Chapter 5
Cost surface DEM modeling of Viking Age seafaring in the Baltic Sea

Inferences in nautical archaeology about sailing routes in northern Europe are based today almost entirely on historical information coupled with results from experimental archaeology. The authors propose here a third method, which combines computer simulation with the aforementioned information sources. Digital bathymetric models (DBMs) of the Baltic seafloor, wind, current, and other real sailing parameters are used to create cost surfaces for modelling early Medieval seafaring. Real sailing data from 2004 sailing voyage of an early Medieval replica, the Ottar, is used to model sea routes in the Baltic Sea. Both GIS-Esri and GRASS GIS are compared as modelling tools and used in least-cost path and anisotropic spread analyses to simulate sea routing in prehistoric land- and seascapes across which humans travelled a thousand years ago.

George Indruszewski† & C. Michael Barton•

† Vikingeskibshallen, Roskilde, Denmark.

• School of Human Evolution and Social Change, Center for Social Dynamics and Complexity, Arizona State University, USA.

Introduction

Maritime archaeology, especially historical research dealing with Viking Age seafaring, has tried for a long time to decipher the reasons behind the choice of specific sea itineraries connecting Medieval trading centres in the Baltic realm. The problem is complex, because explicit itineraries from that period do not actually exist and because the literates who laid them on the parchment for the posterity used their epoch's writing style and conventions. This is the case with King Valdemar's early 13th century journey from Utlängan (Sweden) to Reval (Estonia), where the route follows the Swedish coastline in earnest (Varenius 1995: 189-194). Adam of Bremen's late 11th-century ecclesiastic history, on the other hand, lists just the main descriptive elements of a sea voyage: the departure point, the destination, and the time spent in reaching the destination (Schmeidler 1917: 80).

The situation becomes even more difficult in the Viking Age (8th to 11th century AD). Very few written sources are available for the interested scholar. One such source is Wulfstan's late 9th century account of his sea voyage, included in the Orosian history of King Alfred the Great. Wulfstan sailed for seven days and nights from Haidaby, in the lower Schlei Fjord (in today's Schleswig-Holstein, Germany), to Truso, near the Vistula River mouth (identified archaeologically with Janowo Pomorski located about 4 km south of Elbląg in eastern Pomerania, Poland) **[Plate 1]**. During the voyage, Weonodland was on his starboard side (that is the Land of the Wends in the southern Baltic), and islands under Danish overlordship (Langeland, Lolland,

The authors wish to thank the Vikingeskibshallen (Viking Ship Museum) for supporting this research initiative, Arleyn Simon from the Arizona Research Institute (Arizona State University) who generously provided ArcView GIS resources and research space, and the GRASS international development team for making open source GIS available to everyone. We also offer our thanks to Steve Schmich for his helpful insights.

and Falster), followed by Bornholm, Möre, Blekinge, Öland, and Gotland (the latter belonging to the Svear) were off to port.

The text is important for several reasons. Its briefness, composition, and informal content point to a description of a sea voyage that happened sometime in the second half of the 9th century, and it is one of the very few surviving sailing narrations of the Viking Age Baltic Sea. Furthermore, it describes sea travel between two archaeologically significant trading centres in the Baltic: Haidaby (Haithabu) and Truso. Last but not least, the text provides us with clues about contemporary navigational methods. The author displays a geographical knowledge in employing a maritime orientation system that uses the ship as the central point. That is, he does not orient the coastlines and islands in relation to each other, but in relation to the sailing ship. This contrasts with the orientation system(s) used in Alfred's Orosius (Korhammer 1985: 251-269), and is also unique among historical sources in general. Paradoxically, but not unexpectedly, it is the least ambiguous in terms of cardinal directions. When Wulfstan says that the islands under Danish suzerainty were on the port side and that Weonodland was on starboard all the way until the mouth of the Vistula, it is clear that his ship sailed on a general course from west to east.

The research issue

Nevertheless, that is all that the text explicitly indicates. Specific routing is left to more speculative hypotheses, such as the one envisioned by Crumlin-Pedersen (1983: 32-44). Relying upon iconographic evidence from the Bayeux Tapestry and other Medieval historical sources, Crumlin-Pedersen pioneered a novel conceptual approach to early Medieval Norse navigation that emphasized the importance of depth sounding. He suggested that Wulfstan used soundings to follow a preselected bathymetric line (he proposed using the –10 or –20 m depth lines) running along the southern Baltic coastline, from the mouth of the Schlei to the mouth of the Vistula (Crumlin-Pedersen 1983: 42-43). In other words, Crumlin-Pedersen argued that the primary orientation system for the Viking Age navigator was below the waterline and not above it, and that coastal sailing was the main type of navigation knowledge for that period. Besides relying on iconographic and historical sources that are post-Viking Age, the proposed construct conflicts with the Wulfstan's textual information as well as the character of his voyage. His sea voyage was a routine journey, which required neither sounding navigation nor coastal sailing. This is supported not only by the text but also by the following arguments:

- Sounding as a method of orientation at sea was known since Herodotus' times in the Mediterranean region and was documented in northern Europe later in the Middle Ages. But when documented it is mentioned only in relation to landing or approaching a coastline.
- Wulfstan's route could not have followed a specific isobathic line, since a high resolution bathymetric chart (DBM) of the Baltic Sea bottom clearly shows the sinuosity of these lines. In fact, the route that Crumlin-Pedersen proposed crosses several of these isobaths representing some tens of meters variation in depth—an unlikely route for a navigator following a constant depth.
- Crumlin-Pedersen's route also puts an important island, Fehmarn, on the port side. But this is not mentioned in the Wulfstan text. Fehmarn was a part of the Wendland until the mid-12th century, but was not mentioned with the other portside isles under Danish suzerainty. In the last decades of the 11th century, Adam of Bremen considered Fehmarn an integral part of the Wendish lands: '*Quarum prima Fembre vocatur. Haec opposita est Wagris, ita ut videri posit ab Aldinburg, sicut illa, quae Laland dicitur. […] Ambae igitur hae insulae pyratis et cruentissimis latronibus plenae sunt, et qui nemini parcant ex transeuntibus. Omnes enim, quos alli vendere solent, illi occidunt*' (Schmeidler

1917: 113).[1] It seems unlikely that Wulfstan would not have included it in his list.

- Land was in view but sufficiently far away all the way up to Arkona and Bornholm that soundings were not necessary for orientation, even during night sailing.
- Wulfstan's voyage did not have an exploratory character and would follow established routes.
- Wulfstan underlines in his account non-stop navigation both day and night, which implies sailing away from the coastline. Sailing close to the coastline at night and without navigational aids holds considerable risks even today, because while most of the Baltic Sea bottom is covered by 'till' (boulder clay) and sand, it has stony grounds. This, plus the presence of strong coastal currents that endanger even modern coastal navigation (especially on the long flat Polish coast), would have given Wulfstan little chances for reaching his destination if he used the coastal routing.[2]

Wulfstan sailed non-stop for seven days and nights, and the shortest linear distance between his departure and arrival points is 390 nautical mi (Nmi). Therefore the average minimum speed of his vessel was 2.3 kn (or 55 Nmi every 24 hours). The more the vessel departed from this straight-line route, the longer the distance it would travel and the greater the average speed required to make the voyage in the recorded seven days. We do not know Wulfstan's actual travel speed or his routing, but the historical account provides a set of geographical and temporal constraints within which the voyage took place. Thus, the northern sailing boundary is defined by the southern limits of the Danish archipelago and the southern sailing boundary follows the southern coastline of the Baltic, including its affiliated islands. In navigational parlance, the Danish isles must remain on port while the Wendish (Slavic) lands stay on the starboard side. This means that the historical voyage was of a 'corridor-sailing' type, at least for the western Baltic portion (up to Cape Arkona, the northeasternmost tip of the Rügen Island; for details, see Indruszewski & Godal in press).

In order to go beyond the basic understanding of the text, and also to keep highly speculative constructs at bay, we can employ GIS-based simulation as a new way to develop precise and testable hypotheses about Wulfstan's sea route from the meagre historical information. The simulation presented here does not operate on fictitious values, but is based on both historical information provided by Wulfstan's account and real-time data provided by experimental archaeology. In order to use the data provided by experimental archaeology, sailing voyages replicating Wulfstan's routing have to fulfill several strict conditions, such as natural propulsion (wind, currents, human power); a route from Haithabu to Janowo Pomorski; non-stop sailing during day and night; and no modern navigational aids (including sea charts and a compass). An earlier attempt to sail a hypothetical route of Wulfstan's voyage, by the Danish Marine cutter Barsø in 1993 cannot be used for our simulation since it did not fulfill any of the above mentioned conditions.

In the summer of 2004, a replica of the 11th century Skuldelev 1 vessel, the Ottar, reached Gdańsk, Poland from Schleswig, Germany, after sailing a total distance over ground of 390 Nmi in a little over four consecutive days and nights (A. Englert and W. Ossowski, official communication Wismar 28 September 2004). Although this voyage did not fulfil most of the conditions required of a real experimental voyage (the crew used modern navigational aids, the ship was sailed under motor in the Schlei and in Gdańsk and also stopped at anchor

1. For early Medieval Slavic settlements and artefact distribution see Hucke 1938: 4-43; Harck 1988: 299-314.

2. 'With persistent winds a rate of about 2 kn (100 cm/s) may be experienced, being strongest about 4.5 Nm offshore. With onshore winds and a swell from the NW, a dangerous S set may prevail. Statistics over the last 60 years demonstrate that 25% of all incidents involving vessels grounding offshore, particularly between Świnoujście and Jaroslawiec, about 87 miles NE, were caused by lack of appreciation and allowance for currents. With onshore winds it is advisable to keep well offshore until the weather improves before attempting a landfall' (United Kingdom Hydrographic Office, Baltic Pilot volume II – South part of Baltic Sea and Gulf of Riga, Taunton, 2002: 337). And this advice is for modern ships.

for the first night of the voyage etc.), the Ottar's real-time sailing data, its open sea routing, and the wind and current conditions were used in our GIS-based simulations to emulate the conditions from the real-world of sailing, inasmuch as the sailing capabilities of the vessel and the crew were the closest approximation one can presently get for replicating Wulfstans' sailing itinerary. The Ottar voyage was carried out as a result of a larger research project directed by G. Indruszewski at the Vikingeskibshallen and aimed on the theoretical and practical reconstruction of Wulfstan's voyage. The initial plan of sailing from Haithabu to Janowo Pomorski with a small-size historical replica was cancelled because of the crew's psychological and physical lack of preparation to endure the sailing conditions characteristic of 9th century navigation.

Replicated voyages and computer simulation have been used in other settings to develop and test proposed hypotheses about sea voyages in a systematic way (e.g. Heyerdahl 1950; Levison 1973; Irwin *et al.* 1990; Irwin 1992). While our focus here is on computer simulation, both methods have been applied to developing a more accurate reconstruction of Wulfstan's voyage and more generally for studying Viking seafaring. Through this chapter, we suggest an alternative and complementary means of testing and generating hypotheses about ancient sea voyages through computer simulation modelling. While this has generally been done through customized software, it could be more widely employed by archaeologists and historians if easily available 'off-the-shelf' packages could be used. Modern GIS software includes tools for simple modelling of movement across space. Here we present the initial results of using two types of such GIS tool sets to simulate Viking seafaring, using Wulfstan's voyage as a test case. Real-time sailing data, including routing and wind conditions collected during the Ottar's replicated voyage in 2004, were used to evaluate the GIS-based simulations. We compare sailing routes generated by a least-cost path (henceforth LCP) routine in ArcView 3.1 and an anisotropic spreading routine (hereafter AS) in GRASS 6 GIS (open source) with both the historical information and the real-time data from the replica voyage from Schleswig to Gdańsk.

Research methods

As already mentioned, we employ two GIS methods for modelling movement across surfaces to simulate Viking Age sailing, and for both modelling tests, we focus on wind intensity (velocity) and direction as the primary drivers of a sailing vessel. Currents, although relatively weak in the southern Baltic, would have also affected sailing routes in that period. At this point, however, we chose not to include currents in our simulation. The main reasons for this decision were that we do not have clear information about currents affecting Ottar's voyage in 2004 as we do for wind and, more importantly, the algorithms used in each GIS method of computation do not permit the incorporation of a second force vector to drive movement (though either method could be extended to do so). Below is a brief overview of each simulation method.

LCP modelling has been used extensively in GIS applications for identification of optimal routing based on user-defined criteria. Optimal routing seeks to minimize travel costs between an origin point and destination point across a terrain where movement can be affected (encouraged or impeded) by variables such as slope, vegetation, urban attributes, and water vicinity. In applying LCP to a sailing voyage, a trailing wind is treated conceptually like going downslope on a topographically variable terrain, while a headwind is treated like travel upslope. In brief, the LCP procedure, as implemented in GIS, involves the following steps:

- Create one or more cost surface raster grids, where the value of each grid cell represents the absolute or relative costs of (or resistance to) movement at every location in the research area. In our case this is derived from wind velocity.
- Create an accumulated cost distance grid, where each cell represents the total costs of travel (based on the combination of all relevant cost surfaces)

from a starting location (source or origin point) to all other locations in the study area.

- Optionally, create a backlink grid (cost-direction-surface) from the accumulated cost surface that indicates the directionality of travel costs in each grid cell (e.g. it costs more energy to travel upslope than downslope). We use wind direction in this calculation (i.e. a tailwind decreases movement costs while a headwind increases them).
- Calculate a path that minimizes total costs from the source to a desired end location (the destination) across the accumulated cost surface. This path is the modelled sailing route.

AS is less well-known than the LCP analysis. It models the spread of a phenomenon across a terrain from a point of origin. Perhaps the most common usage of AS procedures in GIS is in modelling the spread of wildfires. The rate and extent of spread for a wildfire can be affected by topography and forces that have both intensity and direction (such as wind), causing it to spread unequally in different directions (e.g. faster downwind and uphill). It might seem odd, at first, to use modelling algorithms most widely used for fire to simulate travel across water. However, in some ways, it may be more realistic than LCP. Conceptually, a vessel is treated as a specific point on a fire front that is driven by wind of variable velocity and direction, over a given time period. The AS routine also can calculate back from any given point on a fire front to its point of origin, tracing the route it took under variable environmental (i.e. wind) conditions.

The AS routine in GRASS is optimized to model the behaviour of wildfires (Jianping 1994). Hence, as input, it requires information about parameters that commonly affect wildfires: the speed and direction of the wind, the slope and aspect of the topography, and characteristics of the vegetation that is burning. In order to use this routine to model a wind-driven sailing vessel traversing the Baltic Sea, we used a level plane 'topography' and chose grassland for vegetation. In spite of waves at local scale, the sea approximates much more closely a plane than a hilly or mountainous terrestrial landscape. Fire spreads variably across space in forest and woodland, depending on such parameters as moisture content, the amount of downed wood, and the relative densities of arboreal and shrub vegetation. Grass, on the other hand, burns quickly and evenly in all directions across a level plane, except as influenced by the wind, as would be expected for wind blowing unimpeded across the sea surface. As developed in GRASS, AS modelling involves three major steps:

- Using a series of raster maps that represent the parameters which influence the spread as values for each grid cell (e.g. maps of wind direction and wind velocity), to create three raster maps showing: 1) the maximum rate of spread (henceforth ROS) in the primary direction of spread (i.e. downwind, in our case); 2) the direction of the maximum ROS; and 3) the ROS perpendicular to the primary direction of spread (this has no impact in our example here, but is required for subsequent steps).
- The three ROS maps produced in the first step are then used to model the spread phenomenon (in this study, wind-driven sailing routes). This second step produces a graphic simulation of the AS, as well as a map of the cumulative duration of spread and a map containing the backlink information.
- In the third step, the backlink map is used to calculate the most probable spread path from the origin point to the destination. This is the modelled sailing route for the example presented here.

In order to make our simulations more realistic, we constrained them to the possible water routes that Wulfstan could have taken. We set all land areas—island and continental—to null value masks so that the costs surface for LCP and spread maps for AS routines would be limited to the grid cells over water and extending eastward from the western coast of Denmark to east of the Vistula River mouth. We used wind data encountered by Ottar during its 2004 Baltic voyage for this test of GIS-based simulation methods. Wind speed and direction measurements were collected for every 10' of latitude and longitude across the Baltic Sea between 54º and 56º N and 10º and 20º E for the duration of the Ottar's voyage **[Plate 1]**. These measurements were then reprojected to UTM Zone 32 and interpolated to continuous raster grids of wind speed and direction at a 1-km resolution **[Plates 2-3]**, using Regularized Spline Tension in GRASS 6 (Mitas & Mitasova 1999; Hofierka *et al.* 2002), that were subsequently used for LCP and AS modelling.[3]

The AS sailing simulation in GRASS

The AS routine models the spread of phenomena over a given surface during a given period of time, taking into account the effects of spatial heterogeneity in local conditions on the unevenness of spreading (i.e. anisotropy) in different directions. Here, relevant spatial heterogeneity included wind velocity, wind speed, and the distribution of land and water. As described above, wind data collected during the Ottar's voyage were interpolated to raster maps of wind speed and wind direction. The interpolated raster maps of wind speed and direction extended to a 20-km buffer beyond the original data grid to minimize edge effects in subsequent models. A digital elevation model (DEM) of the Baltic area, interpolated in GRASS from a file of elevation points for the region (Seifert *et al.* 2001), was then used to mask out the land area from the wind speed and wind direction raster grids. In this manner, all modelling was restricted to those parts of the Baltic Sea relevant to the voyage.

The simulation was done in three major steps, as noted above, using the AS module for wildfire modelling in GRASS 6. For surface topography, we created a level plain DEM to represent the Baltic Sea surface. Wind velocity had to be converted from minute/second to feet/minute for the modelling routine. For the required vegetation input, we empirically tested several U.S. Forest Service fuel models (Rothermal 1983) before settling on a grassland model, as noted above. The fuel models are based on the burning parameters of different categories of vegetation, including the mass of fuel per unit area (fuel loading), fuel depth, fuel particle density, and the heat of burning for each fuel. We tried timber, brush, chaparral, and tall grass. We used default USFS values for fuel moisture in dead and live vegetation in different vegetation communities. Slower burning models (e.g. timber) spread more evenly in all directions and are not driven by the primary wind direction and speeds, as were vessels like the Ottar. Many of these models failed to spread across the Baltic Sea to the eastern edge of the study region, even when we weighted the primary ROS before using it in the spread simulation analysis. Faster burning fuel models (e.g. tall grass) spread most rapidly in the main wind direction, mimicking a sailing ship being driven by wind, and were better able to spread across the entire study region. The fuel model we used had the fuel source input as a constant across the whole study region (rather than as a map of spatially varying vegetation).

The most successful simulation used the tall grass fuel model with standard values of 3% for one hour fuel moisture and 0% for live fuel moisture **[Plates 4-6]**. However, it was still necessary to multiply the maximum ROS and base ROS by ten in order to create a model that would spread across the entire Baltic study area, a much larger area than that of a normal wildfire **[Plates 7-9]**. These issues are related to the specific wildfire implementation of the AS routine in GRASS rather than considerations about the usefulness of the underlying AS algorithm. The starting point of the anisotropic spread was set at the mouth of the Schlei

3. The following data sources were used in this analysis: 1) Sea bottom data: Seifert et al. 2001; Bundesamt für Schiffahrt und Hydrographie 3021/3022 (2003/2004) Charts; Deutsches Hydrographisches Institut, Die Ostsee mittlerer Teil (1930). 2) Wind data: M. Ketzel, Danish Meteorological Institute, Risø, Denmark (pers. comm. Roskilde 2005); Denmark Meteorological Institute, http://www2.dmu.dk/AtmosphericEnvironment/thor/metindexdk.html; Air Resources Laboratory, NASA, http://www.arl.noaa.gov/ready/amet.html; Jet Propulsion Laboratory, NASA, http://poet.jpl.nasa.gov; WindData.com, http://130.226.17.201/site_distrubutions.php?site_code=roedsand&country=Denmark. 3) Sea current data: Bundesamt für Schiffahrt und Hydrographie, http://www.bsh.de/aktdat/modell/stroemungen/Modell1.htm9; and Meteomedia Wetterstationen, http://wetterstationen.meteomedia.de/messnetz/.

Fjord in northern Germany at 54° 41 latitude north, 10° 02 longitude east. By setting all input variables except wind to constants, the GRASS wildfire routine produced a resultant raster grid of the spread and associated backlink grid based on the wind velocity and direction in the study area. This approximates the likely paths taken by a simple sailing vessel outward from Schlei Fjord given the weather conditions recorded during the Ottar's voyage in 2004.

The LCP sailing simulation in ArcView

The LCP simulation was more difficult because ArcView normally requires a single DEM of topography, from which it calculates cost intensity and cost distance from the slope, and cost direction from the aspect. We tried various methods to combine wind speed and direction into a single DEM of sailing conditions, without success. On the other hand, multiple cost variables or cost direction variables can easily be combined. For example, combining wind direction and current direction produced apparently meaningful results **[Plate 10]** from the mouth of Schlei Fjord eastward across the Baltic. This avenue deserves more research in order to be used in subsequent simulations and to model more accurately the parameters affecting sailing.

Fortunately, it is possible to input two separate grids representing cost intensity and cost direction into ArcView. We followed this approach, setting wind strength as the cost intensity (equivalent to slope calculated from a DEM) and wind direction as cost direction (equivalent to aspect calculated from a DEM). As with the AS analysis in GRASS, we set all land grid cells equal to null so that the LCP analysis would only take place on sea grid cells **[Plate 11]**. ArcView calculated an accumulated cost distance map from wind velocity without difficulty **[Plate 12]**. However, using wind direction as cost direction **[Plate 13]** was considerably more problematic.

Intuitively, wind direction values should be 180° from an aspect value in a DEM needed for LCP analysis. This is because a wind from the west will reduce the cost of a vessel travelling towards the east, equivalent to travelling downslope on an east-facing slope. Surprisingly, creating a cost direction grid in this way did not have the desired result but instead produced completely meaningless LCPs, such that no path from Schlei Fjord to the Vistula River mouth could be calculated. After additional testing, we discovered if we used a normal wind direction raster map and allowed ArcView to create a cost direction grid from this map (i.e. another cost direction grid) and this direction grid was combined with the cost distance map created from wind velocity, we were able to achieve a meaningful LCP **[Plate 14]**.

The results of the LCP analysis closely match both the AS analysis and the actual path of the Ottar, suggesting that they are correct if wind velocity and direction are the primary variables influencing the route. However, the final cost direction grid used in the LCP analysis was created automatically from the input cost direction grid (i.e. wind direction) by an undocumented ArcView routine. Because the software is proprietary (produced and distributed by ESRI) and the underlying code is not accessible to users, leaving us uncertain about the wider applicability of this particular approach. There is no documentation in ArcView as to the kinds of values needed for a valid cost direction grid. We tested various possible combinations of values for cost direction and all except the method described here gave spurious results. Hence, we recommend caution when using this routine until it has been tested further or properly documented.

Discussion

The final step in both GRASS AS and ArcView LCP analyses was calculating a probable sailing route from Schlei Fjord, Germany to Janowo Pomorski, Poland as an anisotropic least-cost path in the GIS routines. These routes are shown in **Plate 15**, along with the route of the 2004 Ottar voyage. Both simulations closely match the Ottar's actual route, navigating off the southern coastlines of Lolland and Langeland, southern tip of

Falster, and around Bornholm's southern shores, before heading eastward across the open Baltic.

The AS routine in GRASS 6 seemed to track more closely a sailing route influenced mainly by wind conditions than did the ArcView LCP routine. The change in wind direction at the foot of the Hel Peninsula caused the path to veer towards the northeast, which would be normal for a ship propelled primarily by the prevailing wind and whose skipper is sufficiently skilled to forecast the subsequent wind change. In spite of the cautions expressed above, the ArcView-generated LCP also matched closely Ottar's voyage from Schleswig, Germany to Gdańsk, Poland, although it seems somewhat less sensitive to shifts in wind direction than the AS routine. The fact that both routines produced similar results that closely match a real voyage suggests that GIS-based simulation has considerable potential for modelling ancient sailing routes.

As noted previously, three routes have been proposed for Wulfstan's 9th century voyage: 1) a route developed on the basis of historical and archaeological considerations (the O. Crumlin-Pedersen 1983 line in **Plate 16**, marked OCP 1983); 2) an actual coastal voyage carried out in 1993 by the Danish Navy cutter Barsø (marked Barsø 1993), which attempted to recreate the Crumlin-Pedersen's hypothetical route; and 3) the early Medieval ship replica Ottar's open sea voyage (marked Ottar 2004). The next stage of our GIS modelling of Viking seafaring will be to simulate sea routes based on monthly and seasonal average weather conditions in the eastern Baltic in order to better evaluate which of these (or other) routes are more likely. We also hope to be able to incorporate sea current data into our simulation in the future to better account for the combinations of wind and current conditions that affected Viking seafaring. GIS-based modelling is a promising means of recreating the spatial and temporal dynamics of ancient societies from the static remains that make up the archaeological record.

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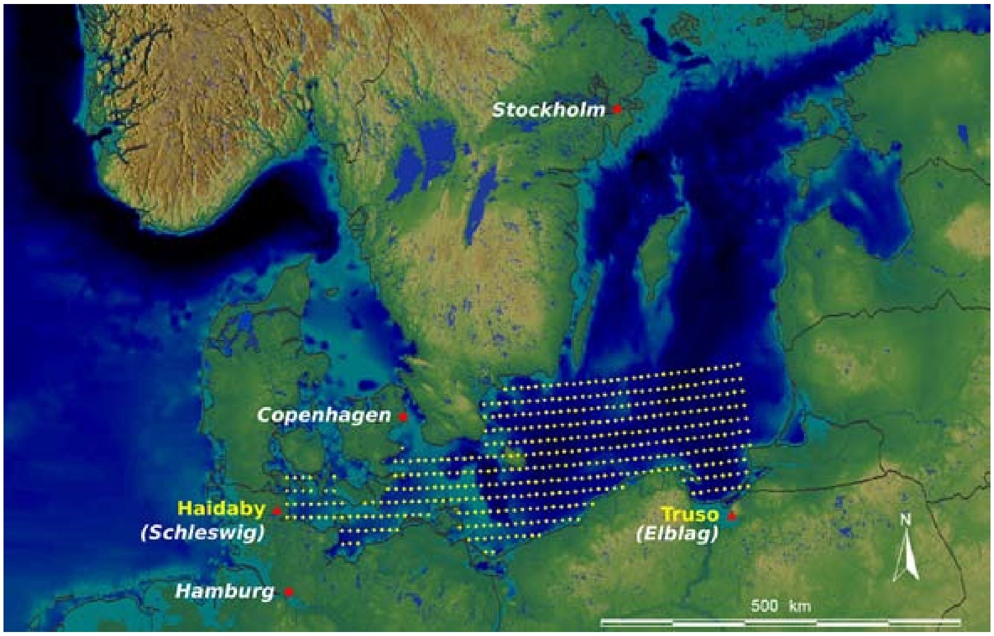
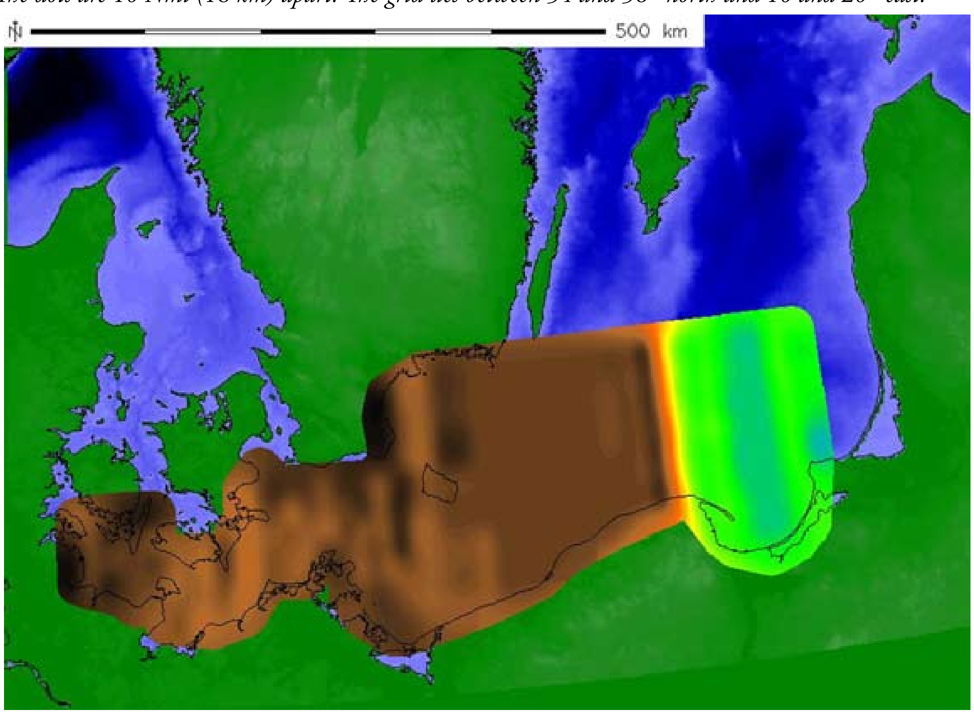
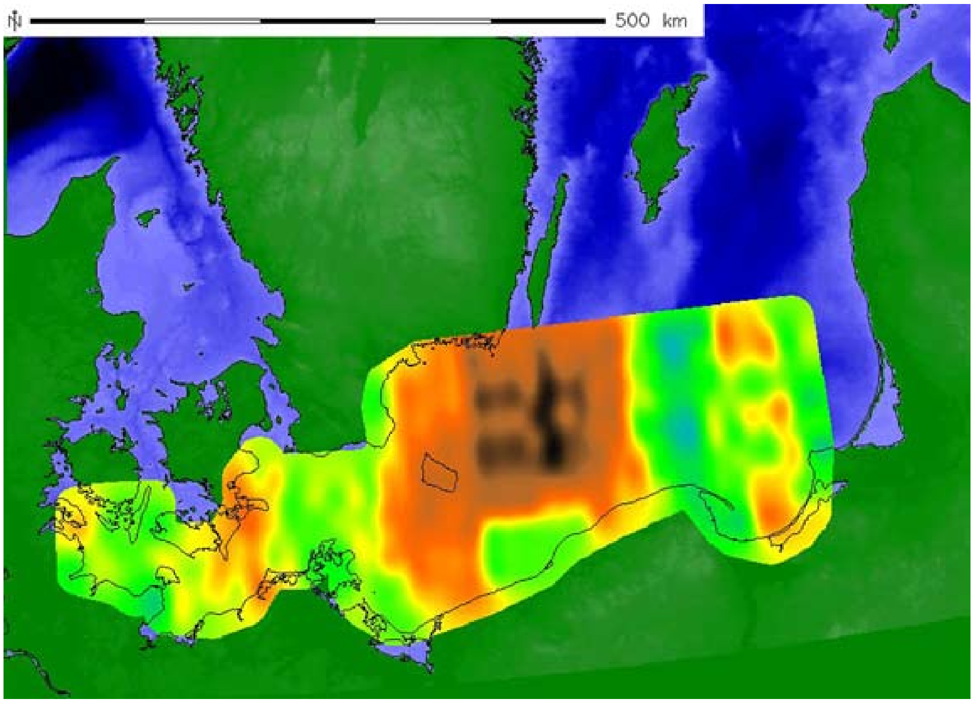


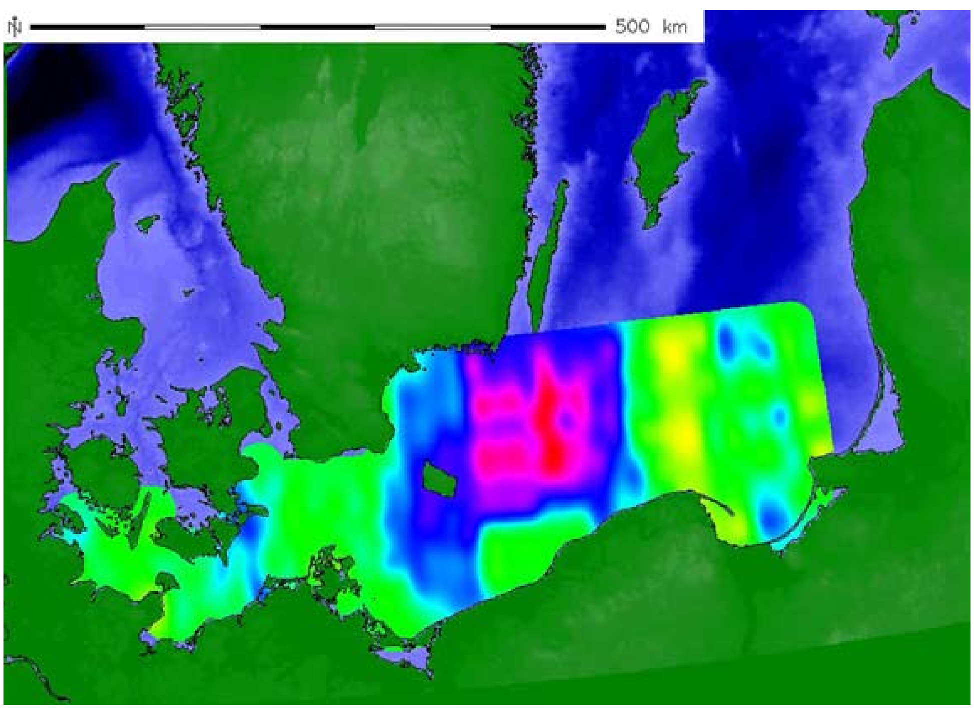
Chapter 5, Plate 1. *Study region in the Baltic, showing the area of Wulfstan's voyage (see text). Locations of wind and current data collected during the 2004 voyage of the Ottar and used in GIS modelling experiments are shown as yellow grid. The grid is used for generating a least cost path (LCP) between the beginning and endpoint. Each dot on the grid contains data on wind speed (raster) and direction (vector). The dots are 10 Nmi (18 km) apart. The grid lies between 54 and 56° north and 10 and 20° east.*



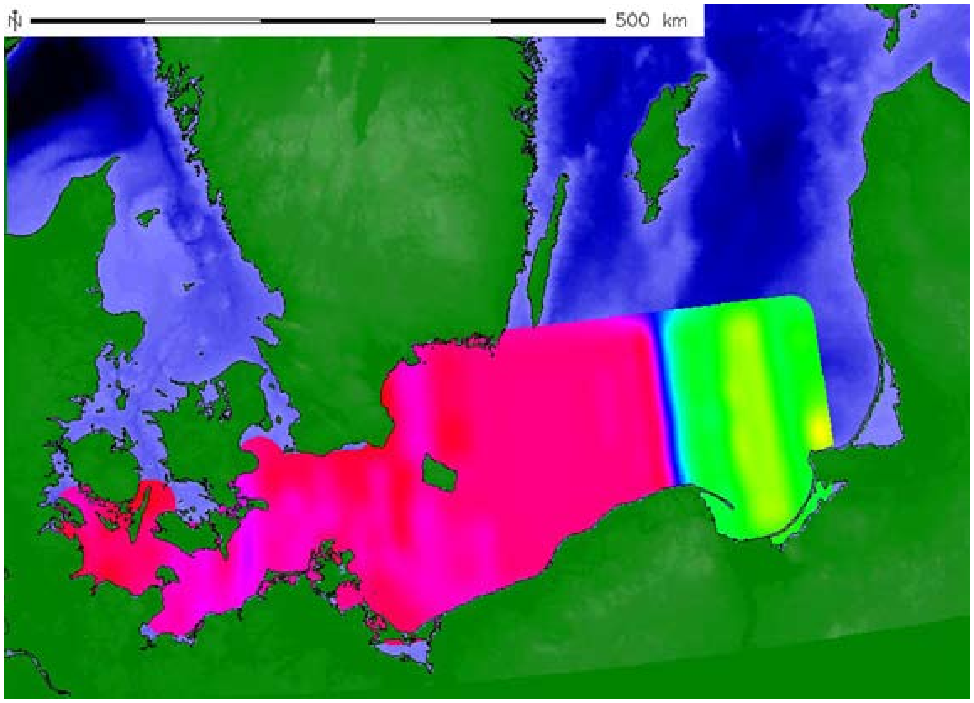
Chapter 5, Plate 2. *Wind speed raster grid map (shaded zone extending eastward from southeastern Jutland) interpolated from 10' data points in GRASS 6. Lighter is lower velocity and darker is higher velocity.*



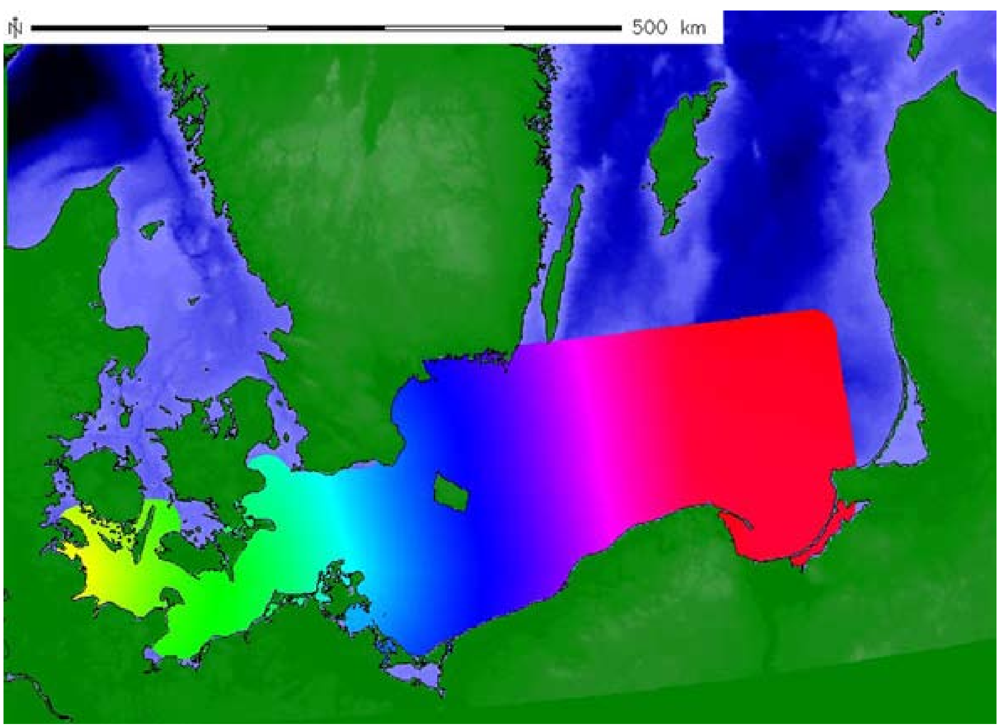
Chapter 5, Plate 3. *Wind direction raster grid map, interpolated from 10' data points in GRASS 6. Lightest is a west wind, darkest is an east wind, and medium grey is a southwest wind.*



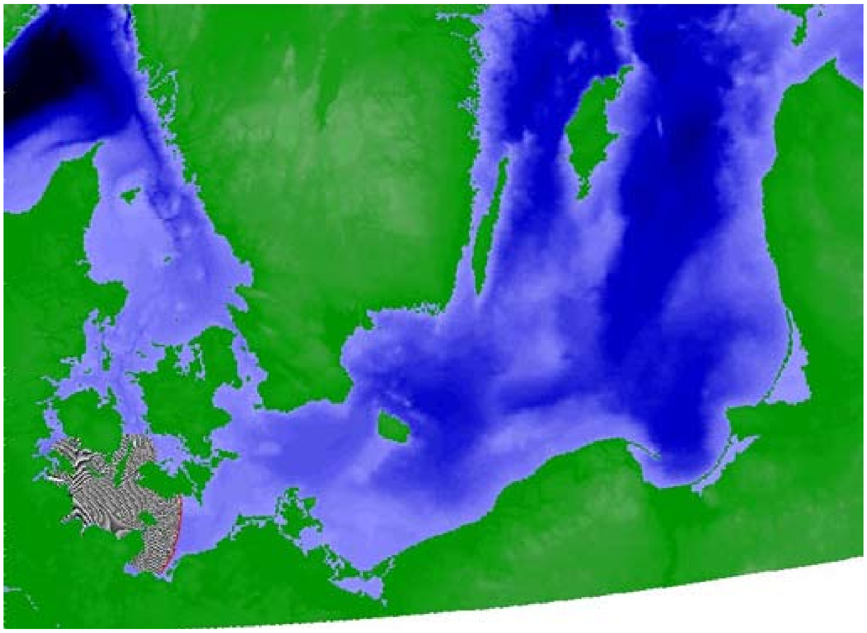
Chapter 5, Plate 4. *Maximum rate of spread (ROS) calculated in the GRASS 6 anisotropic wildfire spreading module with wind as the primary spread-generating parameter. Lightest is fastest and darkest is slowest.*



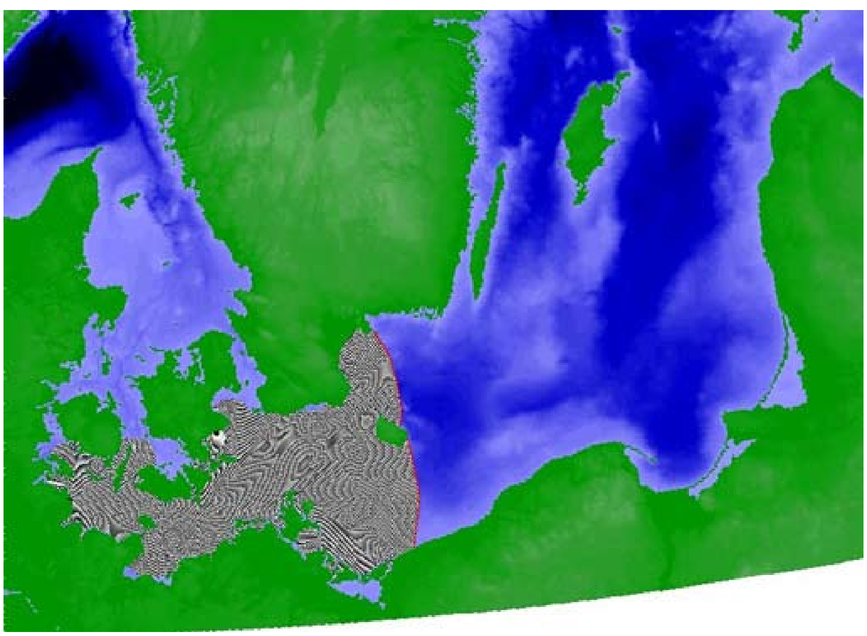
Chapter, Plate 5. *Direction of maximum rate of spread (ROS) calculated in the GRASS 6 anisotropic wildfire spreading module with wind as the primary spread-generating parameter. Lightest is an easterly spread, darkest is a western spread, and medium grey is a northwestern spread.*



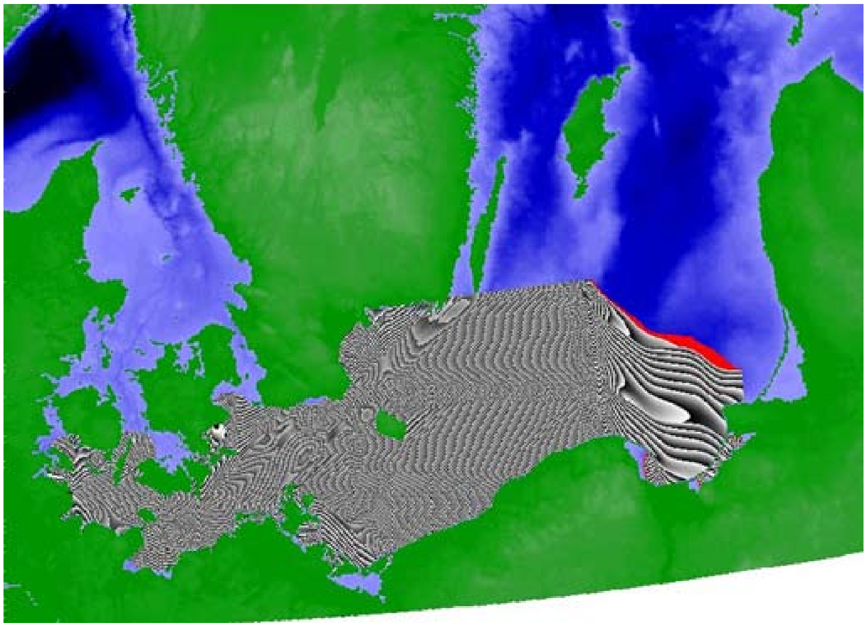
Chapter 5, Plate 6. *Cumulative spread time calculated in the GRASS 6 anisotropic wildfire spreading module. Time runs from lightest to darkest.*



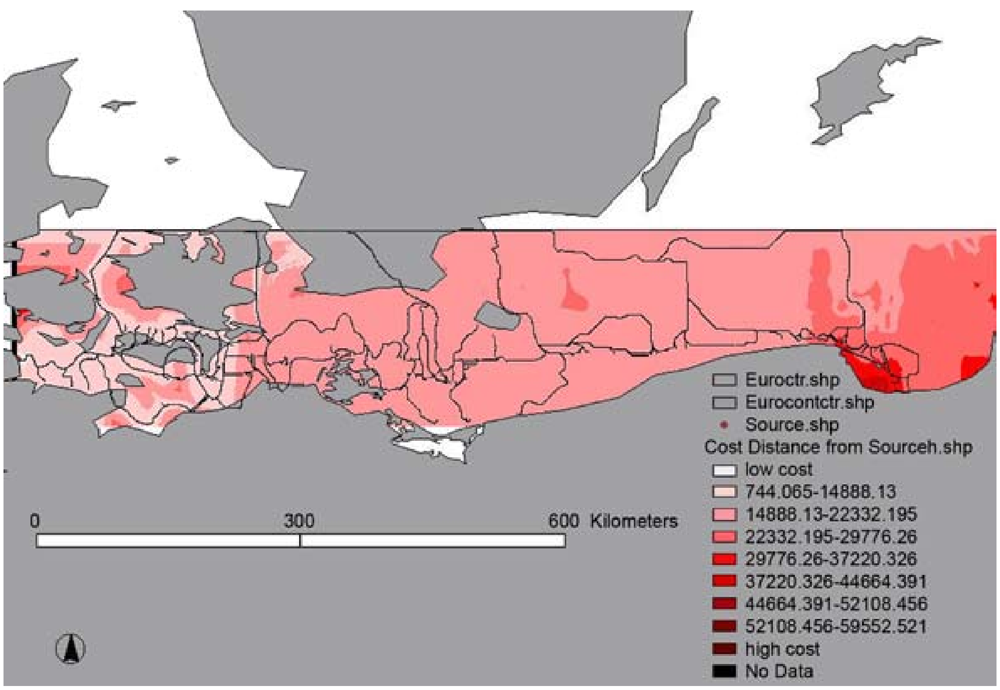
Chapter 5, Plates ***7-9.*** *Screen shots of wind-generated spread simulation generated by the GRASS 6 anisotropic wildfire spreading module. The spread is shown as grey-patterned area beginning at the southeastern coast of the Jutland peninsula and extending progressively eastward.*



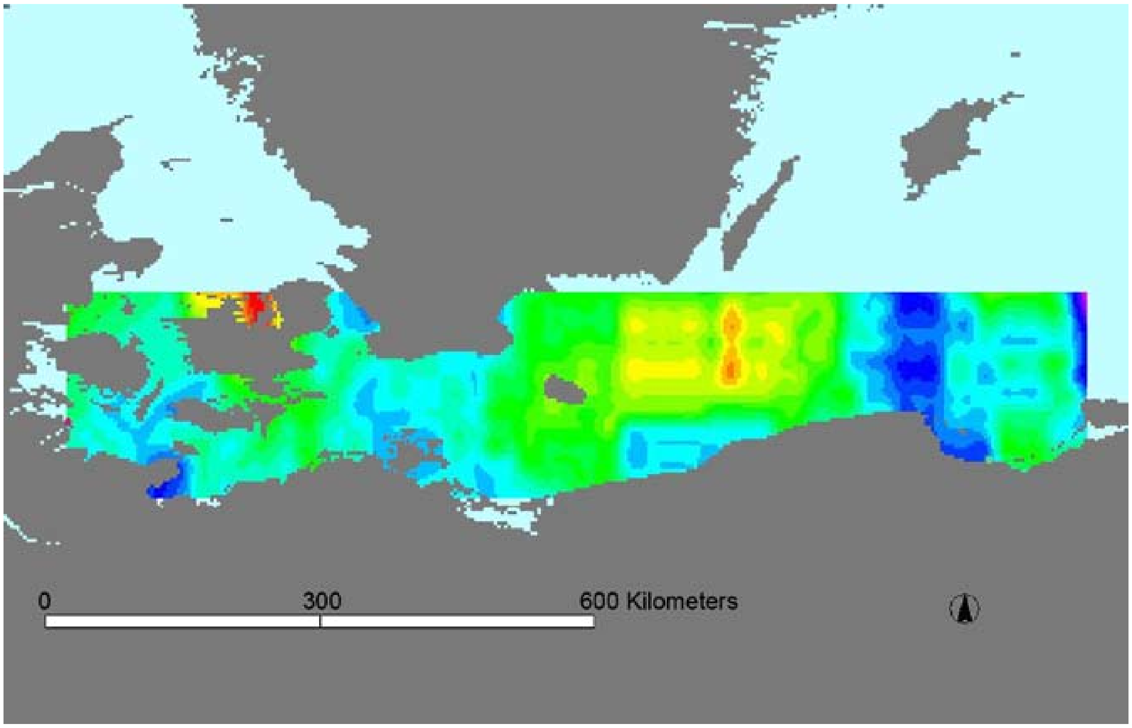
Chapter 5, Plate 8.



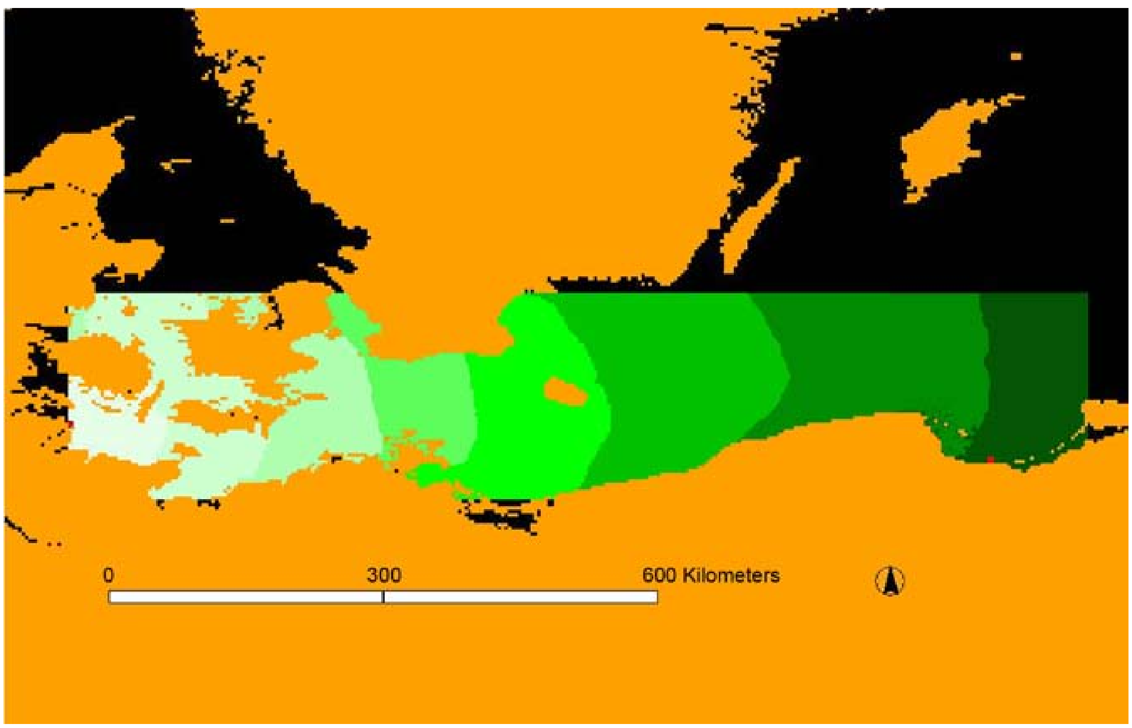
Chapter 5, Plate *9*.



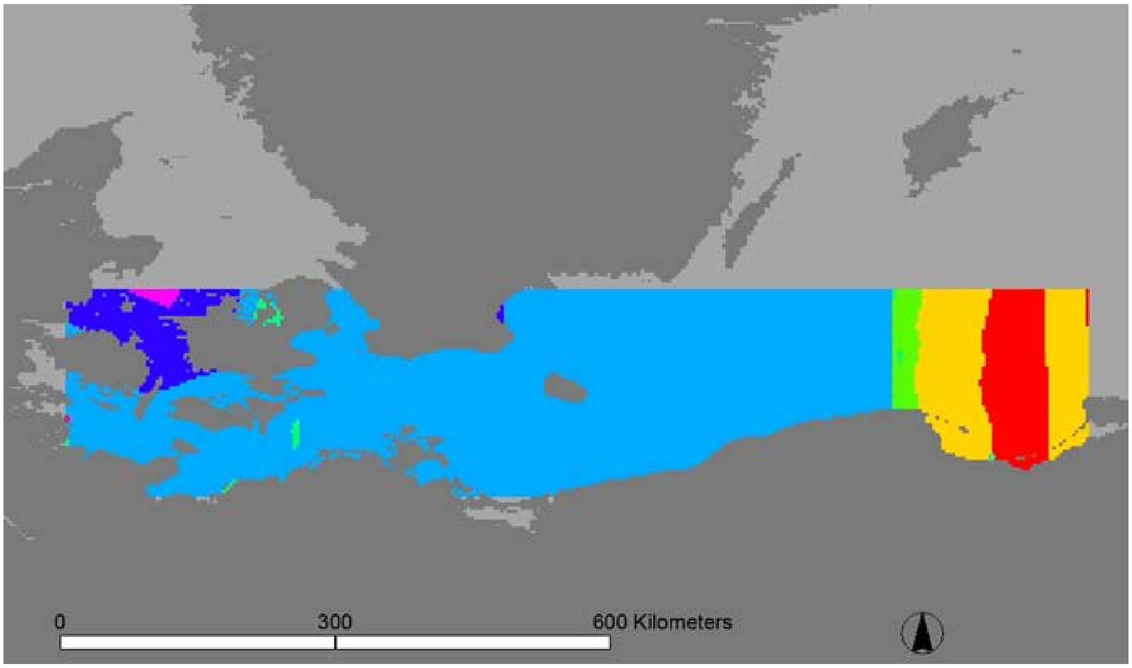
***Chapter 5, Plate 10.** Wind direction grid generated by ArcView 3.1.*



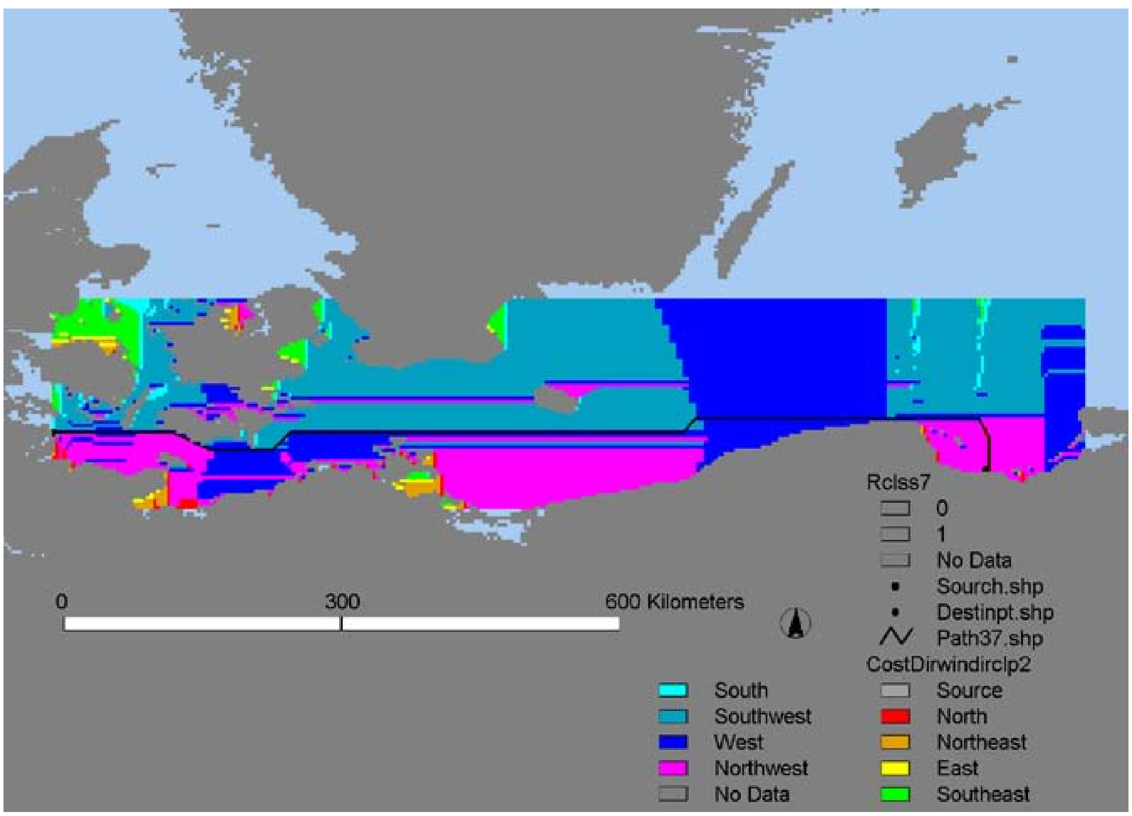
Chapter 5, Plate 11. *Cost surface based on wind velocity generated by the ArcView 3.1 least cost path routine. Lightest is lowest cost and darkest is highest cost.*



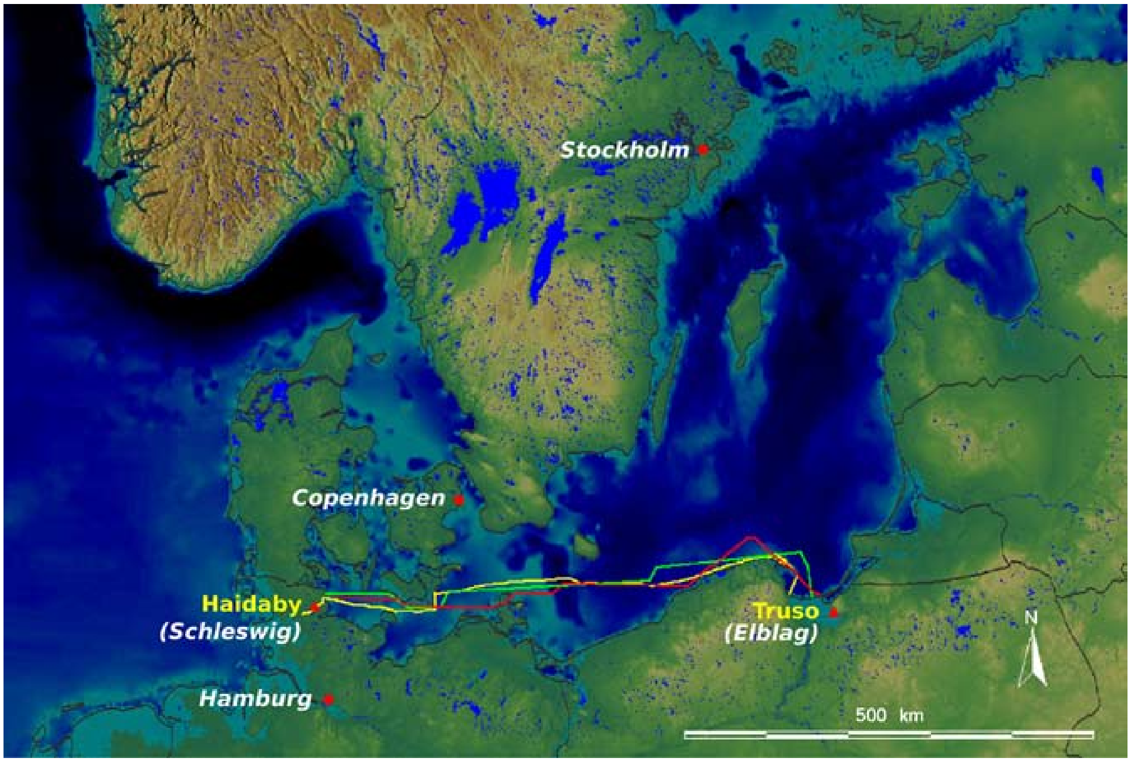
Chapter 5, Plate 12. *Accumulated cost distance grid generated by the ArcView 3.1 least cost path routine. Lightest is lowest cost and darkest is highest cost.*



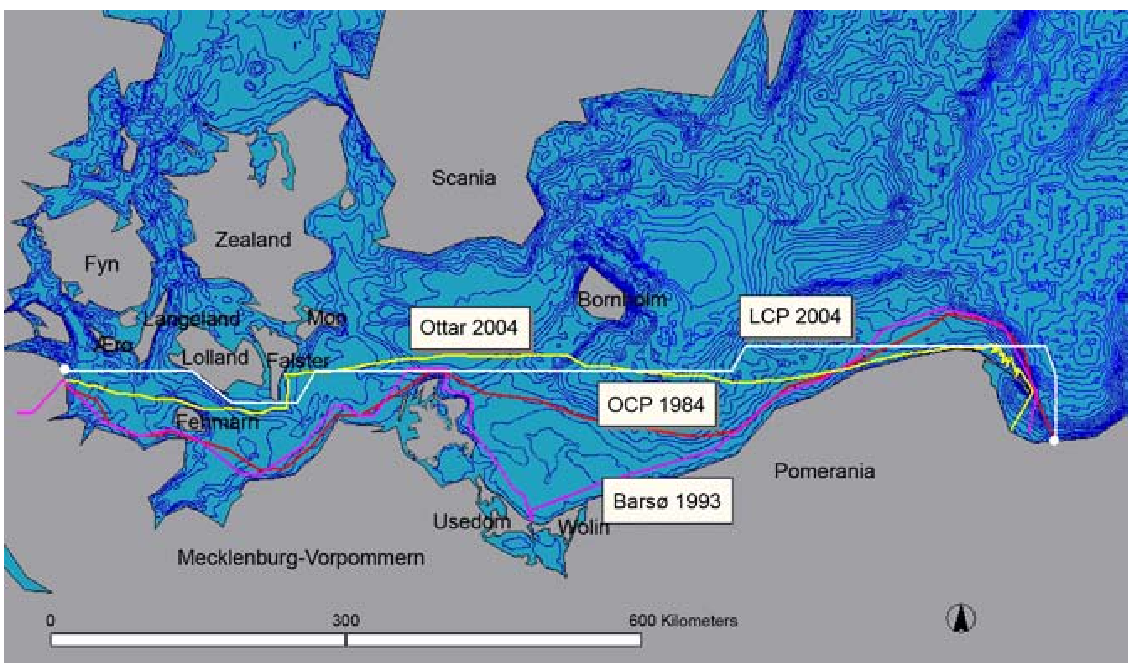
Chapter 5, Plate 13. *Wind direction grid generated by ArcView 3.1.*



Chapter 5, Plate 14. *Backlink least cost path analysis grid generated by the ArcView 3.1 least cost path routine. White line traces the least cost path from Schlei Fjord to Gdansk.*



Chapter 5, Plate 15. *Ottar 2004 route (yellow line) and GIS modeled routes. Most probable spread path from Schlei Fjord to Gdansk generated by the GRASS 6 anisotropic wildfire spreading module is shown in red. The green line traces the best least cost path generated in ArcView 3.1.*



Chapter 5, Plate 16. *Routes of the Ottar in 2004, the Barsø in 1993, and Crumlin-Pedersen's proposed route (see text for explanation). Arcview-generated least cost path shown for comparison.*