Greenland Norse Knowledge of the North Atlantic Environment

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The arcing Norse expansion across the sub-polar North Atlantic ocean traces an inspiring tale of a stoic struggle against the elements. The sequence of accidental discovery, then deliberate exploration and settlement, repeated in turn as Faroe, Iceland, and Greenland were colonized between 825 and 985AD. With each step further west, the difficulty of leading a contemporary Norwegian lifestyle increased. In part, the increasing hardship is linked to the increasing distance from European power, and the dwindling access to essential commodities. Contact with alien native communities is another factor, and it was decisive in obstructing long-term Norse settlements in North America. But at almost every stage, the much colder, more polar, climate in Iceland, Greenland, and eastern Canada dominated the Atlantic Norse decision-making.

Despite the rigors of the climate, the Norse constructed a society in Greenland that endured for nearly 500 years. In total, perhaps 70,000 people lived in the eastern and western settlements in southwest Greenland[1]. Eventually, the farms were abandoned, however, sometime in the mid-to-late 1300s for the western settlement, and sometime in the mid-to-late 1400s for the eastern settlement. The reasons for the disappearance of the Norse settlers has long been debated, and uncontroversial evidence that resolves this issue has not yet been found. What is clear instead is that the Greenland Norse maintained an intimate daily relationship with the North Atlantic environment. Although they did not adopt the native Inuit strategies to survive, the Norse farmed, fished, hunted, and sailed in Greenland with confidence and skill for many generations. Their attitude is

presumably reflected in the modern northern Norwegian saying “Vi står han av” (meaning “we stand tall, regardless of stormy weather”[2]). This close exposure to the unforgiving Greenland climate undoubtedly led to a detailed intuitive knowledge of the sea, weather, and ice.

Exploring this understanding, and its limits, is the subject of this essay. In particular, the aim is to document and discuss Norse knowledge of oceanographic phenomena including tides, non-tidal ocean currents, surface water properties, and sea ice. The clear-cut evidence on these questions is insubstantial. Nevertheless, we propose that medieval Norse knowledge of them was quite advanced, albeit lacking any modern conceptual foundation. A key line of reasoning to support this view concerns driftwood. Timber was a critical resource in the middle ages, and was a premium commodity in Norse Greenland. For this reason, the second theme here is to explore and understand the Greenland Norse relationship with wood, and with driftwood especially. On this topic, the main questions are: how did the Norse colonists use wood, what were their sources, and might lack of timber have contributed to the demise of the Greenland colonies? Again, the North Atlantic environment plays a key role.

The approach is to utilize multiple sources of information, including historical documents from the period, archaeological data from modern excavations, and oceanographic knowledge about the northern high latitudes. In what follows, we refer frequently to

Kristen Seaver's scholarly study of the Greenland Norse[3]. An earlier assessment of Viking knowledge of environmental conditions by the present author is also relevant[4], and is extended and expanded here.

Norse Environmental Knowledge

First, consider what the Norse may have understood about tides, ocean currents, surface ocean temperature and salinity, and sea ice[5].

There are abundant references to the tides in medieval documents from Iceland and Norway. For example, in Erik's Saga Thorfinn Karlsefni reaches Hop (tidal lake) in Vinland, and the story reads “they dug trenches at the high-tide mark, and when the tide went out there were halibut trapped in the trenches”[6]. This is unambiguous evidence of Norse appreciation for tidal range, that is, the tidal variation in water level. Such knowledge is unsurprising, given the important role that water level plays in coastal seamanship. The saga about Karlsefni's Vinland expedition also refers to currents. For example, Erik's Saga tells that early in the voyage the ships entered a fjord and “at its mouth lay an island around which there flowed very strong currents, and so they named it Straum Island (current island)”. The fjord itself they named Straumfjord. Although it is possible that these currents were non-tidal currents, it is unlikely: tidal currents generally dominate the circulation in confined fjords. Indeed, strong tidal currents would have been familiar to many Viking sailors. The northeast Norwegian coast supports the two

strongest tidal whirlpools in the world: the Saltstraumen near Bødo, and the Moskstraumen off the Lofoten Islands (also called the Maelstrom, and popularized by Jules Verne, Edgar Allen Poe, and Herman Melville). The Carta Marina, a magisterial 1539 map of the sea by Olaus Magnus, depicts the Moskstraumen, and an unfortunate vessel it has captured. The Norse circa 1000AD were therefore certainly aware of tidal currents as well as tidal water-level variations. Finally, there is clear evidence of Norse knowledge of the fortnightly spring-neap cycle of the tide--“at full moon the flood tide is again very high and the ebb is strong”--in the King's Mirror, written around 1250[7].

There are no direct references to ocean currents--that is, non-tidal circulation--in the sagas. A number of indirect lines of evidence suggest, however, that both the existence and the basic structure of the surface circulation were known 1000 years ago[8]. Before discussing this evidence, the nature of the flow itself is summarized. **Figure 1** presents the currents. Specifically, it shows contours of (non-tidal) sea-level which are streamlines for the circulation. This statement means that the surface currents flow on average along the contours, and their speed is proportional to how tightly packed the contours are (exactly analogous to the wind blowing along contours of surface pressure on a weather map). Figure 1 is made by averaging measurements from satellites and *in situ* gauges over several years. The flow on any particular day will depart somewhat from what is shown, mainly because of 30-100km-scale eddies, which are akin to atmospheric weather systems. The flow around Greenland, off Labrador and around Newfoundland is

particularly important. The circulation is narrow and strong near the coasts in these areas, and a sequence of currents connects them: the East and West Greenland Currents flow southwest and northwest, respectively, and the Labrador Current flows southeast. The strongest currents are near the breaks in the continental shelves, where the water depth rapidly increases, but there are inshore coastal branches of these currents too. Off East Greenland, the continental shelf is 250km wide near Iceland, but it narrows to just 30km at the southern tip of Greenland (Cape Farewell). Off the eastern and western Norse settlements in southwest Greenland the shelf is also narrow, but the wide, deep Davis Strait bridges Greenland and Baffin Island. Here, the West Greenland Current splits, and a large part flows away from Greenland across Davis Strait to then turn south at Hudson Strait, and feed the Labrador Current. The Labrador Current continues southeast along the Newfoundland continental slope to impinge on the strong North Atlantic Current east of Newfoundland. Here, part of the Labrador Current recirculates offshore to the north and east, and part skirts southwest, inshore of the North Atlantic Current via the Gulf of Saint Lawrence. Away from the continental slopes, in the deep Irminger, Labrador, and Newfoundland Basins, the currents are weaker, and much more variable in direction. The gray shading in Fig. 1 shows how, on average, the surface water flows counter-clockwise in these currents to form a gyre: the narrower the gap between the contours, the faster the current, because the same volume of water is flowing round the circuit on average. Peak speeds in this system are 2-4 knots (1 knot is about 0.5m/s, or 43km/day; for comparison the exceptional Saltstraumen has a peak speed of around 20 knots).

Figure 2 shows the summer surface temperature distribution in the North Atlantic Ocean. The year 2008 is chosen, but this day is typical of modern conditions, and also conditions in the middle ages (changes due to global warming, or year-to-year variations are small compared to the large range of temperatures shown). The temperature map is made using a synthesis of satellite and *in situ* observations. The East Greenland, West Greenland, and Labrador Currents carry cold water, whereas the North Atlantic Current, fed from low latitudes, is much warmer. The water temperatures in coastal Greenland rarely exceed a few degrees Celsius. The strong circulation around Greenland mentioned above associates with a strong gradient in surface temperature, however. In particular, the East Greenland Current forms a front between offshore waters at 10C or higher, and coastal waters at 6C or lower. It is warmer on the offshore sides of the West Greenland and Labrador Currents too, although the differences are less.

The summer surface salinity distribution shows a similar pattern to temperature in the western North Atlantic, as seen in **Figure 3**, for 2003. Salinity, the concentration of dissolved salts in seawater, is harder to measure from space than sea-surface height and temperature, so Fig. 3 shows output from a numerical simulation of the Arctic and subarctic Oceans. Although there are some aspects of the simulation which are not realistic, the surface salinity distribution on the scale of the sub-polar North Atlantic Ocean, is reasonably accurate, and it suffices for the present purposes. The summer of

2003 is shown which is representative of modern and medieval conditions, although east Greenland sea ice extent was below average that year. The map shows that the cold coastal waters are substantially fresher than the warm waters offshore. The salinity contours are tightly packed on the east Greenland and especially the Labrador continental shelves. The freshwater on these shelves has come mainly from melting of Arctic and Canadian Archipelago sea ice. The small scale structure in the salinity contours are due to the eddies mentioned above, which are quite realistic in the numerical model.

A number of aspects of these phenomena were likely known by the Norse. For example, Norse sailing ships could typically make 4-8 knots, occasionally 11 knots, based on experience with modern replica vessels[9]. Ocean current speeds of 2-4 knots therefore make a significant difference to long voyages. A vessel drifting with the current in a calm would cover 40-90 km per day. Fridtjof Nansen drifted in the East Greenland sea ice, for example, while attempting to land and begin the first crossing of the ice cap in July 1888. His party was trapped on the ice for 12 days and covered 50-80km per day in the East Greenland Current[10] (see also discussion below on sea ice). Similarly, the steady progression of the ice in the West Greenland Current can be observed from the outer skerries of the eastern settlement. Careful Norse navigators would have been aware of these phenomena too, and therefore of the boundary current system itself around Greenland and Labrador.

Moreover, the temperature and salinity structure of the boundary current system would naturally aid navigation. Sailing to the Greenland settlements from Iceland would be most easily accomplished by first crossing Denmark Strait to raise the Greenland mountains and reach the cold fresh East Greenland Current. Next, Norse seafarers would sail southwest with the current, keeping with the cold, fresh water, or heading west to regain it as necessary, but avoiding the ice. The prevailing winds off southeast Greenland would also help: the wind often blows from the northeast, parallel to the coast, so one can simply sail downwind for long reaches. Indeed, the earliest records, from the mid-thirteenth century King's Mirror are consistent with these sailing directions[11]. The early fourteenth century Landnamabok also explains how to reach Greenland from Norway by sailing west from Hernar (near Bergen), and then passing Iceland close to starboard, just below the horizon, to reach Greenland[12]. Past Cape Farewell, a similar strategy of keeping inshore to the cold, fresh water would work in the West Greenland Current. To reach Markland, one would sail northwest with the West Greenland Current as far as Davis Strait, follow the offshore current branch west, then coast with the fresh, cold Labrador Current to the southeast. Temperature and salinity differences of about 1C and 1 salinity unit are near the limit of human sensitivity, but the contrasts across the boundary current fronts in Figs. 2 and 3 significantly exceed these thresholds. It is likely that careful Norse sailors would be aware of these facts, and monitor their progress accordingly. Returning home would involve sailing offshore into warmer, saltier waters. The North Atlantic Current would assist the trip northeast to Europe, as would the

prevailing westerly winds, although the variability caused by eddies and storms would make the route unpredictable. Evidence from the early sixteenth century suggests that this route was well known, for example in Nordenskiöld Ruysch's 1508 *mappa mundi*[13]. Returning to Greenland would involve retracing the outbound path by slowly sailing back upstream, before heading offshore. The key issue would be to reach north of 60°–the latitude of Cape Farewell–before sailing east. If Cape Farewell was missed, then a detour of several thousand kilometers may have been necessary. Such a incident occurred in 1347 to a Greenlandic ship returning from Markland, as recorded in the Skálholt Annals of Iceland.

Two other lines of evidence bear on the question of what the Norse knew of the western Atlantic current system and its character. The first concerns the early sixteenth century diagrams and maps of Olaus Magnus, a Swedish ecclesiastic and diplomat to Rome. In his Carta Marina, Greenland is shown with floating shipwrecks and driftwood east of Cape Farewell. In the 1555 History of the Northern Peoples, Magnus describes in encyclopedic detail the scenes from Carta Marina. A woodcut diagram from that work appears in **Figure 4**. It shows the Carta Marina view of Greenland in more detail, now including people on shore living in homes constructed from whale bones. It is known that the Eskimo Thule culture built whalebone dwellings[14], and excavations at Brattahlid, Erik the Red's Farm in the eastern settlement, found that a whale shoulder blade was used as a partition in a barn[15]. It is unclear if the people are natives or Norse, however. The

woodcut draws attention to the risks and challenges of living in Greenland, and particularly points to the importance of wood for home and ship construction. Driftwood, as discussed below, was a vital commodity for the Norse colonies. Greenland driftwood has a non-local origin, however, so the Magnus woodcuts implicitly demonstrate knowledge of the East Greenland Current. The Carta Marina suggests that other features of the non-tidal ocean circulation were also known. Specifically, it has been proposed that the whorls on the Carta Marina east of Iceland are “a surprisingly accurate representation of today's meandering front and the intermittent formation of warm and cold eddies to either side”[16]. The oceanographic front here is not very obvious in Figs. 1-3, but it comprises a well-known feature of the ocean circulation near the Faroe Islands. Magnus' works date from the 1500s, and it is unclear how old his knowledge was when the works were produced. The last recorded evidence of the Norse Greenland colonies dates to 1408, concerning news of a wedding at the church in Hvalsey fjord, from Icelandic correspondence with the Vatican. Magnus, in Rome himself, would therefore have little recent information concerning Greenland to draw on as he prepared his maps. His work therefore probably reflects conditions in colonial Greenland from the late fourteenth century, if not before.

Finally, consider Norse knowledge of sea-ice. Because of its essential role in seafaring, sea-ice conditions would have been keenly observed by Norse sailors. Sea ice also obstructed, or facilitated, essential seasonal activities in the Greenland settlements, such

as seal and walrus harvests, and travel through the Nordsetur hunting grounds north of the Western Settlement. Sea ice forms each winter in Greenland fjords through local freezing of seawater. The drift ice offshore is mainly imported from the Arctic, however. The East Greenland Current is the principal route by which the eastern Arctic ocean is drained of sea ice, and sea ice cover is often high in the cold fresh coastal waters off southeast Greenland (see, for example, Fig. 3, where the 34.5 salinity contour reasonably shows the region occupied by sea ice). Sea ice off west Greenland is much lower than off east Greenland, mainly because the continental shelf is narrower, but off Labrador the concentrations are very high, as the Labrador Current is the principal drainage route for the western Arctic and Canadian Archipelago ice (Fig. 3). Sea ice also carries driftwood, as explained below.

Fascinating references to sea ice exist in the King's Mirror, on the Marvels of the Waters about Greenland[17]. For example, traveling from Iceland, “as soon as one has passed over the deepest part of the ocean, he will encounter such masses of ice in the sea, that I know no equal of it anywhere else in all the earth”[18]. The document describes how sailors trying to reach land have been caught in the floes, how some have perished, and how others have eventually escaped after four or five days, or even longer. Ice floes also, apparently, have peculiar habits, and can “travel with a speed so swift and violent that a ship with a fair wind behind is not more speedy; and when once in motion, they travel as often against the wind as with it”[19]. Such passages from the mid-thirteenth century are

remarkably consistent with Nansen's experience in 1888, cited above, and also the modern view. Ice motion opposite to the prevailing winds commonly occurs, in fact. Sea ice is affected somewhat by the wind, and by stress within the ice floes themselves when the concentration is high, but it drifts predominantly with the surface ocean circulation. The King's Mirror also refers to icebergs (glacial ice, not to be confused with sea ice, which is frozen seawater), and attributes the naming of these ice mountains to the Greenlanders. They “stand by themselves” according to the source, which again accurately reflects the fact that icebergs often move independently of the surrounding sea ice.

Wood and the Greenland Norse

This discussion highlights that driftwood was a key resource that directed Greenland Norse attention to non-tidal ocean currents and sea ice. We now shift focus to explore the importance of wood to the colonists in more detail. The uses of wood, and their sources, are discussed in an attempt to understand how shortage of timber obstructed daily activities, and may have contributed to the eventual loss of the Greenland colonies. Again, the environmental conditions play an important role in this issue.

First consider the uses of wood in Norse Greenland. Several lines of evidence, mainly archaeological, are germane. First, good quality wood was absolutely essential for building and repair of Viking ships, and no other commodity could substitute. The

existence of the Greenland Norse society, and its ability to function, depended critically on boats and ships, and therefore on wood. Indeed, the expertise that the colonies were leveraged on was seamanship[20]. Modern analysis of excavated ship's parts from the eastern and western settlements is revealing[21]. Five out of seven specimens are of larch, one is of spruce, and one is reindeer antler. In two of the larch specimens, spruce nails are also present. Greenland-built boats were not as robust as Norwegian longboats, however, reflecting the shortage of raw materials. For example, in 1189 a Greenlander sailed to Iceland in a vessel that attracted comment because of its use of wooden pegs, and baleen or sinew lashings[22]. Seal oil was also used by Greenland shipwrights[23].

Moreover, wood was very important for the construction of buildings. Norse architecture included longhouses and churches many meters in length, with wide roofs demanding timber beam supports. Wood was used extensively for interior furnishing too. For example, excavation at Umiiviarssuk, in the western settlement, revealed that the platform of a bathhouse was made of planks from multiple ships and barrel tops[24]. Graves excavated at Herjolfsnes (eastern settlement) contain wooden coffins made from both driftwood and Markland wood[25]. Excavations have also discovered many wooden Norse tools and artifacts. A coopered tub with ladle, and a carved crucifix, were found at a farm in Austmannadal (western settlement), for example, all made of driftwood[26]. Bowls, a platter, and a scoop lacking wormholes (which are usually seen in driftwood) were found at the farm beneath the sand, (in the western settlement)[27]. On Skraeling Island, at 78ºN

on the western side of the Kane Basin, more than 1600 km from the main colonies, a wooden carpenter's plane was discovered, probably made of Greenlandic birch, plus fragments of Norse barrels and boxes[28]. Some evidence exists for the Greenlanders wasting wood (for example, by discarding wood chips[29]), or using wood lavishly (for example, at the farm under the sand[30]), and unused birch trunks dating from the Norse period have been found in eastern settlement fjords[31]. It is clear, however, that wood was not easily available in general. Living without wood for ships, homes, and domestic objects, as the Inuit did, would have profoundly challenged the Norse, who were attempting to adhere to a European lifestyle in Greenland.

The sources of wood to the colonists included native Greenlandic wood, imported Norwegian wood, harvested timber from Markland, and driftwood. Each of these sources is now explored in turn. Southwest Greenland contained willow scrub and isolated groves of Greenland mountain birch and mountain ash trees circa 1000AD[32]. Coniferous trees are naturally absent from Greenland because its isolation makes it hard for trees with heavy seeds to invade the country. The conditions are not unfavorable to growth of non-native tree species, however. For example, Scots pine and Norwegian spruce were planted in 1892 at Qanasiassat, across the fjord from Brattahlid. Four of these trees, all Scots pine, survive to the present day and have reached 5m in height. Moreover, Narsarsuaq (near Qanasiassat) now boasts an arboretum with over 200 forested hectares containing almost all northern subarctic tree species and an embryonic forestry industry[33].

Growth rates are slow, however, and it may take hundreds of years for pines and firs to reach 15m height. Cold, dry summers can kill many young trees too. Conceivably, the Norse may have tried planting imported seeds in Greenland, but the slow growth eliminates this possibility as a significant timber source, and no direct evidence supports the idea. Native Greenlandic wood was therefore inadequate for construction of large buildings or ships, although it may have been useful for small artifacts and as a source of fuel.

Imported Norwegian wood was a vital source of timber to Greenland, at least through the fourteenth century. The King's Mirror states that “all the timber used in building houses” must be “purchased abroad”, for example, presumably referring to wood from Norway[34]. The wood was purchased with Greenland naturalia, including furs, skins, wool, walrus tusks and leather, and live Arctic animals. Wood was therefore a vital element in westbound ships' cargoes. Unfortunately, it is difficult to know exactly how much Norwegian wood was imported this way. Some authors stress the importance of Markland as a lumber source for the Greenland Norse, rather than Norwegian trade[35], probably because of the lack of documented Norwegian timber sources. The frequency of ships from Norway likely exceeded that from Markland during the first two or three centuries, at least for the eastern settlement. Norwegian wood must have been the primary source at many places and times, although the details of how this trade operated are still unknown.

The Canadian shore was also vitally important. The present limit of the north east American forest is at about 58ºN, around Napartok Bay (Napartok means spruce), which coincides with the 10C July isotherm[36]. South of that latitude, the coast is extensively wooded. The naming of the northeast Labrador coast as “Markland”--wooded-land--shows at a basic level how the Norse explorers categorized the territories they discovered: Markland was rich in timber. In the Greenlander's Saga, Leif Eriksson says “this country shall be named after its natural resources: it shall be called Markland”. Markland was also rich in driftwood, as Bjorn Jonsson noted in a 1625 marginal remark on the Hauksbok version of Erik's Saga. To exploit these resources, the Norse crossed Davis Strait repeatedly over the years. For example, in 1121 the first Greenlandic bishop, Eirik Gnupsson is reported in Gottskálk's Annals to have voyaged in search of Vinland, perhaps to never return (by 1124 he had been replaced with a new bishop). Such a trip may have been motivated by a desire to inspect natural resources, including timber, and consolidate the church's access to them. Indeed, it has been suggested that Eirik was visiting a long-term Norse outpost in Vinland which, if it existed, would have been a gateway to Canadian forests[37]. More evidence concerns the Greenlandic ship mentioned in the 1347 Skálholt Annals that reached Iceland, having been blown off course returning from Markland. Although the annals fail to elaborate, the most obvious reason for such a trip was to harvest timber and other natural resources. Finally, it appears that the L'Anse aux Meadows Norse site in Newfoundland was used for ship repair, or possibly ship

building[38], in part because of the availability of wood nearby.

The last key source of Norse lumber was driftwood. Driftwood comes from the river banks of boreal forests in Siberia, Canada, and Alaska. Logs blown into the water, or undercut by bank erosion, are carried into the Arctic ocean by rivers. Unseasoned wood floats in seawater for only about a year, on average, partly due to degradation by wood-boring bivalve mollusks[39]. To survive longer periods, the wood must be carried by sea ice across the Arctic ocean and south past Greenland. The main way for driftwood to reach the beaches of southwest Greenland is via Fram Strait (between east Greenland and Svalbard) and the East Greenland Current (Fig. 1). Because Fram Strait drains the eastern and central Arctic, most of the East Greenland Current's driftwood is from Siberian rivers that crosses the Arctic in the transpolar drift. The Canadian and Alaskan rivers feed the western Arctic and drain west of Greenland via the Canadian Archipelago, and eventually the Labrador Current. The time taken for driftwood to make this journey is typically one to ten years, although driftwood can also be re-floated by storm surges after lying on beaches for much longer periods.

The Arctic ocean circulation, and the relative importance of the sea ice flow east and west of Greenland, varies over years, decades, and centuries, and varied with medieval climate perturbations too. In particular, the strength of the Beaufort Sea circulation changes with the prevailing Arctic winds, and alters the location and strength of the transpolar drift.

The intensity of the sea ice and driftwood fluxes passing Fram Strait and through the Canadian Archipelago is modulated by these shifts in the currents. Arctic current variability has multiple causes, but a key player is the North Atlantic Oscillation (NAO). The NAO is the dominant natural mode of variability in the North Atlantic and Arctic Oceans, and is known to significantly affect Greenland climate[40]. The NAO is also correlated with the flux of sea ice through Fram Strait[41]. Assuming that the flux of sea ice through Fram Strait reflects the driftwood flux, it follows that the Fram Strait driftwood flux, and so the rate of driftwood arrival at southwest Greenland, also depends on the NAO. **Figure 5** shows this connection in more detail. During periods of low NAO the Greenland winters tend to be milder. Good examples of low NAO winters are 1968 and 1996; in 1996 the average December-to-March air temperature in Narsarsuaq was 1.9C above the long-term average (data for 1968 are missing from the US National Climatic Data Center[42]). Low NAO conditions also tend to favor a strong transpolar drift that flows over the pole directly towards Fram Strait. This enhanced current supports larger-than-normal sea ice, and therefore driftwood, fluxes. The increased flux of driftwood through Fram Strait and east of Greenland during 1968 conditions is clearly seen in the modeled driftwood tracks in Fig. 5a. For high NAO winters, such as 1984, the anomalies take the opposite sign. Greenland winters tend to be colder (6.8C colder than average in 1984 for Narsarsuaq[43]), and the Fram Strait flux of sea ice and driftwood is substantially reduced (Fig. 5b).

The supply of driftwood to the Norse settlements therefore varies from year to year. Furthermore, these variations are phased to be especially inconvenient to a population attempting to gather the annual driftwood supply. The reason is that high NAO phases cause a succession of disruptive events. First, high NAO winters are very hard in Greenland, with frigid temperatures, that impose greater dependence on stored fuel and food, and a shorter subsequent growing season[44]. Second, high NAO winters cause reduced driftwood flux east of Greenland (Fig. 5b), and hence less driftwood delivery to the Norse settlements. Finally, the cold winter temperatures during high NAO phases cause greater local freezing and sea ice production in southwest Greenland fjords (even though there is reduced Arctic sea ice drifting offshore). So, the small amount of driftwood being carried in the East and West Greenland Currents is obstructed from reaching the Norse beaches during high NAO conditions. During low NAO phases all these effects are reversed, and driftwood in much greater amounts reaches southwest Greenland strands. This boom and bust cycle was particularly hard on the Norse. During mild, easy years, new driftwood was abundant. But when the Greenland Norse were running out of raw materials after long, hard winters, the driftwood supply was severed.

The species composition of driftwood, and its age, provide valuable insight into this issue[45]. Siberian forests are dominated by larch (tamarack) trees, while North American forests are dominated by spruce: larch occurs only occasionally in the Mackenzie river, while spruce is absent from all but the very western parts of Siberia (which do not feed

the transpolar drift[46]. The stranded driftwood near the Norse settlements is therefore almost entirely larch, while Markland stranded logs, and forests, are almost entirely spruce (Mackenzie river driftwood is sometimes found in Greenland, having crossed the western Arctic to Fram Strait, but it is rare[47]). The analysis of ships parts mentioned above, for example, found five larch (Siberian driftwood) samples out of seven, with some spruce (Markland timber or American driftwood). Indeed, the sagas themselves mention North American driftwood, albeit in a different context: When the explorers in Erik's Saga found a ship's keel on a Vinland headland they named the place Kjalarness.

Although this is unambiguous evidence of Norse awareness and exploitation of Greenland driftwood, it is unclear exactly how much driftwood was available, or for how long. Once washed ashore, driftwood can survive for thousands of years before eventually disintegrating[48]. It therefore takes thousands of years for driftwood to accumulate and reach a steady distribution of ages. Such a pristine stock of timber likely existed when the Norse arrived in Greenland in 1000AD; no disturbance by the sparse, nomadic Inuit is expected[49]. Moreover, driftwood accumulates preferentially in some places, and not in others. Driftwood in southwest Greenland appears to be exceedingly rare, with the oldest specimens nearly 10,000 years old, for example, at least near Narssaq[50]. This region may, or may not, have been picked clean by the Norse in the middle ages, but either way the supply rate must be very low. For these reasons, it appears that southwest Greenland driftwood is a slowly-accumulating resource.

Presumably, the Norse used the largest, strongest, most accessible limbs first, and took the less desirable pieces later, and/or made greater efforts, as the stock was progressively exhausted. How long this practice continued, and how much they relied on newly-arriving driftwood is unclear, however.

In conclusion, all of these wood sources declined during the Norse Greenland occupation, especially towards the end. Native wood grows too slowly to be cut in a sustainable way, as do non-native Greenlandic trees, if the colonists ever even attempted to grow them. Newly imported wood from Norway essentially disappeared during the 1400s as European trading voyages ceased, while the English and Portuguese explorers and fishermen who returned to the western North Atlantic in the early sixteenth century were interested in other opportunities[51]. Loss of the western settlement by the late 1300s, reduced the frequency of trips to collect Markland wood by making them logistically harder[52]. And driftwood on Greenland beaches was a non-renewable resource on human timescales; once the prime trunks were salvaged, the rate of resupply was slow and came at inconvenient times. It is unclear how long it took for the Norse to expend the accessible driftwood supply, perhaps many decades, but it appears that they ultimately did. For all these reasons the “poverty of lumber”[53] in the late 1300s and 1400s must have made essential subsistence activities, like building and maintaining vessels and houses, ever harder. Many reasons have been advanced to explain the demise of the Norse settlements, and, almost certainly, multiple causes should be attributed[54]. But a chronic,

deteriorating shortage of the single most important raw material that allowed the society to function, should also be carefully considered.

This discussion has summarized the case that wood was a seriously limiting resource which focused Norse attention on ocean currents and sea ice. Further analysis of Norse artifacts and historical documents to determine wood age, species, and provenance would be worthwhile. A careful study of the relationship between Greenland driftwood origins and fates, and environmental factors--aspects of which were evidently understood by the Norse--would further illuminate this interesting question.

Acknowledgments

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Figure Captions

Figure 1. North Atlantic circulation. The average non-tidal sea-surface height (m) is shown, which is a stream-function for the surface circulation. The currents flow along the contours with a speed inversely proportional to the contour spacing. Typical currents in the East Greenland, West Greenland, and Labrador Currents (EGC, WGC, LC) are about 1m/s. On average, water shaded light gray circulates counter-clockwise, as shown, taking about 1-4 years to complete the loop. The data comes from satellite and *in situ* measurements[55], and the 1993-1999 average is shown. The Greenland Norse Eastern and Western Settlements (ES, WS) are marked.

Figure 2. North Atlantic summer surface temperature (C). The data comes from satellites and *in situ* measurements blended by the OSTIA project, and shows conditions on 30th August 2008[56]. Annotations are as in Fig. 1.

Figure 3. North Atlantic summer surface salinity. The data comes from the NAME numerical model of the northern high-latitudes and is an average for June to September 2003[57]. Annotations are as in Fig. 1.

Figure 4. Woodcut from the 1555 work of Olaus Magnus[58]. The image depicts floating wrecked ships, and driftwood off Greenland. The people on land occupy dwellings constructed with whale bones.

Figure 5. Driftwood trajectories across the Arctic[59]. The spaghetti lines show the estimated tracks of driftwood over 6 years for (a) 1968 conditions (low NAO), and (b) 1984 conditions (high NAO). A model of driftwood motion using sea ice and ocean

current velocities is used to compute the trajectories. Low (high) NAO winters are associated with mild (cold) Greenland winters, low (high) local freezing in Greenland fjords, and high (low) Fram Strait ice and driftwood fluxes.

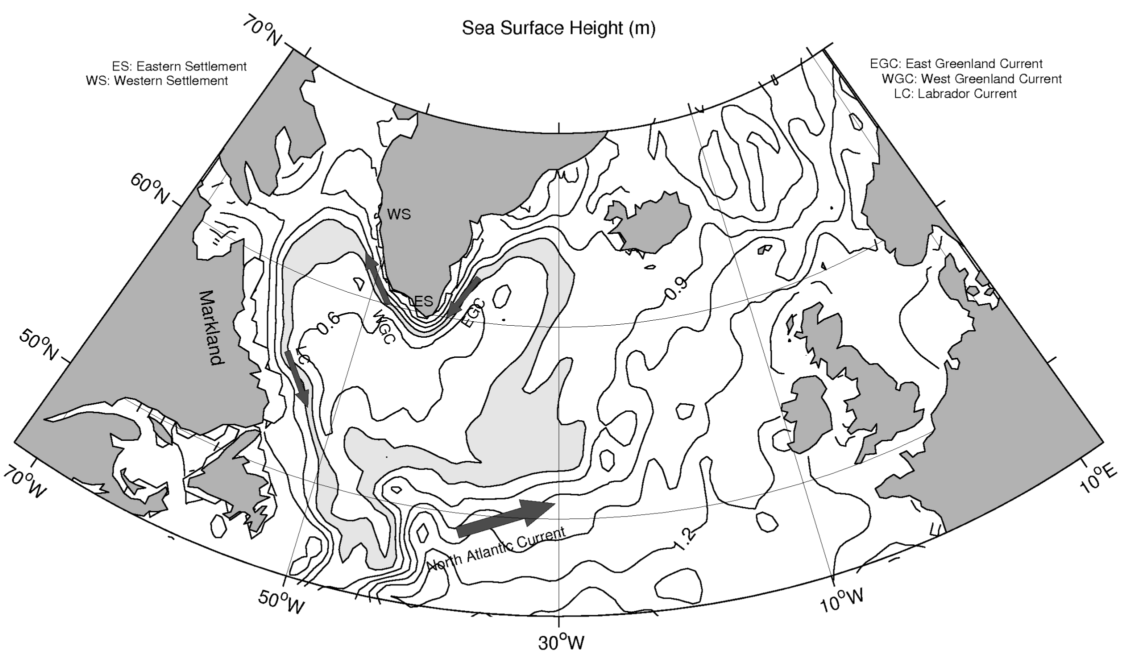
Sea Surface Height (m)
ES: Eastern Settlement
WS: Western Settlement
EGC: East Greenland Current
WGC: West Greenland Current
LC: Labrador Current
WS
ES
WGC
EGC
LC
Markland
North Atlantic Current
0.6
0.9
1.2
70°N
60°N
50°N
70°W
50°W
30°W
10°W
10°E

Figure 1

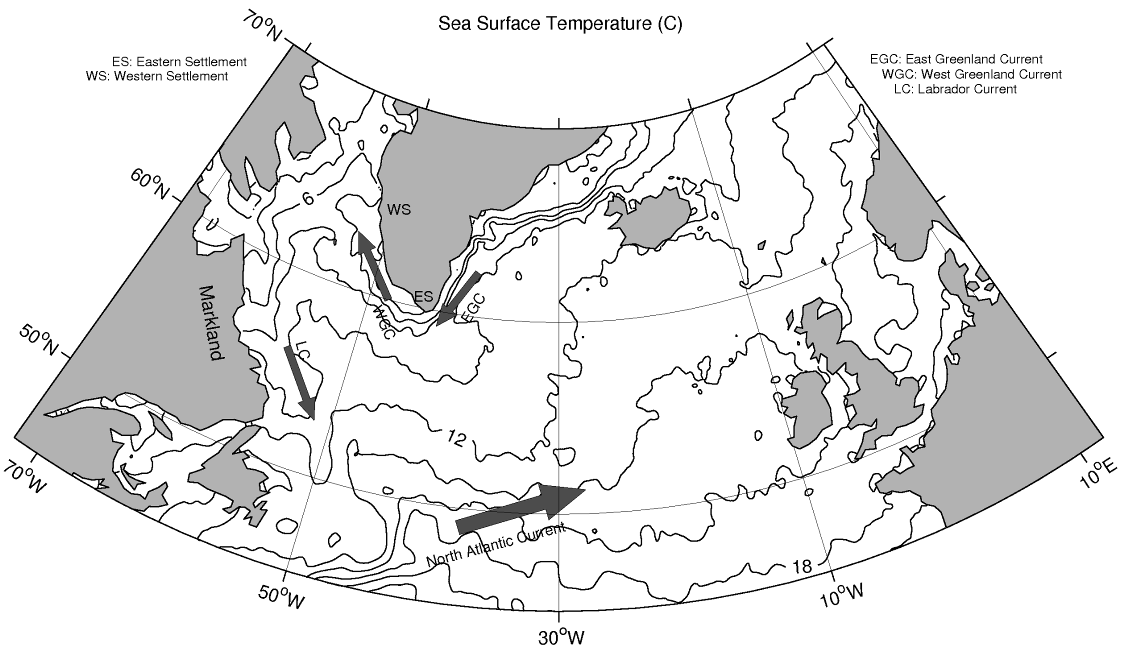
Sea Surface Temperature (C)
ES: Eastern Settlement
WS: Western Settlement
EGC: East Greenland Current
WGC: West Greenland Current
LC: Labrador Current
70°N
60°N
50°N
70°W
50°W
30°W
10°W
10°E
WS
ES
WGC
EGC
LC
Markland
6
12
18
North Atlantic Current

Figure 2

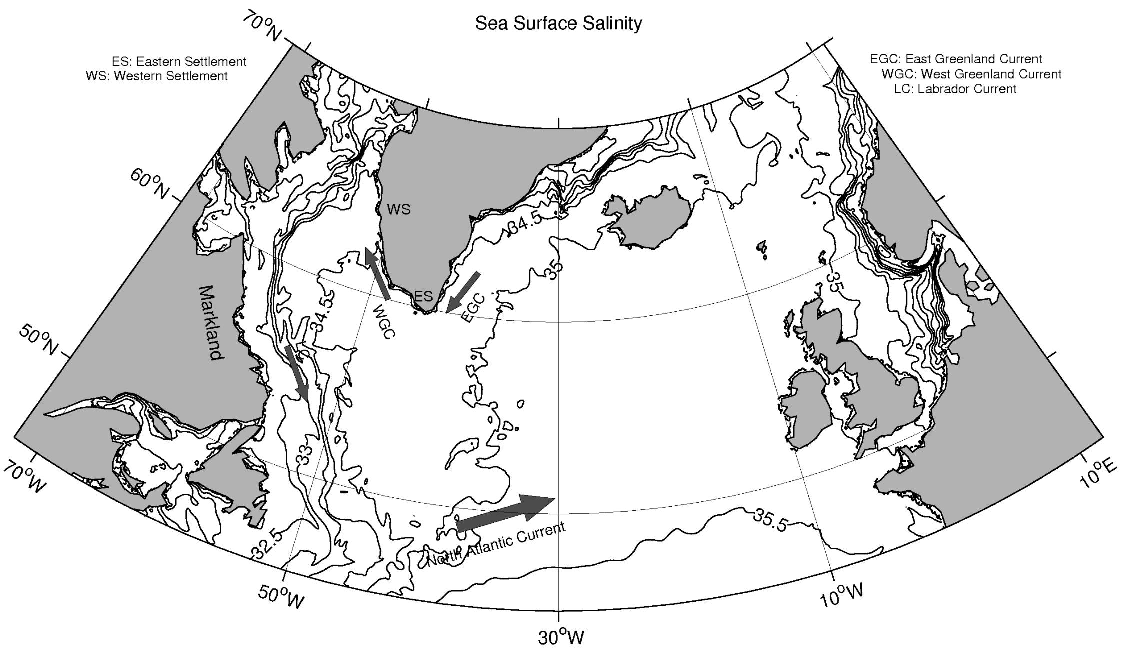
Sea Surface Salinity
ES: Eastern Settlement
WS: Western Settlement
EGC: East Greenland Current
WGC: West Greenland Current
LC: Labrador Current
WS
ES
WGC
EGC
Markland
North Atlantic Current
34.5
35
33
32.5
35.5
70°N
60°N
50°N
70°W
50°W
30°W
10°W
10°E

Figure 3

Figure 4

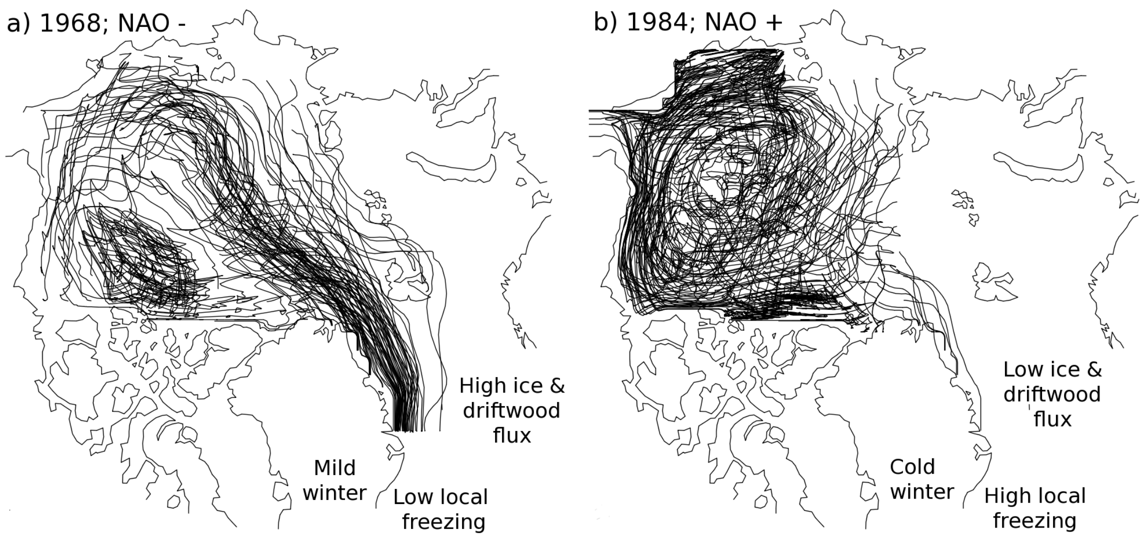
a) 1968; NAO -
b) 1984; NAO +
High ice &
driftwood
flux
Mild
winter
Low local
freezing
Low ice &
driftwood
flux
Cold
winter
High local
freezing

Figure 5

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