeschi 2022). Three aspects of GIS are crucial for the computational modelling: the spatial component, the organization of data into a database, and the functions of the GIS software that processes data. Combining these three aspects is fundamental for an analytic approach to studying an archaeological context, landscape, or in this case, seascape. GIS has such a great impact on archaeological modelling because it allows researchers to collect and process data in its landscape context with a single tool. The greatest benefit of GIS is to provide archaeologists with multiple models or scenarios that can be built upon the collected data and used for fostering new interpretations with an iterative approach where research questions are continuously posed to the system and problematized based on the combined use of modelling tools (Dell'Unto and Landeschi 2022, p. 7).

A few different GIS software programs are commonly used in archaeology. The most popular are ESRI ArcGIS Pro (ArcMap) and QGIS, the latter being open-source. GIS software can manage many data formats: raster (objects made of pixels such as images), vector (points, lines, and polylines), tables, DEMs, and topology (the spatial relationship between vector features). These software can also process large climate data files that tie environmental information to geographic coordinates, through multiple formats (such as NetCDF files). It is this aspect, as well as the ability of GIS tools to pinpoint and assess the change in environmental forces between two points, that makes the tool well suited to modelling seafaring mobility in the past. However, using GIS for maritime modelling can present challenges because it is primarily designed as a landscape analysis tool; modellers must often apply creative solutions in order to present a dynamic seascape.

The following methods of modelling past maritime mobility all describe some form of analysis run through GIS or tools that rely on connection to spatial data. It is important to note that each method of analysis may differ due to requirements based on the platform or software of choice, the importance of different model constraints or inputs, as well as the ability of each methodology to address different aspects of research questions related to movement.

Least-Cost Pathways (LCP)

Least-Cost Pathway (LCP) analysis is one of the most commonly used geospatial functions for modelling routes. Methodologically, it helps to determine where a person or vessel encounters the least cost (i.e., expends the least energy) when challenged by environmental or social factors that may afford or limit access. Prior work to explore the development of terrestrial (e.g., Lock and Pouncett 2010; Herzog 2014; Verhagen 2019; Zaia 2023) and maritime (e.g., Davies and Bickler 2015; Montenegro et al. 2016; Arcenas 2021) LCPs have been used to assess the effectiveness of algorithms to "recreate" past mobility based on human expenditure of time or effort. LCP requires the use of (1) a defined start point from which the model will run, (2) environmental or otherwise cost associated surface on which to base movement, and (3) a direction of movement. The first element, or origin point, should be centred on observed archaeological or historical data or inferred from contextual environmental clues. The other two elements are more influenced by the researchers' methodological choices, including input variations and research questions. When developing an LCP model, researchers should both ensure that the environmental parameters reflect actual historical conditions, and they should carefully evaluate post-modelling results relative to the record of the past.

LCP in GIS software (such ArcGIS or QGIS) is based on the geomorphology of the terrain, in other words, a DEM or other environmental data that can be designated as a static value by grid. For maritime routes, LCP can be calculated using bathymetry as a DEM or environmental data such as wind or current measurements. These bases form a grid of information, where each cell representing a hill or force is assigned translatable human cost (in time or energy). This grid of cells forms a cost surface, which can be used to calculate an LCP. To draw the path, the model's algorithm will calculate what progression of cells within the cost surface totals the lowest cost between two set points. These points, or origin and destination, typically reflect specific archaeological caches or known resource procurement zones. Additionally, this method can be used to calculate the time necessary to reach one destination by navigating through assigned waypoints, such as harbours.

Within computational seafaring modelling, addressing the development of a cost-surface on which to base an LCP can be difficult due to the changing nature of the sea's surface. Unlike the topography of slope-grade in a DEM, current and wind factors are not static throughout the year, or even throughout the same day. As such, modelling LCP for water-based movement requires a substantial number of routes modelled to achieve an average which can be assessed for accuracy based on human constraints, seafaring toolkit, and connection to known archaeological evidence (Jarriel 2017; Slayton 2018). It is also important to note that with the requirement for extensive modelling runs also comes the need to assess route placement through corridors of movement (e.g., Mills 2017), as it is generally more valuable to look for consistent patterns returned by the model than one single least cost route. For example, with the average navigation speed and the hours of navigation known, it is possible to identify the potential location of the stopping points along a given route. This process can be useful to calculate the days of navigation needed to reach a known destination. Obviously, this time will vary depending on the season of navigation.

Evaluating consistency within LCP routes can also be beneficial outside of observing prominent travel corridors, as it can reveal outliers to route placement that could indicate other forms of maritime connections. Identifying routes that are not optimal within an LCP framework, but do appear optimal for their connection to other elements observed either in the archaeological record or learned from ethnographic accounts of seafaring best practice, can indicate additional corridors of movement (Slayton 2018). This appears to be a unique advantage of using LCP in modelling maritime mobility contexts, as the consistent change to environmental factors impact on routes does not happen to the same rate of consistency as change in conditions typically used as the base for modelling land-based LCP.

Additionally, the sphere of connection evaluated within an LCP could drastically impact the resulting placement of the routes, and subsequent search for travel corridors. To date, seafaring modelling efforts have focused either on broad colonization and land settlement or on oft-used trade routes that connect coastal communities on a continual basis. Either of these scenarios may require a different resolution of focus for an LCP. Depending on the dimensions of the area of interest, one might consider creating smaller mosaics according to the regions in which LCP will be performed. The cost surface used as the base of the model may return different results if the cost surface area requires varying environmental data resolution quality. Many explorations of seafaring LCPs also include the evaluation of connected land-based movement as well, as routes in the past often utilized both maritime and terrestrial spaces (e.g., Scheidel 2015; Blankshein 2021; Bilotti et al. 2024). This requires selecting terrestrial and maritime data whose resolution is complementary.

As a method, LCP has drawbacks; the results of evaluating single pathways risks being unrepresentative of the past or too environmentally deterministic (for a broader discussion of limitations in LCP, see Herzog 2014). When determining whether corridor-based movement analysis is suitable for your project, consider the following: (1) are environmental factors central to your study, (2) have you established specific origin and destination points, and (3) to what degree does your research question necessitate evaluating not only the optimal paths but also outliers or unexpected routes.

Agent-Based Modelling (ABM)

An agent-based model (ABM) is an open-ended approach developed in the context of social science. Agent-based models are typically used to simulate the interaction of computational entities—the “agents”—within a simulated environment. By repeating simulations under different parameter sets, analysts can gauge the effects that different components of the model have on the functioning of the simulated system (see Lake 2014). As such, movement-based ABMs tend to be more descriptive and less predictive than computational approaches built on routing or path-finding algorithms.

In the most basic sense, an ABM consists of three components: (1) a sampling component that passes data to a simulated agent, (2) a decision-making component that determines how agents in the model respond to that data, and (3) a simulation component that attempts to predict the effects of that behaviour to inform the next iteration of the model. This process can be repeated until a cutoff point or desired environmental state is reached. For example: (1) a simple maritime ABM might contain a module that samples wind direction at particular times/coordinates from a NetCDF file, (2) a module that checks whether the wind at each agent’s location is blowing towards an intended destination point, and (3) a module that predicts the locations of each agent after sailing towards the destination point for a set amount of time with a following wind. This process could then be repeated using the iteration's output location as the input location for the next iteration until all the output locations are within a distance of the intended destination.

In the context of maritime movement, applications of ABM have drawn on earlier maritime analyses in which experienced sailors used maritime data and "rules of thumb" to describe potential voyages (see McGrail 1983). Callaghan and Scarre's (2009) analysis constitutes a "semi-computational" ABM, in that it follows the structure of an ABM but requires the operator of the model to make decisions on behalf of the agent at each iteration of the model. Fully computational ABMs build on the capabilities of 3D GIS coding platforms to reduce the "heading-selection" component of the model to a (relatively) simple set of instructions (see Davies and Bickler 2015; Smith 2020).

Although agent-based modelling is well-established within archaeology, there are currently no widely-used methods for creating maritime ABMs—although it is possible in ABM platforms like NetLogo. This situation presents a barrier to researchers without coding proficiency, but also affords modelers considerable flexibility. For example: sampling components can be designed to accept datasets with different sources and encodings; the processes by which agents make decisions about these datasets can also be more or less complex; and other types of analyses (i.e., visibility, energy expenditure, capsize conditions) can also be incorporated into custom-made ABM frameworks. Although maritime ABMs are not a new phenomenon, they have been rare relative to other modelling techniques. As more agent-based models are created and published, it will become possible to refine these models into software tools and to better evaluate their effectiveness.

Isochrones

When it comes to human mobility, proximity is often a metric of the interaction between communities. However, geographic distance and nearness are not always the same thing. Especially with maritime mobility, varying environmental, technological, and cultural conditions may mean that locations which are geographically more distant than others may be nearer in terms of the time it takes to move between them. Travel time is often a more meaningful measure of nearness than distance. Therefore, modelers may opt to produce isochrones of different zones of interaction. Isochrones visually represent the area accessible from a starting point within a given amount of time.

Ethnographic evidence shows that tolerances for regular intervals of travel, such as commuting, vary among cultures and across different time periods (see Roscoe 2016). For example, Marchetti (1994) and Ausubel et al. (1998) found that mean daily travel times were around one hour each day, while Halstead and Jones (1989) estimated a maximum two-hour round-trip for walking to agricultural fields. Ethnographic studies have tended to focus on terrestrial travel. However, Tartaron (2013) discusses varying meaningful time scales for Mycenaean Greece in the Aegean Bronze Age, including the concept of the small world in which a person could travel out and back in two days' time. For Tartaron's research area, the small world connotes a time scale in which meaningful relationships between communities may be habitually maintained.

Isochrones are particularly useful in understanding potential zones of interaction in a study region, especially for areas where investigation of the archaeological record may be lacking. Places of overlap between known starting points may aid in discoverability of new archaeological sites. Isochrones can also show the high degree of variation in potential connectivity seasonally or over time, especially compared to distance-based models (e.g., Jarriel 2018, p. 61).

Like LCP, isochrones represent an econometric approach to understanding mobility, meaning that they assume that humans will optimize routes towards expending the least amount of energy possible (see Kosiba and Bauer 2013). In practice, there are many other priorities humans might make along a voyage, including following navigational waypoints and culturally meaningful routes. Therefore, it is important to contextualize isochrones in the material and historical record to accurately represent human decision-making in the past.

Alternative Mapping

Most representations of the sea tend to portray it as a flat surface on which activities, tracks, routes, sentiments, and symbols can be depicted. Indeed, with the challenge of mapping the earth, cartographers had to translate a three-dimensional surface on a two-dimensional surface. Earlier maps and depictions of the seas and oceans might have lacked the spatial accuracy we speak of today, but they embodied elements of the watery space that were later overshadowed in the quest for more precise maps. Mostly, these earlier maps exemplified perceptions and experiences of space of the mapmaker and their times. As maps became conventional, defined by rules and measures, in their conformity they portrayed above all a Cartesian space that users can interrogate to deduct their location and assist in wayfinding. As spatial-analytical tools, the value of maps and their underlying spatial models never ceased (Gillings et al. 2020); and with the tools offered by digital mapping and cartography today, opportunities are feasible for alternative approaches and for the confluence of information within an interpretive framework that adheres to an archaeological internal critique and standards.

Alternative mapping, as a methodology, alters conceptions of space and with the remit of digital methodologies to channel diverse viewpoints and experiences, not necessarily those conceived of by the archaeologist(s). In doing so, maps offer diverse ways of seeing present and past worlds (Aldred and Lucas 2019, p. 32) and by virtue of constitution, their underlying models do just the same, be they of a quantitative, qualitative and/or experimental nature. Finding ways of mapping that provide an alternative to Cartesian space is particularly significant to the maritime world. In its ever fluid state, the mobility it gave rise to cannot be captured in one frame of analysis. It calls for multitude of approaches and engagements pushing against, rather than an archaeological reality or truth about the past, the multifaceted humanised perceptions of maritime space.

One approach for alternate mapping is the distorted map. Distorted maps, or cartograms, are maps in which at least one aspect, e.g., distance or area, is distorted according to an element/human variable of interest (Dorling and Ballas 2011). They are also known as diagrammatic maps (Raisz 1962), a representation where "*spatial geometry is distorted to reflect a theme*" (Slocum et al. 2005). The distortion involved in cartograms is based on mathematical and statistical calculation such as bidimensional regression. Cartograms' distortion aims at generating a deeper understanding and examination of research questions and problems. Unlike conventional maps, which can be characterised as equal area cartograms, any variable of interest can be the source of distortion of a cartogram, e.g., human population. Safadi and Sturt (2019), for instance, use distorted maps to re-conceptualize the maritime space of seafaring of the Bronze Age eastern Mediterranean (see Fig. 5). Their approach takes into consideration the GIS

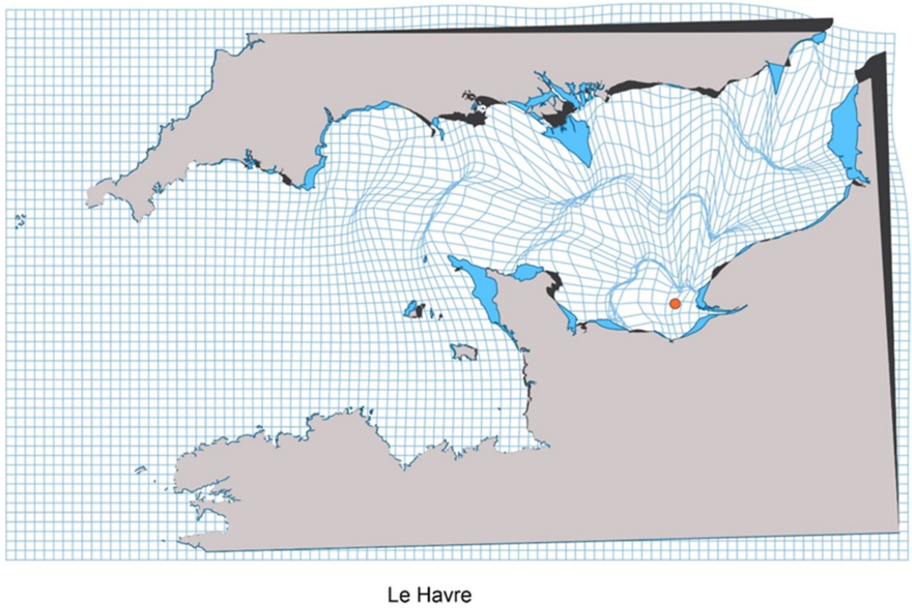

Fig. 5 Distorted maritime space–time in the English Channel based on Neolithic mobility and travel time. Contributed by Safadi

computed performance of Bronze Age sailing vessels under different weather conditions and extends to re-modelling and representing known Mediterranean geography based on sailing time and maritime connectivity. The results are distorted geographies of the Mediterranean representing sailing time rather than Cartesian distances.

Cartograms have also been applied to model past mobility for the island of Ta'u in West Polynesia (Di Piazza 2014) and are integrated as an output in the Orbis geospatial network of the Roman World. In GIS, area cartograms are easily generated, and tools or toolboxes exist to integrate with the software of choice. Distance cartograms however may necessitate the use of bespoke software such as Darcy 2.2. Linear cartograms provide a more useful representation of maritime space, embedding it with a temporal texture, one that can be further interrogated and explored.

General Challenges for Deciding Which Model to Use

When dealing with modelling and prediction, we must consider a degree of approximation. All these methods were developed mostly for tactical and military reasons, have now become commercial and we can use them for archaeological research. However, they were not developed to answer archaeological questions, and therefore have some structural limitations. In some cases, this can extend to include challenges working with maritime data in a software primarily developed for land-based analysis. How data are updated in or processed by a model may be a function of how it was collected or how the method employed engages with it. For example, some datasets, such as the DEM dataset, are available only for the current earth surface and cannot fully encompass large environmental changes that occurred in the past—such as sea level rise. This forces our calculations to an approximation in which we suppose that the seascape or landscape hasn't changed so much since the archaeological time we are taking into consideration. It is crucial that we acknowledge these constraints and ensure transparency in how we communicate our methods to our audience.

Outputs

Once the method for analysis has been applied to the research question, and the processes run, it is time to evaluate the model outputs. This is a complicated topic for computational seafaring modelling due to the variety of methods that can be employed to do this research, and even multiple forms that outputs can take even when run under the "same" modelling methods. As the field becomes more established and modelling methodologies more defined and consistent between projects, we need to develop a common practice for compiling information and making information openly accessible. A key objective for any emerging computational analysis field is to achieve reproducibility and comparability between research projects—an area that still needs development in seafaring modelling. This requires standardization of data management and data sharing practices.

Data Management and Data Storage

Due to the evolving nature of the field, archaeologists now need to be adept at working with big data and sharing their findings. This is particularly true for those modelling seafaring, due to the nature of computing paths across a variety of environmental contexts (i.e., changing currents or wind data, the influence of tidal or wave direction). Hundreds if not thousands of runs are required to identify changing mobility patterns against seasonal trends or linking various shorelines through the deployment of holistic cost surfaces that need to be generated to address environmental variability. The sheer number of these outputs requires particular focus be paid not only to the storage of these records, but also into methods used to share data with the field for evaluation and comparison.

There are some best practices that can be adopted by researchers to ensure that results of modelling are made accessible. This includes creating systems that enable yourself or future users to better understand model outputs, such as file naming protocols, file storage structures, and detailed documentation both regarding the modelling process as well as the parameters of the model outputs. For example, addressing both the practical concerns for model origin points, as they relate to both the archaeological input as well as the model process can be vital information for comparing the several runs of the model that are produced.

Though not related to outputs, the concern for properly maintained data extends to large scale data inputs, such as climate data that forms the base of so many of our models. Researchers are also required to address the needs of archiving and making accessible any climate data that is used as an input for modelling. If we are to achieve the goal of reproducibility, having access to or detailed records for the climate data we used is as important as accessing model outputs. In this case, where the data is publicly available, documenting both the creator of the data but also a detailed description of the generation of the input data is important to allow for future assessment of results and analysis.

These needs inevitably lead to a discussion of data storage. When considering storage for data, both in the form of outputs or the underlying input data, identify resources that both align with the goals of the project as well as longer term storage needs. Recognizing that storing data may come with an extended cost—and could require both considerations for personal storage on hard drives or personal cloud server accounts or in institutional repositories. Where possible, it may be valuable to rigorously document where data is both archived and accessed for initial modelling efforts to offload personal storage commitments. We recommend that prior to modelling, researchers develop detailed strategies and document them for how and where they will be storing this information. This will allow for others to both access the data as well as open results for interpretation by peers.

Sharing and Interpreting Results

Sharing modelling data can be complex, not only due to the storage needs for archiving large data as described above, or for appropriate documentation. Indeed, permissions for data sharing in any research field can be complex, especially when considering that the inputs for the models we use may have certain licensing restrictions for re-use or exploration by third parties. This is compounded when we consider that different methods of building outputs likely will coincide with different methods of accessing or reading model products. It is not only allowing access to the data but also enabling access that can make data sharing difficult. In this case, future work needs to be done to allow for bulk sharing of model outputs to enable better access to the full scale of research done in computational seafaring models.

Though outputs are an incredibly important part of the modelling process, it is difficult to fully address all concerns for sharing computational seafaring modelling returns due to the diversity of outputs that come from the myriad modelling practices addressed above. While making data practically accessible is crucial, it is equally important to ensure the results are intellectually accessible. Alongside thorough documentation of model outputs as data, it is essential to describe the modelling process itself. This enables others to interpret the results within the archaeological context, especially in a field where many researchers are developing their own methods for modelling and analysis.

Evaluating model results effectively hinges on our ability to properly understand not only our model inputs, but the constraints and opportunities of the methods of analysis we use. As a field, we need to further develop processes for understanding large climate data sets, as well as being able to consistently compare results within our own models to different research questions to ensure their viability when applied to real world constraints. Looking to the future, developing practices that allow for comparisons between different computational seafaring model outputs is critical to extending the reach of our research, and the findings we have confidence in.

Looking Forward

As we build upon past examples of seafaring modelling and address gaps in current research, it is important to acknowledge the up-and-coming challenges within modelling practice. Limitations largely relate to computational capability, data access, and the separation of contact between people with expertise related to seafaring modelling. Challenges facing the field relate to areas that have yet to be fully explored by modelers, including exploring alternative mapping strategies, energetics, and other lesser-explored modelling methodologies. For example, as researchers who work with ethnographic data, we appreciate that human cognitive function has a great impact on past navigational practice. However, until complex processes for modelling human decision making (possibly through the advancement of machine learning or more robust agent-based strategies), it is difficult to robustly incorporate these elements into models. As we continue to further develop seafaring modelling practice, as a field, we should critique weak areas in methodological exploration and carefully expand on how we replicate past practice as model inputs.

This dilemma is showcased in each of the modelling methods described in this paper, all of which have their own advantages and limitations. The fact that there is no universally accepted method for creating maritime movement models speaks both to the developing nature of the field and to the variety of research questions that we attempt to answer with our models. To conclude this paper, we highlight here some challenges that face maritime movement models in general.

Methodological Challenges

Maritime movement models share many methodological challenges with their terrestrial equivalents. Debates over the relative merits of reductive and descriptive models, the degree to which movement models are environmentally deterministic, and the reproducibility of modelled results are all well-established in broader movement-focused research (see Burrough and McDonnell 1998; Wheatley and Gillings 2002; Zubrow 2006). It is important that maritime modelers continue to contribute to these wider modelling debates, and to foster similar evaluations within our own field.

Data Challenges

Finding and producing datasets is also a particular challenge for maritime movement modelers. Most techniques described in this paper require large, continuous, detailed datasets to produce accurate, robust results. Where these datasets already exist, they are frequently products of large-scale satellite missions or environmental monitoring—in other words they attempt to represent phenomena in the present or the future (and may be cost-prohibitive to access). The challenge of moving beyond modern data in our attempts to understand the past is complicated by the fact that deriving datasets of similar quality from historical or palaeoenvironmental sources can be extremely difficult for archaeologists without relevant experience in environmental modelling or GIS. Practitioners of terrestrial computational movement studies have addressed anachronisms in their data by developing methodologies for manipulating that data—for example by deriving elevation models from historic maps (i.e., Gillings 2005) or by developing elevation models from simulations of past landscapes (i.e., Kempf 2019). Development of similar methodologies and tools will make it easier for models to be applied more broadly, and for new researchers to enter the field.

Communication

The variety of disciplinary contexts in which maritime movement models have been created—archaeology, anthropology, environmental science, geography, and others—presents a particular challenge to the development of maritime movement models. Both new and established researchers may be unaware of models developed in fields adjacent to their own. We must continue to encourage communication—of results, methodologies, and (if possible) code—which is crucial to the future development of maritime movement models. This has recently taken place at regional and disciplinary conferences (e.g., Slayton and Smith 2021; Kyriakidis 2022; Slayton et al. 2022; Slayton 2023) and at the CAST workshop in 2022. Keeping lines of communication open and encouraging new researchers to participate in a community of maritime movement modelers will help break down the silos in which many of the techniques described in this paper have been developed.

Future Strategies

This primer acts as an introduction to the most broadly used methodologies. It is not a comprehensive list. Indeed, this entire volume was created because so many researchers have attested that they began modelling on their own without access to advice from other scholars. It is likely that many of us who are working in this field are employing different modelling strategies, utilizing different types of data or humanistic inputs, and evaluating the outputs in myriad ways that may not be comparable between systems. In this sense, and to reiterate the importance of communication between researchers in the field, opportunities to interconnect and learn from other modelers are paramount to moving the field forward. We hope this work has provided a solid introduction to these methodologies and sparked interest in expanding the current research avenues.

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Authors and Affiliations

Emma Slayton[1] · Katherine Jarriel[2] · Alvaro Montenegro[3] · Crystal Safadi[4] · Karl Smith[5] · Sara Zaia[6]

✉ Emma Slayton
eslayton@andrew.cmu.edu

Katherine Jarriel
kjarriel@purdue.edu

Alvaro Montenegro
montenegro.8@osu.edu

Crystal Safadi
C.El-Safadi@soton.ac.uk

Karl Smith
karl.smith@arch.ox.ac.uk

Sara Zaia
sara_zaia@g.harvard.edu

1 Carnegie Mellon University, Pittsburgh, USA

2 Purdue University West Lafayette, West Lafayette, USA

3 The Ohio State University, Columbus, USA

4 University of Southampton, Southampton, UK

5 University of Oxford, Oxford, UK

6 Harvard University, Cambridge, USA