RESEARCH

State of the Field

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Abstract

Computational approaches, methodologies, and theoretical considerations for studying seafaring have developed rapidly in recent decades. However, these approaches often remained isolated from traditional archaeological discourse, with researchers working separately from each other and practitioners, while independently developing overlapping methodologies. Researchers can struggle to contextualize their work in this complex and rapidly developing field. Therefore, those interested in engaging with this discipline for the first time need a clear entry point. As we attempt to connect with each other to create improved, cohesive methodologies, we should learn from one another's work to define and push the field forward. It is important to understand the interdisciplinary influences that established our shared history in order to assess what challenges we currently grapple with and anticipate what lies ahead. This review of the 'State of the Field' aims to evaluate the origins and development of this research. With a clear reference to historical development and scope of work, we create an initial framework for the discipline of computational analyses of seafaring, exploring current trends, as well as potential and future opportunities. Through synthesis and co-operation, computational, technological, and theoretical development can help us address new challenges and further our capabilities and data production as we move towards more diverse, interdisciplinary work.

Keywords Computational modeling · Seafaring · Mobility · Field review

Introduction

The 2022 Computational Archaeology and Seafaring Theory (CAST) Workshop was, in our community's opinion, a necessary step in the development of our field. Scholars that joined the CAST workshop at the Stanford Archaeology Center often found (and still find) themselves isolated in academic and institutional spaces that were adjacent to their research, lacking a wider network of collaborators and support. Through conversation, computational archaeologists and seafaring theorists recognized that our research goals and methodology are similar (at times, identical), leaving us to independently reinvent the wheel without connecting with fellow academics and practitioners whose expertise would improve the work. To avoid deepening this issue, we created CAST to forge connections across our institutions and regions of study, to promote collaborations across diverse

backgrounds, and to establish best practices for carrying out our interdisciplinary projects. The 2022 meeting identified commonalities in how we approach our research questions and opened new ways to formulate these questions in the first place. Just as seafaring connects different regions of the world, CAST reached across the intellectual islands our community members found themselves in and broadened the networks of scholars whose research fits well into our adjacent fields (e.g., landscape archaeology, climate science, disaster studies). Additionally, our workshop was fittingly coeval with the beginning of the United Nations Ocean Decade, as CAST community members work often touches upon several of the ten challenges for collective impact. Being brought together in this forum allowed us to discuss the state of our own work and where we feel the field of computational seafaring modeling is headed. This article discusses both the history of seafaring modeling and a selection of current issues that should be considered by those already doing this research and those who are looking to join our community.

Computational archaeology has its roots in archaeological modelling and theory as well as the inherent link between empirical and formal models and their input into a computer (Lock 1995). Despite Aldenderfer's (1991, p. 232) prediction that "the growth rate of simulation applications in archaeology will remain flat", a quick review of the literature for the last 30 years clearly shows that this did not hold true, with a particularly strong increase in computational archaeology publications after 2010. This significant increase both in the number and variety of computer applications applied to archaeology has led to some conflict over the term 'model' and its general use in archaeological discussions. For clarification here, and in the context of CAST, when we use the term 'model' or 'modelling' we are referring to a *computational* model as opposed to a theoretical model (unless explicitly stated otherwise). Similarly, while we acknowledge the long history of computational application to archaeological research, here when we discuss certain developments in the field, we are specifically focusing on those that directly pertained to seafaring theory—the focus of CAST (Fig. 1).

One prediction of Aldenderfer (1991) that has aged well is the increasing relevance of computational simulation to the modelling of dynamic systems and processes of long-term change. This is particularly true for applications to seafaring theory where the abundance of variables (e.g., winds, currents, distance, and visibility) across wildly different regions and time periods hampered the extension of many land-based models out into the sea (e.g., Field and Lahr 2005). However, the availability of increasingly more detailed global and regional datasets on these different variables as well as other paleo-climatic and -geographic models in recent years (e.g., the GEBCO One Minute Bathymetric Grid first released in 2003), has enabled seafaring models to greatly expand their scope at last. The establishment of dedicated maritime archaeology research centers, such as the University of Southampton Centre for Maritime Archaeology in 1995 and the Texas A&M University Center for Maritime Archaeology and Conservation in 2005, has further supported the establishment of CAST as a distinct subset of the discipline.

Just as the members of CAST found themselves often disconnected to others in the same field as a result of geographic or disciplinary barriers, the application of computational archaeology methods to questions of seafaring theory suffered from a lack of direct focus and review. Classic examples of this are the classification of seafaring models within the generalization of 'settlement modelling' in broader discussions of archaeological simulation methods (e.g., Aldenderfer 1991; Lake 2014), and the way in which early efforts to simulate voyaging (i.e., Levison et al. 1973; Wild 1986) were seemingly 'forgotten' for decades at a time (see Irwin 1992; Field and Lahr 2005). Considering both these issues and the veritable explosion in the last ten to 15 years of published prehistoric seafaring models
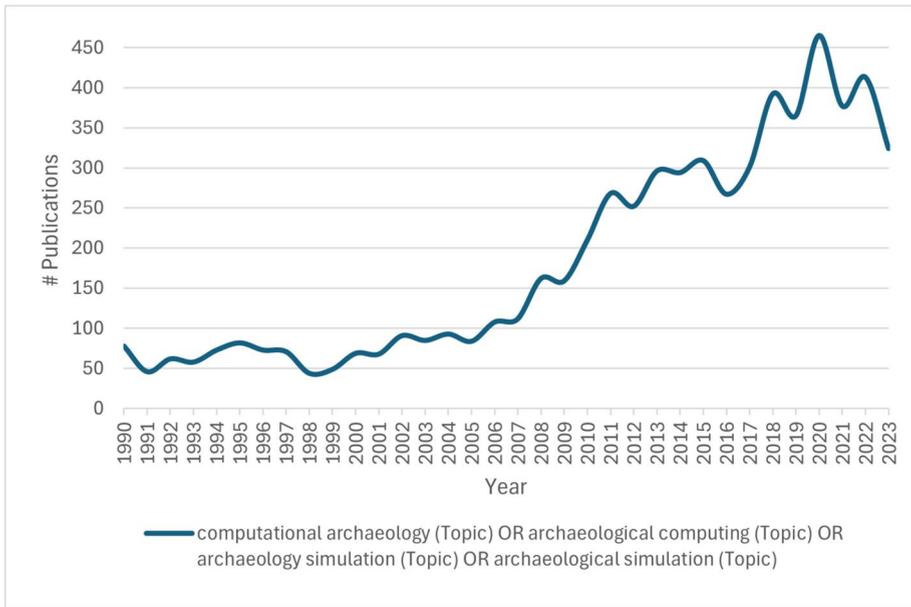
Fig. 1 Graph produced by analyzing the results of a document search on the Clarivate Web of Science website for "Computational Archaeology" in scientific publications from 1990 to 2023. Exact search terms are listed on graph and were not restricted to precise phrases. 'Topic' refers to terms occurring in the title, abstract, or indexing of the articles

for different portions of the globe, we consider it imperative to compile this review for the success of future research.

By assessing the state of the field and acknowledging the historical roots of computational seafaring modeling, the CAST workshop contextualized our community's research and drew connections between the themes we cover. This chapter is laid out chronologically, grouped roughly into decades, each with a dominant theme from that period. We feel that this format will allow readers to track the progress of our small, but growing, field from its crucible in landscape, maritime, and early computational archaeology, to the establishment of prevailing methodologies, to our workshop, and goals for future work.

Beginnings (1990s–2009)

There are multiple fields within archaeology and anthropology that contributed to the development of seafaring computational models. In particular, *maritime archaeology,* or the study of human interaction with or within bodies of water as well as submerged cultural remains of seafaring, and *landscape / seascape archaeology*, or the study of human–environment interactions and the impact of the landscape or seascape on movement through space. Perhaps first used in the mid-1970s by Aston and Rowley (1974), landscape archaeology as a terminology increased in journal publications beginning in the 1980s and has grown each subsequent decade (David and Thomas 2016). It has come to mean the exploration of how human societies have shaped or been shaped by the physical environments

they inhabit over time. In this sense, the landscape is not only a container for human action, but an active influence in human decision-making.

Though computational methods in archaeology have been applied since the late 1960s (Chenhall 1968; Whallon 1972), the growth in researchers focusing on landscape archaeology in the 1990s and early 2000s may be tied to the rise in computational resources such as ready-built spatial analysis software used by many landscape archaeologists. The introduction of Geographic Information Systems (GIS) enabled a computationally analytical approach to evaluating human engagement with the environment. In the 1990s, many researchers began to explore how to document their work and explain more broadly GIS methodologies for use in archaeology through edited volumes (e.g., Allen et al. 1990; Lock and Stancic 1995; see also Lock 2000; Bevan and Lake 2016). The apparent acceptance of GIS as a major force in archaeological research seems to have been set by the early 2000s with the creation of books outlining standard practices for spatial analysis. For example, works by Wheatley and Gillings (2000) and Connolly and Lake (2006) act as treatises on the use of GIS in archaeology and remain relevant to the discussion of uses of computational systems to answer specific spatial questions.

In particular, the GIS researchers focus on not only an individual's position within the landscape but their engagement with it, as we evaluate how people see their relationship to geography (e.g., Leusen 1999; Wheatley and Gillings 2000; visibility related to mobility see Llobera et al. 2011; Lock et al. 2014; for visibility related to sea-based mobility see Friedman et al. 2010; Kealy et al. 2017; Smith 2020), their movement across various terrains and ecosystems (e.g., Bell and Lock 2000; Connolly and Lake 2006; Herzog and Posluschny 2010; Llobera and Sluckin 2007), as well as the geo-spatial relationship between peoples and the objects they create or use (e.g., Brantingham 2003; Duke and Steele 2010). Researchers also worked to build and integrate methods for computer simulation into spatial analysis applications, including agent-based models (ABM) (Bevan and Lake 2016). These methods helped to spark a deluge of papers on past mobility corridors and transportation practices for movement across landscapes (e.g., Carballo and Pluckhahn 2007; Mills 2017; Whitley and Hicks 2003).

There is a longer theoretical tradition and greater diversity of models based on land movement than on seafaring. This is due in part to the limited number of researchers in this subfield as well as the complexity of modeling movement over a dynamic sea surface. Instead of being based on one exigent factor (slope), analysis of movement across the seas surface must contend with push factors of variable current and wind as well as the forces of manpower against it to force movement towards the correct destination (Davies and Bickler 2015; Slayton 2018). Early models reflect this, as complex processes are summarized in the minimum time between two points as either directed (Irwin et al. 1990) or drift mobility (e.g., Callaghan 1999; Levison et al. 1973; for more examples, see Slayton 2018, Table 1, pp. 55–57). These models were concerned with using appropriate environmental data, but also evaluating technological capabilities of vessels. For example, Irwin et al. (1990) discusses the abilities of crews to tack, or to move into the wind, while Callaghan (1999) looks specifically at how the use of different vessel types within models may alter outcomes for drift voyages.

As referenced above, computer simulations have had a powerful impact on the study of movement in archaeology. Interestingly, there is perhaps a greater proportion of early simulated models relative to theoretical ones for seafaring than for travel over land. This difference is perhaps due to the more complex interactions of ocean crossing parameters which make their interpretation by eye significantly more difficult. The extensive research surrounding the origin question of the Pacific islanders has also encouraged greater

developments of computer simulation in this area. While early attempts such as Birdsell (1977) and Irwin (1989) were theoretical-only models of sea crossings, both these models have since been tested via computer simulations (Irwin et al. 1990; Davies and Bickler 2015; Kealy et al. 2018). This trend in mapping colonization or exploration efforts of past mariners is evident in many of the works related to this period (e.g., Montenegro et al. 2006; Avis et al. 2007), which tend to focus less on short-hops between neighboring islands or around the same island (e.g., Callaghan and Scarre 2009; Di Piazza et al. 2007). Evaluating these earlier approaches to modeling for their advancement of the field, or in many ways genesis of it, is an important step in defining initial interests in the field—such as long duration voyaging and the comparison between drift and directed models. In this context, drift voyages refer to models that incorporate one or more forces to advance a vessel (i.e., current, wind, human paddling, etc.) without a set destination, whereas direct voyages occur between two known points in geographic space (Slayton 2018, p. 48). These early efforts not only laid the groundwork for subsequent advancements in the field but also established foundational distinctions in how researchers' model and understand the complexity of ancient seafaring practices.

Building on Trends (2010–2019)

The number of computational approaches to ancient and historic seafaring grew substantially in the 2010s. Expanding Slayton's (2018, Table 1, pp. 55–57) collation (1973–2017) to include 2018 and 2019, the number of formal seafaring models roughly doubles in the 2010s compared to the previous decade (additional examples from 2018 to 2019 include: Gustas and Supernant 2019; Poullis et al. 2019; Safadi and Sturt 2019). There was a similar increase in the variety of model types published and the degree of their interdisciplinarity. Most scholars prior to 2010 used least-cost routes to model either drift or directed voyages. Following these foundations, more modelers in the 2010s expressed voyage length not in physical distance, but in bands of time. Leidwanger, for example, maps the length of various voyages in the Archaic and Roman Mediterranean in contours of sailing days from a single port to all coastal and marine spaces in his study area without immediate emphasis on the exact routes followed by ships (see also Cooper 2010; Leidwanger 2013; Safadi and Sturt 2019). Most simulations of the 2010s continued to use the available tools of licensed software such as ArcGIS, but others increasingly incorporated their own programming (e.g., Davies et al. 2015; Slayton 2018). Models of the decade covered a wide chronological and geographic spectrum, with particular confluences on the Mediterranean, Pacific Ocean, and Caribbean. They focused especially on research questions related to early colonization, navigational strategy, trade patterns, and commercial exchange. In broad terms, in the 2010s there was additional attention and more diverse approaches related to three main modeling elements, discussed in sequence below: (1) the temporal and physical resolution of seafaring; (2) the degree of human agency and accuracy of vessel performance; and, (3) the accessibility of models and datasets to non-specialists. It is crucial not to interpret these changes in the field through an evolutionary framework. Model designs reflect the priorities of the researcher, and not all "improvements" relating to data resolution or simulation methodology are necessary or appropriate in every case.

The resolution of the environmental and geographic inputs of any seafaring model heavily dictates its real-world and historical accuracy. Increased efforts in the 2010s to refine these aspects led to a variety of new methodologies related especially to the effects of

seasonality and coastal topography on mobility dynamics. Adjusting the cell size of the simulation environment (e.g., the scale of the wind and current data) during model programming represented an immediately possible option, encouraged by the concurrent development in the decade of software, hardware, and analytical techniques to reduce processing times. For instance, Davies and Bickler (2015) augmented previous models in the Pacific by focusing on the underlying cost surface of the water. They used wind and current data collated at a 0.25° and a 0.33° resolution, respectively, making their model less susceptible to rounding issues than others. For comparison, Irwin et al. (1992), used a wind friction surface in the Pacific with a 5° resolution. Gustas and Supernant (2017, 2019) focused not only on the sea surface, but also the ancient topography, given their focus on coastal migration in British Columbia, Canada around 16,000 cal. yr BP. They employ high resolution bathymetric and terrestrial elevation data with the goal of recreating past shorelines and identifying high-use coastal movement corridors and possible submerged landing sites using least-cost path analyses. Others focused closely on how the seasonality of wind, current, and weather patterns conditioned maritime interaction (e.g., Montenegro et al. 2016). Slayton (2018) modeled inter-island connections in the pre-Columbian Caribbean archipelago using wind and current data collected in three-hour intervals to account for the varying circumstances of transport over the course of a single day and various seasons (Slayton 2018, pp. 64–67). The database created by Poullis et al. (2019, p. 6) for "The Seafarers-2," a strategy-based computer game on seafaring in the Classical Mediterranean, also incorporates environmental data at three-hour intervals, curated over a five-month period at the time of publication. Safadi and Sturt (2019) created cartograms for Bronze Age sailing in the eastern Mediterranean, highlighting the differences in connective potential across the Levant and Egypt over four seasons in the year and two times per day (the morning and afternoon).

Since the earliest efforts to computationally simulate maritime transit, scholars have highlighted the importance of human agency alongside environmental conditions. The central challenge remains how to code for the flexibility and spontaneity of realistic human decision-making within the necessarily generic confines of software programming. In the 2010s, there were more efforts to incorporate these types of considerations, especially aspects related to navigational strategy and mariner fatigue. Vessels in the Pacific models of Davies and Bickler (2015, pp. 219–221) turned directly towards a landmass if in sight, could tack when faced with adverse winds, and if traveling beyond a latitude of 22°S, automatically adjusted their headings. Montenegro et al. (2016) aimed to establish the role of short-hop voyages in the prehistoric colonization of islands in Remote Oceania beginning around 3400 yr. BP. Vessels in their model sought routes with the shortest distance between coastlines as part of longer trips across the space. They either sailed downwind or with a given heading towards target islands. Fitzpatrick and Callaghan (2013) employ similar types of crew strategies, limiting maximum possible voyages to 200 days based on ethnographic accounts. Slayton (2018, pp. 67–70) analyzed in detail the physical constraints of canoe-paddling in the pre-Columbian Caribbean using ethnographic accounts, experimental voyages, physiological studies, and measurements from her own experiences in order to devise an accurate upper-limit for the trips in her seafaring model. Collectively, these attempts—and others like them—highlight the greater incorporation in the 2010s of the "human experience" in simulations, and others emphasize this element through increased attention to accurate vessel performance in different conditions and at various points of sail. Alberti (2018), Poullis et al. (2019), and Safadi and Sturt (2019), for example, tailored the ship speeds of their Greco-Roman Mediterranean models following the work of Leidwanger (2013).

In each instance, the goal was to combine detailed experimental and ancient accounts of seafaring to provide the simulated mariners with the most realistic flexibility of movement and performance depending on wind and current conditions.

As the field grew—both in terms of the number of modelers and the broader scholarly awareness of seafaring modeling as a concept—issues of output accessibility became paramount. As such, some researchers invested in the creation and maintenance of public-facing seafaring models. "ORBIS: The Stanford Geospatial Network Model of the Roman World" serves as one example launched in 2012 (Scheidel 2015). ORBIS models a variety of different travel modes in the Roman Mediterranean. Sea travel in ORBIS utilizes a network of 1026 sea routes (513 pairs of port sites in both directions) at two sailing speeds (fast and slow), depending on prevailing wind, current, and foul weather patterns in four seasons (Arcenas 2021). The popularity of ORBIS and other public-facing programs substantially expanded the awareness of seafaring modeling both within academia and beyond in the 2010s, a key transition in a decade which on balance represented a greater increase in these approaches than any previous era.

Increasing Complexity (2020–2024)

The pandemic changed our way of analyzing archaeological information. With the restrictions put in place between 2020 and 2022, fieldwork was canceled or curtailed in most cases, especially for people working outside of their home countries. Some museums made use of technologies, such as online educational programs, virtual museum visits (e.g., 360-degree museum tours), virtual reality exhibitions, and 3D object exploration (e.g., Ciecko 2020; McKeever 2020; Romano 2020). With fieldwork still suspended, archaeologists found themselves turning to the computer to analyze past field data, prepare publications, and most importantly for the present discussion, explore new digital methodologies.

In recent years, discussion about the need to reevaluate the connection between land and water environmental data with new forms of modeling has increased. Several projects continued to build on prior work, focusing on creating new methods to incorporate environmental data when modeling seafaring (e.g., Blankshein 2022). Researchers continued to use changing environmental factors to generate cost-surfaces that focus both on least-cost pathway (LCP) and isochronal approaches (e.g., Bilotti et al. 2024; Blankshein 2022; Jarriel 2021; Perttola 2021; Pertola et al. 2024; Slayton 2020). In addition to building on past work, new advancements in how we assess the outputs from our models have enabled us to be more aware and critical of model results. For example, Jarriel (2021) analyses outputs within both the confines of changing environmental inputs but also with broader understanding of climate disasters and community resilience. In the 2020s, modelers are moving beyond static acceptance of results, which is also pushing researchers to move away from static or traditional model inputs.

Other methods of cost are being integrated into models, including incorporating the wear and tear of seafaring on the human body, or the human body's ability to weather a voyage. Montenegro et al. (2023) discuss the 'energetics,' or the energy balance held by a body when enduring changes in temperature or other adverse conditions, or while facing sailors of different sizes crewing a Polynesian vessel. The impacts of the body's insulation on crew performance, as well as on their general physicality, will likely be the focus of several modeling efforts in the coming years. Models are also expanding to focus on how seafaring toolkits may impact voyaging, including vessel constraints like planking

or hull shape (e.g., Fauvelle and Montenegro 2024). This issue has only been limitedly addressed since the early days of seafaring modeling (Callaghan 2001), with researchers focusing more on vessel speed as a static function. Advancing how we can interchange vessel parameters in models may also open new pathways to discuss changing or weighting inputs to both make models more accurate and also to more accurately assess outputs within a specific period and in a region of study.

Another example of this shift in focus can be seen in an increase of agent-based modeling (ABM). Some attempts to introduce ABM to archaeology were already made before the pandemic (Cegielski and Rogers 2016) but this tool was improved greatly in the past few years. More and more case studies have been published, and software was developed specifically for the application of the ABM in archaeology (Romanowska et al. 2019, 2021). The recent online tutorial by Erasmus + 'Agent-Based Modeling for Archaeologists' supports beginner learning of the method. ABM approaches have allowed archaeologists to include inputs that allow for models to facsimile human decision-making. This is just one example of the push for incorporating the human element in archaeological seafaring modeling (e.g., Holzchen et al. 2022; Smith 2020). Smith's (2020) dissertation on modeling seafaring routes across the English Channel and around the British Isles incorporates both human decision-making and skill level using ABM methods. Smith bases the agent's judgment on both environmental factors (winds) and what is visible through viewshed analysis, which has opened new possibilities to analyze the impact of the cross-coastal cultural landscape.

Other developments include more critical consideration of how we integrate historical information as start points or waypoints models (Perttola 2021; Slayton 2020). Perttola (2022a, b) specifically compared historical documents, such as the Seldon Map which documents shipping lanes in the China Sea from the early seventeenth century, with outputs from a least-cost pathway model that updates environmental wind data during the course of a simulated voyage. Comparisons to recorded historical voyages also open the question of how we can assess differences between various computational models and the evidence from the past. In particular, Perttola, Slayton, and Vadillo (forthcoming) has compared different least-cost path models for the same region and time period and assesses each model's success by understanding the variable nature of types of outputs returned from different methods. More projects that comparatively assess different computational models like this will improve modeling accuracy. Fortunately, the groundwork for these comparisons was set in the 2010s, with a concerted effort to communicate across disciplinary and institutional boundaries and to curate publicly-available data.

Awareness of new modeling techniques and research has grown significantly throughout the 2020s, largely influenced by communities like CAST. However, the challenge of discoverability of recent work persists and is now exacerbated by an increasing number of researchers entering the field. The present overview is not comprehensive, and there are undoubtedly other innovative computational seafaring models introduced over the past five years. This highlights the urgent need for broader dialogue among colleagues to develop best practices, establish new norms, and explore uncharted ideas within the field.

The Future: The Next 10 Years—the Ocean Decade and Beyond

Some central themes that have arisen in recent literature related to computational archaeology and seafaring theory include improved paleoenvironmental models (Sandweiss and Kelley 2012, Table 1; Fitzpatrick et al. 2015), the increasing usage of artificial intelligence (AI) and machine learning (Karamitrou et al. 2022; Küçükdemirci and Sarris 2022; Castiello 2022), the incorporation of more nuances in human decision-making (Madl et al. 2015; Epstein et al. 2017; Verhagen et al. 2019), greater collaboration with Indigenous communities (Atalay 2019; Steeves 2019; Britton and Hillerdal 2020), and community resilience (d'Alpoim Guedes et al. 2016; Hussain and Riede 2020; Rick and Sandweiss 2020; Boivin and Crowther 2021). Increases in the complexity and accessibility of paleoclimate models led to an upsurge in multidisciplinary research collaborations between archaeologists and environmental scientists (e.g., Sandweiss and Kelley 2012; Borreggine et al. 2022; Hill et al. 2022; Kuijjer et al. 2022). Similarly, technological and accessibility advances in AI and machine learning have produced new methodological approaches for computational archaeology (e.g., Lawall and Graham 2018; Palazzolo et al. 2021). As the field continues to improve models of past human-landscape interaction, diverse approaches to human will and decision-making that move away from simple cost–benefit analyses have gained ground (e.g., Kinoshita 2019; Chliaoutakis and Chalkiadakis 2020; Skelly et al. 2023). In the same vein, efforts to decolonize the field of archaeology have in some places modified the central aims of research (Atalay 2006), foregrounding Indigenous voices and cultural goals (e.g., Supernant 2017; Shearn 2020; Berard and Biar 2021). In the face of anthropogenic climate change, human-environmental interaction and resilience (which are both named as "grand challenges'' for the archaeological field in Kintigh et al. (2014)) have become a growing focus in the literature (e.g., Redman 2005; Cooper and Sheets 2012; Jarriel 2021). To address these emerging questions, nontraditional interdisciplinary methods have concurrently become more common (e.g., Leidwanger 2013; Ulturgasheva et al. 2015; Gustas and Supernant 2017).

Archaeology and Climate Science

The recent deepening interest in paleoenvironmental modeling in the archaeological community can be attributed to a coalescence of distinct factors. One emerging consideration is the increasing pressure across research communities to make environmental models and their output open access (Jucker 2018; Willmes et al. 2020), removing one significant barrier to their incorporation into archaeological research methodology. Commonly-used climate models and related data are the Community Earth System Model (CESM) from the National Center for Atmospheric Research (NCAR), the MIT General Circulation Model (MITgcm) from Massachusetts Institute of Technology (MIT), the UVic Earth System Climate Model (ESCM) from University of Victoria, the Model for Interdisciplinary Research on Climate (MIROC-ESM) from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the University of Tokyo, the Canadian Earth System Model (CanESM), the Paleoclimate Modeling Intercomparison Project (PMIP, which encompasses some of these models and several others), the Cooperative Holocene Mapping Project (COHMAP), and PAGES 2 k Network (Past Global Changes). Of the 22 climate models listed here (including those that are a part of PMIP), only seven are open access. Despite being in the minority, the advantages of open-source modeling software are clear.

The formation of the CAST community was motivated in part by a similar logic: transparency about research methodology benefits reproducibility *and* reduces the chances of repeat labor across similar projects. Many conversations at the December 2022 workshop revealed that attendees had replicated the near exact methods of other attendees in their work, an experience that illustrates the siloed nature of computational archaeology and seafaring theory work at present.

Another important factor in the rise of interdisciplinary archaeological research is the mutual benefit between archaeology and climate science (Izdebski et al. 2016). Crabtree and Dunne (2022) label this study of "past coupled nature-human systems" which brings in explicit environmental context and adopts the questions, data, and approaches from both archaeology and ecology, "archaeoecology". This term parallels the rise of geoarchaeology, environmental archaeology, and paleoenvironmental archaeology (Sandweiss and Kelley 2012). These integrative approaches address head-on the issue of research being isolated to one field, lacking context from others. The utility of climate science for archaeological questions is primarily one of scale—different temporal and spatial scales can be addressed when using paleoclimate data and model output (Burke and Riede 2023). However, it is important to note that not all paleoclimate data is created equally. Climate models take in and output specific environmental parameters (e.g., topography, wind, atmospheric temperature, ocean currents, sea surface temperature, sea surface salinity, land use categories, to name a few). Archaeological models may use as input one or several of these variables. Researchers should use data appropriate for their studied region and timescale. That is, they should be critical of global average or discontinuous paleoenvironmental data applied to a specific region and utilize data specific to the decade, season, month, etc. of interest (d'Alpoim Guedes et al. 2016; Burke and Riede 2023). Some paleoclimate data also allow for dynamic applications, updating agent-based models incrementally and allowing for more points of decision-making (as in Perttola 2022a, b; Callaghan et al. 2022; Borreggine 2023). The finer the temporal and spatial scale, however, the larger the uncertainty (in these cases, averages can be just as (in) accurate as fine scale paleo data). Future archaeological investigations may also benefit from climate science by using more accurate paleotopography (Borreggine et al. 2022; Clark et al. 2022; Hill et al. 2022). Together, archaeological finds and field-based paleoclimate research can establish powerful multi-proxy approaches (e.g., Erlandson et al. 2007; Loveluck et al. 2018). Sandweiss and Kelley (2012, see Table 1) point out the increasing collaborations between climate scientists and archaeologists over the last several decades, and they note that archaeological sites have the potential to fill regional gaps in climate studies. Archaeologists and environmental scientists alike have much to learn from each respective field and should heed the call to seek out education and training in both spaces.

It would be remiss not to mention the ongoing and impending impacts of climate change on the field of archaeology. The changing climate threatens the archaeological record (Britton and Hillerdal 2020), and consequently, the material history and culture of the peoples to whom those artifacts belong. For example, several of the UN Sustainable Development Goals (SDGs) touch on climate and society. Archaeological work with an environmental science context can produce meaningful outcomes. To study future climate change, we must understand past climate dynamics and how previous societies responded to changing environments. The inclusion of cultural resource management is key to this type of work (Rockman and Hritz 2020). We cannot answer questions about past human–environment interactions without sufficient context from both the human and environmental perspective (Haywood et al. 2019). From these integrative inquiries, we may be able to find solutions to

the contemporary challenges we face from rising sea levels, more frequent extreme weather events, and increasing global temperatures (d'Alpoim Guedes et al. 2016).

Recent literature on the rise of environmental science and archaeology collaborations also provides guidelines to produce thoughtful work. First, open-source models help to remove one barrier to collaboration. However, the complexity of climate models often necessitates a considerable amount of research time for each project, and the number of paleoclimate modelers willing and able to do this work is finite. Climate models are also computationally (and therefore, financially) expensive, so the support and resources available for archaeologists to learn and utilize these programs is similarly limited (Haywood et al. 2019). In order for archaeologists to critically engage with climate models and their output, education about the basic workings of these models is paramount. This includes awareness about the methods of calculating the model output (e.g., interpolation, forecasting, randomization, etc.) and the critiques of using modern observational data (which is subject to anthropogenic climate change) for archaeological studies. Secondly, scholars in all fields should avoid embracing environmental determinism, acknowledging that environmental conditions influence human activity rather than control it (Hussain and Riede 2020). When comparing paleoenvironmental and archaeological data, it is important to be wary of overly simplistic causal explanations which may improperly conflate (or overvalue) environmental changes with societal changes. Climate changes must be situated in the context of each particular society's landscape and resource usage practices (d'Alpoim Guedes et al. 2016). Interdisciplinary studies should be explicit about the framework they are using to combine archaeological and environmental data to aid transparency and reproducibility (d'Alpoim Guedes et al. 2016). Researchers must also grapple with the consequences of employing mathematical models which make assumptions about the (lack or presence of) knowledge past peoples have and may further entrench a Western approach to human-landscape interaction (Burke and Riede 2023).

Artificial Intelligence and Machine Learning

In addition to the advancements archaeology has seen in climate model usage, there has been a burst in utilization of artificial intelligence (Mantovan and Nanni 2020; Bickler 2021). These models are "trained" using large amounts of input data (text, images, numerical information, or otherwise) and are subsequently able to classify characteristics of further input data. While there has yet to be a significant uptick in seafaring-specific applications of AI, adjacent archaeological fields have developed new methodologies using this technology. These approaches can be used to aid in site selection, model creation, or in the evaluation of model output. There are numerous innovations that have arisen from AI applications in archaeology, such as evaluating large swaths of data more efficiently, making modeling more accessible, and engaging with the landscape in new ways. However, just as many critiques of these fast-growing technologies have been made. Debate about the role of human oversight, precision, Indigenous ontologies, and even labor equity accompanies the publications that illustrate AI advances in archaeology. Here we assess the current AI trends in fields adjacent to seafaring archaeology, potential developments within the CAST community, and critiques of this new research direction.

A recent paper by Bickler (2021) aptly notes that the main benefit of utilizing AI in archaeological methods is decreased processing time for large-scale numerical, textual, graphic, and geospatial datasets. In the pre-planning stages, researchers may quickly locate

sites or features within known sites (especially those that are remote or inaccessible; Bickler 2021; Castiello 2022) for further study. For example, with the rise of remote sensing (Fitzpatrick et al. 2015) resulting datasets may be analyzed to identify potentially relevant sites (see deep learning method applied in Soroush et al. 2020). Argyrou and Agapiou (2022) also note that AI methods have created a new tool for site selection that can center cultural and artifact preservation (i.e., one can choose a site that may damage the landscape the least). The related method of predictive modeling has been shown to be useful for thoughtfully engaging with landscapes for land-based archaeology and managing risk (Danese et al. 2014).

Once data has been collected, AI presents new ways to organize data, identify different categories, and classify typologies (e.g., pottery styles). Image processing is one of the most common uses of AI, but primary source evaluation, translation, cultural resource management, museum exhibit design, study of human remains, and site reconstruction are also promising avenues (Mantovan and Nanni 2020; Bickler 2021). Code and scientific paper writing and publication can be made more accessible to non-specialists by open access, user-friendly AI technology (Holguin 2023). Models that use AI can even be more accurate than those that do not (Argyrou et al. 2023) and aid in decision-making processes (see marineai.co.uk for manned and unmanned vessel operation as an example with potential for archaeological applications). Uncertain or incomplete data can also have gaps filled by interpolating computer methods (Castiello 2022).

It is important to consider several critiques that have been leveraged at the burgeoning use of AI both within and beyond our field. These new techniques are inherently human as they require human oversight, which means they are limited and may reproduce biases. For example, the accessibility of these models and methods may mean that they become a "black box", where researchers employ this technology without understanding their mathematical and logical underpinnings. To avoid this pitfall, scholars must guide the input and determine which factors are the most important for their research questions, and develop a secondary method for validating model output (Castiello 2022). Bickler (2021) suggests that AI/ML methods be accompanied by additional analysis, such as fieldwork and lab work. The author also points out that these models are only viable when one has sufficient input data, and may be unable to process fine-scale variations commonly present in archaeological data without exhaustive input. Additionally, the basis for many of these techniques is energy optimization, which can obscure certain Indigenous ontologies and lead to incorrect data analysis. Practitioner knowledge is an essential part of the work carried out by the CAST community, and the cultural context that is necessary to interpret archaeological research is, at this time, not possible to automate (Bickler 2021; Holguin 2023). The methods are additionally limited by the information contained in the "training" data, and by a propensity to mistakenly produce falsehoods as facts (Holguin 2023). That is all to say, while these methods are faster, they may be less detailed than traditional analysis (Roalkvam 2020). There are also pressing issues of equity to consider. Some methods are more accessible than others, consequently researchers without funding for AI techniques (or the computing power to apply them) will not see the benefits. Concerns have also arisen about particular AI tools, such as ChatGPT, that displace intellectual labor to workers earning poverty wages in the Global South. Archaeologists hold a responsibility to be critical of these methods and intentional in their usage as they become more commonplace.

Modeling Nuances in Human Decision-Making

Another theme that has become more common within the CAST community and adjacent fields of research is the exploration of human decision-making complexity. Particularly for the consideration of navigational decision-making, approaches beyond the classic cost–benefit analysis and least-cost pathway model have emerged. The conceptualization of most ABMs for seafaring requires refinement of environmental, neurological, and social factors to more accurately reflect past human movement (Blankshein 2022). An important component of this refinement is understanding the *goal* of a seafaring event (or pattern). For example, are people(s) moving for better resources or potential opportunities (Chliaoutakis and Chalkiadakis 2020)? Is the local environment changing in a way that impacts their way of life? Are there social complications? From planning to navigation to arrival at a goal location (Madl et al. 2015; Epstein et al. 2017), simplistic considerations of cost minimization remove meaningful context from decision-making at sea. Adopting a cost definition with a diversity of factors and updated modes of agency can improve model performance (Chliaoutakis and Chalkiadakis 2020).

As discussed in the previous section, there is a need for more accurate regional, time-appropriate paleoenvironmental data in order to better assess how agents will make decisions while navigating at sea. Seafaring models also require input from archaeological fieldwork, yet these dates and artifacts can be limited (Verhagen et al. 2019). Models that integrate statistical methods, data from experimental archaeology, paleoclimate model output, and combine overland and sea migration come closer to simulating an environmental cost surface similar to the ones past humans would have had to negotiate (Verhagen et al. 2019; Blankshein 2022). At the same time, it is critical to expand beyond environment- and climate-centric models, lest the configuration adopt a deterministic point of view (Hussain and Riede 2020). Improving the theoretical basis of an ABM is just as critical as honing the environmental inputs (Verhagen et al. 2019).

The combination of cognitive and navigational models is a promising new interdisciplinary field. Understanding the mechanics underpinning human decision-making can improve our simulations of human movement over sea. One theme that has arisen in neuroscience and navigation research is dynamic decision-making. That is, the recognition that new information (e.g., changing environmental conditions) may present itself throughout a seafaring event, and agents should respond to this information (Farr 2006). Navigational markers, human-made or otherwise, along a route also factor into navigation (Verhagen et al. 2019). Discrete environmental events, like volcanic eruptions, may additionally impact the decision process at sea (Chliaoutakis and Chalkiadakis 2020). Another theme from neuroscience is the importance of nonphysical spaces—temporal awareness, cognitive maps, and social landscapes are all integral to navigational decision-making. Physical markers in space allow agents to connect their internal maps and memories to the seascape over time (Farr 2006; Madl et al. 2015; Epstein et al. 2017; Verhagen et al. 2019). The social context a journey at sea occurs in is also influential in determining "optimal" routes, though modeling social factors can be elusive (Madl et al. 2015; Epstein et al. 2017).

The study of seafaring activity provides a unique lens through which to discover past relationships and practices. However, traditional environmental knowledge (TEK), as we refer to it today, and social landscapes are not wholly captured in most ABMs. The local knowledge, oral traditions, and shared memories accessed to navigate particular regions, as well as the individual and collective construction of identity resulting from these activities, should be considered in modeling maritime spaces (Farr 2006; Blankshein 2022).

When ABMs move beyond the individual to the network scale, simulation output has been shown to vary and more closely reflect the archaeological record (Chliaoutakis and Chalki- adakis 2020; Blankshein 2022). There are several interconnecting factors that contribute to, as Chliaoutakis and Chalkiadakis (2020, p. 1) state, "construction of the social space". The social cost surface that agents navigate when at sea is connected to local knowledge because seafaring is hardly an individualistic undertaking—knowledge and costs are shared in decision-making (Farr 2006). Learning and applying TEK (e.g., through celestial navigation, or observing cloud patterns and ocean currents, or lore) is inherently connected to relationships with others (Lewis 1994; Farr 2006; Proulx et al. 2021), and can in fact lead to superior navigational skill (Verhagen et al. 2019). In addition to the environmental conditions that agents must decide how to navigate, there are economic, cultural, political, and social factors that impact decision-making (see Sect. 11.3.1.5 in Verhagen et al. 2019). For example, relationship maintenance (Kinoshita 2019), conflict (Skelly et al. 2023), the location of negotiation hubs (Skelly et al. 2023), and resource trading (Chliaoutakis and Chalkiadakis 2020; Skelly et al. 2023) can motivate and shape maritime movement.

Another important concept in human decision-making worth mentioning is resilience, specifically the ways past societies displayed or related to it in the face of environmental change. More and more, scholars are looking to past human–environment interactions for clues about how societies have collectively responded to a changing climate. Especially as we look towards the balance of the UN Ocean Decade, ocean-based solutions to cli- mate change have become increasingly attractive. Indeed, there is a growing body of litera- ture concerning the utility of archaeology in the face of environmental challenges, and in turn, the impact of climate change on the archaeological record in the past and today (see collected references and ensuing discussion in the conclusion of Burke and Riede 2023; Cooper and Peros 2010; Sandweiss and Kelley 2012; Haywood et al. 2019; Hussain and Riede 2020; Rick and Sandweiss 2020; Burke et al. 2021; Boivin and Crowther 2021; Rob- erts et al. 2021). Other resilience-adjacent publications relevant to human decision-making models include Burke et al.'s (2021) exploration of spatiotemporal scales of human–envi- ronment interaction, Haywood et al.'s (2019) discussion of human systems, and Hussain and Riede's (2020) research on human behavior.

Co-creation with Indigenous Communities

Part and parcel of examining the complexities of human decision-making in our work is the increase in research that has been co-created with Indigenous communities. As a field, archaeology is reckoning with the colonial roots of our theory and practice, including the fact that Western knowledge systems have conventionally been prioritized over others (Atalay 2006; Schneider and Hayes 2020). Contemporary concerns and values shape the questions that are deemed worthy of investigation (and funding) in archaeological research. The institutions where this research takes place (primarily within the walls of academia) are simultaneously addressing calls for decolonization, as focusing on traditional knowl- edge has historically not been rewarded or valued (Atalay 2019). The agency of Indigenous communities and others can be diminished when colonialist modes of inquiry are upheld (Atalay 2006; Steeves 2019). Working towards an archaeology that is "collaborative and sustainable" (Atalay 2019, p. 514) is essential.

One motivating circumstance for moving away from traditional archaeological prac- tices and towards interdisciplinary, community-oriented work is the fact that Western

approaches to research are often misaligned with Indigenous ontologies. For example, the longstanding question of when and how people first arrived in Australia can be seen to be at odds with some Indigenous Australian dreamtime traditions, which state that they have been on the continent "with the first sunrise" (Munro 2008, p. 4). Western scientific approaches may also place a stark division between people and nature, and this distinction is often reflected in archaeological literature (Britton and Hillerdal 2020). Further, archaeological research is at times presented as a window into an obscured past, whereas Indigenous communities may not experience the past as absent in the first place (Schneider and Hayes 2020). In reality, heritage in the form of cultural sites is at risk of damage and loss today due to climate change, a consequence of the ongoing harm of colonialism (Britton and Hillerdal 2020; Boivin and Crowther 2021). A proposed solution to these issues is increasing support for community-based archaeological practices, which have the potential to more closely reflect the lived experiences of Indigenous people and mitigate the cultural impacts from climate change (Britton and Hillerdal 2020).

By engaging in interdisciplinary methods that center communities, we can move beyond the assumptions that are built into the traditionally adopted theory and models and toward research that acknowledges the reality of past people. We must acknowledge that the norms we use to model human behavior can be exclusionary of non-Western ontologies. For example, when Indigenous perspectives are incorporated into seafaring models, they often challenge the utility-maximization basis upon which most least-cost pathway models are built in order to appreciate both the knowledge and cultural conventions of seafarers (Supernant 2017; Shaw 2018; Callaghan et al. 2022). Attention to local knowledge makes space for elements that may influence human behavior beyond purely environmental ones (i.e., social, cultural, political, economic, spiritual, and other factors (Supernant 2017)). Fieldwork, archival work, ethnohistorical research, experiments, interviews, observations, and modeling can be combined to produce work that does not rely solely upon the archaeological record, but instead broadens the scope of our research goals (see Biar 2017; Shaw 2018; Shearn 2020; Berard and Biar 2021). These methods can reveal details about the past that more singular approaches can obscure (e.g., the importance of watercraft production processes and the expertise they reveal (Biar 2017; Shearn 2020), the categorization of past societies (Shearn 2020), individual and group identity construction (Shearn 2020), the relationship between social costs and the environment (Shaw 2018), and more).

When work centers the communities being researched, they become collaborators, rather than subjects. The process of producing collaborative research can create outcomes that help communities, and shift to a model where they have greater autonomy over research goals and methods (Atalay 2006; Schneider and Hayes 2020). The benefits to both the researchers and the community when moving away from colonial, Western practices are clear that embracing an Indigenous archaeology can challenge institutional biases (Atalay 2019), reinvigorate cultural knowledge at risk of being lost (Biar 2017), directly connect past issues to the experiences of descendant communities (Steeves 2019; Berard and Biar 2021), build resilience (Britton and Hillerdal 2020), and make space for multiple worldviews at once (Atalay 2019). In pursuing these methods, it is crucial to acknowledge the expertise that communities hold about their own past and present and avoid assuming that all Indigenous people and Indigenous worldviews are a monolith (Supernant 2017; Steeves 2019; Britton and Hillerdal 2020). From the inception of a research project concerning Indigenous groups through its completion, the values of the community at hand should be considered. Those in decision-making positions regarding institutional curriculum should aim to educate students about decolonization and best practices when engaging in community-based, collaborative archaeology (Schneider and Hayes 2020).

Conclusion

CAST is a small, but growing, field at the crossroads of computational archaeology and seafaring research. In December 2022, we gathered in person for the first time at the Stanford Archaeology Center with the goal of identifying our community members, discussing the state of our field, and determining future directions. This chapter of the special issue is the outcome of that initial (and many continuing) discussions in our community. Here, we have identified different phases in the development and establishment of CAST as a proper field over the last several decades. Our field finds its roots in the 1990s to 2009, where the increase in seafaring archaeology publications began. Landscape, maritime, shipwreck, and experimental archaeology all actively influenced what has become CAST research today. Over time, the transition from land-based work to ocean-based work laid the foundation for this field. From 2010 to 2019, the trends we discuss in this chapter solidified. The number of disparate seafaring models increased, as did interdisciplinary methodology. Model complexity broadened to include different types of vessels, human agency, dynamic environmental data, and concerns about accessibility. 2020 was a turning point in our field, as it was for all fields globally. The last four years found CAST research limited by pandemic-related challenges to collaboration, as well as the inability to perform fieldwork and lab work. This generally led to a focus on modeling (and combining different types of models) and a further focus on accessibility. We also summarize here the trends we expect to define the future of our field, including paleoenvironmental data integration improvements, increased usage of artificial intelligence and machine learning, further considerations of human cognition in decision-making at sea, and project co-creation with Indigenous communities. As a burgeoning field, we challenge ourselves to build a body of work that honors our roots, while embracing the full potential for new research from the themes we have explored here.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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