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Modeling distance with time in ancient Mediterranean seafaring: a GIS application for the interpretation of maritime connectivity

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ABSTRACT

Investigations of Mediterranean connectivity have increasingly turned toward maritime landscape models to frame questions of seaborne exploration, marine resource exploitation, trade and exchange, and seafaring culture. Environmental and technological parameters are consistently acknowledged as crucial for understanding when and why different relationships developed across the sea, but their formal employment in the modeling and interpretation of maritime space remains quite limited. The methodology outlined here utilizes Geographic Information Systems (GIS) to integrate environment and technology as analytical tools for exploring the complexity of seaborne connectivity. Focusing on sailing days as practical units of distance and using an Archaic Greek shipwreck off Turkey as a case study, this preliminary model demonstrates how a more nuanced spatial approach can inform the human geography and socioeconomic structures of ancient maritime interaction.

1. Introduction: visualizing and analyzing maritime space

Alongside a renewed interest in connectivity as a theoretical framework for investigating past Mediterranean societies (Horden and Purcell, 2000), new and energetic methodological scrutiny has been directed at the social, technological, and environmental conditions of ancient seafaring. Proposed analytical models account in different ways for these influences on ancient mariners' choices and, more specifically, as possible explanations for the historical trajectories of seaborne connectivity attested in the archaeological record: from prehistoric resource exploitation to Greek colonization and Roman pan-Mediterranean trade. Discussions of maritime connectivity frequently posit natural routes of communication, often seasonal and based on generalized environmental factors like predominant winds and currents that allowed for comparatively easy or reliable voyaging, especially between sites that are intervisible or in relative proximity (e.g. Pryor, 1988; Bass, 1998; Castagnino Berlinghieri, 2003; Farr, 2006, 2010).

The prehistory of Aegean island hopping has formed one major focus of study, especially since Broodbank's (2000) pioneering work situated evidence for Neolithic to Early Bronze Age material connections within the framework of the natural marine environment. Subsequent considerations of Aegean interaction, particularly those by Knappett et al. (2008, 2011) focusing on the Middle Bronze Age, have diversified and systematized new modeling techniques to analyze the development and efficiency of networks across maritime space and to study shifts in their structures through time. Where actual voyages are attested in later historical sources, these provide selective but valuable evidence for specific network links, which in turn allow us to add ties, to test inferred routes and the importance of natural proximities, and to map the basic sea lanes crisscrossing the Classical Mediterranean (Casson, 1995: 270–299). Arnaud's (2005) study of Roman maritime connections, for example, draws together a wealth of scattered references to outline a scaled network of '*navigation segmentée*' linking larger hubs and outlying ports.

The resulting models conceive of real or hypothetical directional routes over which communication and exchange flowed, but distance and time often are arbitrarily imposed on this network topology, or in some cases are left out entirely. In the prehistoric Aegean, 100–150 km has been suggested as a reasonable upper limit for a day's sailing distance (Broodbank, 2000: 345; Knappett et al., 2008: 1014), while Greek and Roman sources tend to posit a roughly equivalent average in ancient measurements: 600–700 stades or approximately 105–125 km (Arnaud, 2005: 74–87). Such figures reflect a reasonable and expedient benchmark for routine voyages in generally favorable conditions (Fig. 1), but they leave little room for the complexities of real seafaring in a dynamic

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Fig. 1. Sailing times from Bodrum/Halikarnassos, derived using an isotropic surface showing a daily sailing distance of 115 km.

environment where universal averages may not be consistently meaningful: for example, outbound and return voyages in contrasting winds (and perhaps different lading), and changing capabilities according to different vessel sizes, construction techniques, and rigging configurations. While broad challenges of the marine setting are acknowledged, models of Mediterranean seaborne interaction have struggled to weigh natural conditions in a systematic and flexible manner that avoids the basic pitfalls of environmental determinism.

Formal spatial analyses that incorporate more nuanced environmental data and time into communication and exchange were pioneered in the waters of the Pacific and northern Europe, where a primary focus has centered on the innovation of seafaring and the commencement of maritime contacts and colonization (e.g. Anderson et al., 2010). Early simulations by Levison et al. (1973) and Irwin et al. (1990) tested environmental and technological factors in the discovery and settlement of the islands of Polynesia and across the Pacific Ocean. A well-developed program of research has brought the dynamic environment of seafaring to the forefront of scholarship on communication and cultural contact around the North Sea and Baltic Sea (e.g. Westerdahl, 1995; Van de Noort, 2011). Off the British coast, for example, the 'western seaways' have gained considerable attention for nearly a half century, with a number of studies evaluating the natural environment and conditions of early seagoing ventures (Garrow and Sturt, 2011). Callaghan and Scarre (2009)—employing computer simulations originally developed for testing prehistoric Caribbean maritime contacts—brought seafaring models to their explorations of Neolithic crossings from Brittany to the British Isles. Other formal models of maritime space have incorporated network analysis or Geographic Information Systems (GIS). Sindbæk's (2007, 2009) network approach to Iron Age and Medieval Scandinavia addressed the development of sea routes and site centrality in long-distance maritime systems. Utilizing a historically attested 9th-century AD Baltic Sea voyage, Indruszewski and Barton (2007, 2008) have integrated wind data alongside historical accounts and experimental archaeology to hypothesize plausible routes, providing an innovative step toward harnessing environmental data for GIS models of seaborne voyages.

Analyses of time and cost as factors in ease of land transport and communication are becoming more common in certain areas of the ancient Mediterranean world with good documentary and material records: for example, the travel itineraries of Roman Iberia have proved useful for mapping ancient road systems (Graham, 2006; Isaksen, 2008; de Soto, 2010). Yet few attempts to develop a formal methodological framework for interaction have been applied to the Mediterranean Sea itself. Carreras (2010) attempted to explain ceramic distribution patterns along the Atlantic shores of Roman Europe through a GIS model of relative costs of product movement by water and land, derived from prices in the Edict of Diocletian (AD 301). The resulting figures offer one view of maritime space, but remain insufficiently flexible for the range and complexity of sea travel in multiple directions and at different scales. Previous network approaches, while dynamic in measuring contacts, have favored fixed linear distances that bear little relationship to human experience at sea (Knappett et al., 2008, 2011). Scheidel's recent interactive ORBIS project (orbis.stanford.edu), which seeks to evaluate the costs of seaborne and other transportation across the Roman Empire, represents a step forward in approaches to maritime space. This geospatial network incorporates a set of basic routes with separate bidirectional costs, facilitating a more nuanced temporal dimension based on sailing speeds.

Certain progress has been made in analyzing Mediterranean connectivity, yet significant challenges remain in translating the techniques for formal spatial modeling of routes to quantify time and distance in seaborne mobility as affected—but not solely determined—by natural conditions. We need tools designed to explore both idealized networks of routes as well as the vast range of real seaborne relationships evident in the archaeological record of ancient maritime communication. The methodology explored here contextualizes seafaring within a GIS-based analysis of wind (direction and speed) data, using the material assemblage from a modest 6th-century BC shipwreck excavated at Pabuç Burnu, Turkey. This case study provides one example of how an analytical GIS tool can contribute to a broader understanding of maritime connectivity based on the archaeological record. The particular data and GIS modeling serve as a single demonstration of a specific methodology; comparative analysis of a wider variety of vessels will be necessary before any single environmental or economic model can be posited for larger currents of seafaring in the Archaic eastern Mediterranean and beyond.

2. Modeling ancient seafaring in the eastern Mediterranean

All models are grounded by some degree of generalization. Estimating likely sailing capabilities and integrating wind data require considerable simplification that can hardly account for the full range of possible environmental and technological variables. A number of wind patterns affect seafaring capabilities, but prevailing seasonal winds were probably the crucial factor; they were both the strongest and the most reliable through the sailing season, and appear most frequently in seafaring accounts. Yet even in the height of summer, the northerly (Etesian) winds can occasionally give way to southerly (Scirocco) gusts. The diurnal cycles of land and sea breezes were also known by Greek sailors, who probably used these local phenomena opportunistically to gain some advantage, especially when sailing against predominant regional winds (Morton, 2001: 51–53). Navigational hazards would have presented sailors with a dilemma that was at least somewhat predictable. On the other hand, storms, though infrequent in the sailing season, could not always be anticipated.

The technological capacity of ancient mariners to harness different wind conditions (direction and speed) for propulsion presents another critical challenge. Some details can be gleaned directly from the archaeological record of a particular shipwreck—in this case the Pabuç Burnu vessel—but the general scarcity of reliable material or literary evidence from the Archaic Greek world necessitates the employment of other sources. Available historical accounts are intermittently helpful, but span a millennium and tend to report the better performances achieved along a route. For the current model, the bulk of sailing performance data is derived from sea trials undertaken by the *Kyrenia II* vessel, a replica of a Greek ship of ca. 300 BC excavated off Cyprus (Katzev, 2005). Though several centuries later than the Pabuç Burnu vessel, this ship provides one of the few examples where the extensive remains of a shipwreck and its subsequent full-scale reconstruction have allowed for the correlation of ship design and performance characteristics. Elements of hull shape and construction varied slightly between these two vessels, which were similar in size and likely comparable in sail and rigging configuration. Direct archaeological evidence for rigging elements is rare, and no examples survive among the remains at Pabuç Burnu, but iconographic evidence alongside material remains from the Kyrenia ship confirm that the square sail featuring brails (lines for shortening sail) was a principal rig of choice among Greek sailors during the Archaic, Classical, and Hellenistic period (Casson, 1995: 47–48).

The estimates derived here should be understood as 'good' sailing, representing a maximum normal distance covered in a given time. Weather conditions, rig and hull design and maintenance, and human ability may have imparted considerable variability in actual performance and reduced somewhat the effective speed (Palmer, 2009: 328–329; Whitewright, 2011: 91–93). While repeated journey times may differ, adopting a simplified 'standard' Archaic Greek sailing vessel allows sufficient flexibility in the model while still reflecting figures that should approach the 'mean' performance of many routine trips. References among works of geography and periploi attesting to 'rule of thumb' or anticipated sailing times underscore the extent to which Mediterranean mariners likewise thought in terms of approximate durations for standard journeys (e.g. Strabo 10.4.5). Such normative sailing times no doubt also provided the basis for the sea transport pricing scheme elaborated in the Roman Edict of Diocletian (Arnaud, 2007).

2.1. Wind parameters for GIS

The primary means of propulsion at sea, wind is the crucial environmental factor in determining performance of ancient vessels. Comparison between modern tables and ancient references suggests that prevailing regional patterns have not changed markedly (Murray, 1987), so recent data can provide essential parameters for a model. Since Mediterranean currents and tidal streams are generally minimal—within the range of 0.25–0.5 kn (Hydrographic Office, 2008: 18)—they would have had a comparatively minor impact; they are excluded from consideration here for simplicity. Likewise, wave directionality, which bears on a vessel's ability to maintain a steady course (Morton, 2001, 30; Whitewright, 2011: 7), closely parallels wind heading in the eastern Mediterranean (Soukissian et al., 2007: B33–B38), so it need not be factored independently.

The model developed here incorporates speed and directional wind data gathered from available onshore weather records at major coastal (or near-coastal) towns. Daily (7:00–19:00) observations from meteorological stations, available year-round for the period of 2001–2009 (www.windfinder.com), provide the basis for modeling near-shore patterns; 16 of these fall in the region of the southeast Aegean relevant to the present case study at Pabuç Burnu (Fig. 2, indicated by hollow arrows). Since these observations are restricted to coastal locations, they have been contextualized against offshore data derived from the *Wind and Wave Atlas of the Mediterranean Sea* (Med-Atlas Group, 2004). This atlas represents a collaborative venture that synthesized actual buoy and satellite measurements with numerical models to produce year-round estimates for weather conditions, which were then sampled regularly across a grid at 0.5°–1° intervals of latitude and longitude, equivalent to linear distance intervals of ca. 45–55 km in many cases, and otherwise up to ca. 90 km. Nine points fall within the southeast Aegean region (Fig. 2, indicated by solid arrows) for a total of 25 wind datums throughout the study area.

Combining data from these two sources allows interpolation of rasters for year-round prevailing wind heading (using a simple trigonometric function for mean, Fig. 2) and mean wind speed (Fig. 3). A basic Inverse Distance Weighted technique was used, and a cell size of 500 m was established and carried through the analysis. These parameters produced results that were adequate for the resolution of the available data, yet reasonable in terms of processing demands. While such a combination of data sources yields coverage sufficiently detailed for the purpose of broadly estimating regional journeys, a finer resolution—were it available throughout the region—could facilitate a more locally nuanced approach to smaller maritime patterns. Such mean weather conditions do not model environmental extremes affecting (generally negatively) a

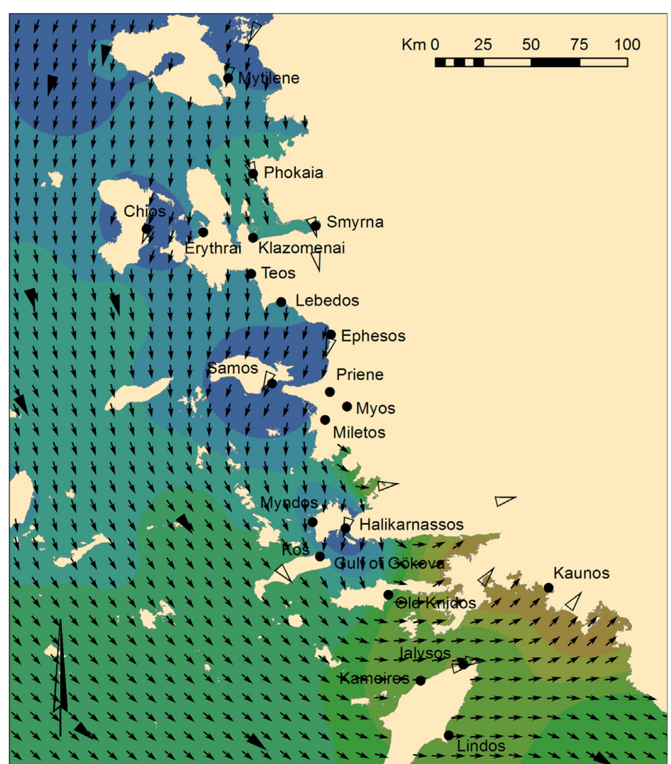

Fig. 2. Mean wind heading (large arrows indicate the locations of data points).

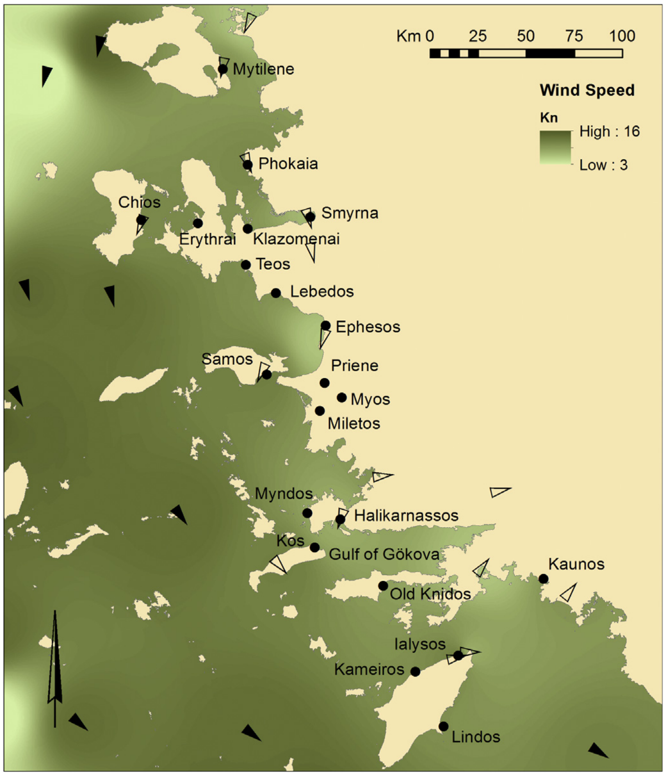

Fig. 3. Mean wind speed (arrows indicate the locations of data points).

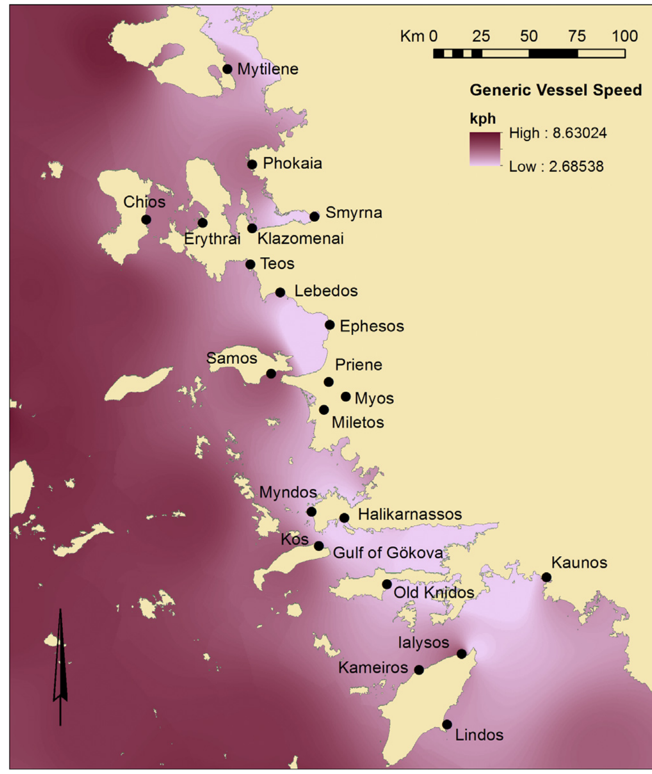

Fig. 4. Generic vessel speed.

vessel's progress, but the data set drawn from these sources provides reliable parameters for investigating typical performance of ancient sailing vessels.

2.2. Sailing performance in GIS

Data logged over the course of the *Kyrenia II*'s outbound and return journeys between Piraeus and Cyprus provide proxy evidence for performance of ancient vessels in different conditions (Katzev, 1990; Cariolou, 1997). The results vary considerably, but allow reasonable suggestions for speed and handling in mean force winds within the study area. Although extreme winds can eventually compromise control and stability, more wind normally correlates to greater propulsion. A broad reach (wind from behind at an angle) was generally the most advantageous point of sail for ancient ships, often more so than a run (wind directly astern). With reasonable skill and a well-trimmed sail, an ancient mariner could effectively accomplish a beam reach, utilizing winds perpendicular to the intended direction of movement (Arnaud, 2011). The overall impression regarding points of sail is consistent with the theoretical and experimental analyses of Whitewright (2011) and Roberts (1995). These conditions also accord reasonably well with sporadic ancient descriptions of journeys in the eastern Mediterranean (Casson, 1995: 270–299; Arnaud, 2005: 207–230).

Casson (1995: 282–291) and Whitewright (2011: 9–10) have each suggested that vessels could sail 4–6 kn across open water in helpful winds, and at best 1.5–2 kn in the intended direction ('velocity made good') when operating against the wind, achieved by tacking or gybing. This set of observations and the detailed logs kept by the *Kyrenia II* sea trials provide a basis for calibrating true wind speeds with theoretical ancient sailing speeds, allowing the establishment of 'generic vessel speeds' across the region. For the purpose of the model, suggested speeds are represented not as knots but rather as cost in time (Fig. 4).

2.3. GIS analysis of travel cost distance

Wind data, speed grids, and sailing parameters provide the necessary background to develop a GIS model of vessel performance. Of paramount importance is a surface allowing calculation of accumulated costs (here, cost is time) that are dependent on the direction of movement through space. The present study employs tools within ESRI ArcMAP 10.0 to accomplish this analysis (particularly 'Path Distance'), but comparable methods from other commercial software packages might likewise be utilized to implement the anisotropic spreading function described here with similar results. The modeled surface determines each cell's friction not in terms of static weight as is typical of most GIS cost surfaces (Conolly and Lake, 2006: 221–224). Rather, it assigns each cell a dynamic weight that varies according to a second independent factor; in this instance, that factor ('Horizontal Factor' in ArcGIS) defines sailing capabilities relative to wind direction: here it reflects the difference in angle between prevailing wind and vessel heading. In other words, the generic time cost for the vessel to pass through a cell is modified to depend on the particular heading on which the ship moves into that cell.

The sea trials and historical data described above allow for a reasonable estimate of relative performance in different wind directions (here using 10° increments), providing the basis for establishing a table of factor values. Taking a factor of 1.0 as an average 'good' speed achieved while running (0°–20°) or on a beam reach (80°–110°), more helpful winds on a broad reach (30°–70°) were assigned a smaller factor (that is, a reduced friction) of 0.8. Conversely, winds beyond a beam reach (≥120°) require tacking or gybing and are less efficient; a factor of 3.0 was utilized here to represent a modest velocity made good. The shape of the Pabuç Burnu vessel's hull below the water line is unclear, so its vulnerability to lateral drift on reaches may have differed somewhat from that of the Kyrenia ship; the model errs toward a conservative performance in this calculation. As is the case with raster-based functions generally (Conolly and Lake, 2006: 223–224; Tomlin, 2010), the calculation of accumulated costs using this GIS method suffers slightly from the neighborhood limit of eight directions of cell-to-cell movement, though an additional factor may be introduced to smooth the surface and to resolve in part this grid constraint (Supplementary Text 1).

The resulting analysis calculates how far one could normally expect to sail in a given time across a particular environment, here using a hypothetical origin for a vessel in Bodrum, ancient Halikarnassos in Turkey (Fig. 5). Local prevailing winds from the north translate to a 24-h day's sail from Bodrum that ranges considerably from about 48 km for a northbound journey around the peninsula, to 68 km on a westerly course, to more than 172 km on a southbound run. Note that a rough average of these figures gives a daily sailing distance similar to the static figures used in earlier studies (Broodbank, 2000: 345; Arnaud, 2005: 74–87; Knappett et al., 2008: 1014), but the GIS-derived day's sail in any given direction contrasts sharply with these earlier estimates (Fig. 1).

Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.jas.2013.03.016.

3. A case study of seafaring in the southeast Aegean: the Pabuç Burnu vessel

Beyond the general implications for visualizing maritime space as relative ease and cost of connectivity, the GIS method outlined here bears directly on the interpretation of specific shipwreck assemblages within the maritime material record. The excavation of the Archaic Pabuç Burnu merchant vessel off the Turkish coast provides a case study for using this model as an analytical tool in the interpretation of a specific archaeological context. Study of the ship's cargo and construction is ongoing in preparation for final publication of the site; the parameters used here to demonstrate the GIS method reflect preliminary analysis and discussion (Greene et al., 2008).

Lost east of Bodrum probably during the second quarter of the 6th century BC, the ship was carrying a primary liquid agricultural cargo of over five tons in some 260 transport amphoras. The cargo is represented by jars of several broadly regional forms that—as is often the case with Archaic Greek amphoras—cannot always be attributed to precise locations, but reflect broad forms best distinguished through typological variances alongside visual and chemical analyses of fabric. Approximately two-thirds belong to a type whose fabric appears closest to that of nearby Halikarnassos (Bodrum). The two major remaining types can be attributed broadly to southern Ionia, including one form representing one-fifth to one-quarter of the jars that is similar in fabric to later ceramic production on Rhodes, although a source on the adjacent mainland cannot be excluded. The remaining few jars appear in only one or two examples each; these include two types that can be securely assigned to origins further north at Klazomenai and on the island of Lesbos (Supplementary Text 2).

Even if it is impossible to determine the specific port of origin for the ship's final voyage or the exact locality of certain regional productions (i.e. the location within southern Ionia or on Rhodes), the analytical process described here allows a gauge of distance traveled for each cargo component based on current hypotheses. Two-thirds of the shipment had probably traveled no more than a few hours from Halikarnassos when the vessel was lost (Fig. 5). If the second largest group of jars originated on Rhodes or the opposite mainland, a ship could have carried them against predominant winds northward to Halikarnassos or elsewhere in the Gulf of Gökova within two to three days (Fig. 6). Despite the difficult sailing in one direction, a round trip between the Halikarnassos area and the sites of Ialysos and Kameiros on the north shore of Rhodes could have easily been accomplished within three to four

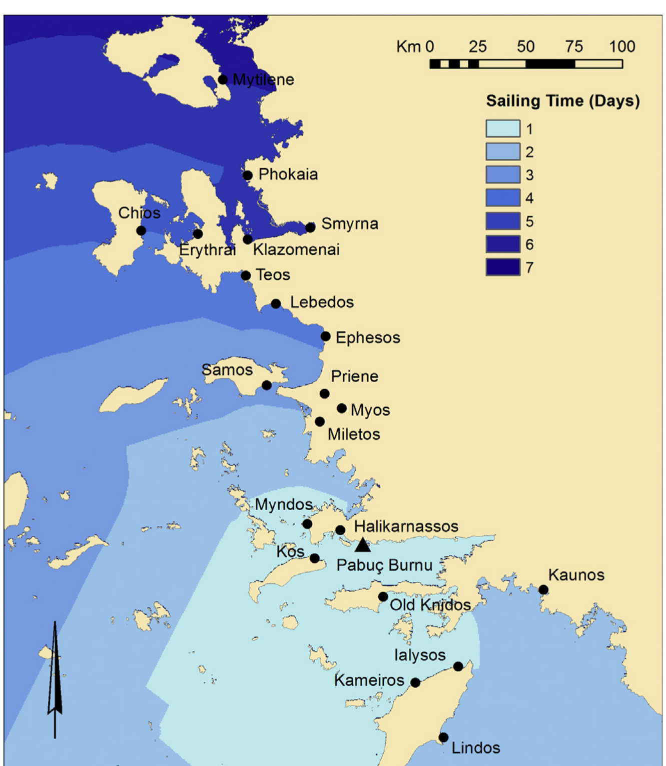

Fig. 5. Sailing times from Bodrum/Halikarnassos, derived using an anisotropic surface.

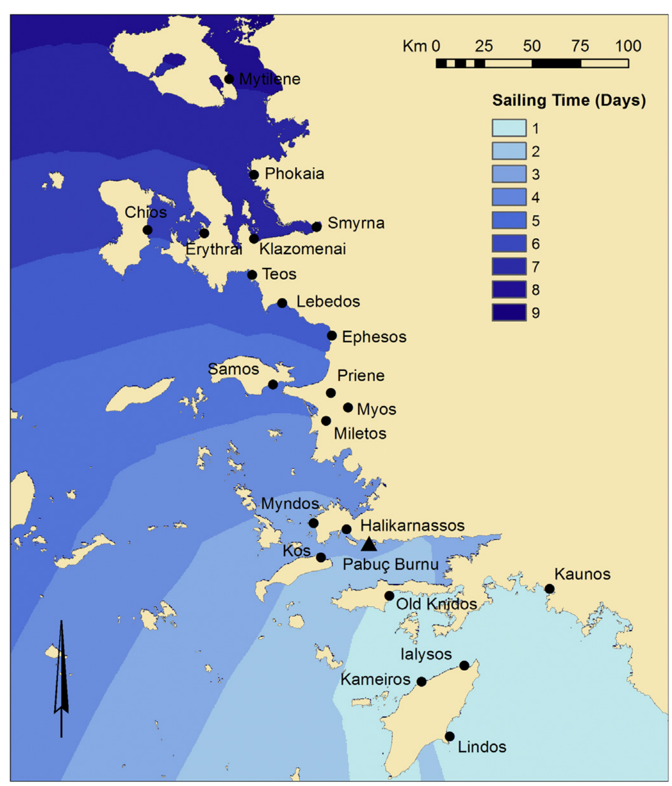

Fig. 6. Sailing times from Rhodes (Ialysos or Kameiros), derived using an anisotropic surface.

days thanks to favorable winds during the opposite leg. The few but comparatively exotic Klazomenian and Lesbian jars represent more distant imports; a round trip from either Klazomenai or Mytilene (Lesbos) to the Gulf of Gökova would have required over a week's journey.

The utilitarian wares that served the crew's daily dining and mercantile needs—pitchers, cups, and bowls—provide a glimpse into the possible cultural associations of the mariners themselves. This pottery is predominantly in two fabrics that again appear closest to those tentatively assigned to nearby Rhodes and Halikarnassos. A single worn and repaired cup from farther north, in the area of Phokaia, represents the most distant connection from the non-cargo assemblage, but even in this case the normal round-trip sailing time between Phokaia and Halikarnassos was perhaps no more than about seven days.

This limited southeast Aegean zone between Halikarnassos and Rhodes appears to indicate both home and primary activity area for the Pabuç Burnu merchant. The ship's mariners focused on short hauls that left them at sea for perhaps no more than three days on their longer round trips. Many journeys may have been accomplished in a single day, such as the shipment of produce from Halikarnassos to outlying towns around the Gulf of Gökova and nearby islands. The scarcity of farther-flung (Klazomenian and Lesbian) imports and the notably greater distances they represent suggest they were picked up for secondary distribution from some larger port in the local area like Halikarnassos, a rather restricted economic geography that is likewise supported by the special status in which the repaired Phokaian cup was clearly held (Greene et al., 2008: 704). In light of this short-haul focus, it should not be surprising that the assemblage shows little evidence for extensive food preparation or overnight journeys (hearth, lamps, etc.). The implications for such a narrowly regional geography of exchange are potentially significant, particularly since individual journeys entailed comparatively modest investments of time and resources. Were these the types of casual enterprises envisioned by Hesiod (*Works & Days* 630–632), who endorsed maritime exchange as an occasional side business for farmers? Or were these professional merchants, well-situated to undertake frequent repeat short-haul trips that could have fostered reliable communication, shared knowledge, and social bonds, leading to greater economic integration throughout their southeast Aegean neighborhood?

4. Conclusions: time and space in maritime connectivity

How we approach, represent, and understand maritime space bears directly on how we view the related material record, and in turn how we use that record to construct broader paradigms about seaborne communication and trade. If one of the ultimate goals of studies of Mediterranean maritime connectivity is to explore the development and dynamics of communities situated around the sea, then analysis focusing on the geographical and temporal scale of these links offers a window into the rhythms of socioeconomic life. Quantifying seafaring costs in GIS provides a tool for analyzing connectivity in light of environmental conditions; this in turn facilitates an alternative to uniform daily sailing distances alongside a more nuanced conception of proximity and remoteness among coastal communities. Contextualized within this geography, the material record for seaborne exchange helps to reveal the practical local relationship between environment, sailing capabilities, and maritime contacts. By looking at the relative distances that a ship sailed or over which a cargo changed hands, the impact of time and space upon the development of maritime networks and regions becomes clearer. In addition to radically different durations, outbound and return journeys might assume very different courses that carry implications for how we understand—and problematize how we depict as linear features—the routes over which goods and information flowed. Contrasting durations and most efficient paths imply different experiences over these two legs, and may have prompted a range of choices that shaped different maritime structures embedded in the archaeological record. Sailing days offer an alternative spatial scale that emphasizes the relationship between contacts visible in the archaeological record and underlying socioeconomic institutions.

The Pabuç Burnu shipwreck illustrates one environmental model that can be constructed from the material record using GIS: a southeast Aegean economic region connected by merchants operating primarily over distances of one to three days' sail. Other Archaic Greek shipwrecks will yield diverse models, and different geographies and rhythms of merchant traffic in other regions and periods will reflect not only local environment and topography, but also the particular social and economic structures underpinning exchange. While the economic geography or social context of the Pabuç Burnu ship reflects a single example of seafaring in the Archaic eastern Mediterranean, this GIS case study provides one view of regional seafaring that merits comparison with other maritime assemblages. How does this image of a short-haul mariner compare with interregional merchants carrying larger cargos over longer distances (see Inline Supplementary Fig. S2)? To date, only about six other 8th- to 6th-century BC shipwrecks have been published from the area (Ballard et al., 2002; Greene et al., 2011, in press), and only the wreck at Pabuç Burnu has been excavated. With so few early Greek cargos investigated in the eastern Mediterranean, gaining maximum understanding and contextualization from each assemblage should be vital to building larger socioeconomic paradigms for Archaic seafaring and exchange. The application of formal spatial analysis tools to diverse maritime archaeological sites offers a way to test models and refine their validity and interpretive potential.

Inline Supplementary Fig. S2 can be found online at http://dx.doi.org/10.1016/j.jas.2013.03.016.

The GIS tools explored here provide opportunities for characterizing the diverse range of links that structure maritime connectivity. To address properly such complex networks as Mediterranean trade, individual economic ties must be grounded, to the extent possible, in the varied experiences of a dynamic maritime topography. These models could be productively combined with other analytical approaches ranging from cost functions on land to regression analysis of imports to harbor sites. On a practical level, the GIS platform allows the results of maritime analysis to be more easily integrated alongside landscape models of transportation and communication. For example, in association with GIS analysis of road and river travel times, this approach could help to yield relative approximations of profitability and long-term productivity of maritime exchange. Quick modifications of model parameters would allow exploration of different technologies like paddling or rowing by early voyagers in the Aegean, or the potential interplay of technological change and patterns of travel. Given the growing trend toward employment of formal network analysis tools to questions of connectivity (Knappett, in press), GIS analysis provides an opportunity to add temporal and spatial depth to the fundamental links from which these networks are constructed.

Other environmental factors and technical variables remain to be explored: seasonality, diurnal wind cycles, storms, navigational dangers, etc. The methodological framework presented here aims to provide a starting point for more detailed analyses tailored to the specific data, contexts, and questions raised by the maritime archaeological record. This approach to modeling the opportunistic topography within which ancient mariners interacted, and by which people were differentially connected, provides a step toward more flexible yet methodologically rigorous incorporation of time and distance into studies of maritime connectivity.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2013.03.016.

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