Oceanic Mobilities:

An interdisciplinary analysis of the influences that shape the movement of ships

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Acknowledgments

The Road goes ever on and on
Down from the door where it began.
Now far ahead the Road has gone,
And I must follow, if I can,
Pursuing it with eager feet,
Until it joins some larger way
Where many paths and errands meet.
And whither then? I cannot say.

This song from the Lord of the Rings summarizes well on my feelings right now; one part of my Journey is over, so it is time to take a short moment and look back. The last four and a half years have been a challenging but happy journey, and I have an incredible group of people to thank for its successful completion.

First of all, I am extremely grateful to Thilo Gross, my main supervisor, who has taught me in many more ways than fit onto this page. From writing and coding, over the science of networks, to the philosophy and outlook of modeling, you have been an unceasing and eager well of knowledge. But that is just one half of the picture. I also want to thank you for your patience with me and the incredible freedom and trust I was afforded to shape the course of my research.
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The old proverb says that it takes a village to raise a child, and I would like to get this closer to myself. Therefore, I want to say that it takes an institute to raise a young Scientist. The young HIFMB has excelled at giving me the best upbringing I could have wished for. Sadly, there are too many to name here individually, but I will keep fond memories of FIKAs and Pomodoros of Cale tours and the inevitable end at Marvin's.
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As my next steps will remain close by I look forward to walk another stretch of the way with you.

Abstract

The public is used to conceptualizing ocean space as the blue void that starts beyond the continents. This perception, though, is in stark contrast to the richness and diversity of the natural and anthropogenic cycles that happen in the sea. Transport shipping moves over 80 percent of all trade, making it the beating heart of the global economy and an essential human activity. On the other hand, shipping is a major contributor to the pollution of the oceanic environment. To protect ocean space and to find ways for sustainable cohabitation, global regulation on shipping will need to be introduced. The basis for such a set of rules needs to be an extended understanding of ships and shipping.

In this work, I approach the challenge from the ship's viewpoint. The sciences that deal with ships and shipping are scattered over a wide range of disciplines. In order to make connections and gain mutually intelligible insights, I apply the mobilities framework. Mobilities research is looking for the influences that motivate and inhibit movements rather than focusing on the fact of movement between two points.

This work contains three main sections. The first section takes the perspective of transport geographies and networks. These are employed to model the changes to the shipping route utilization that follow major changes to the distances that must be traversed between ports. These fall into two categories. The first are different scenarios for an opening of the Arctic for ship traversal, leading to a significant reduction in the length of routes that connect the Atlantic and Pacific Oceans. The second group models the effects that a closure of the main shipping canals in Suez and Panama would have, which would lead to a significant increase in the length of northern Atlantic and northern Pacific connections. Based on the distances and the sizes of the ports in the network, a radiation model is applied to estimate the resulting ship traffic. The outcomes focus on the traffic flow on the central shipping connector for different scenarios. The results are then visualized to provide an idea of the positions of major routes and the areas of greatest change.

I conclude the chapter with the insight that this view of shipping is incomplete, as it disregards the agency and activity of the singular vessels. Still, I find the first set of mobilities, the margin of profit, maintenance cost, and the price of insurance.

The second section approaches mobilities closer to the ship itself and utilizes ship positional data to find spots of immobility. The data is provided by the Automated Identification System. Immobility represents the state where influences motivating a movement are less powerful than the ones inhibiting movement. A regular annual immobility pattern has been identified in the covered area comprising the continental United States. This pattern is disrupted by the COVID-19 pandemic, though unexpectedly not by an increase in immobility but by a sharp reduction. Other patterns can be identified from the ship type and spatial relations to the centrality of the area where ships become immobile.

A bridge to the third chapter is created by a series of visualizations of raw shipping data that unveils the full spectrum of human activity at sea. This is expanded into a discussion on the merits of Automated Identification System data for research,

especially for fields that currently are not engaging with quantitative data. To do this, I first introduce the current utilization of the data in broader research as well as the limitations of the technology. Then I draw out possible gains and connections for the field of Human Geographies of the Sea to attain a deeper understanding of the human and cultural mobilities of ships.
In summary, I am searching for the mobilities of ships on different levels, from the global network to the personal choices of the crew. Mobilities are created from the demand for transportation but are opposed by the maintenance of the ship. They are built into the hull but need to be insured against danger. The movement is prone to regulation and environmental impacts. But the ultimate control is with the captain and crew, their decisions and experiences.
These results contribute to a more sound perspective on ship behavior. They deepen our understanding of these core components of our global economy. Only through dialog and mutual understanding will it be possible to develop shipping into a future where the negative influences are outweighed by the positive ones.

Abstract Deutsche Fassung

Im allgemeinen wird der Ozean oft als blaues und leeres Gebiet jenseits der Kontinente verstanden. Doch diese Wahrnehmung steht im starken Widerspruch zur Fülle und Vielfalt von natürlichen, aber auch menschgemachten, Prozessen im Meer. Eine zentrale menschliche Aktivität ist die Transportschifffahrt, die über 80 Prozent des globalen Handels bewegt. Auf der Kehrseite ist die Schifffahrt aber auch für massive Schäden an der Umwelt verantwortlich. Um nachhaltig mit dem Ozean zu leben, müssen Regeln und Gesetze geschaffen werden die den Ozean schützen. Doch um damit Erfolg zu haben, muss zu allerest das Verständnis für die Schifffahrt vertieft werden.

Ich nähere mich dieser Problematik aus der Perspektive des Schiffes. Da Schiffe nicht in einer einzigen wissenschaftlichen Disziplin beheimatet sind, folge ich dem Konzept der Mobilitäten. Die Mobilitätenforschung versucht Bewegung nicht als Prozess zwischen zwei Punkten zu verstehen, sondern die der Bewegung unterliegenden Motivationen und Hemmungen zu ergründen. Dadurch, dass unterschiedliche Perspektiven zusammen betrachtet werden können, ermöglicht dies ein umfassenderes Verständniss .

Diese Arbeit umfasst drei Hauptkapitel. Im Ersten betrachte ich die Schifffahrt aus dem Blickwinkel der Transportgeographien und Netzwerke. Diese werden genutzt um Vorhersagen darüber zu treffen, wie sich die Nutzung der Schifffahrtswege entwickelt, wenn sich der momentane Status quo nutzbarer Passagen signifikant verändert. Dabei treten zwei Gruppen von Szenarien in den Vordergrund. Die Erste ist eine Öffnung des Arktischen Ozeans für die Schifffahrt, dadurch verkleinert sich die Distanz auf Routen zwischen dem Atlantischen und Pazifischen Ozean. Die zweite Gruppe von Szenarien verfolgt nach, was passiert wenn die Kanäle von Suez und Panama geschlossen werden. Dadurch kommt es zu einer signifikanten Verlängerung der Routen zwischen Atlantik und Pazifik. Um den Einfluss auf den Schiffsverkehr vorauszusagen wird ein "Radiation Model" angewendet. Als Ergebins der Modelierung präsentiere ich die veränderte Auslastung des Schifffahrtsnetzes durch die Betrachtung von wichtigen Passagen und die Erstellung von Kartenmaterial.

Am Ende des ersten Kapitels komme ich zu dem Schluss, dass diese Sicht auf die Schifffahrt unvollständig ist. Die Mobilitäten der individuellen Schiffe werden begrenzt abgebildet, wobei Profit, Unterhalt, Größeneffekte und die Versicherbarkeit von Reisen als Mobilitäten hervortreten.

Dies bringt mich zum zweiten Kapitel, in dem ich die Mobilitäten durch den Einsatz von Schiffspositionsdaten erweitere. Die Daten wurden über das Automated Identification System gesammelt. Ich nutze sie, um herauszufinden wo und wann Schiffe, die nur während sie in Bewegung sind Profite generieren, stationär oder unmobil werden. Was ich dabei in meinem Studiengebiet finde, ist, dass die Unmobilität unter normalen Umständen jährlichen Zyklen folgt, die aber durch die Covid 19 Pandemie durchbrochen werden. Dieser Befund fällt dadurch auf, dass die Unterbrechung, entgegen der Erwartungen, während der Pandemie die Form einer starken Reduktion in der Unmobilität annimmt. Ansonsten treten Muster in der Position der Unmobiltät und zwischen Schiffsklassen hervor.

Was mich zum dritten Kapitel bring, ist eine Reihe von Visualisierungen der unge-

filterten Positionsdaten, welche das volle Spektrum der menschlichen Aktivitäten auf dem Ozean abbilden. Dies regt die Frage an, wie weit der Einsatz von Schiffspositionsdaten in den Wissenschaften verbreitet ist. In diesem Kapitel erläutere ich zuerst den momentanen Stand der Forschung und die Einschränkungen in der Nutzbarkeit der Daten. Dann argumentiere ich für eine Erweiterung des Einsatzes in die Domäne der Ozean Geographien, welche als Geisteswissenschaften keine starke Verbindung zu quantitativen Methoden haben. Dies verfolgt das Ziel, in Zukunft bessere Aussagen zu den menschlichen und kulturellen Mobilitäten der Schifffahrt treffen zu können.

Zusammengefasst identifiziere ich Mobilitäten der Schiffsbewegung auf verschiedenen Ebenen. Diese Mobilitäten entstehen aus dem Bedarf nach Transpot, aber auch den Kosten für den Unterhalt des Schiffs. Sie werden mit dem Schiff gebaut, aber müssen durch Absicherung erhalten werden. Weitere Einflussfaktoren sind aber auch Regularien und Umweltbedingungen denen das Schiff unterliegt. Am Ende hängen sie aber auch von Kapitän und Mannschaft ab, von ihren Entscheidungen und Erfahrungen, welche das Schiff steuern.

Die Resultate dieser Arbeit helfen dabei, Schiffe als tragendes Element der modernen Welt besser zu verstehen und sie geben Ansätze, wie das Verständniss noch weiter vertieft werden kann. Nur im Dialog und gegenseitigem Verständniss wird es möglich sein, die Schifffahrt so weiterzuentwickeln, dass die negativen Einflüsse von den positiven übertroffen werden.

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Acronyms

AIS Automated Identification System

ECDIS Electronic Chart Display and Information System

EEZ Exclusive Economic Zone

IMO International Maritime Organization

ITU International Telecommunication Union

MARPOL International Convention for the Prevention of Pollution for Ships

MMSI Maritime Mobile Service Identity

NSR Northern Sea Route

NWP North West Passage

USA United States of America

SOLAS Safety of Life at Sea convention

SODTMA Self Organising Time Domain Multiple Access

UNCLOS United Nations Convention on the Law of the Sea

VHF Very High Frequency

VTS Vessel Traffic Service

1 Introduction

When looking at maps of our planet, it is common to see in great detail the topographies of the continents, their vegetation and climatic zones, or in easily distinguishable colors, the shapes of the countries we have split into the space of our planet. They are usually surrounded by a light blue background, very pleasing to the eyes; this blue color represents the global oceans, areas that are commonly conceived as empty and smooth. That makes it easy to declutter the image to focus attention and also put a legend or descriptive text within the perimeter of the map. To a degree, that is a fair practice, but all too commonly, it reinforces the idea of ocean space as empty, flat, uniform, and unknowable. The interesting and noteworthy parts end at the shoreline, maybe a couple hundred meters out from the low water mark, where ships do not need to fear running aground anymore.
A deeper chasm between reality and imagination can hardly be conceptualized. The ocean is a system of immense activity and value for the working of the planet. It produces roughly half of the vital oxygen (Grégoire et al., 2023), regulates and smoothes the climate, and helps in restocking the water vapor that provides the basis for rain and through this water to all landed life(Bengtsson, 2010). For humanity, the importance of the oceans further exceeds its importance for the planet; while laborious to access, the ocean provides us with a growing number of benefits(Fleming et al., 2019; Nash et al., 2022). From ancient times, fish has been a main source of protein for whole populations, and the ocean has been a pivotal area for transportation and exploration(Lavery, 2017, P.9). Over time, additional functions have become vital to different societies, from the maintenance of empire and projection of power over the increasing volume of goods that need to be transported to the current time(Reidy and Rozwadowski, 2014; Davies, 2022). Lately, a recognition of the recreational value and exploitation of ocean space for electrical power generation takes place(Ehler, 2021). The ocean and humanity's relation to it has shaped our world, physical and constructed into the form we find today. All of these functions correspond to properties of ocean space that are deeper than the shapeless blue next to the colorful continents.
Early maps filled the ocean space with creatures, angels, demons, and gods of all kinds; while this is artistically pleasing, science has evolved further in understanding the mechanics that govern what happens within and below that often not-so-flat surface(Lin and Yang, 2020). Part of the problem with representing the ocean is that it is a nonstationary entity(Peters and Steinberg, 2019). Land areas also change over time, but the timescales of oceanic reshaping are far quicker. Understanding how and what moves the ocean is the key issue, here a number of fields have made significant contributions:
Physical oceanographers have identified the great currents that move water around the globe, be it in reaction to celestial bodies like the moon and sun or following the density of the water through the measures of conductivity, temperature, and depth. Meteorology can complete the predictions for the behavior of water at the boundary to the atmosphere, currents due to pressure differences, and wind-induced currents, which help understand the remaining flow.

The atmosphere is the main driver for the structure of the ocean surface as well as the impacts the ocean and its behavior have on the weather over the continents (Lin and Yang, 2020; Cai et al., 2015).
Sonar allowed for a charting of the sub-sea surface and beyond into the soil. On top of these very deterministic processes, marine biology and ecology have made great inroads in understanding what happens within the churning water bodies. Nutrients and life follow the flows or lives by their own rhythms and patterns. Species migrate and settle; they follow resources, change environments throughout their developmental cycle, or react to global change. The ocean environment does not make it easy to unveil these patterns, but the combined effort of researchers drives the understanding of the biological layers within ocean space further(Costa et al., 2012).
The ocean is not just a physical space; it is also a human construction borne from a long-standing tradition of living at the coast. Humans have built their relation to the sea into culture (Nash et al., 2022). The establishment of rules for movement and dominion over ocean space underlines the political construction of ocean space. The international community has agreed to give coastal states dominion over limited areas of ocean space close to their shores, extending local governance outwards. All of the rest of ocean space is conceptualized as a common heritage of mankind, here different bodies have cooperated to produce rules for those who enter international waters(UN General Assembly, 1982).
Wherever we look at the ocean's dynamics, the patterns encountered feed into each other. The sun creates density differentials, and density differentials create current systems. Current systems well up nutrients, and the nutrients feed algae and plankton, which attract fish, and fish attract fishery. For humans, the ocean is a challenging environment to operate in for prolonged amounts of time; our ability to swim and undertake work at the same time is limited, and we need protection from salt, waves, hypothermia, and the sun. Ships provide a shelter against the environment and a platform that allows our land-evolved features to stand, work, and rest. To become a vessel, the platform needs a way of propulsion and steering. These basic requirements have been true from the earliest paddled dugout canoe, over the rowing and sailing hybrid galleys or long-ships and the fully rigged giants of the age of sail to the modern Panamax+ Container vessel[1] being powered by heavy fuel combustion engines(Lavery, 2017). The ships have co-evolved with the human uses of ocean space, and especially in the modern era, are purpose-built for specific tasks and environments. The core function, however, remains to provide a stable and navigable platform above the water that allows for human movement, making the more than 70 percent of the planet's surface accessible that is covered by water(Lavery, 2017, P.388 f). The most significant role ships play today is enabling the globalized economy by providing the largest share of transportation. More than 90 percent of all goods undertake at least one journey in a transport ship during their production cycle(George, 2013).

[1]The dimensions and build features of shipping canals create an upper limit on the size of vessels that can pass through them. These are known as Panamax (currently Length 366m, Width 49m and Drought 15.2m) and Suezmax (Max Height 68 m, Width 77m and Drought 20.2m) size. Vessels that exceed these dimensions are known as Panamax+ or, respectively, Suezmax+ ships

This has some very good reasons: ships for transportation do scale very well, and they can float as much weight as the amount of water they displace with their hull, which makes the application of heavy building materials like steel feasible, allowing for the large constructs. The water surrounding the ship is a comparatively low friction medium. This causes ships to have a smaller loss of momentum over distance in relation to their bulk. These initial benefits have been augmented by the rise of the container, which made the operation of ships less volume but far more operation time efficient. Together, this creates the most cost-effective way of transport on a by-volume or by-weight basis(Malchow, 2017; Rodrigue, 2020, P.176).

Ships do require little infrastructure to function well in proportion to the amount of cargo they transport (Schroten et al., 2019). Major infrastructure projects like the canals in Panama and Suez make great contributions to improving the transport network efficiency, but the system can still operate without them. The most difficult part of maritime transport is making the connection to the land, meaning the creation of loading docks that can facilitate the large ships and interface them with the rest of the logistical network. The port operators also need to ensure the water depth in front of the ports and all the way to the open ocean. Especially for ports situated further inland, maintaining waterways like, for example, rivers at the required parameters is a constant fight against sedimentation and erosion(Mahmoudzadeh et al., 2021). Once at sea and for the greatest part of their Journey, ships can rely on the depth of the ocean to facilitate their dimensions.

Ships, as the primary interface between humans and the sea, are also points for the introduction of disturbance to the oceanic environment(Nunes et al., 2017; Kim et al., 2024; Dąbrowska et al., 2021). Especially when thinking through the scale of global shipping, it is necessary to account for its impact on the marine environment. For looking at the direct impacts, it is useful to understand all kinds of introduced harm to the natural environment as pollution. The problem with ship-based pollution is detecting it in the ocean environment, though technological development makes the task easier(Saliba et al., 2022; Viatte et al., 2020). As the ships are remote from regular populations, only either larger disasters, like oil spills, or systemic problems, like ship breaking on beaches, are easily recognized by the public(Hossain et al., 2016). There is international regulation against some forms of pollution; for the shipping sector, this is represented by the International Convention for the Prevention of Pollution from Ships(MARPOL), but these provisions are hard to enforce out at sea(Saliba et al., 2022).

State-of-the-art commercial ships run on fossil fuels, and while technologies and gains in efficiency are reducing the amount of fuel necessary, none have changed this basic fact(Liu et al., 2021). On a per shipped unit basis, the statistics for fuel consumption and the connected air pollution look good in comparison to other forms of transport(Cristea et al., 2013). Still, by absolute value, ships are enormous contributors to CO2 emissions. On a global scale, it is estimated that 3 percent of all emitted greenhouse gases are caused by container ships(Cristea et al., 2013).

Ships do not need to burn the cleaner, higher-processed fuels other sectors rely upon but can run on heavy fuel oil, which makes them polluters not only in the climate sense but also hazardous in the more immediate term through the emission of SOx. The emissions are significant enough to make shipping routes visible even from high-orbit atmospheric measurements(Dalsøren et al., 2013). Transport ships are built from steel, a material that must be protected from marine environmental corrosion. The protection is achieved by coating every surface of the vessel with protective paint. The paint is constantly eroding, being exposed to sun and water, temperature shifts, intense weather, and the constant flow of wind or water surrounding the ship. This erosion causes ships to leave a constant trace of paint microparticles in the water(Kim et al., 2024; Saliba et al., 2022). Not only is it corrosive to ship hulls, but the ocean is also full of life that continuously tries to settle every surface exposed to the water. This growth is called biofouling, and it causes major problems to the operation of the vessel(Lindholdt et al., 2015). It increases water traction, thereby reducing fuel efficiency; the more the ship gets settled, the worse this problem gets. It also can contribute to corrosion that eats directly into the ship's body. To prevent the ship from overgrowing, anti-fouling agents are employed; these also pollute the waters through either additional particles or highly toxic residue in the water(Amara et al., 2018). On the topic of biofouling, the next major form of shipborne pollution is bio-invasion. Ships connect over the world's oceans. When they take up water or when fouling grows on the hulls, a ship will carry the organisms to new waters. If the carried organisms survive the journey and are viable at the port where the ship ends up, they can enter the local ecosystem(McCarthy et al., 2022). The ship is an inhabited space not only by fouling and other species stowing away but also by a human crew that needs to eat and has personal needs. This produces plastic and biological waste, like every household. The waste must be handled according to protocol, and non-biodegradable waste must be carried back ashore(Dąbrowska et al., 2021). Transport ships are imposing objects of high inertia and require significant power to navigate; this causes them to disturb the water physically(Parnell et al., 2024). To larger animals like whales, it can be the direct threat of ramming, but smaller lifeforms are also potentially impacted by the ship's movement through the water. The engines cause vibrations and sound, and the propellers scythe through the water(Kadir et al., 2024). The ship's journey is accompanied by a wake that can cause significant impacts, especially in shallow water. When ships get stationary, they also secure themselves with massive anchors that can cause major damage on the seafloor and even dig up pipelines (Naggea and Miller, 2023).

The current operation scheme for the shipping market will have to deal with rising challenges in the future, such as climate change, its consequent conflicts, and political shifts. At the same time, voices are rising that shipping companies need to engage proactively with the damage they do. To achieve improvements without crippling the global economy, governance, regulation, and practice within the transport sector will need to be adapted (Tadros et al., 2023; Lister, 2015). This requires an understanding of the dynamics that do not only drive the larger system but the single vessel as well.

In relation to the importance of ships for the operation of the modern world, it is curious how little research is undertaken into understanding their movements on an individual basis(Ducruet, 2020). Where ship movement is the focus, it is either researched through the lens of networked patterns in logistical networks or approached through those bodies traveling onboard. Emblematic of the latter approach is the analysis of the social spaceships created by being isolated islands of movement in a hazardous void of salty water(Hasty and Peters, 2012). The concern is with the fate and fortunes of people, things, and information aboard, as well as how the movement of ships enables modern worlds and understandings. This lack of interest in the maritime industry, especially in transportation, where far more interest is garnered by cars and airplanes, is representative of a broader trend. This has been theorized to have its origin in the developing societal relationship with ships(Ducruet, 2020; Álvarez et al., 2021). The ship has been replaced as the primary form of transport for humans, supplanted by air transport and cars that are able to deliver human cargo far more quickly and close to where they want to end up(Sheller and Urry, 2006; Gössling and Peeters, 2015; Rodrigue, 2020, P.173). A second factor is automation in port operation. Before the advent of the container, large groups of workers were necessary for the operation, loading, and unloading of ships at port. Automation has streamlined the processes and drastically cut back the number of workers necessary(Birtchnell et al., 2015). Thirdly the increases in time efficiency from containers comes at the cost of port space utilization. New ports are too big to maintain their positions inside the city, instead they are build downstream in opportune areas away from population centers(Monios and Wilmsmeier, 2015).

Together, these factors have caused a marginalization of ship-related topics and interest in the broader population(Peters, 2010; Lambert et al., 2006). The reduction of ship and port-related jobs reduces the sector's visibility. In addition, the maritime transport system runs smoothly enough for the cost of shipping and its role in the everyday supply of consumer goods to become invisible. The societal separation is further exaggerated by the physical remoteness of ships, moving over uninhabited oceans directly into industrial centers. For a long time, it has been difficult to track ships systematically as soon as they leave the shore(Ng et al., 2014; Álvarez et al., 2021).

Overlaying the more established natural patterns of the ocean with the human-made ones helps to understand the conflict between the need for maritime transport and the toll it takes on the ocean. With this work, I want to make a contribution to the general perspective of how we view the movement of ships at sea and how the lenses of different fields of research may benefit from cross-examining each other. This broadening of the understanding of ship movements is intended to make a small step in reaching the ultimate goal of enabling both the prevention of harm to the vital marine environment and a continuation of the system of transportation, enabling a globalized world.

To do this, I will first introduce three different ways to conceptualize the movement of ships coming from different fields of geography (transportation, mobilities, and human geographies of the sea). This will lead to an understanding of mobility that is useful for discussing the nuances in the rest of this work. Then, following these field-specific conceptualizations of movement, I will provide examples of the

benefits and questions the different fields open up.
Chapter two will follow a framework of transport or logistics where shipping is conceptualized as a network of port connections. This leads to my first research project on predicting the reorganization of the shipping network over a changing seascape. Changes in distance here can be due to an opening of the Arctic passages or the closure of important shipping straits. In this chapter, the background is necessary for understanding the shipping network as well as the steps necessary for the application of a model that predicts the flow of traffic based on a minimum of suppositions. The results show that for the distance behavior of shipping arctic scenarios, it is of minor relevance which arctic route would open. At the same time as expected, major reorganizations for shipping in the case of an opened-up arctic ocean or the severing of the important canals at Suez and Panama are predicted. Acknowledging the limits of a networked approach when it comes to the movement of individual vessels, I move on.
Chapter three moves further to a framework of mobility, looking at those factors that motivate movement or, better, those that overcome the incentive to move and force stasis. Here, I introduce ship positional data or, more specifically, Automated Identification System(AIS) data to the conversation. Monitoring positional data allows us to follow the ships on their journey with high precision. As an applied case, I present my work on detecting immobility patterns around the United States. An analysis of the ship positions reveals distinct patterns of immobility for both space and time. The spatial patterns show the location of immobility around areas of high centrality in the global shipping network. In the time patterns, a regular yearly rhythm with a peak of immobility in early summer and the lowest detections occurring in late autumn is detected. The study time does include the first two years of the Covid-19 pandemic as well as the two years before that, this lead to the observation that contrary to initial expectations of a slowdown in freight manifesting in an increase of immobility, the immobility actually decreases. The strong fluctuation led me to try to connect the encountered patterns to the fluctuations of the oil price, a calculation that did not provide clear results.
In the process of working with the positional data, I visualized the unfiltered data of the ships. This has produced a map that draws the ocean as an intricate space of activity. While the maps have been published, they also serve as a perfect counter to the perception of the ocean being a void. While occupation is not permanent, it is a very much living space. The degree of detail leaves me wondering where else AIS can be of use for understanding the human-made ocean. Chapter four extends the discussion of AIS, and I take a broader look at current applications in research. Seeing the sea through the lens of AIS opens up the discussion on where the applications of this technology are currently at in science, to do this current literature has been reviewed. I will utilize this to make a case for utilizing AIS data not only in the economic and ecologic fields that are already expanding the application of the technology but also for the more geographic and societal studies of ocean space where AIS can augment discussions on marine mobilities.

This will lead to a more general discussion on the findings of my work and the merits of utilizing AIS as the tool for gaining an understanding of ship mobilities and how this connects to current challenges that are felt in the research and governance of the ocean domain.
Finally, I will zoom out again, trying to chart a map and course for where the field will develop further. In conclusion, I will try to connect all these different perspectives on ship movement and provide an idea of where the dialogue might drift next.

1.1 Understandings of Movement

Thinking about movement or, more broadly, change is central to most sciences. The object of interest and the way the movement is conceptualized is what makes the difference. The divergent perspectives are useful and have been tailored to serve their respective fields. Understanding the ocean in connection to the movement of ships is not a centralized effort, so this work links different existing fields to get a more complete picture(Ducruet, 2020).
To gain a deeper understanding of what ships are doing at sea, it is important to delineate between movement and mobility(Sheller and Urry, 2006). Movement describes the relative change of position over time for ships(Sheller and Urry, 2006). This can be measured either in relation to the water through logging or technical systems such as Acoustic Doppler Current Profilers or "absolute" in relation to fixed points and determining the time that has passed while on the route between them. The rise of the global positioning system has made the latter more feasible as it allows for a more precise and time-of-day independent determination of ship position(Olsen, 2024). Mobility is a term that is more casually used between different fields without a heightened awareness of how different the meanings of the word are (Sheller and Urry, 2016; Rodrigue, 2020, P. 4). As its own form of scientific research mobilities has been formulated quite recently(Sheller and Urry, 2006), that does not mean that ideas feeding into the research have not been followed before, but in their foundational paper, "The New Mobilities Paradigm," Sheller and Urry have consolidated ideas for this epistemology of movement. The main concern is understanding movement through more than the factual description of the positional change between a and b but as the sum of all influences acting on an object of study that cause it to move. Or alternatively to cite from Shaw and Hesse (2010)
"... it (Mobility) elucidates the framework conditions underpinning the generation of movement, the experience of movement and the implications thereof, and the wider impact of movement across a whole range of sociocultural, economic and political milieux."
This allows for exploring movement over the boundaries of very different fields, approaching ships and shipping from a qualitative angle (Geographies of the Sea) and a quantitative angle (Transport geography). To make sense of these seemingly contradictory approaches to the topic, a solid framework (Mobilities) and an overview of the fields will be necessary. The following section will introduce the mobilities framework and then relate it to the two other fields. This will help in connecting the different components of my research.

Mobilities broaden the perspective, and its core tenants divide the movement into differing aspects. As mobilities are highly context-dependent, the next section will be general on the aspects that are shaping the movement and serve more as a starter to illustrate the topics that can be of interest. Still, general interest in mobilities is connected to:

- Motivations. Movement does require the expenditure of energy; therefore, it usually happens with a goal in mind(Cresswell, 2010). These goals can be small and direct, like the fulfillment of basic needs or commuting to work to make an income(Bissell, 2014). They can also be very personal, like imaginaries of a better future in the case of emigrants (Sheller and Urry, 2006) and the need for safety motivating refugees to leave their homes(Gill et al., 2017). Or anywhere in between.
  A motivation that is central to modern societies and the work on shipping is profit(Cresswell and Martin, 2012), making money by organizing and enacting the movement of people, goods, and ideas(Rodrigue, 2020, P.1). Motivation does not need to be rational; it can also be driven by curiosity or feeling, for example, in relation to music or dancing(Merriman, 2015).
  Movement is often but not always voluntary to those it acts on, such as trafficking, slavery, or displacement(Merriman, 2015). These create mobility surrounding the people on the move while suppressing individual mobility(Gill et al., 2017).

- Capabilities. This can refer to the mode of movement, as a single person through walking, swimming, sailing, driving a car or as a vehicle by utilizing jet or steam engines, carriage by horse or the titanic engines of container ships(Birtchnell, 2016).
  This includes personal factors like the ability to make the upfront investment to start moving or the proper papers to overcome borders(Hannam et al., 2006). It can be infrastructural, the ability to rest and refuel along a journey, or the availability of an airport to land a plane(Sheller and Urry, 2006). The capacity to enact movement is also closely related to the speed at which movements might happen (Cresswell, 2010).

- Constraints. This is the opposite force to Motivations, the reasons not to start moving or to seize movement(Adey, 2006). Again, these can be personal, emotional, and binding to a place or responsibility to take care of family or property (Hannam et al., 2006). There are cultural constraints on the ability of different groups or genders(Adey, 2006) to move.
  Moving is also connected to risks for personal health and wealth. These risks can also be external, such as in the case of volcanoes preventing certain air traffic (Adey and Anderson, 2011) or ships getting stuck in major canals(Markkula, 2022). Within the school of mobilities, being stationary describes the state where the influences motivating movement are overpowered by those constraining it(Birtchnell, 2016).

- Experiences. Movement is something that can be mundane, like the daily commute to work, or extraordinary, like moving to a new country. The experiences or feelings of those who move vary greatly with the context that

is provided by the rest of the aspects (Cresswell, 2006, P.4).
However, the experience of the traveler also shapes the movement, especially in determining route and timing. A commuter can choose a time and mode of travel that are best fitting for their Journey, and a seasoned traveler can plan for additional waiting times at borders or give some slack to planning to account for delays(Löfgren, 2008). The journey also shapes the traveler, as documented in the travel diaries movement, creating new connections and opinions, thereby changing the traveler's outlook(Lean, 2012).

These influences are in constant flux and interplay. A sailor needs to consult the tides and weather before making a decision to set sail; this is based on motivation to reach a goal but also the experience of their own capabilities. They play out over different scales; the need to rest or refill a tank leads to a temporary seizure of movement, but it does not mean the termination of the overall journey (Cresswell, 2010).
At its core, mobility sees the world through a lens of change, especially the more recent publications that connect it not only to movement but also more general as shifts through form, function, and meaning (Sheller and Urry, 2016). Immobility, or as it is often called moorings, remains essential as a world without points of reference is impossible to describe(Adey, 2006). This focus on change makes mobilities a good lense for thinking through the structures of ocean space, not only for my deliberation on ships but the greater community of all who fill the ocean with additional depth and understanding.
For ship mobilities, I approach this from two different fields of research that complement each other in scope and the insights they provide/ search. The first lens is transport geography, and the second is human geographies of the sea.
Transport Geography provides the big picture for shipping mobilities, it deals with the smooth running of the transportation system and helps to explain the main motivation for ship transport, profit that can be created by providing movement of goods. To take the definition of the field from its central Handbook: "Transport geography is a sub-discipline of geography concerned about the mobility of people, freight and information and its spatial organization considering attributes and constraints related to the origin, destination, extent, nature and purpose of movements."(Rodrigue, 2020, P.1).
Transport Geography has a detached relationship with ships. While maritime transport is responsible for the greatest share of global moving goods, it is not at the center of attention. In a recent study, it was estimated that roughly 2.6 percent of all published papers deal with maritime transport (Ducruet, 2020). The areas where effort was put in have mainly been vulnerability to disturbance, flow optimization in terms of fuel usage and reliability, and the discovery of general network patterns. Ships are conceptualized as vectors or numbers representing the connection between ports, focusing on the flow of volume or mass and the time delay between departure and entry into a target port.
Transport geography has adopted a positivist framework that situates the fields closer to natural sciences and especially networks scholars, while links to the more human-focused aspects have regressed. This has caused a rift in thinking and publication between it and other fields (Ng et al., 2014).

For network research, transportation systems are ideal test cases for real-life applications of theory, especially structures like small worlds and scale-free networks that can be identified depending on how connections are drawn(Ducruet and Zaidi, 2012). As the movement of people has been generally taken over by planes (except for ferry services) (Rodrigue, 2020, P.176), the field has grown most closely to the forces that make ship transport necessary namely the economic sector of geography or economics in general.
For transport geography, the main concern is the flow of goods; for this, it is more useful to conceptualize ships as vectors of flow generating a flat transport capacity per time. This enables the construction of a multi-modal network of transportation and the determination of what transport geographies conceptualize as mobility, the ease of moving an idea, person, or object(Rodrigue, 2020, P.4).
As the name suggests, the Human geographies of the sea have the goal of extending geographic thought to the "empty" ocean. This movement gained momentum in the early 2000s, spearheaded by the works "The Social Construction of the Ocean" by Phillip Steinberg(Steinberg, 2001) and later "Currents, vision and Voyages: Historical Geographies of the Sea" by Lambert et al.(Lambert et al., 2006). These researchers formulated their ideas on the social dimension of the ocean(Germond and Germond-Duret, 2017), recognizing the unjust marginalization of the ties between people and the oceanic environment as well as the connections that bind together oceanic imaginaries and the sea(Steinberg and Peters, 2015; Peters, 2010).
The ocean's contribution to human well-being creates a deep connection to people as individuals and societies at the seaside(Anderson and Peters, 2016). The relation with the sea can take many forms, from understanding maritime traditions and folklore(Anderson, 2012) to critical observations on the role oceans and ocean-related action have played in colonialism(Belhabib, 2021), slavery(Anim-Addo, 2013), or globalization(Hasty and Peters, 2012). Understanding these factors and influence is important as they drive the decisions that shape ocean space taken by the people on the coast materializing in shifts to the fish population(Bear, 2016; Satizábal and Dressler, 2019) rebalancing of sediment transportation, or introduction of pollution(Choi, 2022).
Perceptions of oceans can be full of hope and opportunity, as in the case of immigrants of almost any era (Anim-Addo, 2013), lawless and freeing(Langewiesche, 2010), allowing the subversion of state repression(Gomperts, 2002; Peters, 2012). Opportunity can also be found in the ocean itself, exploiting its vast resources or disposing of bothersome objects. Other perceptions are mysterious and dangerous, when stormfloods and tsunamis ravage the coastlines or loved ones vanish with their ships.
All these are factors that shape the relationship between humans and the sea. In the context of ships, the traditions and lives of seafarers are of great interest(Borovnik, 2012). Contrary to common understandings, the ocean is not a sedentary but a permanently inhabited environment. Ship crew can serve on a vessel for years at a time, making ocean space their home(Borovnik, 2012). Geographies of the sea try to question the Western tradition where a lot of this has been smothered. Technocratic approaches to the exploitation of the sea, universal systems for navigation, and a mindset of predictability have made the engage-

ment with the more traditional views on the ocean far less relevant(Anderson and Peters, 2016). Industrialization has made work at sea a more arcane undertaking than in ages before, as the jobs have become very specialized, requiring extensive training to do correctly(Borovnik, 2022). The regular business of seafaring has been shunted to workers from developing countries, leading to exposure to topics of seafaring vanishing from everyday dialogue(Borovnik, 2022). At the same time, the broader population in the West has isolated itself from the aspects of the ocean in their everyday life. With the triumph of the container, the workforce required to operate sea transport has been diminished. Other cultures have retained more of their ancestral connections to the ocean, such as, for example, those of south-east Asia. For them, ocean space is an inevitable part of life(Anderson and Peters, 2016).

Where I want to position this work is between these perspectives. Both fields have a space for ships in them, but they are detached from thinking about the movement of ships themselves, while transport loses the single ship to the large scale, making it one of over 10000 entities feeding the system. Human geographies of the sea lose themselves in the stories and meanings of the individual and cultural. As ships are in the liminal space between these extremes mobilities does provide the framework for thinking through both understandings of the movement.

The next chapter will demonstrate more closely what kind of questions can be asked by taking the bird's eye perspective of transport and networks.

2 Mobility on a Network

When looking at marine transportation from the mobilities side, it can be argued that the first focus should be on the central motivation of building, maintaining, and operating ships. This is the generation of transportation and its sale(Rodrigue, 2020, P.4). Modern transport ships are reliant on port infrastructure for loading and unloading(Ducruet and Notteboom, 2012). This makes the global shipping system a facsimile of a network and allows the viewer to analyze shipping through the lens and language of network science(Lin and Ban, 2013). In the next section I will introduce networks and the language surrounding them in order to understand and discuss my findings within a network context.
The basic components of a network are nodes and links. A node or colloquially vertex is a defined point, especially in geographically located networks in the case of shipping. This refers to fixed locations such as ports or entries and important features such as straits or canals. A link or edge is a connection between two nodes, a direct path or train line, shared ownership, or a flow of goods. To describe networks, it is sufficient to list the full set of nodes and the full list of node connections. But, especially for large and dense networks, it is more effective to create an ordered network matrix with every row corresponding to one node. As the port name information is not conserved, it is important to remain cognizant of the specific order in any entry referred. An interaction between node i and j can be found in row i column j; if this interaction is quantified through a number, it is called a weighted matrix or weighted graph(Barabási, 2016, Section 2.2). Different possibilities to link the nodes produce their own specific networks. Checking for an interaction between the nodes without assigning weights or a direction for the connection leads to a simple graph, as is the example of the adjacency matrix, that represents the possibility of getting from node i to node j in a binary fashion. Groups of nodes that can be reached through the network form so-called components. In the shipping case, the global ocean is one big component that has been expanded further by the building of canals and deepening of rivers to span even further, even up to the otherwise landlocked Caspian Sea or North American Great Lakes. This makes the ocean shipping network "fully connected" (Wang and Wang, 2011) because as long as a deepwater port is there, no additional infrastructure is needed to facilitate the movement.
Following a single ship over time, it draws its own network between the ports, following its assignments. For the perspective of transportation this single entity is of lesser interest, instead the movements of many transport ships are compounded into one larger network.
For this research, two weighted matrixes of the network are of special interest. First is the distance matrix, while everything can be reached this describes how much effort needs to be expended in order to move between two nodes. Different measures would be sensible to define distance, accumulated travel cost, fuel spending, or journey time. The upside of these other measures is that they might paint a more accurate picture for defined subsets of vessels, but my dataset is quite diverse with ship types and sizes. Therefore, I opted for a distance that more faithfully follows the classical understanding of the term. All of the distances are geodesic, this means while determining the distance between two points we ac-

count for the round shape of the earth(Karney, 2013). A more detailed description of the process of determining distance is provided later in this chapter. The second matrix describes the flow of vessels between the ports and will be referred to as the flow matrix. Flow can be determined through different means, in this research the flow has been determined from an analysis of positional data (Kaluza et al., 2010), the data more often is taken from port operators or shipping companies such as Lloyds List(Gastner and Ducruet, 2015). Flow is directed information, meaning the direction of the link is important and must be accounted for. Ships are treated as a conserved quantity. While new ships are introduced and old ones are scrapped, this only accounts for a small number of journeys.
The number of edges that originate or end at a vertex is called its degree. In a directed graph, the degree can further be broken down into incoming and outgoing degrees(Barabási, 2016, Section 2.3). From the perspective of the single node, this indicates how well connected the node is and defines its surroundings, but when looking at the statistical spread of degrees or better the degree distribution in the network, bigger structures emerge that allow for a classification (Kaluza et al., 2010).
The Network of shipping can either be set up as a system of direct connections or full paths over the network (Ducruet and Zaidi, 2012). The direct network is more straightforward in structure, as it reduces the number of connections between the individual ports. Long-distance travel happens in a number of successive steps. This is an advantage in the description of the current state and flow between regions but a downside for identifying the motivations for the ship movements as the information on the flow between origin and destination on the incentive level is discarded. Therefore, in this work, I will focus on the global all-links network. While it is more complex in structure and more dense, it preserves the origin and destination of the flow. Thereby, it is also a better basis for the modeling of long-distance connections that will be a central topic for this chapter, as there are no established short port-to-port steps through arctic waters (Ducruet and Zaidi, 2012).
The language of networks allows for useful shorthand descriptions of phenomena in shipping. The first issue is the diameter of a network or, better, the longest shortest path between any two nodes in the network. For the shipping, this describes the longest travel between any two nodes necessary while still traveling over the network in an optimal way(Barabási, 2016, Section 2.8).
The problem of determining the shortest paths between any two nodes while traversing the network is an old one. For my work the most important method for achieving this is Dijkstra's shortest path algorithm, it allows for a reliable determination of the optimal path, not only through counting steps but also in weighing the connections by the distance or other constraining factors. The algorithm works by determining the distance of all other nodes from the starting position step by step, always going for the closest so far unchecked node until the distance to the whole network has been determined. From there, the resulting shortest path is determined in a second step, tracing the optimal path from end to beginning (Dijkstra et al., 1959). This is necessary because, while in theory, the network is fully connected, in reality, this would be an inefficient mode of organizing shipping, as it discards one of the greatest benefits, the economies of scale.

Container cargo is instead organized in so-called hub and spoke systems(Wang and Wang, 2011; Ducruet and Notteboom, 2012). This means multiple local ports are forming a small component with their neighbors; one of these ports is bigger and connects to other bigger ports for long-distance connections. This structure makes the shipping network surprisingly small in diameter and makes it fall within the perimeter of so-called small-world networks(Kaluza et al., 2010).
The second network-based descriptor for the shipping sector is centrality. Centralities are a class of measures that provide insight into the importance of a single node in the network's overall structure(Kanrak et al., 2019). My focus is mainly on betweenness centrality as it highlights the main ports and current bottlenecks such as straits (Malaka, Dover) or the canals of Suez and Panama(Kanrak et al., 2019). To calculate the betweenness centrality, the shortest path between all pairs of ports is determined. During each calculation, the nodes along the shortest path are recorded. Finally, it is counted how often every node is part of a shortest path. As this measure is relative to the network in question, it is of interest to discuss the relative height of the betweenness centrality rather than the absolute value(Kanrak et al., 2019).
A structure that can be found in the shipping network specifically are gateway and intermediate hub ports (Ducruet and Notteboom, 2012), this is focussed around the role they play for the goods within the network. A gateway is a port receiving a significant amount of flow because it is the point where goods enter and/or exit ship transportation. Large flow is directed towards them, but they are low in centrality for the network overall. This is exemplified by the main ports of the United States, where the strength of their economy is turning over to the water. The intermediate hubs are filling a different role. They are nodes where trade routes intersect. A relatively small amount of goods is entering or exiting ships here. Instead, they function as pivots, organizing the traffic flow(Rodrigue and Notteboom, 2010). Containers are processed and stored in the port facilities to change between ships. This allows for a minimization of travel times and greater utilization of the employed ship hulls. Intermediary ports are high centrality nodes; the greatest examples of this function are the ports of Singapore and Rotterdam, where the trade between Europe and Asia is bundled from the region of origin and dispersed after arrival in the region of destination.

2.1 Shipping Scenarios

With the insight to the network structures that describe shipping at the transport network scale we can further our understanding of shipping mobilities. From the research into the network structures, we can identify current high centrality nodes in the canals, and we can ask the question of how the shipping sector would react to the establishment of new routes.
The most likely scenario for a major opening of so far unpassable waters is the sea routes through the Arctic(Mudryk et al., 2021; Ng et al., 2018); these would make Atlantic to Pacific travel significantly shorter as they cut the need to go through the Mediterranean, Suez, and then around India to the east Asian ports. On the American continent, the detour from the US east coast through the Panama Canal to reach the west coast or Asia. How much these routes are cut will be

determined later in this chapter.
The opening of the arctic waters is a consequence of climate change(Mudryk et al., 2021), with the average maximum and minimum ice extend reducing over the last 40 years(Ng et al., 2018). This also means a quicker melting of the sea ice in spring, lengthening the season of plausible arctic traversal for ship traffic(Melia et al., 2016). Currently, there are only a few exploratory voyages and supply runs through the Arctic, but there is already a measurable increase in traffic(Gunnarsson, 2021). In the future, it is foreseeable that commercial shipping might utilize the routes, even without vessels that have an ice class(Ng et al., 2018). [2]
This is a danger to the remote and, so far, relatively pristine arctic coastline. Both potential accidents and the establishment of arctic intermediary ports will increase anthropomorphic pressures such as pollution in the region(Qi et al., 2024). Determining the potential for utilization might provide impetus to establish the rules for the passage even before they enshrine themselves into unregulated customs.
There are two sea routes most often discussed in reference to arctic waters: the Northern Sea Route (NSR) that runs along the northern Russian coast and the North West Passage (NWP) that charts a course through Canada's arctic archipelago. Depending on the development of global climate change, a passage through the central Arctic is also imaginable (Figure 1). It will be included in this consideration as the least constrained scenario for shipping.

The currently most reliably usable passage is the NSR. This makes the passages not only a significant economic and ecological factor but also a political one(Savitzky, 2016). This complex interplay between different entities shaping the shipping through the Arctic will be a test case for improving the understanding of the mobilities that play out to shape the systemic movement of ships. The model that is introduced in this chapter will establish a baseline to compare future developments against, opening up the questioning on the driving mobilities.
The second major impact on the shipping infrastructure is the security of the major shipping straits. The Panama Canal is no longer suitable to allow for the biggest ships to pass, leading to the establishment of the post-Panamax ship size class (Kuroda et al., 2005). The Panama Canal has continued to have problems maintaining its water level. Due to changes in precipitation patterns the gatoon lakes that previously provided the canal with waters are running low, endangering the passage even for vessels that have been specifically build to be able to go through the canal(Carse, 2024).
The vulnerability of the Suez Canal is of a different nature and has been far more visible in the grand scope. In 2021, the vessel Evergiven got stuck in the canal, blocking it for nearly a week(Markkula, 2022) and causing global delays in the usually smooth-running system of shipping. The most recent problem has not been directly linked to the canal itself. A militant group has undertaken strikes at ships going through the Red Sea, a required passage to use the canal. This caused major shipping companies to reroute their vessels around the southern tip of Africa until the attacks were stopped by international navy actions.

[2] An ice class rating is undertaken by different National Authorities, what it universally classifies is the ice conditions a ship can navigate without endangering its safety of travel(Ng et al., 2018).

Figure 1: An opening of the Arctic does create four possible scenarios, a shippable Northern Sea Route, an open Northwest passage, both at the same time, as well as a completely central cross-polar route (Portal, 2015), all of these routes meet in the Bering strait

What makes these cases especially interesting is the observed reorganization or dismissal of distance as the main measure of cost. Post Pamanamax vessels serve as a reminder that economies of scale can even outperform a several thousand-kilometer detour around the southern tip of South America. The same can be said about the utilization of the Suez Canal in crisis, while a sudden breakdown of the infrastructure has caused massive delays and activity spikes around the world, the deliberate reaction to reduce traffic flow almost to zero instead of taking the small chance of an attack has caused less of a commotion, though the pressure on the international community was high enough to react quickly and remains unresolved (Notteboom et al., 2024).

2.2 Determining Distance

The radiation model relies on the distances between ports and their populations to predict flows. These distances are accumulated in a matrix and represent the main difference between my shipping scenarios. The population is based on the AIS dataset used by Kaluza et al. (Kaluza et al., 2010). To understand how the differences arise, I will introduce the process of generating the distance matrix step by step.

The first step is the selection and preparation of a polygon representing the land areas of our planet; the one chosen is the standard Matlab coastlines set. To save on computation and reduce artifacts this shape is cleaned and simplified. First, Antarctica has no major ports and is remote from the other continents, so no shortest paths run along its coasts. Therefore, a new and reduced shape is introduced. Second, the dataset is cleaned of lakes, they create artifacts and provide little insight to the global shipping system. Finally, the shape of the coast is simplified.

In the second step, a matrix of points is created that represents the shape of the land and the positions of the ports. The polygon from the first step is Geo-referenced, so the points necessary for drawing it can be extracted, as well as middle points for stretches of coastline that are too long. This is complemented by the introduction of points for all ports from the dataset. The ports in the set are geo-referenced but need to be adjusted so every port has a connector to the coastline if the provided position is within the land area. To do this, a point on the closest coastline is created as long as the point is not too close to one already in the matrix.

The third step is the most computationally demanding. The goal is to check ship connectivity between every pair of points in the matrix. Ship connectivity means that the route between the points does not cross over land areas. Every pair of points is checked against this shipability, though due to being undirected, the connections only need to be checked in one direction, halving the necessary checks. In order to account for the three-dimensional rounded shapes of the earth that allows for travel in a straight line, quite impossible on a flat map, a geodesic algorithm is employed. The code also breaks down every route into 13 parts to allow for gradual connection lines over the planet's surface. Each segment is then checked against crossing the land polygon. If they cross land, the connection is marked as impossible; if the connection is open, the geodesic algorithm is employed to determine the real distance between the points.

The fourth step is adjusting the distance matrix and creating the scenario for a frozen Arctic. The current process creates a number of connection anomalies due to the detailed grade of the map and fails to adjust for the man-made connectors in shipping. Therefore, manual connections representing the Panama, Suez, and Kiel canals are introduced, and a manual connection to the Black Sea and the Sea of Azov is made that would otherwise be unconnected. Then, to introduce scenarios with a closed Arctic, a new distance matrix is created where Arctic connections are disabled. The original matrix is duplicated, and then every connection running north of 70 degrees latitude is removed.

The fifth and final step is creating a distance matrix between the ports, as required for the radiation model. So far, the distance matrix created, while including the ports, only accounts for direct connections between the points. To get to the port distances now, a shortest path algorithm like Dijkstra's Shortest Path Algorithm (Dijkstra et al., 1959) is employed between every pair of points connected to a port. This then creates the port distance matrix.
In the project, I set out to check different distance scenarios, and these different parts of the process have been amended. The Ice/ no ice scenario has already been described in step four. For shutting off the canals they are not added in step 4. To get to the differing ice lanes is more involved, here I introduced a nonexistent "landmass" to the arctic region. This island would differ between the scenarios and allow for either a passage along the Northern sea route, the North West Passage or both, this in combination with a not cut off at 70 degrees latitude matrix provides the different distance matrices.

2.2.1 Results of Distance Determination

This method of determining the distance does provide insight into the effects the scenarios would have. An opening of the Arctic and the closure of the canals would lead to new shortest connections between ports (See Figure 2). To provide an idea of where these new connections are created, the connections can be drawn on a globe.

To make the effects more palatable, I have created two tables showing the distance between different regions of the shipping network. The first contains the length under the current scenario and the relative change to the scenarios; the second can be found in the appendix(4) and contains all rounded values. The regions are here represented by a single Port: For Europe, it is Rotterdam; for East Asia, it is Shanghai; US Westcoast, it is San Francisco; and for the Gulf of Mexico, it is Galveston. These ports are only examples, but they serve as good indicators for the patterns that are found, and as will be shown, a focus on regional patterns does provide the effects produced by the scenarios.

Connection	Current (km)	Ice Free	Passages	NSR	NWP	No Canals	No Suez
Europe to East Asia	19130	0,68	0,75	0,75	0,77	1,32	1,29
Europe to US West	14850	0,80	0,89	0,89	0,91	1,69	1.0
East Asia to Gulf of Mexico	18540	0,94	0,94	1,0	0,93	1,69	1,0
US West to Gulf of Mexico	8730	1,0	1,0	1,0	1,0	2,89	1,0

Table 1: Relative distance change between regions: the first column presents the distance in the current scenario in kilometers, and the rows afterward show the relative change between the alternative scenario and the current state. Connections between East Asia and the American Westcoast(9910 km), as well as between Europe and the Gulf of Mexico(9060km) have been excluded as they are not impacted by the scenarios

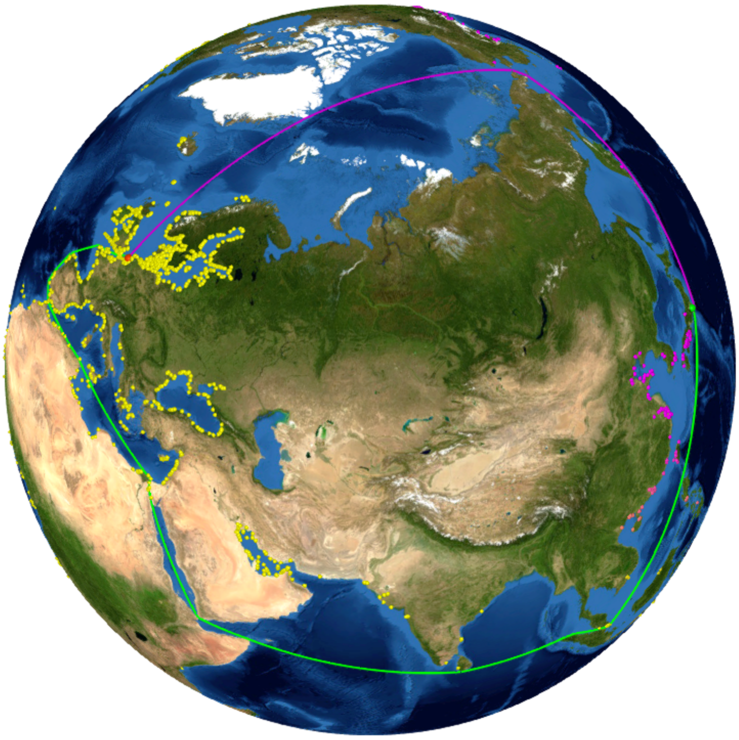

Figure 2: With the opening of the Arctic, new shipping lanes become accessible. Here, a globe is utilized to show the new shortest path between the port of Rotterdam (Red Dot) and Tokyo (Green Dot). This is portrayed under scenario two, which represents an Arctic with no ice at all. The green line follows the traditional route between Europe and South East Asia, through the Mediterranean and Suez Canal, then to the Strait of Malacca, around Singapore, and finally to Tokyo. In magenta, the Northern Route is considerably shorter; from the Northsea, the Ships aim directly for the Bering Strait and, from there, down the Coast to Japan. A secondary Information has been integrated to this image, the Ports that are visible in this perspective are colorde by the Impact the scenario has for the length of the shortest connection starting from the Origin in Rotterdam. Yello Dots represent a port with no gain at all, while the more purple they get in color, the greater the Impact of the Icefree Scenario. A positive change in route distance is achieved for ports in Vietnam and further North.

The first main result is that traffic staying within one of the oceans, so across the Atlantic from Europe to the east coast of America (including the Gulf Coast and the Caribbean) or East Asia to the west coast of America, is not impacted by my scenarios at all and has therefore only been left in table 4. This is a repeating pattern in the data as, for example, the shortening of the paths only impacts connections longer than 10000 km in length (see figure 3). In the scenarios with canals closing, impacts are felt most strongly on the inter-ocean routes and close to the canals. This becomes visible when the greatest relative length growth is determined between the Gulf Coast and the American West Coast. However, due to the central position of the canals, the shortest influenced connections start at the length of the canal itself and then their surrounding areas.

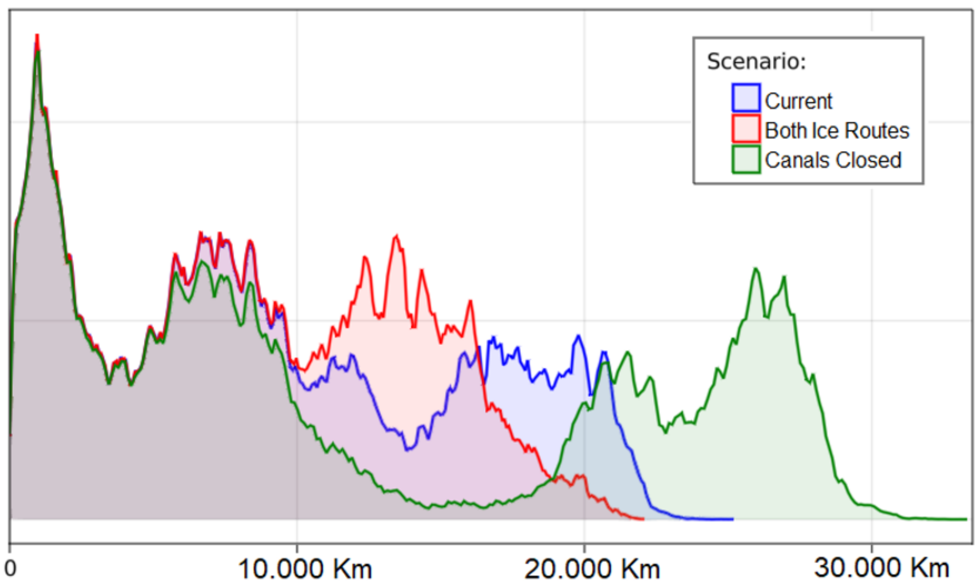

Figure 3: Distribution of the lengths within the global shipping network. The x-axis shows the length of connections, while the y-axis represents the percentage of all connections of the corresponding length. The blue trend represents the current scenario, the red trend represents a scenario where both arctic passages are open, and the green trend represents a scenario with closed shipping canals. The short connections do not differ between the scenarios.

The Europe to Asia connection is the one influenced the strongest by an opening of the Arctic; the connections could be cut by up to a third in length. This has the same magnitude of impact the canals have on the current system, where the distance without the canals is a third longer. This effect is followed by more Northern ports on the American East Coast (New York to Shanghai is reduced to 72 percent from 19460km to 14200 km). These have not been treated separately a Northern position, in addition to closeness to the shipping canals are the main axis of influence here(See Figure4). The Influence of the current canals becomes visible in Europe to the American West Coast example. Here, the savings are smaller. The Panama Canal seems to have a bigger relative impact on the distances that need to be traveled, though this could be due to the selection of the representative ports. It manifests in two ways, the first are the smaller possible gains through the availability of the Arctic, including the only outlier where an Arctic route is longer than the traditional one for an opening Northern Sea route. Interestingly, a closure of the Suez Canal leads to some Europe to Asia routes being redirected through the Panama Canal.
The overall distribution of path lengths repeats the patterns and demonstrates the impact of the different scenarios. As the number of connections is constant, the scenarios are directly comparable. The distribution strengthens the insight from table 1. This shows the structure of the shipping system, a large number of port connections are short, they are not impacted by the scenarios at all. They manifest as a peak of short-distance connections. These represent within-region connections between the hub and spoke ports (less than 5000km) or journeys crossing the Pacific or the Atlantik (5000km -1000km). Changes to shipping

route availability impact the long inter-regional connectors. An opening of the Arctic routes leads to the number of long connections receding while increasing the number of medium-length connectors. The closure of the canals has the opposite effect. Medium and shorter-distance connections are reduced in number while the number of routes that are more than 20000km in length is increasing. These represent North Atlantik to North Pacific connections.
The average route in the current conditions has a length of 9224 km. An opening of the Arctic will impact 18 percent of all port-to-port connections; the average impact on the shortened routes is 10,4 percent, representing a shortening of 790 km. The effect closure of the canals impacts 54 percent of all connections and has led to an average port-to-port length of 11335km; here, the distance that has to be traversed increases on average by 22 percent, leading to an additional 2100 km that needs to be traversed. The closure of just Suez mainly impacted the European Asia trade, which becomes visible in table 1.
Looking at the average distance change per port reveals more patterns. A north-to-south gradient is detected for the scenarios with an opening arctic, and the northernmost ports are receiving the greatest reductions(Figure 4). What is interesting is the impact on the southern Pacific region, where a direct northern route shortens travel distance from both sides of the north Atlantic region, leading to a recognizable reduction of the port's connection distance (Rotterdam to Brisbane changes by 4000 Km 21800km to 17700km).

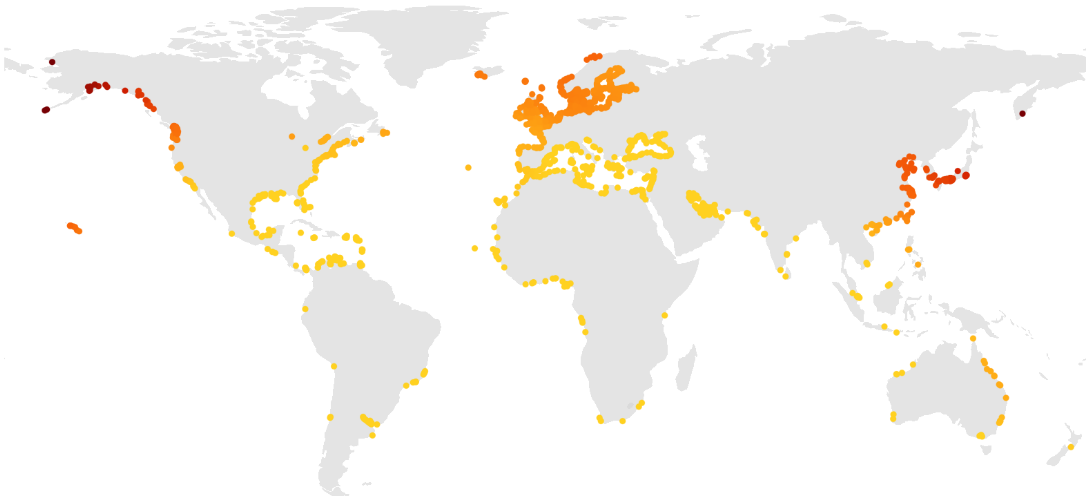

Figure 4: A global distribution of the ports provided by the dataset. The color corresponds to the impact an opening of the Arctic has on the average lengths of all connections to the port in question. Yellow represents no change or impact; the redder the color gets, the more the distances are reduced. The greatest reduction happens in the northern Pacific region, followed by northern Europe. There is an overall north-south gradient on the impact of an open Arctic.

When comparing the different sea ice scenarios, considerable overlap is calculated between those with a partly traversable Arctic. While a completely open arctic produces the most significant reduction in the journey lengths (Table 1), the scenarios with limited arctic traversability produce very similar outcomes(Figure 5). Therefore, when referencing a partially traversable Arctic, we will reference only one of these, the scenario with both routes open.

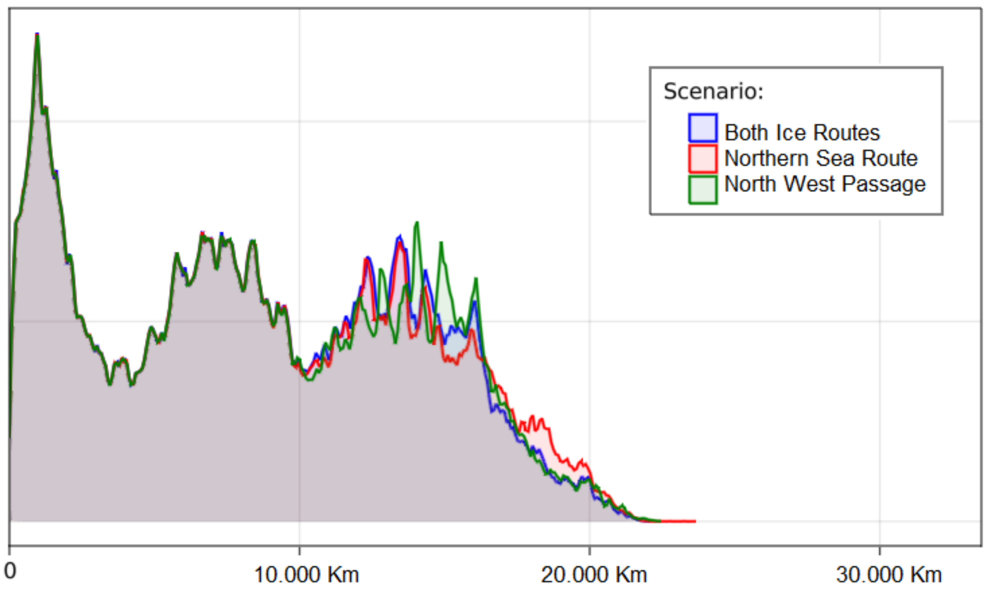

Figure 5: Distribution of the lengths within the global shipping network. The x-axis shows the length of connections, while the y-axis represents the percentage of all connections of the corresponding length. The blue trend represents the case of both passages being open, the red trend represents a scenario with an open Northern Sea Route, and the green trend represents a scenario with an open North West passage. The scenarios show a strong overlap, with the NSR having the worst overall distances.

Now that the distances for the different scenarios have been determined, the next step is to model the impact that the new distances have on the global flow of ships.

2.3 Flow Model

The quest to understand human movement is an ongoing one, mobilities research is approaching it mostly from the qualitative side(Manderscheid, 2016), but there is also a path through modeling that makes predictions based on quantitative data. This meshes well with the positivist worldviews predominant in transport geography. Tackling the mobilities of ships at this level does provide a look into the main motivator for shipping, namely the profit from providing the service of transportation.

Models are working representations of reality, they allow for an approximation and prediction of the behaviour in the system they where made for. Models do

not claim to get to a perfect answer, just one that is close enough to reality. This is undertaken on the basis of as few assumptions about the system as possible.
Two core components are necessary for modeling movement as I will do it: a potential gain (a reason to move) and the cost of movement (an obstacle to movement). Three main models have been proposed for the modeling of movement(Barbosa et al., 2018), the gravity model, the intervening opportunities model and the radiation model.
In the gravity model, a pull between two places (or nodes to stick with networks) is determined. An agent in the start node is feeling a push to leave and a pull by the neighbouring nodes to visit them instead. What is preventing them from always going for the greatest pull is the distance they have to overcome in order to make the journey(Kaluza et al., 2010; Ducruet et al., 2020). An intervening opportunities model looks at the likelihood of being distracted from the original course of action by finding a better or similar offer at a lower cost on the route(Stouffer, 1940). The radiation model determines the probabilistic likelihood that the best opportunity in relation to distance can be found in every reachable node of the network (Kang et al., 2015). The merits of these models have been discussed at length in the literature(Lenormand et al., 2016; Barbosa et al., 2018). For this application, the radiation model was selected, as it runs on fewer assumptions and promises a better result for the long-distance connectors characteristic for shipping(Simini et al., 2012). Especially the ability to run without extensive fits to real data is beneficial for exploring a vastly different world of connections(Simini et al., 2012).
As models of movement are generally starting from land based observations of human traffic a central role is played by the so called population of a node. This is a measure for the amount of opportunities the node offers, for cities it is useful as larger population centers tends to be richer in industry and jobs. In the case of shipping we take the amount of ships entering and exiting the port as a measure of attractiveness, this is also called the node strength. The assumption is that Ports are points of focused opportunities, the bigger they are, the more likely it is; they offer profitable business for the vessel.
The Radiation model determines the likelihood of the best opportunity for trade being found in any node when compared to all cheaper-to-reach nodes(Simini et al., 2012). This makes it a more systematic extension of the original intervening opportunities model(Kang et al., 2015)). It gets the name radiation model from treating the modeled objects like nuclear radiation emitted from a source. Every emitted particle will end up at some other atom absorbing it. The likelihood for every single one is calculated by the relative sizes of the atoms surrounding the source(Alis et al., 2021).
Only a few parameters are needed for this: the node strength for every node and the distance matrix between them, as determined in the last section. While the original model is based on positional distances, network-based distance determination has also been employed for the radiation model(Ren et al., 2014). If I am speaking of the best opportunity in the following section, this refers to the greatest gain at the lowest distance to the origin. The radiation model has been introduced and formulated in 2012(Simini et al., 2012).

In the model, the flow T between nodes i and j is the probability that j contains the best opportunity for a vessel multiplied by the total number of vessels emitted from i, T_i. For this calculation, i is always the starting node and m refers to the starting node's population, j is always the target node and n refers to the target node's population. The opportunity is calculated by the product of the total populations of i and j divided by the product of the population of i added to the population of all other nodes that are closer to i than j, called s_{ij}, and the added population of i,j and s_{ij}.

Or better expressed in an equation:

$$\langle T_{ij} \rangle = T_i \frac{m_i n_j}{(m_i + s_{ij})(m_i + n_j + s_{ij})}$$

This can alternatively be understood as the outflow term T_i and the probability term p_{ij}:

$$\langle p_{ij} \rangle = \frac{m_i n_j}{(m_i + s_{ij})(m_i + n_j + s_{ij})}$$

$$\langle T_{ij} \rangle = T_i p_{ij}$$

The physical radiation model works based on a system with quasi infinite boundaries, this is not a property of the shipping system, we are confined to the limited boundaries of oceans with a finite number of ports to absorb all shipping that is emitted. If not accounted for, the model systematically underestimates the flow between the nodes(Masucci et al., 2013). To account for this and to make sure all vessels that are emitted end up in a port, the model has to be normalized (Kang et al., 2015). A very general case for a normalization is the factor:

$$\kappa_I = \frac{N}{N - n_i}$$

Leading to the Formula for flow:

$$\langle T_{ij} \rangle = T_i \kappa_I p_{ij}$$

To optimize the results of the model additional constraints and factors can be introduced, like a distance elasticity coefficient, adjusting the results to fit better with the results(Kang et al., 2015). It was decided against this approach as we lose the benefit of not requiring an extensive fitting dataset to adjust this parameter. The radiation model can be employed in two directions: emission and absorption-based (Kang et al., 2015); the absorption model turns the focus around and determines for every node how likely it is that it does contribute to the flow into the target node. This also introduces terms for normalizing the flows into the nodes. This results in a different probability function based on the destination rather than the origin. This leads to the probability function p_{ji}

$$\langle p_{ji} \rangle = \frac{n_i n_j}{(n_i + s_{ij})(n_i + n_j + s_{ij})}$$

Based on the model proposed by Kang et al. (Kang et al., 2015), different variations of the radiation model have been tested against each other prior to the work. The best outcomes have been produced by a model where the probability is based on the ship emissions from the origin, but the flow is based on both emission and absorption and a normalization for both. To achieve this a normalisation is determined in a process that is similar to the doubly constrained gravity models. It introduces the factors K_i as the normalization of the flows out of i and L_j as the normalization of flows entering j.

$$K_I = \frac{1}{\sum_{k \neq I} L_k T_k p_{ik}}$$

$$L_j = \frac{1}{\sum_{k \neq j} K_k T_k p_{kj}}$$

As these values are dependent on each other, the normalization is approximated in an iterative process over all nodes of the network. The process runs as long as it takes the maximum change on any of the k_i or l_j to be not greater than $1e^{-8}$ percent. With these in place, the formula for determining the flow between I and j used for this work is:

$$\langle T_{ij} \rangle = T_i K_I T_j L_j p_{ij}$$

As the flows into and out of ports are conserved in this approach, the main analysis is determining the redistribution of ship traffic. The flow between ports allows for the construction of flow over sea lanes; this is approached in a way similar to the betweenness centrality. I return to the global network of shipping links constructed from step four of the distance calculation between ports. Then I recalculate the shortest path between each pair of ports, the flow between the ports is added to all links along the path. In this fashion, I can make a prediction on the expected global shipping reorganization in the scenarios.

2.3.1 Results Radiation

The Radiation model does provide a prediction on how the traffic between ports will change. The analysis of flow garners results for the global network of shipping, and allows for a reconstruction not only between ports but more importantly the sea areas that are utilized.
The pathing distance network has more than 6799 individual nodes, leading to 23109801 possible links. Even excluding those links that were not utilized leaves us with an enormous number to discuss. Therefore, I have selected a small group of links to look at more closely to represent specific interests. The first two are the Suez and Panama Canal; while they are turned off and therefore zero in some scenarios, they give great insight into the amount of change for the northern routes and provide a good frame of reference. Third is the Bering Strait, as this is an inevitable bottleneck that all Arctic traffic needs to pass. Next are the Cape of Good Hope and the Strait of Magellan as indicators. the last two are the main routes that have to be taken in case the canals are closing and show a potential change in the southern hemisphere in the case of the opening Arctic.

Connection	Current	Ice Free	Passages	No Canals	No Suez
Suez Canal	48116	0,54	0,83	0,0	0,0
Panama Canal	28691	0,9	0,91	0,0	1,26
Bering Strait	0 (15119)*	0,31	0,22	0,0	0,0
Cape of Good Hope	7224	0,99	0,99	5,72	2,47
Magellan Strait	258	0,81	0,83	14,30	1,11

Table 2: Relative change of flow on selected shipping lanes: the first column presents the number of vessels in the current scenario, and the rows afterward show the relative change between the alternative scenario and the current state. *The Bering Strait is a special case, as no commercial traffic has been detected in the current state. The number in brackets represents the scenario of a fully open Arctic. The base for comparison is the Suez Canal to have an order of magnitude. The full numerical table is included in the appendix table. 5

In the current shipping regime, the Suez Canal is detected as being the most central passage for global ships, with an annual throughput of 48116 vessels (See Table.2). A reorganization of the shipping network due to open passages in the Arctic would mean a reduction to 54 percent of the current usage. Accordingly, the Panama Canal is affected by the current traffic of 28691 ships per year, which is reduced to 91 percent to 26143.
Under present-day ice conditions, the Bering Strait is not utilized for commercial shipping at scale (or at least not encapsulated by the dataset); with an opening of the Arctic passages, this is expected to change as all routes traversing the Arctic have to navigate this bottleneck. To still have a frame of reference, it will be compared to the Suez Canal under current circumstances. From currently 0 ships, the Arctic passage would be used by 15119 ships in case of a fully opened Arctic, which means it has traffic equivalent to 31 percent of the current Suez Canal utilization.
To get insight into the shipping networks overall, I have visualized them, allowing for contemplation of the network. The effects of the scenarios become most apparent when visualized. For the visualization, an azimuthal projection of the earth with a focus on the North Pole has been chosen as this provides the greatest amount of detail for the Arctic region while also being lower on distortion along the major shipping routes situated in the northern hemisphere. Antarctica has been removed as it is not a central hub for shipping and is a remote region from shipping lanes.

Visualizing the differences between the scenarios(See Figure 6), a general pattern emerges that matches the findings from the distance realignment. The results correspond to the expectations from the actual system. In the current state (Figure6), a multitude of connections serve the global system; the greatest number of them connect the wealthy nations of the global north and the strong exporting nations of Asia. Traffic between the US and Europe for example is happening over almost the whole Atlantic.

Figure 6: This represents the shipping densities in the global shipping network under current conditions; the color and thickness represent the amount of flow. The thicker and more yellow a line is, the more traffic runs through it in the model.

The current regime is built on the available east-west water passages, and the inter-ocean connections represent the strongest concentration of traffic. They funnel ships through the canals, from Europe to Asia Suez and from the American East Coast to Asia through the Panama Canal.

The most significant impact is predicted on inter-ocean routes, which is confirmed by the reduction of shipping through the canals at Suez and Panama and the connections feeding into them. Opening up the arctic waters around the outer edges of Arctica reshuffles the trend; while there is still significant traffic along the old routes, the ability to traverse arctic waters reduces their utilization. As ship movement on the northern routes and the pathways to the Arctic increases(See Figure 7). The major difference between the ice route scenarios is in the access ways and the route itself. The NSR does have a slightly greater impact on Eu-

Figure 7: This represents the shipping densities in the global shipping network under the opening of both arctic passages; the color and thickness represent the amount of flow. The thicker and more yellow a line is, the more traffic runs through it in the model. The new ship routes become visible in the arctic waters, though the greater volume of ships starting from the European ports leads to a greater utilization of the NSR.

rope, and the NWP has a slightly greater impact on North America (Figure 7), but overall, they do not differ significantly. What becomes very apparent is the canals' impact on streamlining overall flow.
The closure of the Suez Canal leads to a major reorganization in traffic around the southern tip of Africa and an increase in traffic through the Panama Canal (Table 2), which becomes a viable alternative for long-distance connectors. What also becomes apparent in this picture is the significant amount of traffic still undertaken close to the canals; this is created by the fact that the canals are also optimal places to situate major ports in the current regime. These ports remain untouched in the model therefore they still need to be serviced. However, a stepwise adaptation/reorganization of the port sizes could be an interesting pathway in the future.

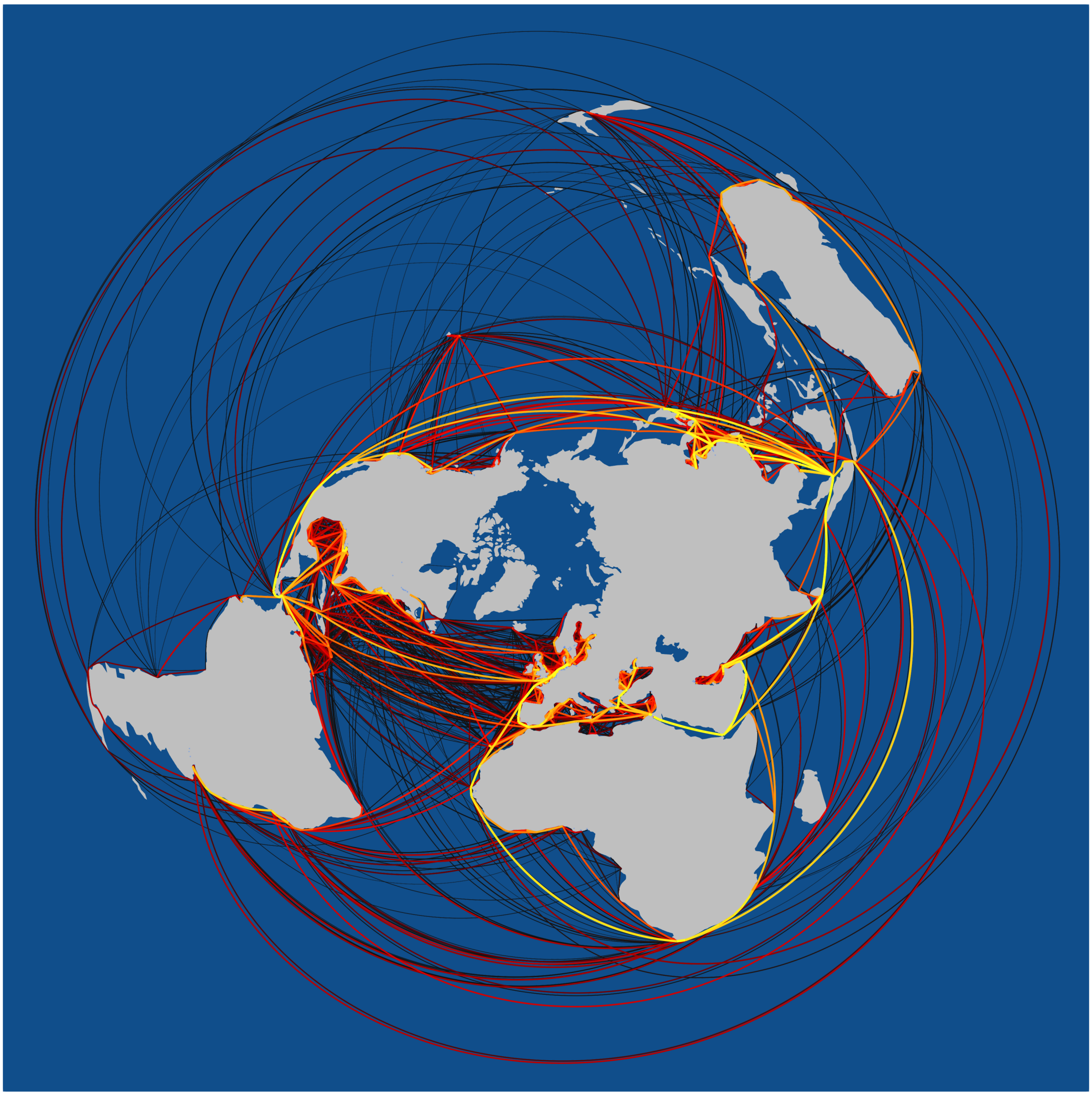

Figure 8: This represents the shipping densities in the global shipping network under the closure of the Suez Canal; the color and thickness represent the amount of flow. The thicker and more yellow a line is, the more traffic runs through it in the model.

While a suitable tool for visualization of the resulting shipping networks overall, Figures 6; 7, and 8 contain dense information that makes a comparison between the scenarios possible but not easy to interpret. Therefore, the following figures have been created to underline the effects on the network and make comparisons easier. What is plotted is the difference between two scenarios, as indicated in the captions. The Reference scenario is the current state. As the topic is change, it needs to be stated that a reduction in traffic does not equate to a seizure of traffic. The Suez Canal retains 54 percent of the traffic in the open arctic scenario, which still makes it one of the most significant global waterways.

The scenario without any ice shows a strong focus on the traffic as these new routes are very competitive. This underlines that the shortcut becomes more and more attractive to shipping when less ice is at the pole.

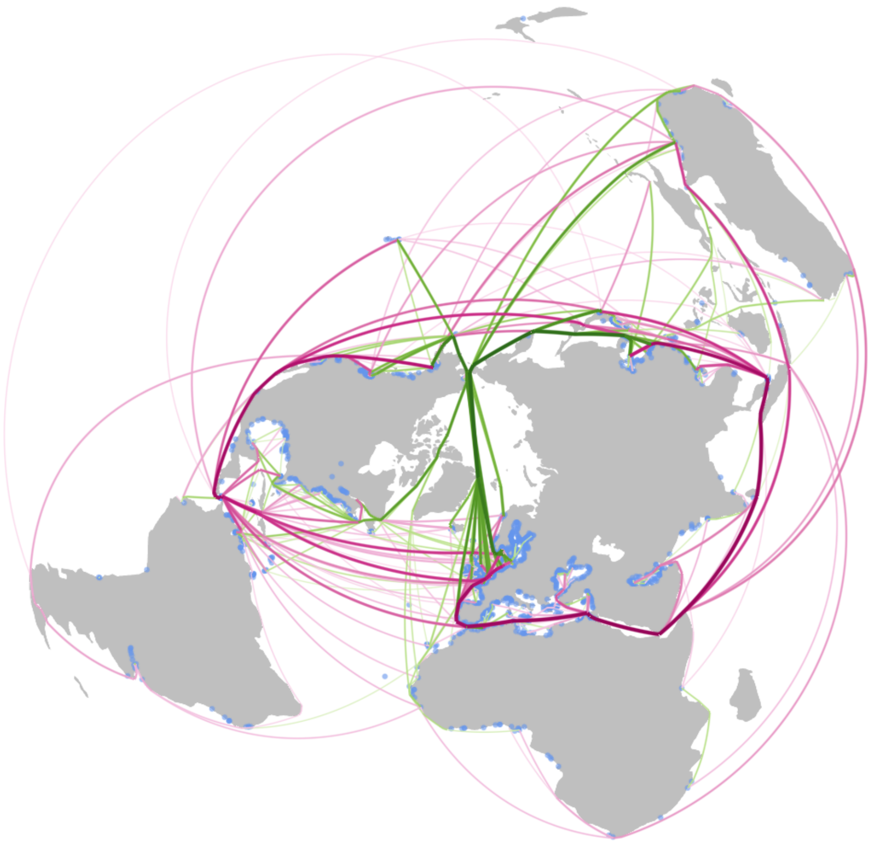

Figure 9: This represents the differences in shipping densities between the scenarios of an ice-free Arctic and the current state. The differences occur on the global network of shipping. A green connection signifies an increase in flow, while a magenta connection shows a reduction in flow. Color intensity and width indicate a greater difference. The open Arctic offers improvements on the longest current connections, leading to a rebalancing towards North-South connections at the cost of the East-West established ones. Notice that Australia/Oceania is the only southern global region to receive increased traffic from the opening Arctic.

We see the same patterns remade that have already been indicated in the distance matrix—connections through the Arctic and to the South Pacific increase. The connections crossing the Atlantic and Pacific Oceans are perturbed only in the case of the Europe to American West Coast connections. This is visible due to the Atlantic lanes with reduced utilization, concentrating on the Panama Canal. (see Figure9).

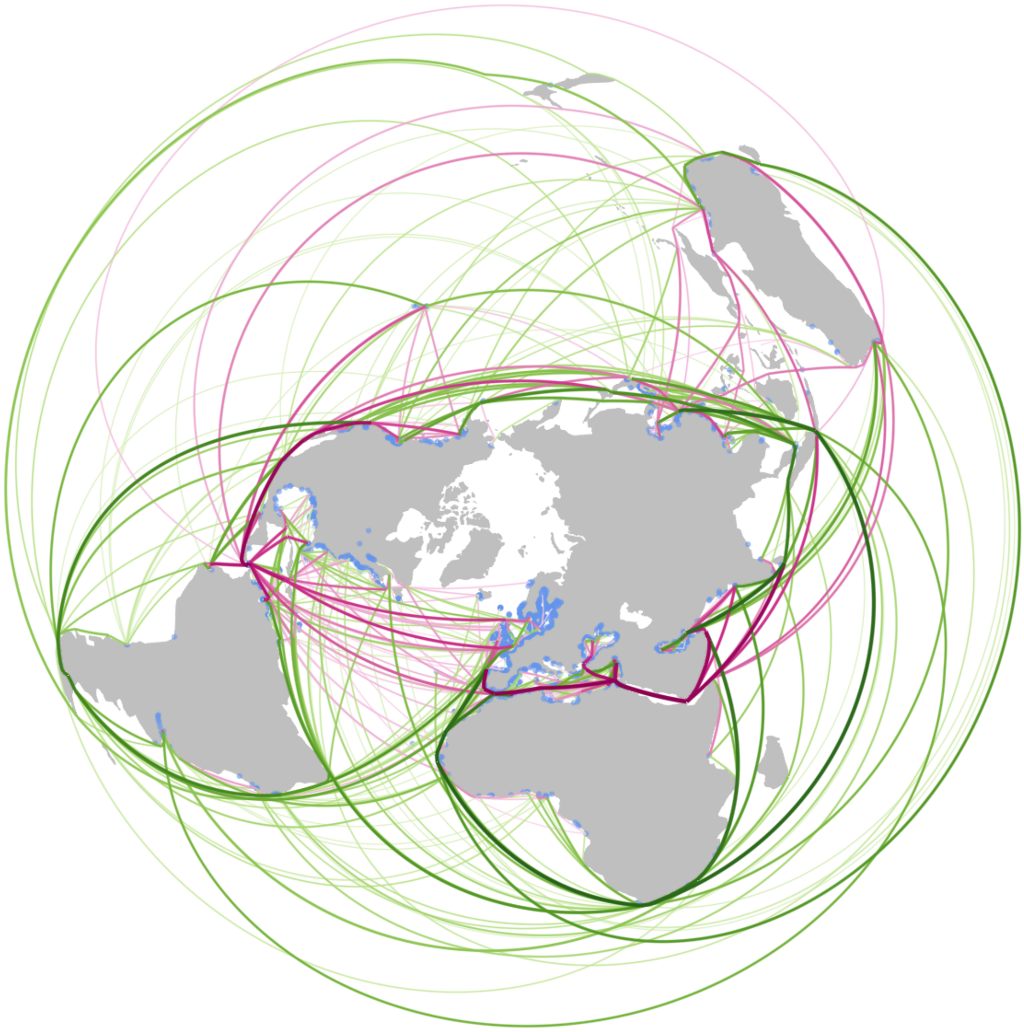

Figure 10: This represents the differences in shipping densities between the scenarios of closed shipping canals and the current state. The differences occur in the global shipping network. A green connection signifies an increase in flow, while an agent's connection shows a reduction in flow. Color intensity and width indicate a greater difference. With the removal of the shipping canals, traffic to the southern hemisphere is increasing as the new closest inter-ocean connectors are located there.

A closure of the major shipping canals also leads to a north-south reorganization of traffic as new connections need to be established. Traffic between ocean regions needs to circumvent the southern tips of Africa and South America, which serve as pivots for the system(Figure 10). A second observation is that the canals have a role in streamlining transport. The ocean lanes are far more diverse with them not being available anymore.

2.4 The Different Futures of the Shipping Network

This section had the central goal of exploring the mobilities of ships from the perspective of transport geography. To do this, I first introduced the networks' basics and the scenarios I am working with. Then, I went through two steps in determining how changes to the accessibility of shipping routes shift the global flow of vessels. The first step was the determination of the new distances that are a consequence of making the Arctic accessible to shipping or closing major shipping canals. Opening the Arctic shortens the distances in global shipping while closing the canals extends the route lengths. As a general pattern, the further north aport is positioned, the more it benefits from an accessible arctic.
Based on these determined distances and the amount of shipping that runs through the ports of the network, a radiation model is introduced and applied that predicts the flow of ships under the changing distance conditions. I find and visualize the impacts of this model. Starting by analyzing the impact on significant shipping passages, I find that an open Arctic would facilitate traffic equivalent to a third of what currently passes through the Suez Canal.
The main impacts on ship traffic are found on routes that travel between the oceans, leading to only connections of more than 10000km benefiting from an opening of the Arctic. For the canals, the impacts are more immediate those ports closest to them lose the most from their closure. The routes along the canals also still produce strong signals even if the canal is no longer available. This is due to the adapted nature of the shipping network, which is not accounted for in the model of the northern routes.
Looking at the different Arctic scenarios, it becomes apparent that the specific scenario for an open Arctic is less relevant as long as the shortcut can be taken. The differences between scenarios three, four, and five are marginal from the distance perspective. This leads to similar results for the shipping networks, with the caveat that only a single passage opening focuses all the traffic into one area, while a completely open Arctic spreads out the ships better.
The Arctic, at least for parts of the year, as the shortcut looks almost inevitable(Ng et al., 2018), has enormous potential for cost savings. What will remain interesting is the (im)mobilities that work against this logic of cost savings. Optimal routes are not the only determinator for ship mobility; building a post-Panamax and/or Suezmax ship is a strong indication that already tells us that the economics of scale can overcome the rules of distance. Another interesting case for how the mobilities of ships are shaped comes from the two crises for the Suez Canal; the short-term disruption caused a massive traffic jam that, resonated through the shipping sector(Pratson, 2023). On the other hand, the attacks against ships in 2023/24 show that if the reaction time is just a bit longer, the system is very capable of switching over to a non-Suez mode. Even though the distance was greater, the value and the likelihood of being attacked were low. Shipping companies rerouted due to insurance reasons. Ship insurance is also proposed to be one of the main reasons for the glacial pace in the adoption of the northern routes, even though passages have been open in the last few years(Gunnarsson, 2021).
A final observation is that those countries most responsible for global warming stand among the first to profit from its disastrous effects on the environment for shipping. as shown in the north-south gradient for distance. This also includes

the long-term perspectives, the future development of ports will be strongly linked to their positions along global trade lanes, like it has been in the past with the northward shift in shipping developing nations might find themselves further from inclusion to the global networks than ever.
The real development in the long run will be quite telling for the mobilities of ships, this model has been based on the perceived main driver, opportunity and main inhibitor, cost /distance. As models try to approximate reality just close enough, it will be interesting to see whether my inference holds true (Alis et al., 2021; Hong et al., 2019). The points where made predictions fail will be of the greatest interest in uncovering the top-level mobilities of ships. Insurance has already been mentioned, but the ownership structure of ports and shipping companies and their interconnections also play a role in the designation of ship movements (Ducruet and Zaidi, 2012). For the future of this project, I would recommend a new and more up-to-date dataset, including the ports. Many directions are imaginable, it could be interesting to separate out the hub and spoke ports, as mainly the hubs are interconnected the gain of information resulting from the spokes is limited. The dataset utilized here does not account for tanker and cargo transport. These two do follow different patterns, as will be shown in the next chapter.

Statistics to Actors

Keeping with this view on shipping is not suitable for our goals; the flow of goods is completely abstracted from the happenings at sea. Therefore, to gain insight into how shipping interacts with its environment, we want to look closer. One important act of protecting ocean space is limiting its usage to maintain natural function (Kelly et al., 2019), which requires more close information. The problem with the modeled view I take for this first chapter is that it expects ships and journeys to be optimal; to get a feeling for the real movement of ships, other perspectives will be necessary.
The logic of transportation and the flow model applies to ships but abstracts them to terms that are universal to any form of transportation (opportunity and cost). This works well for understanding the broadest possible view of the shipping sector, but a different conceptualization is needed to get closer to the vessels themselves.
From the (Ducruet and Beauguitte, 2014)perspective of mobilities, we are simplifying our model to the most basic components: motivation is created from port size, and inhibition is created from distance. While this serves well to explain the broad features, the impacts on the ocean are more localized. Even taking into account different ways of creating these global networks does not generate the information needed. What needs to happen is a perspective closer to the ship, linking individual behavior to mobilities.

3 Mobility of the Ship

The limits of the network view on shipping become visible when looking at the problems ship movements and pathing entail. In the introduction, the scalability of ships and the low friction of the ocean were presented as the main upsides, together with the availability of free ocean space to navigate once out of the confines of land. This remains true but also endows ships with enormous momentum and limited capabilities to maneuver at speed. Straits like the Britsh Channel or Malakka at the same time funnel ship traffic into confined areas, creating a high risk of collision between ships or of ships with the coast(Peters, 2020a). Ship collisions are major environmental hazards, spilling fuels and toxic cargo into the vulnerable ocean ecosystem and spreading these threats over far distances through the natural turnover processes of ocean space(Wan et al., 2022). The loss of ship(s) and cargo is also a major monetary loss to shipping companies or their insurers as ships are large long-term investments and, due to their size, carry significant amounts of goods. The networked view does not capture the problem; the traffic estimations from the radiation model might serve as an indicator for the position of high-traffic intensity sea areas, but this is unable to account for the individual movements or local mobilities of the vessels. This requires us to venture out to sea to find another source of data for the exploration of more individual mobilities.
Following the problem of collisions leads to the second perspective on how the movement of ships is understood or how a look at their mobilities might be undertaken. This chapter will focus on the AIS, a communication technology for following the movements of ships in close to real-time. It also enables us to track the ship's movement history from archived data. I will first introduce how the technology has been established, what its purpose is, and how it became an internationally recognized requirement to carry AIS. Then, I will provide a technical rundown of the technology and data provided. Finally, I will use Data generated by AIS to look at ship mobilities through a framework of nonmovement.
To reduce collision risk, countries employ pilots and so-called Vessel Traffic Services (VTS) that help ships to become aware of their surroundings(Harati-Mokhtari et al., 2007), be it for the local seascape (pilots) or other vessels (VTS). Historically, VTS has been based on land-based radar and radio reports when reaching specific waypoints in the strait for vessels within the managed area of the station(Young, 1994). Still, the navigation and prevention of collision is reliant on the observance and attention of the crew upon the ship's bridge, with VTS trying to provide warning to potential arising dangers but no direct possibilities for intervention to the course.
The events that would ultimately turn over the traditional way of traffic management were kicked off with a bang, or better, a crash, on the 24th of March 1989 in Prince William Sound, Alaska. Shortly after Midnight, the Exxon Valdes, a modern and large oil tanker, did run aground on Bligh Reef(Birkland, 1998). The severed hull spilled 41.000 cubic meters of oil into the arctic ecosystem and, in consequence, devastated more than 2000 Kilometers of coastline(Barron et al., 2020). While there was no injuries to the crew and the ship has been repaired the clean up did cost the United States more than 5 Billon Dollars, to this day, after more than 30 years the ecosystem is still not recovered from the catastro-

phy(Barron et al., 2020).
The investigation following the incident found a couple of culprits for what had happened: the bridge was understaffed, the officer at the helm was overworked and left alone in a high-pressure situation, and the VTS was unfit for its task of chaperoning the vessel safely out of the critical area or even recognizing the danger(Birkland, 1998)). This was due to the inappropriate adjustment of radar systems and the degradation of radio communication infrastructure. The management or reaction plans for a spill of that scale were nonexistent on the coastguard or terminal operators' side(Birkland, 1998).
In reaction to the disaster the US Coastguard had to reevaluate their approach to VTS not only in the Prince William Sound but at 22 locations all around the country, a need for increased traffic control was determined. To prevent accidents, the infrastructure would need to be upgraded, including visual measures and improved radar and radio surveillance. In Alaska, this led to the establishment of the so-called Automated Dependent Surveillance System, where ships would transmit their positions regularly over Very High Frequency (VHF) radio and be plotted accordingly within the management area. This garnered international interest, and in coordination with the International Maritime Organization (IMO) and the International Association of Lighthouse Authorities, technical requirements for the implementation of an AIS have been established in 1998. The solution to address the requirements at an acceptable cost was identified in VHF radio communication utilizing a Self Organising Time Domain Multiple Access (SODTMA) transmission protocol. To facilitate the radio communication two frequency bands, Channel A 161.975 MHz (87B) and Channel B 162.025 MHz (88B) have been set aside by the International Telecommunication Union (ITU) for the exclusive use by AIS in 1999(World Radiocommunication Conference, 2019). Finally, the AIS was formalized into international maritime law through an amendment of chapter five of the Safety Of Life At Sea Convention (SOLAS) in 2000 (International Maritime Organisation, 2001).
The IMO document expanded the aims of the system, standardised international VTS was joined by collision prevention between ships and an increase in littoral states awareness on what happens within national waters. Collision prevention is achieved by making the AIS a two-way system that transmits and receives at the same time, informing ships about all major commercial vessels in their vicinity. Ships transmit data that increases the awareness on activity in the national waters(International Maritime Organisation, 2015).
The AIS was made mandatory for large transport ships, new-build ships from 2003, and all vessels from 2005 onwards(International Maritime Organisation, 2001). The ships that are required to operate an AIS transponder at all times are vessels with a gross tonnage of more than 300 on international journeys and a gross tonnage of more than 500 conducting only national trade, as well as all vessels primarily transporting passengers. This baseline requirement is further augmented by national requirements for AIS carriage(IMO, 2024). State-operated ships, as well as military vessels, are not required to keep AIS active at all times; they usually carry a system though for the improvement of situational awareness. There are different clssifications of AIS transceivers, here the focus will be on transport shipping so the class we are dealing with is "A". The other classes are either

paired down and lower priority as for class B, that is used for private vessels, or relate to landstaions, navigational aids or search and rescue usages.
What created additional traction and expanded the role of AIS were worries about weaponized ships following the 9/11 terror attacks. The AIS is instrumental in creating the marine domain awareness called for. As vessels are visible at all times, a deviation from expected behavior can be called out and checked on quick notice, allowing for rapid response to arising danger. This early warning to irregular vessel behavior is also helpful in more mundane situations to check up on vessels that are suspected to be in peril due to regular/technical failures, like in the case of the vessel Simushir in 2013 (Bishop et al., 2021) where early warning to the loss of power aboard and the consequential start of drifting in heavy weather allowed the coastguard to prevent a disaster by coordinating and taking the vessel into tow.
AIS works by transmitting a standardized set of messages over radio signals to organize the flow of data and prevent information overlapping. The SODTMA creates and allocates time slots for discrete information transfer. The information is encoded into a string of 27 different messages, which can be differentiated into three broader categories: static, voyage, and dynamic. To become legible, some information needs multiple messages to be transferred, for example, the position in longitude and latitude(International Maritime Organisation, 2015).
Static data contains information on the Vessel itself and is hard coded to the AIS at installation or in case major changes to the vessel are made, like being sold or refitted to a new ship class. These include a full set of identifiers,

- Mobile Maritime Safety Identity(MMSI) and IMO number, these identify the vessel, the IMO number is bound to the hull and does not change at all throughout a ship's lifetime
- Vessel name and call sign
- Ship type, this number identifies the official function of a vessel as provided in the AIS Specifications
- AIS transceiver class
- ships dimensions and relative installation of the positioning system, this allows for an accurate positioning of the vessel in space

Voyage data contains information on the current operation of the vessel; it is to be updated as necessary by the bridge crew. The information provided is:

- Ship draught, this changes due to load and ballast take up; therefore, it needs to be updated whenever changes occur
- Indication on Hazardous Cargo and if onboard its nature
- Current destination and expected time of arrival, the indication is supposed to be provided in UN/LOCODE
- Waypoints, at the ship master's discretion

Dynamic data contains information on the current movement of the vessel and is directly fed into the AIS by the ship's systems. An important contributor here is satellite-based positioning, for example, through the global positioning system, as they provide a ship with independent, precise ways to share current universally legible coordinates. The transmitted information is:

- Position and integrity status of the positioning system, precision should be within 10 m

- UTC ship time in seconds

- Speed and course over ground, current speed in knots, and course as a direction from 0 to 359 degrees

- Planned course or heading, during maneuver the intended end course is provided

- Rate of turn, an indication of direction and speed of course change

- Navigational Status, a number indicating the current status of the vessel as provided in the AIS Specifications

Finally, there is also a text field for safety-related messages. This is text information meant to warn either all vessels in the area, for example, about the presence of ice, or individual vessels about upcoming dangers. The transmissions and number codes have open slots that can either be utilized and assigned by coastal nations for their navigational needs or give space for expanding the future use of the AIS protoco(International Maritime Organisation, 2015).
There are 2250 time slots per minute per frequency band, for a total of 4500 slots per minute. In the case of very dense traffic, it is also possible to "overload" a frequency by more than 400 percent, with the first messages that would be lost being the most remote from the receiver. In order to save bandwidth, the static and voyage data are only transmitted every 6 minutes or at request, while the transmission rate of the dynamical data is based on the vessel's current activity and ranges from 3 minutes at anchor and stationary to 2 seconds while moving at more than 23 knots and/or changing course at more than 14 knots(International Maritime Organisation, 2015).
For VTS, the data allows for close management of traffic, especially in straits or high-intensity areas, organizing the movements that are occurring and preventing dangerous situations before they even can occur, in the same fashion as air traffic.
For optimal integration into the bridge and, thereby the best effect for preventing collisions, the AIS should be bundled with an Electronic Chart Display and Information System (ECIDS) as well as radar-based monitoring systems into one overview that provides a complete picture and allows for the timely prevention of dangerous situations(Harati-Mokhtari et al., 2007).

As AIS is based on very high frequency radio it is basically line of sight communication, the detection range is therefore dependent on antenna installation on the transmitting and receiving side, between ships the range is up to 40 Km for landstaions with high antennas up to 100 km(Goudossis and Katsikas, 2019). Nearshore areas and ship-to-ship contact were thereby always possible to monitor, but from the start, there was also the idea of collecting the signals from space; in 2010, the Columbus module of the International Space Station got put into orbit, it did include the NORAIS antenna array purpose build for the reception of AIS signals (Fournier et al., 2018; Skauen, 2016). This started the final important jump in technology to make AIS coverage global. This allows for a complete view of ship movements around the globe. The Data from the ships is not only tracked live but also archived by companies that make the data available to paying customers. Figure 11 draws the flow of data out schematically. Other entities that collect and make available AIS data are either run by the government, such as the Marine Cadastre operated by the United States of America's Coastguard, or conglomerates of private AIS data collectors that share their information, such as AISHub.

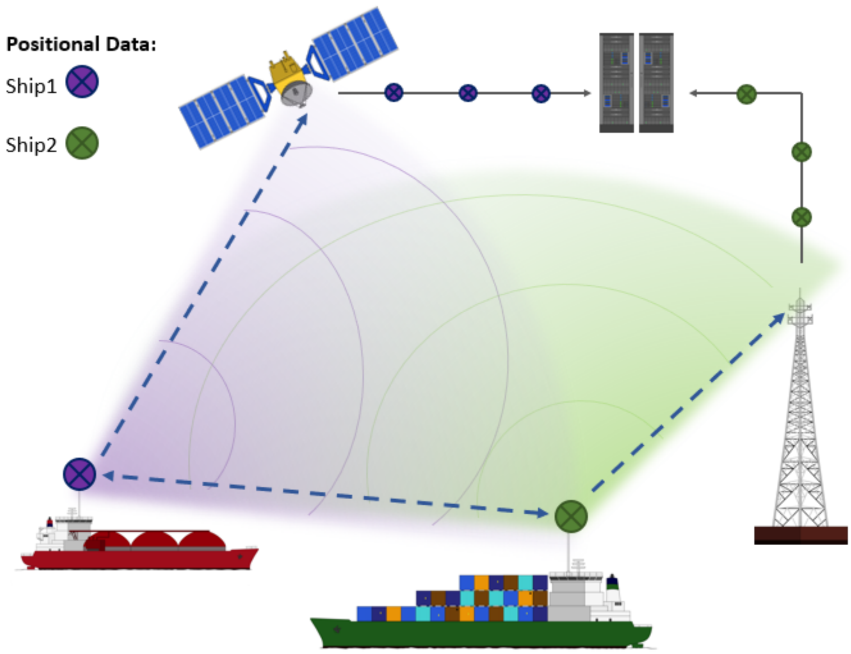

Figure 11: Schematic view on the flow of data in the context of AIS. Collusion prevention is done by sharing information between ships, but these signals are also received by land stations and satellites that create positional databases.

The utilization, sharing, and publication of AIS data are not endorsed by the IMO (IMO, 2024); I will get into the discussion on the dangers and merits of utilizing the technology outside of the initial use cases, as well as current scientific utilization in section 4.2. For now, the focus will be on the direct merits of employing it to understand the mobilities of ships.

As a source of data, AIS offers an angle to understand the mobilities of ships that are cognizant of the movement behavior between the ports of origin and destination. What is received is a complete and granular history of the movements of all vessels we can get AIS data for. Still it is important to approach the field with care as we have a log of the consequences of mobility in the form of movement, we can see how it manifests, where it is interrupted or expedited. Where it gets more murky is in searching for mobilities, the AIS does only superficially provide ideas for why the movements have occurred. Differentiating between a ship that reduces speed in order to optimize fuel consumption, mechanical problems, crew discretion, or limits to engine output is almost impossible. Taking a slightly adjusted route can be due to the experience of a master or pilot, expected heavy weather, reaction to traffic, or avoiding natural obstacles like ice or drifting degrees.
Where this data gets interesting without further context is the statistical evaluation of movement patterns, which reveals more general mobilities. In the next section, I introduce my second project on the detection of stationary in the shipping system based on AIS to illustrate how such a larger-scale investigation of movement patterns can be done.

3.1 Looking at Immobility

Having introduced the basics and background of AIS, this section will introduce the second major project contributing to this thesis. This project has been conceptualized as an interdisciplinary work and expanded over time to now contain three different publications. Following the data-driven work of the next chapter, I will introduce the topic of immobility in the mobilities context and show how AIS can be utilized to find the patterns in ship immobility (Müller et al., 2024). Then, visualizations of my data open up the discussion on the broader potential for the exploration of AIS data for understanding the ocean as a living part of society and less of an empty void of water(Müller et al., 2023). The focus in section 4 will shift to the utilization and potential of AIS data in contemporary research. Special attention will also be paid to fields that usually do not engage with this kind of quantitative data(Müller and Peters, 2024). The papers Müller et al. (2023), Müller et al. (2024), Müller and Peters (2024) have been published based on the same work that went into this thesis; they share a significant overlap but are not viewing the matter through the centralized framework of this thesis.

Visiting the coast is a great recreational activity, allowing the view to wander and enjoy the fresh air(Borja et al., 2020). This was a particularly important function in the early months of 2020 when the world was experiencing the first wave of the COVID-19 pandemic. Still, visitors to the coast in some areas were exposed to an unexpected spectacle. Commercial ships, which usually stay on their shipping lanes far in the distance, were moving close to the coast and got moored there. They stayed not only a couple of hours to wait for the processing at a port but for weeks as the lockdowns slowed down the economy (Schaben, 2021; Crump and Dalling, 2020).
A general conception is that when a ship becomes stationary, it is only for as short a time as possible and in particular areas designated as so-called roadsteads

(Monios, 2023); these are located at convenient places close to major ports or shipping lanes. Ships are built to move, as only by providing transport are they profitable.

In reality, the relationship between stationarity and movement is more complicated and a great case to explore the mobilities of ships further. This is due to the simple observation that stationarity is a state where those mobilities constraining movement overcome the mobilities that motivate it(Cresswell, 2010).

While the observed stationarity is traceable to the economic slowdowns and increased processing times in ports caused by the pandemic, it still raised my curiosity. When is immobility normal for ships?

The field of transport geography provides us with first insights, while a perfect just-in-time organization for the transportation of ships would be optimal on an operational level. In reality, such an organization would suffer from the multitudes of small interceptions that occur in port operations(Cresswell and Martin, 2012). One ship being delayed due to small damages to vessel or cargo, a short waiting time in the on boarding of a pilot. The need to let another ship leave the port. All of these are minimal delays, but in a system without margins, they build up rapidly. Therefore, it is of interest to plan with a bit of slack in the timetable. Most often, this is done by making the ship not run at its maximum speed all the time, a practice known as slow steaming(Maloni et al., 2013). By adjusting the speed to arrive at the port with marginal wait times, the consumption of fuel is reduced without reducing the operational effectiveness. Immobility can also be a product of the regular operation of the vessel in the form of maintenance, repair, refueling, or crew exchange(Notteboom et al., 2009).

Most attention to immobilities themselves has recently been paid in reaction to the pandemic; comparisons have been drawn between short and long-term disturbances and their impact on the global flow of goods (Cariou and Notteboom, 2022). The key difference between the early pandemic and the financial crisis has been in the nature of shipping sector internally and externally induced crisis (Notteboom et al., 2021). The interest within the field of transport geography is again in the analysis of the flow of goods and does not connect to the movement behavior of vessels.

In times of upheaval, these expected general immobilities are overlayed with specific ones(Cresswell and Martin, 2012). For example, the already mentioned closure of the Suez Canal caused not only a traffic jam at the canal over a couple of weeks, but the vessels that were coming through in haste also did congest ports at their destination, leading to more stationary vessels(Pratson, 2023). The financial crisis in 2009 brought to light another very specific form of immobility, so-called layups.

A layup is a form of stationarity and a consequence of the internal dynamics of the shipping market. The market has an unsustainable mode of financing new vessels, leading to a cyclical overbuilding of shipping capacity. This, in turn, leads to an over-abundance of transport capacity and deterioration of freight rates under the profitable margin (Sibilia, 2019). As a reaction, vessels become stationary in opportune areas to save on their operational costs while reducing the globally available ship capacity. This fixes the price of transportation to the point that shipping companies can operate at a profit. In 2009, awareness of the phenomenon was driven by the port of Singapore, where a thousand ships were put on layup to weather the crisis, leading to their moniker as the 'Ghostships of the Recession'(Sibilia, 2019; Mason, 2009). Research on the phenomenon has been qualitative and has not moved far from the port of Singapore.

With the pandemic on the rise, the question has been whether a comparable effect could be detected on ship movement. Little effort has so far been invested in understanding ship waiting, be it for layup or otherwise, to add to the body of understanding the dynamics of shipping (Monios, 2023).

The mobilities literature recognizes immobility a central concern wihtin the field. The reasons for this are manifold but usually focused on the interrelationship that forms our "worlds on the move"(Adey, 2006; Cresswell, 2006; Hannam et al., 2006; Sheller and Urry, 2006). First, viewing the world through a framework of change such as mobility makes it difficult to even describe where you are going. This has made it a core issue of mobilities to explore moorings or other relative areas of stationarity. In establishing points of reference, the field grounds itself(Salazar, 2021). The second major part is the meaning of stationarity or being stuck, especially in early mobilities literature, which was heavily focused on the airport. The mobilities of privilege in the form of wealth or passports manifest different patterns of movement. The "mobile elite" (Birtchnell, 2016) is able to bypass all barriers while the common passenger has to stand in line and wait/ endure immobility. Another concern close to this line of thinking is the mobilities of refugees, here first a situation uproots the population, breaking their settled and valued stationarity(Mountz, 2016). Then the refugee searches for a new and safe place to stay, on the way to such a place many obstackles have to be overcome in order not to get stationary in an insecure place. These obstacles can be borders and oceans, hunger and illness; all of these happen in a complex interplay of mobilities and immobilities(Cresswell, 2010).

In the case of shipping, there is interest in immobilities(Peters, 2017), but they have been discussed mainly from the perspective of special circumstances(Hasty and Peters, 2012; Peters, 2015; Peters and Steinberg, 2019; Monios, 2023). Disasters to the ship itself, such as loss of cargo(Cresswell and Martin, 2012) and the beaching of large vessels(Peters, 2020b). Or concerns for the ships crew and passengers as in piracy and kidnapping (West et al., 2010), forced shipping of convicts to foreign lands(Peters and Turner, 2015) and the politics and practice of migrants transported in the containers (Squire, 2015).

Regular and irregular patterns of immobility are covered more broadly in non-ship-related settings. For example, in the spread, prevention, and consequences of infectious diseases, which have garnered much attention since the beginning of the COVID-19 pandemic(Adey et al., 2021; Jensen, 2021). The pandemic provides an interesting background for the exploration of immobilities. It represents an extraordinary circumstance for immobilities that are added on top of the regular workings of the shipping sector. Understandings of short and long-term immobilities are extended beyond the Singaporean example by utilizing positional data to unveil the patterns of immobility, (Sibilia, 2019). Though a separation of the causes for short-term immobility as well as the rhythms of inactivity remains hard to disassemble due to the large number of possible causes and their overlapping(Cresswell and Martin, 2012; Adey, 2006).

The perspective taken here differs from the broader mobilities field (Cresswell and Martin, 2012) by searching for both exceptional and mundane immobilities that cause stationarity in shipping. I set up five questions to analyze the spatial patterns and temporal linkages of immobilities that do require greater attention (Peters, 2015):

1. What are the spatial patterns of immobilities at sea?
2. What are the temporal patterns of immobility?
3. Are layups detectable in the study area?
4. How is immobility shaped by the COVID-19 pandemic?
5. Can immobility be linked to other external drivers?

The greatest strength the quantitative approach offers over the qualitative description of stationarity that has been undertaken so far is the possibility to identify underlying patterns(Schwanen and Kwan, 2009). The data perspective is less likely to be influenced by the shifting attention of the public or a need to associate with shipping companies closely. Focus is on the ship level, this separates the spread on the network from the local phenomenon. The method works on all scales, with the limited dataset available here, but also potentially global coverage that is most constrained by the availability and quality of AIS data.
In the next section, based on Müller et al. (2024), I will introduce the data and methods that have been utilized to identify the immobilities and then discuss my findings.

3.2 Immobility from AIS Data

For this analysis, I utilize a dataset provided for free by the Coastguard, the Bureau of Ocean Energy Management, and the National Oceanic and Atmospheric Administration (NOAA) of the United States of America(Bureau of Ocean Energy Management(BOEM) and National Oceanic and Atmospheric Administration (NOAA), 2023). The unfiltered data used includes entries captured in the range of all receiver stations operated by the institutions in the years 2018-2022 (for an impression of the covered area, see figure 12). The AIS relevant columns for the recognition of patterns in the movement of single vessels are position, speed, timestamp of transmission, and vessel type(Müller et al., 2024).
The primary method is the reduction of the dataset to only keep a single position per stationary vessel and day to improve performance. Otherwise, the set contains all complete data transmissions per ship, meaning every couple of minutes when the static data is transferred as well. The dataset as received from the source is analysed per day, the first step is grouping the data based on MMSI. Vessels are filtered by class. As the main drivers of global commerce, only commercial cargo vessels in the form of tanker(AIS Class 80-89) and cargo(AIS Class 70-79) are included in this analysis. A broader inquiry into the differing patterns shown by the vessels based on their purpose might expand our understanding (Robards et al., 2016) but was excluded to remain in scope(Müller et al., 2024).

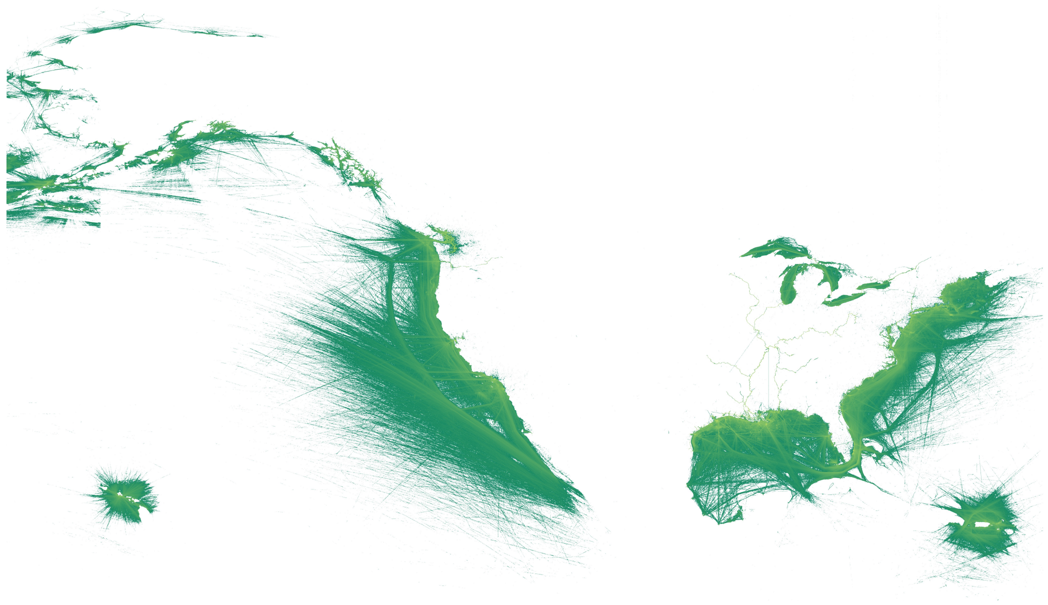

Figure 12: Representation of the area covered by the dataset. The density of all received positions is shown in one year, 2019. The positions trace the outline of the continental US, the Great Lakes, and major rivers.(Müller et al., 2024)

Then, the ships are filtered for their movement speed by two conditions: a ship during the period must not exceed a speed of 2 knots. Stationarity at sea is not absolute, as micro mobilities in the form of wind, waves, and tides move ships on the roadside where they are moored at buoys or anchors. Fastenings limit the range of motion, but there is enough slack in the mooring that a slow shift in speed and position is expected and needs to be accounted for (Robards et al., 2016; Peters, 2015). The second condition is that ships must remain within one kilometer from their starting position. Slow and steady moving vessels are therefore not counted as immobile(Müller et al., 2024).
The final filter is applied to the vessel's position. The interest of this work is on marine immobility, vessels in port are following their regular patterns be it for freight operation, maintenance or repairs, therefore in port vessels are excluded. To do this, the geographical boundaries are set from the coast of the continental United States of America to the edge of its exclusive economic zone(UN General Assembly, 1982). The coast is represented by the baseline as the recognized border between inland and external waters(UN General Assembly, 1982). The Exclusive Economic Zone (EEZ) is a recognized area of the ocean that has been set aside for a single states rights to exploitation and development, it is recognised since 1982(UN General Assembly, 1982) and usually extends 200 nautical miles from the baseline. Lay up, the initial phenomenon raising interest in immobility, is taking place in the outer harbour limits in order to prevent fees (Sibilia, 2019) so I exclude ships within the national baseline. Using the outer limits of the EEZ also has the benefit of eliminating ships that are processed in the ports of Mexico or other nations. The unfiltered data (Figure 12) shows the reception of positions within the ports of other nations(Müller et al., 2024).

3.3 Patterns of Immobility

For the analysis of the Immobility five driving questions have been set up in section 3.1. In the dataset if the pre pandemic years are referred to it is 2018 and 2019, the pandemic years are 2020 and 2021.

The first question(What are the spatial patterns of immobilities at sea?) is related to the spatial patterns of immobility that are normal within a system. Here, the data's recorded immobility positions have been used to create plot hotspots. Areas of immobility show no regional reorganization during the pandemic. The distribution of immobility phases strongly suggests that waiting positions are connected to the centrality and size of ports.(Figure 14). The greatest number in the study area are found at the coast of the Gulf of Mexico near Galveston and at the entry to the Mississippi River. On the West Coast, Los Angeles emits a strong signal of oceanic immobility. On the East Coast, immobile ships are detected near the ports of New York and at the mouth of the Delaware River. In the Gulf of Mexico, offshore oil rigs and ships waiting near them are found as sources of extended immobility. These findings show that this study of immobility replicates the anticipated spatial patterns of known ocean use(Müller et al., 2024). As introduced in the last chapter, centrality is an important measure for analyzing the global shipping network. More central areas allow for quicker reaction as they put the ships closer to opportunities for profitable cargo. The ports close to the hot spots of stationarity in this analysis are the most central in the US-American context (Ducruet and Notteboom, 2012).

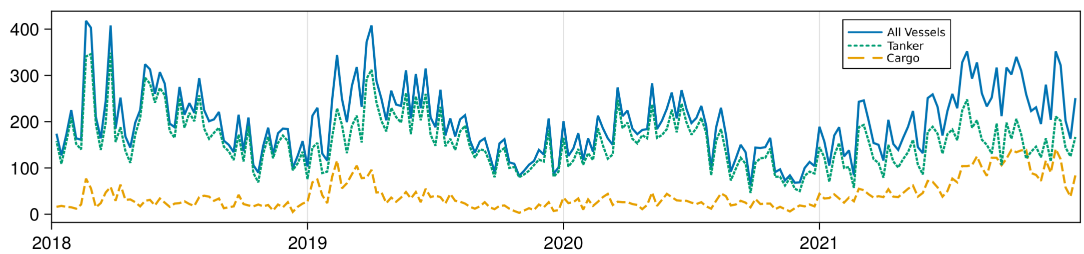

Figure 13: A Long-term comparison of the number of immobile ships per week through the analyzed period (2018-2021), portrayed are the total number of stationarity (blue/solid), stationarity of tanker vessels (green/dotted), stationarity of cargo vessels (yellow/dashed). The overall trend in immobility is dictated by tanker vessels. (Müller et al., 2024)

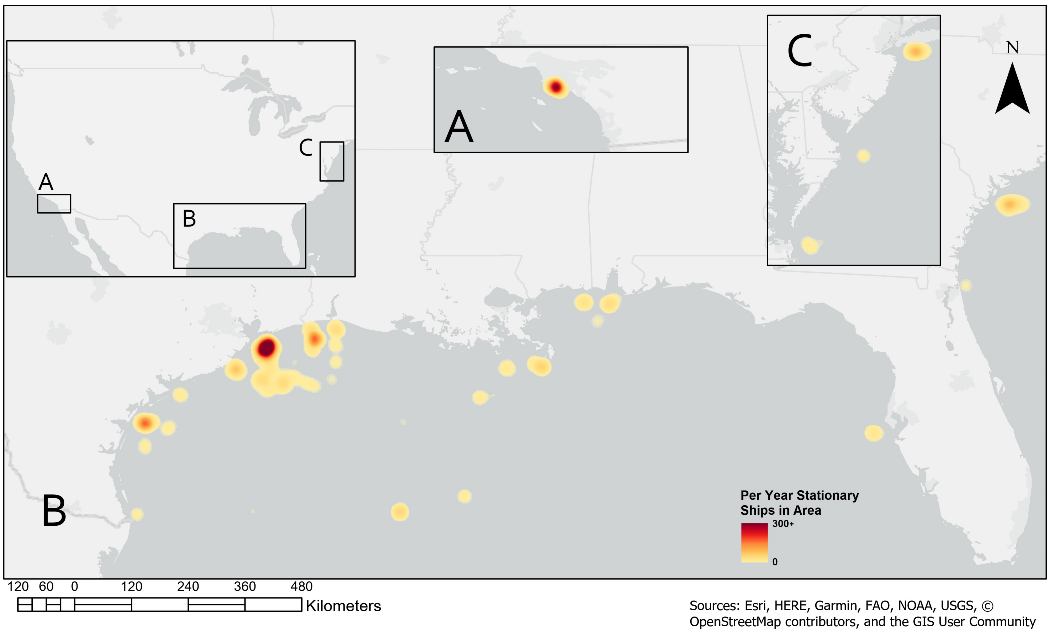

Figure 14: This heat map shows the areas where ships are stationary. Main clusters of immobility are identified on the southern coast of the US especially around Galveston, other areas of concentration of immobility are the east coast of New York and the mouth of the Delaware River and on the west coast at the coast of Los Angeles.(Müller et al., 2024)

For the second question (What are the temporal patterns of immobility?), I am comparing the number of immobile ships on a weekly basis. This reveals a distinct pattern. Firstly, in the pre-pandemic years, there seems to be seasonal behavior. The minimum of less than 100 stationary ships per week is present in late autumn and peaks in early spring, with over 400 immobile vessels in a single week, then it recedes again to the autumn minimum(Figure 13). The COVID-19 years have a disrupted pattern of immobility that deviates from this usual seasonality in stationary vessels. In 2020, immobility did not peak as strongly (maximum of 280 stationary vessels in one week), and in 2021, the trend is reversed, as most immobility happens in autumn. Analyzing the number of vessels, the pre-COVID years of 2018 and 2019 had 10710 and 10467 immobility events, which fell by 19 percent down to 8562 immobile vessels in 2020. After the initial shock, the year 2021 saw an increase in stationarity by 11 percent above pre-pandemic levels to 11602 immobility events.(Müller et al., 2024)
When we analyze differences in immobility, focusing on ship classes produces additional insights. The data shows that the yearly trend is mainly influenced by tankers. There is less stationary activity for dry cargo ships, and the overall fluctuation is smaller. However, an exception to this trend arises towards the end of 2021 when the number of stationary cargo ships increases to over a hundred per week. As a result, freight shipping reaches the same level of immobility as tankers.

To answer the third question(Are layups detectable in the study area?) I looked at the relationship between ships remaining stationary and then becoming mobile again. The idea here is that long-term layup is a planned and mid-term strategy that is different in nature from systemic immobility or just waiting. The expectation is that ships in layup become less likely to become active again with each passing day, while a ship that experiences regular periods of being immobile (i.e. waiting) has a constant likelihood of becoming mobile again as soon as the issues causing the stoppage are resolved. To recognize the pattern, a distribution over the length of individual phases of immobility and their durations was plotted. The relationship is shown to be linear in a semi-log graph. (Figure 15).In this context, a linear decay indicates that the likelihood of a ship remaining immobile decreases exponentially as time passes. This pattern suggests that the probability of the ship becoming mobile again is constant and does not depend on the duration of immobility.
These insights suggest that being in layup is not the main reason for immobility in the study area. If ships are in long-term layup, it means that after a few days of being immobile, they are less likely to become mobile again as they enter long-term stationary states. The probability of a stationary vessel becoming mobile again is constantly at 44.5 percent per day.

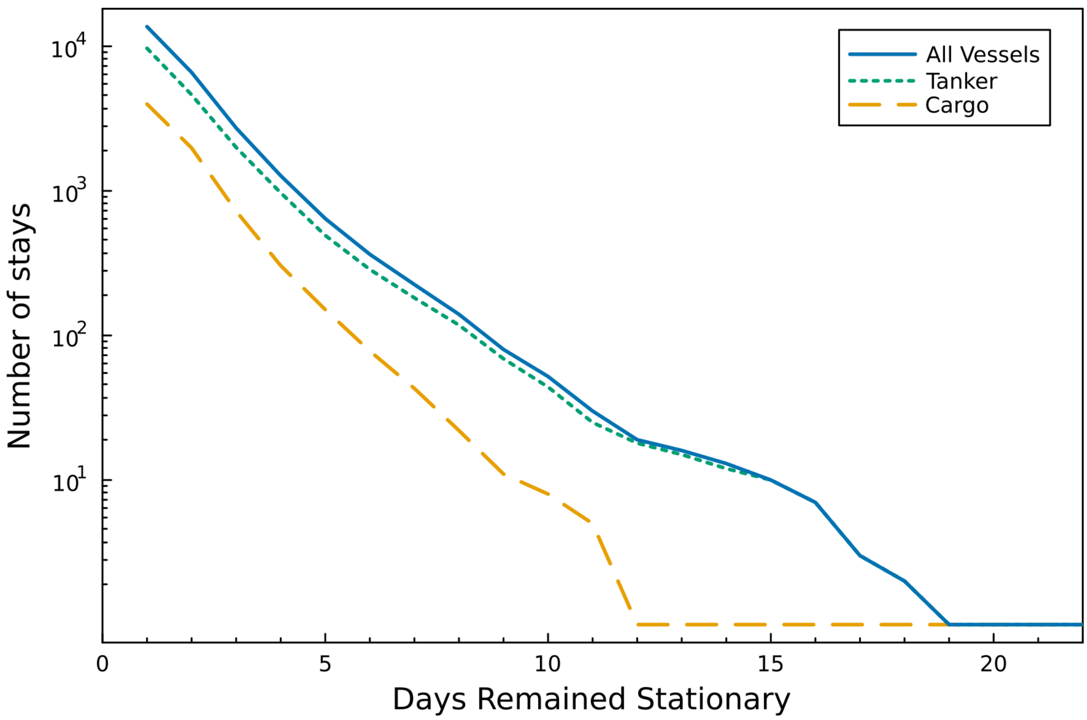

Figure 15: Semi logarithm plot over the number of ships that remained stationary for the number of x days. No power law distribution has been identified, meaning ships have a constant probability of becoming mobile again no matter how long they have been immobile before.(Müller et al., 2024)

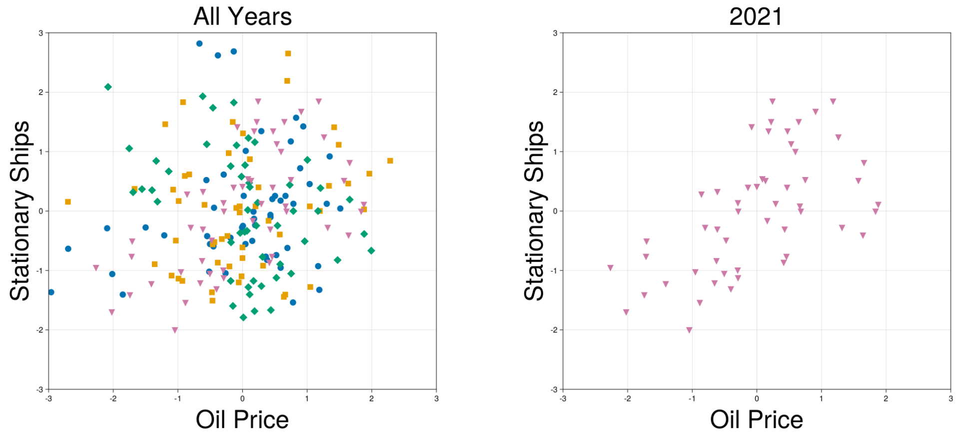

Figure 16: Plot of the standardized values for oil price and number of ships stationary. The multi year plot on the left shows no arising trend, the years are differentiated by color and symbol.This does not estabil a long term correlation, though single years produce better results, 2021 on its own, plotted in the right image shows a positive relation.(Müller et al., 2024)

The data presented so far provides us with insight into question four (How is immobility shaped by the COVID-19 pandemic?). The pandemic disrupts ship immobility not by increasing it but through a decrease; this is unexpected as the slowing down of the global economy and observations kicking off this project are suggesting that more ships should become immobile(Grzelakowski, 2022).In the study areas, I did not observe an increase in the number of stationary vessels in connection with the pandemic, which would have been expected if there had been a reaction in the form of systematic layup. The pandemic doesn't appear to make any additional change in the behavior of ships becoming stationary, neither in the driving of the ship classes nor the areas where stationarity occurs.
This leads to the final question five (Can immobility be linked to other external drivers?) searching for alternative modes of explanation. This requires a link to indicators for the global economy.I attempted to establish a connection between the number of stationary ships and economic factors by examining how the oil price relates to the number of stationary vessels recorded in the data. This was chosen as an indicator because the immobility is mainly influenced by tanker vessels. The comparison was made from the standardized total number of stationary ships per week and the standardized average weekly oil price from the US Energy Information Administration (U.S. Energy Information Administration, 2023).
The plot did not lead to conclusive results (Figure 16). While single years, for example, 2021, show a connection (Figure 16), An overall trend could not be determined, though the single year of 2021 for example show a weak connection. This might be a consequence of the COVID-19 pandemic, but additional data would be needed to confirm this. The findings suggest that immobility is influenced by various factors beyond just the direct impact of resource market forces. It would be interesting to explore these connections further to gain a more comprehensive understanding. To sum up, a greater perspective will be needed to gain an understanding of the forces that stop the movement of ships.

3.3.1 Construing Immobilities

The results of the analysis leave us with two central findings, one is the role of the us waters for waiting and immobility and the other relates to the treatment and approach to immobility within the mobilities field.

The EEZ of the United States of America (USA) is not an area for layup or other systemic immobilities as a reaction to the crisis imposed by the covid 19 pandemic. The opposite seems to be the case as the overall waiting times in the study area do decrease against expectations. The expectations are fueled by observations and research on the impacts of the pandemic(Grzelakowski, 2022). In the study area, the location of immobility does not change over the pandemic, so at least in relation to my initial case, the USA is influenced differently than the UK. Global shipping did slow down as exporting nations enforced strict regulations from March 2020 onwards, leading to a detectable decline in ships arriving in the United States with a 4-week delay (Verschuur et al., 2021; Millefiori et al., 2021; March et al., 2021). While global shipping slowed down, this did not manifest as increased immobility in the study area. Especially systemic long-term immobility, such as layup has not been detected, as shown in question 3. This mismatch between expectation and encountered data can be approached from different angles that could be tested against further data.

The position of the US in the global shipping market: As mentioned in the last chapter, these ports are perceived as major gateways(Ducruet and Notteboom, 2012), but they are low in the betweenness centrality. This leads to slower reaction time to opportunities arising in any part of the shipping network, making the area worse for waiting.

A second explanation is the cost of labour in the area, the US is not a major hub for commercial shipbuilding and maintenance(Hossain and Zakaria, 2017). The refurbishment of vessels to meet seaworthy status after prolonged inactivity is the main cost of layup or other waiting strategies. The cost of labor in the US, in comparison with those areas of Asia that are already closely linked to the maintenance of ships, will be higher. And Asian ports are also close to decommissioning yards for the case that longer-term stationary turns into decommission when refurbishment gets so expensive that costs can be cut by breaking the ships(Hossain and Zakaria, 2017; Sibilia, 2019).

A third explanation might be the import focus during the crisis, the US did increase their spending on goods in the pandemic making the waiting close to the producers in east Asia more beneficial. This manifested in the 2021 container crisis when the usually balanced flow of the containers (referring to the boxes themselves) broke down as the containers accumulated in rich countries at the same time as the producers in Asia reduced production due to COVID-19. Spiking the price of a container as availability was unbalanced(Cullinane and Haralambides, 2021). This leads to a final possible explanation: the shipping sector has not been impacted as deeply as during the financial crisis, especially since the nature of the external disruption allowed for speedy recovery (Notteboom et al., 2021). Part of the recovery after the financial crisis has been the broader application of slow steaming to deal with wait times at ports and fuel costs. This and other measures helped to cope with the instability, especially in the early stages.

To get more clarity on the issue and global immobility behavior, the study area needs to be expanded to global coverage. This would necessitate further analysis in the filtering steps, not excluding everything outside the EEZ of the US but instead classing by EEZ region for stationarity. The standardized nature of AIS datasets makes applying my method to different areas rather straightforward. This would provide two major insights into the global extent of stationarity and its behavior over the pandemic and a more detailed map of where waiting happens to allow us to delve deeper into the mobilities driving stationarity(Monios, 2023). Research that has been extended in this way provides deeper indications of the internal workings of the shipping sector and what factors correlate to long-term and short-term immobilities. The strong suit of the work with data is that it may point researchers to typical or extreme examples of the phenomenon; looking at these will provide insight into the underlying mobilities that shaped the encountered behavior.

The dynamics of normal immobility are interesting. Especially the seasonal behavior is a facet of the mobilities of ships so far not described in research. The low flexibility of container shipping in times of crisis(Notteboom et al., 2021; Cariou and Notteboom, 2022) is an attribute that might explain the differing patterns between ship classes. Still plotting them out is an exercise that reveals the internal dynamics in the shipping industry.

The treatment of short immobilities as a regular occurrence in the fields of transport and logistics for the smooth operation of ship transportation (Notteboom et al., 2009) is confirmed in this project. It shows that the current approach within the mobilities field, to focus on exceptional circumstances for ship immobilities, should be expanded to facilitate the whole spectrum. Waiting is demonstrated to be a regular part of the system, an expected disruption to the flow that, in turn, can be disrupted by circumstance.

These regular disruptions and their dynamics are a vital part to mobility, rest, maintenance and legal procedure are as much a part of moving as walking or driving. For other sectors like air, train, and automobile movements, this is recognized better already(Adey et al., 2021; Jensen, 2021). A deeper discussion on the nature of the disruptions and also what a perturbation to the disruptions means for the system at large will extend our understanding of mobilities for shipping and beyond. Identifying global areas where most immobility takes place is just the first step. In the long run, identifying companies and people on board and how these quasi-permanent residents of ocean spaces conceptualize their environment will foster a better understanding of the dynamics of the maritime system.

An observation from the study is that during times of crisis, a wealthy nation like the US tends to attract goods towards itself, leading to issues with container shipping in late 2021 as empty containers clog up the system. This also means that waiting for shipping opportunities at the US coast is not very promising. The externalization of the waiting has potential negative effects, such as environmental damage leading to the endangerment of artisanal fishery, which are generally overlooked by citizens of Western nations.

This chapter has introduced the AIS and how it can be utilized to gain a deeper understanding of the movement (or better nonmovement) patterns of ships. What has been left thin so far is a broader discussion on the application of AIS in other fields of research, as well as the potential errors and trappings in working with the data. The next intermediary chapter will provide an insight to what might be glimpsed from the data that is available to us. It provides a strong motivation for the full chapter after it, discussing the application of AIS for research purposes and how it might enrich especially the human side of ocean geographies.

3.4 Images of Ocean Space

To gain insight into the extent of the data and the density of its coverage during the work on the layup project, I produced a visualization(Müller et al., 2023). The process was, first, creating a one-degree minute by one-degree minute reference grid for the continental United States. Then, as a second step, all data points from one of the years would be added to the grid based on their position. This provides a whole picture of all activity within the study area. The distribution across the grid is very uneven, making a logarithmic scaling necessary for the visualization. At first glance, the results looked to have fulfilled their original purpose, showing the extent of the data and giving insight into where data is received from (Figure17). This serves as an onset to think about the extended information that can be garnered from AIS Data, not only for detecting immobility or shipping but also as a tool for scholars from different fields to make sense of marine areas. The rest of this section will give an insight to some of the activity profile and features on the sea that can be observed in the data and will be followed by a more through discussion on scientific application of AIS in the next chapter.
To structure the insight, I would like to focus attention on four core observations that can be made from the Dataset.

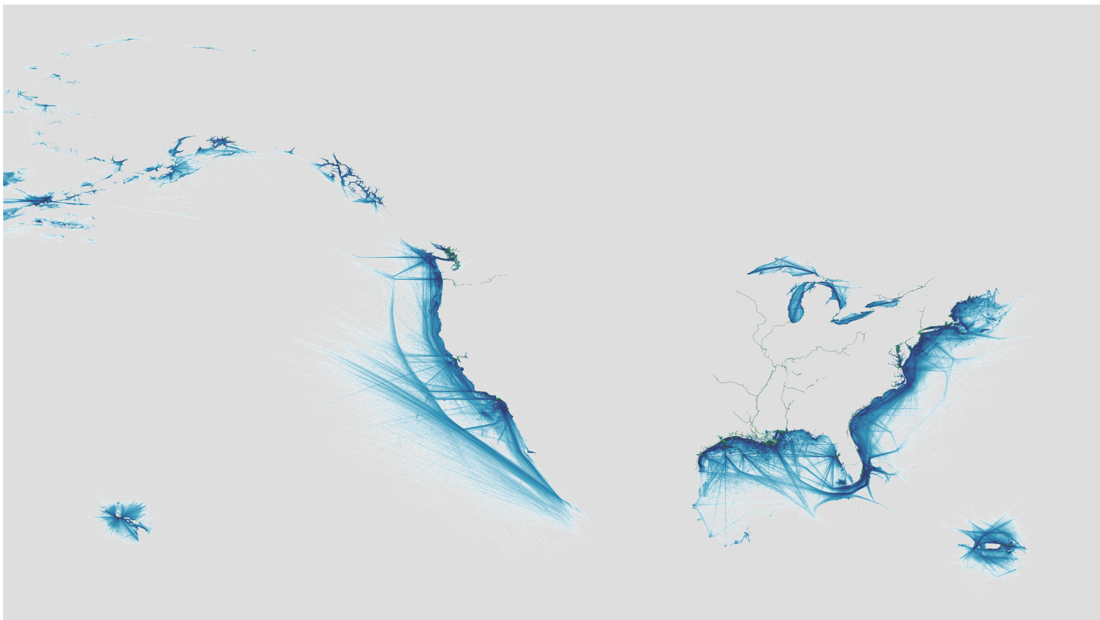

Figure 17: Full visualization of the AIS data provided by Marine Cadastre for the year 2019. The ships draw out their domain in a belt of received positions surrounding the points where AIS receivers are operated by the United States Coastguard. This way, an outline of the coastline, major rivers, and the great lakes emerges. A focus on smaller areas unveils the activities at sea.(Müller et al., 2023)

Observation 1: Counter Map

The Ships draw a very precise outline of the US sea borders, even without support from a base map. The coastline becomes apparent; this reverses the classical approach to mapping the sea, which starts on land and moves on from greater detail in the coastal area to flat blues when out in the ocean. The Map provides a different kind of structure, where the ocean use presents the marine realm. The realm of the ships is not strictly tethered to the ocean, as the recorded positions create a thin shippable line following the Mississippi across the whole country and into the Great Lakes. The Maps also show the limitations of AIS, especially in remote areas where the influences from single receiver stations become visible. To show the outlines but also limitations here, the complete extent is shown, as well as a picture of the outlines of the Hawaii archipelago (Figure18). The contrast, especially in the Hawaii image, shows how much detail is contained in the picture while also underlining the limitations of terrestrial AIS, as the waters around the islands are not connected to the rest of the ocean.

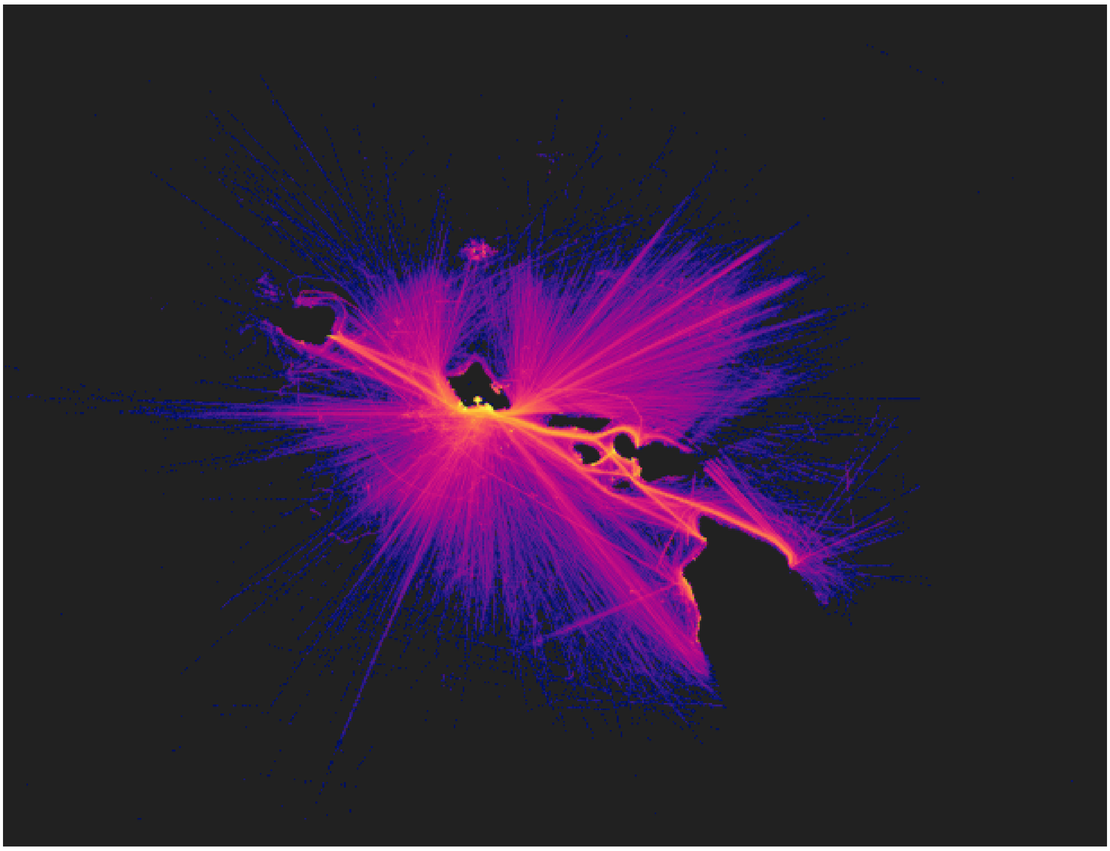

Figure 18: The strong contrast in the visualization magnifies the zones of not ocean created by the islands of Hawaii and how these zones are interconnected through ships. It also signifies the dependence of terrestrial AIS on visibility, as reception is limited by the receiver station. (Müller et al., 2023)

Observation 2: Marine Activity

The picture of Hawaii also contains strong visual cues to maritime activity as connections between the islands in the form of the bright lines of the ferry services and the patterns that occur north of the central island. Another feature is the long-distance connections over the ocean, which point towards major ports in the far distance.

To add to this impression of marine activity, a cutout of the US East Coast has been included in Figure 19. It is extremely diverse in activity from the ferries connecting the northern parts, the "searchlight" cone in the water where whale watching vessels go out from Rhode Island, fishing, and shipping lanes.

Even more than in the picture of Hawaii, the organization of traffic becomes apparent; commercial shipping has to follow corridors close to the land that function much like roads with one lane for each direction. There are no road signs or designations out at sea, instead they are internationally agreed-upon areas for shipping.

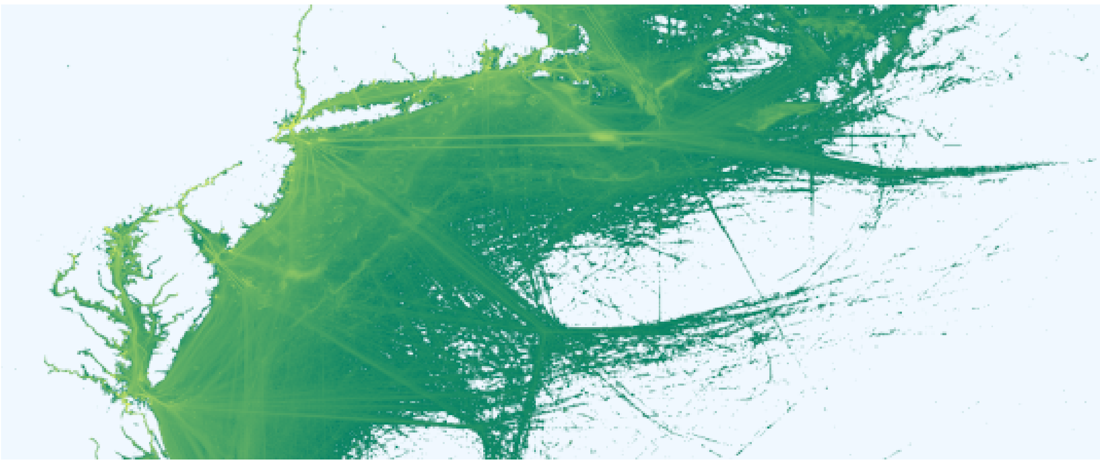

Figure 19: The focus is on the US East Coast around New York and Long Island. The patterns not only show the ferry connections between Long Island and the Shipping lanes from the big ports, but subtly also point towards other features such as whale tourism and the mixing of the Labrador and Gulfstream. The detailed depiction of the Chesapeake bay in the bottom left also underlines the precision of the outlines generated by the ships.

Observation 3: Regulatory Features of Ocean Space

The shipping lanes are some of the most set-in-stone features of ocean space(UN General Assembly, 1982), not the only regulatory influences visible. Other examples are drawn out at the state boundaries of sea areas, to highlight this figure 20 has been included, showing the difference in ship movement between the EEZ of the US and Mexico. The movements of fishing vessels characterize the Mexican waters, while the United States waters are organized around shipping lanes, and access to oil drilling platforms.

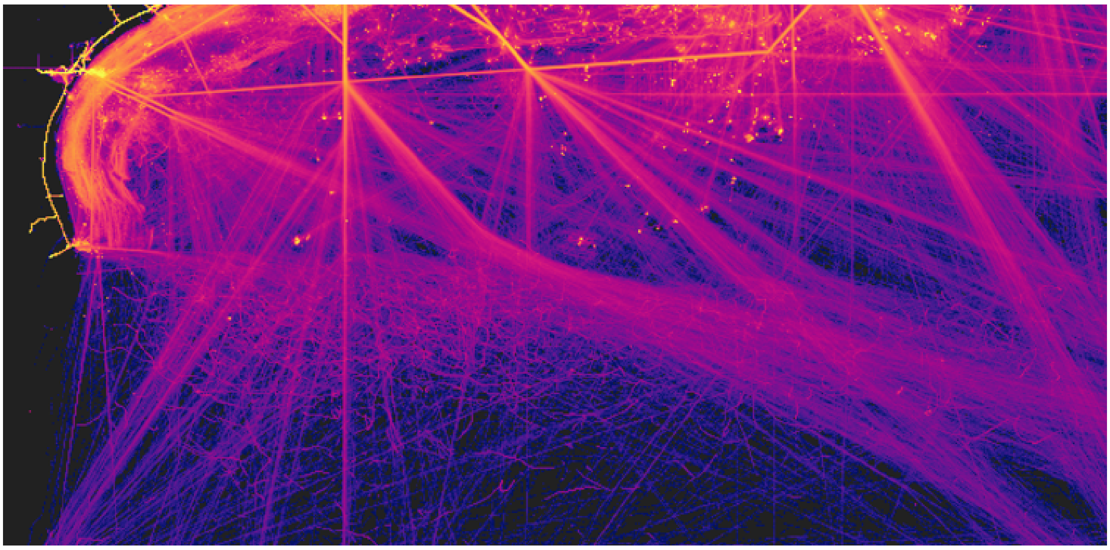

Figure 20: Here we see the difference between administrations, there is a line running through the middle of the picture below is a weave of smaller lines above it straight lines seem to prevail. This is the border between the Exclusive Economic Zones of the United States and Mexico. Fishing is far more prevalent in Mexican Waters. While the US is dominated by the corridors of trade vessels. Out at sea, there seem to be small activity spots, which are generated by deepwater oil rigs, and the tanker vessels visiting them carry the crude oil to land.

Observation 4: Natural Features

While looking at the pure shipping data, some natural features of marine space can be identified. Ocean currents, in the middle of figure 19, is a winding line in the water. This is the demarcation line between the Labrador and Gulf Stream, a zone with high fishing productivity. So, fishing vessels go there and fish over the current again and again, marking the position on the map of shipping. Similar features can be identified in the St. Andreas current on the US West Coast. Another natural feature is the availability of resources such as hydrocarbons; these become very visible in figure 20 where oil rigs and their support ships draw patterns of activity into the Gulf of Mexico.

These map images and observations are a by-product of the main project described in this chapter, and they provide an easier-to-grasp entry to the scale of human activity on the ocean. They invite the onlooker to think about ocean space and its interconnections with society. Still, this view is shallower than the possibilities AIS offers to the scientific community when trawling the datasets in depth. AIS helps us unveil the facts of movement at sea, which will also help those scientists trying to disentangle the mobilities of ocean space. The next chapter will explore more deeply how science is currently utilizing AIS data and contain a call, especially towards the more qualitative fields, to increase the utilization of data like this.

4 A Sea of Mobilities

The visualization of the AIS data allows for a perception of an ocean that is full of activity. The possibilities that this perspective offers are recognized in a number of research fields, but still, especially the fields closer to the humanities do not engage with it yet. In this section I will first introduce the fields that are already applying AIS in their operations and introduce the errors that can be contained within the data. Followed up by the introduction of the major problems and criticisms that arise with AIS usage. This will be followed up by a discussion of the merits of AIS especially for the subfield of geographies of the sea(Müller and Peters, 2024).

4.1 AIS in Research

While collision avoidance traffic regulation and national security have been the main reasons for the introduction of AIS, a number of fields have already picked up on the opportunities such a treasure of data has for undertaking research (Robards et al., 2016; Fiorini et al., 2016; Svanberg et al., 2019) and see Table 3).
To structure the overview, I will introduce seven main categories or fields of research that are concerned with AIS. These are based on the way they relate to the ship and the data. Following from these broader fields, I have identified core topics and challenges where the application of AIS has been established. Then, I provide more specific cases that have been worked on in the scientific literature.

Navigation

The navigational work on AIS is closest to its original purpose and have therefore been implemented from early on, the focus is on the ship and its domain so the amount of space it needs to maneuver without causing an accident. The accumulated data is most generally used to identify dangerous situations, such as close calls (Zhang et al., 2015). The knowledge that is gained from past situations also helps in smoothening out the planning of routes long before any dangerous situation could occur(Chen et al., 2015b). With awareness of maneuverability and early warning of dangerous situations, this focus on the ship has also recently been expanded to foster the establishment of autonomous shipping(Pallotta et al., 2013).

Network of Ships

The shipping sector has attracted the interest of scholars who are focused on the networks they create. Here the ship itself is not a major concern, instead the links the ships produce are the focus. As introduced in the networks section, AIS data is one of the possible sources of recreating the global shipping network(Kaluza et al., 2010), next to port entry records or shipping company fleet operation information(Ducruet et al., 2020). These prove to be a good case for applying the theories of network science to real-world applications.
Where positional information is required is the automated locating of ocean space

features, such as ports, or the response within shipping to events, such as in the reports of UNCTAD (2020).

Transportation

As established in sections 1.1 and 2, the field of transport geography or more general scholars interested in transportation and logistics view ships normally through the lens of the provision of flow. In this, they are close to network scholars, but their core interests are different. They are looking for possible optimizations of traffic flow and port operation. Of main concern and using the data of individual ships, they also establish indicators that highlight ports that need improvement(Jia et al., 2017b) and the possibilities to optimize operational costs and fuel usage(Andersson and Ivehammar, 2017b).

Environmental Impact of Ships

Ships are a large vector for the introduction of disturbances into the ocean environment. Research fields that want to establish better models for these damages utilize AIS. The ships are represented as both, links between the ports, but also individual vessels. When it comes to systemic problems such as air pollution, the data serves to give an insight into the density of polluting vessels to be checked against (Jalkanen et al., 2009). Similarly to this ships pose a danger for the introduction of invasive species both on a systemic level (Seebens et al., 2013) and as a more distinct link to remote areas (McCarthy et al., 2022).
The ship as an individual vector of damage is at the core when it comes to collisions, such as collisions with whales(Guzman et al., 2013) or the impact strikes of anchors(Broad et al., 2023). While AIS is also a great tool for identifying the culprits of oil pollution events(Fernandes et al., 2016).

Governance

The field of ocean governance treats ships either as densities that need to be accounted for or looks at the behavior of single vessels to check for compliance with regulations. The planning site maps, such as those in section 3.4, prove very important as marine spatial planners need to account for all ocean uses while maintaining the shipping lane regime(Vespe et al., 2018). The allocation of space to different ocean uses for management plans requires in-depth knowledge on activities at sea(Shelmerdine, 2015).
At the same time, the plans that have been set up need to be enforced(Guzman et al., 2020). As vast ocean areas are hard to monitor otherwise, data on the behavior of single vessels is of great use for identifying unregulated behaviour(Ford et al., 2018). Especially NGOs like Global Fishing Watch have been active in finding parties that try to circumvent AIS in order to avoid detection (Paolo et al., 2024); recent gains on the topic have been made by cross-referencing AIS with other sources of large-scale offshore information such as satellite imagery.
Vessel trafficking services, which are also a part of navigation, do fit in here as the utilization of real-time data allows for ocean management that is far better tailored to the local situation(Peters, 2020b)

AIS Technology & Reviews

The last two main categories of scientific engagement with AIS are more related to the technology itself and the progress made so far. The systems that run the AIS have been developing alongside the usage of the technology, especially the capabilities of very small satellite-based systems for reception, which have improved further in the decades since their first proofs of concept(Skauen and Olsen, 2016). Furthermore, the technology to find and recover broken data, as well as improvements to the data infrastructure, have been proposed(Skauen, 2016). To this category, I also allocate those papers more critical of AIS or discussing its errors (Harati-Mokhtari et al., 2007).

Whats Missing?

When looking at the summary of this data (see table), it becomes apparent that AIS has been introduced into almost all fields that deal with the movement of ships. Though what is missing is a connection with the human dimension of ocean space, attempts have been made to link AIS patterns to working conditions, but their results are controversial (see 4.3). I will return to this after the next section, introducing the limitations of AIS and connected data.

4.2 Limitations to AIS

So far, I have been only positive about AIS and its contribution, but to get a full grasp on the applicability of the technology, it is also important to be aware of and discuss limitations to its capabilities. I see these limitations in three main areas. The first area is the technology itself; this includes the data transmission, the collection of the data at the ship, and the capacity to receive data, especially by satellites. The second are efforts directed to interfere with the recording of positions, here the deliberate turning off of the system, the introduction of false data and the recent developments on meddeling with GPS sattelite reception is of interest. The third area contains political issues, this includes the possibility to access the data, discussions on the safety of making AIS data unencripted and a general resistance against the utilisation of AIS for purposes exceeding its original aims.

4.2.1 Technical Errors

Technical errors can be introduced to the AIS at multiple stages of the process, from data collection to transmission and VHF signal communication. The collection of data to transmit has differing pathways, depending on the nature of statical, voyage, and dynamical information(Harati-Mokhtari et al., 2007). The static data is introduced to the system by a technician on installation. The name, IDs, and dimensions of the vessel are fixed and should be checked by the crew after installation. Still, errors could appear here if the data is not correctly updated after the change of ownership or a refitting of the vessel. Here, especially, a repositioning of the GPS antenna and possible changes to vessel type can introduce systemic error in the static data.

Field	Topic	Aspect & Sources
Navigation	Collision Prevention	Risk determination (Montewka et al., 2010; Rong et al., 2020), Close calls (Zhang et al., 2015), Speed control (Mou et al., 2010),Risk awareness(Su et al., 2012; Li et al., 2018)
	Route Planning	Avoiding Ice (Löptien and Axell, 2014), Traffic influence (Li et al., 2018), In straits (Chen et al., 2015a)
	Ship Automation	Prediction of ship behaviour (Pallotta et al., 2013), Optimal reaction to dangerous situations (Su et al., 2012)
Network of Ships	Network Properties	Structure (Montes et al., 2012; Kaluza et al., 2010), Flow Matrix (Alessandrini et al., 2017)
	Spatial Patterns	Traffic (Arguedas et al., 2017; Jia et al., 2017c), Vessels (Shelmerdine, 2015; Etienne et al., 2015), Shipping Lanes (Dobrkovic et al., 2018; Breithaupt et al., 2017)
	Temporal Patterns	Seasonality (Jensen et al., 2015), Reactions to Events (UNCTAD, 2020; Fang et al., 2018)
Transportation	Indicators	Port performance (Jia et al., 2017b; Chen et al., 2015b; d'Afflisio et al., 2021),Trade Volume (Adland et al., 2017)
	Economic Optimization	Speed Adjustments (Jia et al., 2017a; Andersson and Ivehammar, 2017b), Fuel Consumption (Andersson and Ivehammar, 2017a),Sea Land Interaction (Guerrero et al., 2017)
Environmental Impact of Ships	Pollution	Sound/Vibration (Erbe et al., 2012), Oil (Fernandes et al., 2016), Air (Jalkanen et al., 2009), Water (Parks et al., 2019)
	Invasive Species	Ships as vector(Seebens et al., 2013), Remote Areas(McCarthy et al., 2022)
	Physical Disturbance	Anchor Strikes (Broad et al., 2023), Whale collisions (Guzman et al., 2013)
Governance	Marine Spatial Planning	Current Ocean Utilization (Shelmerdine, 2015; Vespe et al., 2018), Capacity Planning (Le Tixerant et al., 2018)
	Surveillance	Fisheries (Ford et al., 2018; Vespe et al., 2016), Oil Spill (Fernandes et al., 2016),Waste Dumping (Parks et al., 2019) ,Traffic Separation(Guzman et al., 2020)
	Real Time Management	Traffic adaption to whales (Guzman et al., 2020; Peters, 2020b), Vessel Traffic Systems(Pallotta et al., 2013),Collision Early Warning(Su et al., 2012)
Technology & Reviews	Technology Improvement	Sattelites (Skauen, 2016; Skauen and Olsen, 2016), Data structures (Ou and Zhu, 2008), Detection Limits (Santamaria et al., 2017), Data Reconstruction(Dobrkovic et al., 2018)
	Meta Research	(Robards et al., 2016; Fiorini et al., 2016; Svanberg et al., 2019)
		Falsification(Mazzarella et al., 2017)

Table 3: Prospective overview on current applications for AIS in research. The fields represent general interest groups, topics are applications within the field, and aspects are specific applications with sources. Adapted from (Müller and Peters, 2024)

The voyage data needs to be updated regularly and diligently by the bridge crew. Missing this will lead to the transmission of wrong information. Errors here can be attributed to differing behaviors, as, for example, the destination field is recommended to follow a formulaic approach stating from where the vessel is going. Locations should be provided in UN/LOCODE (International Maritime Organisation, 2015) as names of places might refer to multiple places, and spellings diverge, leading to confusion for other vessels and VTS.
In the dynamical data multiple sources of error coincide. These are related to the different systems feeding the information, sattelite positioning systems like GPS or Galileo are only precise within margins, these are providing the position as well as the speed over ground. As the positional data is essential, the system also transmits an indicator for the precision and reception quality of the received positional data. The current heading is determined by the ship's compass. The time information is based on the time the data package was created. In the SOLAS regulation, bridge crews are prompted to regularly check their own transmitted signals to ensure the navigational safety of their vessel(International Maritime Organisation, 2015); errors in the dynamic data should not persist for prolonged periods. The dataset utilized for the detection of immobilitiy still does contain visible errors where traces of single vessels travel over land on a straight North South axis, indicating an error in the longitude reception of the vessel.
The radio transmission of the data is also prone to errors. These errors are caused by interference with the radio signals, faulty projectors or receivers, the messages are made unreadable or the sorting of the signals causes a superimposition of signals over each other. On both the sending and receiving side, the Antenna can be faulty. While the radio signals are not likely to be influenced by weather conditions, the signals can be interfered with by other electronic devices on board vessels. The signals themselves are, as stated in the introductory section, pretty much line of sight; therefore, large objects like buildings or mountains can reduce the ability to receive data (This also becomes apparent in the visualized shipping data). The relatively short range of land-based AIS receivers makes them unlikely to be overloaded with the number of vessels in the reception area, and compression, as well as a prioritization of close vessels, secures the ships against their AIS being overloaded. For the satellite reception, on the other hand, this poses a larger problem. In areas with a lot of vessels the gathered information becomes more unreliable, luckily the greatest congestion occurs in straits, these are normally in range of land stations, or possibly reception buoys that do not have the same problems. The development of better satellite reception is an ongoing effort and a field that has greatly improved in the last decades(Skauen, 2016).

4.2.2 Intentional Meddeling

Apart from genuine errors, there are a number of incentives that drive ship operators to meddle with the AIS. For a long time before AIS, it was almost impossible to create a broadly applicable accountability for ships at sea, be it on where routes are used, where trash or chemical pollutants are dumped, or where fishing is practiced. As especially the satellite AIS makes it easy to follow vessels and their behavior, it has become harder to shroud illegal activities at sea(d'Afflisio et al., 2021).

The least intrusive way is the deliberate input of false or leaving out of journey information, this does not necessary happen in an illegal context, the US for example recommend against including information on the cargo in the AIS transmissions. Or a shipping company might not want to unveil their exact draught to shroud the current degree of utilization on their vessels. Reasons for this can be founded in security concerns and the main function of the AIS for traffic security remains in place(Pezzani and Heller, 2019).
In order to evade this monitoring, a number of strategies have been observed. The first is often called going dark and is practiced by turning the AIS device off (Kontopoulos et al., 2020). Military vessels or law enforcement are allowed to operate this way, at least within the bounds of international treaties. But in general, it is prohibited in order to maintain the function of preventing collision. Going dark is connected to fisheries in two ways, for a long time fishermen where classing their fishing spots as intellectual properties and therefor wanted to prevent competitors from going there, this has been banned in 2011 (EU Dir 2011/15/EU) (Vespe et al., 2016) but might be a thing to consider when utilizing older datasets. Going Dark is also almost a prerequisite for illegal fishery (Bunwaree, 2023), though recent research has started to address this by combining the AIS with satellite imaging(Paolo et al., 2024). Not transmitting the position is also unavoidable for smuggling operations or vessels that try to circumvent trade embargoes.
The opposite can also be achieved, the introduction of false information to the system. This might be necessary in combination with going dark for masking activity in the future. To achieve the introduction of false AIS data, two pathways can be chosen. First, AIS, as a radio-based technology, is prone to the introduction of false information by feeding a genuine AIS module with falsified information and placing it in reception range to a receiver station(Androjna et al., 2021). Though what is far more likely is the feeding of false information directly into the datastreams, as this has a smaller likelyhood of garnering the attention of other ships expecting to encounter a vessel in an area(d'Afflisio et al., 2021).
A highly sophisticated technology that only gained public attention in the last couple of years is the manipulation of GPS signals. The goal is to make the vessel's positioning system believe it is in a different spot than it actually is. A number of recent anomalies suggest that different states employ such technology(Harris, 2019).

4.2.3 Politics of AIS

The third main limitation to AIS utilization is the politics surrounding it(Pezzani and Heller, 2019). More specifically, the question is who should get access to the data and signals and who is represented in the data. This manifests in the availability of data, safety concerns on transmitting unencrypted sets, and the question of the core purpose of the system is undermined by incentivizing the shrouding of offshore activity.
At its core the technology has been developed to maintain maritime safety, with all this research and public scrutiny of the data incentives are raised to meddle with the system which betrayes the initial mission. Ship bridge crews are already schooled not to become overreliant on the AIS and remain vigilant. With an increasing number of ships not transmitting or transmitting false information, it

becomes increasingly difficult to make informed decisions on the bridge and in the VTS centers(Kristić et al., 2021). The IMO was able to push the legislation under the remits of safety at sea. If it had been known for what the data would end up to be used in addition a greater resistance might have arisen to the technology and its open design nature. The shipping sector is used to operating invisibly out at sea and might not want the public to be aware of all their actions, this has manifested in the statement on the IMO website that AIS should not be utilized for anything but its original purpose(IMO, 2024).

The universal legibility of the data has also been identified as a safety concern(Creech and Ryan, 2003); the data does allow pirates or other actors that target ships to pinpoint the position and type of a vessel with high precision and choose their targets.

The US sharing the data collected by their infrastructure is an anomaly in the international landscape. Most other nations do not make the dataset available to the public. Instead, the data is collected and sold by private companies, such as Marine Traffic or Fleetmoon. These services are usually designed to facilitate shipping or logistics companies to follow their fleets of vessels instead of delivering large-scale datasets. Where data is made available to researchers, it is done so under strict limitations to its usage.

AIS has a bias in the representation of vessels. Data is mainly provided by either larger commercial vessels or private boat owners who are wealthy enough to afford an AIS transponder. The paired-down Class B receivers are cheaper but still represent a major investment to less well-off seafarers or, for example, artisanal fishers. This makes being seen by the system a privilege and biases any observations of ocean use against poor or disenfranchised boat owners.

4.3 AIS for Qualitative Fields

Now, having built a deeper understanding of the applications and limitations of AIS, let us return to the discussion where the data is currently not employed. As mentioned in the research section AIS is applied to the different dimensions and roles of the ship, with only the human component being left out. This human component could be established in the field of mobilities, but it also has a major overlap with the geographies of the sea. In this section, I will try to fathom the rift that has grown between the qualitative and quantitative geographies of shipping and the ocean. The focus here will be mainly on the gains for the ocean humanities, as recognition for potential gains is already building from the field of oceanic networks (Ng et al., 2014; Ducruet, 2020). For the discussion of the mobilities of ships, the human geographies of the sea cover a blind spot that has so far been neglected, the experience and influence of those who are onboard and how it shapes the observed movement of vessels. AIS is a useful tool for ship officers, but the final decisions have to be taken by the crew on the bridge, by pilots or traffic managers. On the network level, the crew might be seen as a regular part of maintaining the ship's function, but looking closely; they are the ones shaping the day-to-day movement of the ship (Borovnik, 2022).

In the human geographies of the sea, shipping is a central issue relating most closely to the lives of seafarers, the role of ports and movement for society, the history pathways that have been shaped, and the meaning of seafaring to coastal societies and identities. It explores ways to think about the deep interconnections humans as individuals and societies have formed with the ocean. It also frames how the ocean has formed us and might shape our outlook on the world(Peters and Steinberg, 2019). The field is deeply routed in qualitative methodology, trying to understand these factors through the eyes and experiences of the people or even more than human elements of the ocean (Bear, 2016).

This is a result of the emancipation of the humanities-focused fields of geography from the measurement-focused ones. The trend started in the 1960s with the realization that purely numerical data-based models, especially for understanding urban areas, were producing poor results when compared to real data. Instead, the humanities explored new avenues of understanding their environment, which they found in Marxist, critical, postcolonial, and feminist studies. This emancipation from the positivist fundamentals is also core in the human geographies of the sea(Kwan and Schwanen, 2009).

The lines of separation to other fields also concerned with ocean matters, such as transport geography, have grown deeper during the course of this development. Transport geography has chosen a different pathway; it embraced greater integration with economists and, therefore, a positivist worldview(Manderscheid, 2016; Kwan and Schwanen, 2009). For marine transportation, this was also connected with the shift of the role of ships from a main transporter of people and goods to an almost exclusive goods focus. As mentioned in the introduction, the ship moved away from the population centers and public attention, reducing the interest in the human influences on transportation. This ultimately led to publications on transport and the ocean humanities not happening in the same journals anymore (Ng et al., 2014).

The fields are following very different questions nowadays (Ducruet, 2020), a fact that is mirrored in the recently published Handbook of Ocean Space (Peters et al., 2023) that provides an overview on the current dynamics within the human geographies of the sea. Here, while AIS, for example, is mentioned as a kind of information, not a single chapter can be identified as being quantitative in nature.

In recent literature on the marine transportation side, there is an understanding that building back the connections with the human elements of ocean space can offer new explanations and questions on the role of shipping (Ducruet, 2020; Ng et al., 2014). This is mirrored by some scholars on the ocean humanities side (Peters and Squire, 2019). The current lack of conversation between transport geography and human geographies of the sea misses the chance to build on shared concepts (I.e., mobilities and networks), potentially hindering research progression.

Mobilities would be a great framework to establish a shared language between the humanities and transport side. The recognition of this fact has also led me to adopt it as a connecting framework. The problem is that there is also a separation within mobilities, one small part is extremely interested in the macro patterns of movement, the other focuses on the extremely local and personal. This has led to mobilities also not embracing quantitative or mixed methods on a greater scale(Manderscheid, 2016). While not directly opposed, there seems to

be a lack of interest in engaging in a quantitative manner similar to the human geographies of the sea.
This is not to say that the use of AIS is completely unproblematic from the standpoint of getting a holistic understanding of ocean space. Like any data use, AIS points and the knowledge they reveal are shaped by the process (and politics) of their collection. As mentioned above, not all ships may switch on their transponders, leaving gaps in the ocean's 'data double' (Paolo et al., 2024). At the same time it provides a limited vision of the ocean, especially for the use in coastal waters, here there is a danger to overlook small vessel activities like artisanal fishing as these boats are not outfitted with transmitters. Instead, an overreliance would reinforce existing power structures as those wealthy or big enough to carry a transmitter shape the outlook at sea. To become a positive force for the humanities-based fields, a cautious approach will be essential.

4.3.1 Potential Gains for Humanities of the Sea

The main reason for a mixed-method approach to the humanities of the sea is the widening of the questions that can be asked and answered (Peters and Squire, 2019). In this section, I want to establish potential gains from widening the field. First potential gains for the broader field and conceptual reasons to engage with quantitative methods are introduced. Then, I will connect these gains back to the stationary of ships to illustrate more closely how the concerns of stationarity relate to ocean humanities. Working with quantitative data like positional information, such as AIS, is a gateway to bring new lenses to the established questions posed within the framework of the geographies of the sea. The idea remains to build a holistic understanding of ocean space and the relations with the people touched by the sea(Peters and Squire, 2019).
Quantitative methods focus on the analysis and generation of numerical datasets. This research excels at finding patterns and establishing expected behavior. The focus is on testing hypotheses and determining measures for the significance of findings. These advantages are gained by a focus on statistics and commonalities between entities within larger datasets(Manderscheid, 2016).
At the same time, the methods are limited in their capacity to establish reasoning; unexpected results or missed descriptive variables throw predictions off and require deeper adjustments. The ability to reason and describe previously unknown phenomena is the great strength of qualitative research(Schwanen and Kwan, 2009). The gain of a fusion between the methods is the "'bigger picture' context to the 'small stories' of qualitative work" Lorimer (2003). Seeing as we have done here the global spread of the locally encountered stationarity or layup. Alternatively, it draws out the set of circumstances that created a larger trend by identifying those contributors that are typical or atypical within the context of the trend. Focusing on a specific case, identified from large datasets, and drawing out the underlying details by speaking to those who are directly engaged with it. For example, gaining insight into what vessels are stationary for a prolonged time allows for an inquiry into those connected with the vessel:

- The owner side: What made you choose this vessel and place to become stationary?
- The crew side: What are the living conditions and fates of those that remain onboard?
- The ship's environment: How does a stationary vessel influence the coast and those that live close by?

These questions that result from quantitative methodology are core concerns for understanding the human dimension of life at sea. To gain a deeper longitudinal understanding of ocean relations aimed for by the human geographies of the sea, it will be necessary to embrace the methodology. Otherwise, global-scale topics like influences that cause friction or stationarity, trends on vessel types and behaviors, or the reaction to geopolitical crises and economic development will be hard to conceptualize.

A core concern with the establishment of quantitative methods is the introduction of positivism into the workflow of human geographers of the sea (Manderscheid, 2016; Schwanen and Kwan, 2009). Positivism is a school of thought that reasons, that for knowledge to be genuine, it needs to be based on measurable and observable facts(Kwan and Schwanen, 2009). Following that line of thought would overemphasize the authority of the generated patterns and estimation of normal behavior. A quantitative, not positivist, approach to research means that the strengths of quantitative data to generalize and recognize patterns are utilized while they are not thought of as the sole source of explanation for the encountered patterns, instead, they engage in dialogue with the human geographies of the sea and mobilities(Manderscheid, 2016).

The central precondition for the application of any quantitative analysis is the existence or creation of a suitable dataset. Linking causes and effects based on AIS may be difficult due to the fact that AIS only shows the final movements and large intentions in the form of destination information. Motivations on smaller movements need to be inferred. Awareness of the limitations of data and algorithms is a key factor for not overclaiming the produced results. An example from my own work is the correlation of the oil price as an economic indicator of ship immobility. While some years present a weak correlation, the linking is not strong, and additional factors will be necessary to explain the yearly cycle of immobility (Section 3.3).

Another challenge for the broader introduction of quantitative data is the matching of temporal and spatial scales between different sets. In my case this is the limitation due to spatial availability of data, limited to what I have been able to access for free, therefore I am missing the global areas where greater immobility might happen. Raw AIS data has the comparative advantage of high temporal resolution and spatial precision. An analysis of other possibly less dense data might encounter even greater problems. For example, a study of positional data trying to relate turtle sightings and gill-net fisheries to facilitate protection in ocean management encountered major problems when combining disparate datasets. They concluded that it is "difficult to derive meaning ... because the turtle data are vague (users are not told what "average" means in this 1979–2003 dataset) and

because the gill-net data are limited to an entirely different three-year period (2011–2013)"(Boucquey et al., 2019, P.492 f).
The project on ship immobilities demonstrates how positional ship data may help to develop links between mobilities and marine geographies research (Peters and Squire, 2019). It provides an example of how the research in the liminal zone between the traditional fields is expanded and how the stories emerge from the data.
The start of the research from a qualitative observation, during the pandemic unexpectedly stationary ships have been sighted at the british coast(Crump and Dalling, 2020). As the observation meshed well with a world that experienced sudden immobility, it has led to an interest in the immobilities of "COVID-19 affected" ships. Attention to the nonmovement of ships has before mainly been given to layups in the context of the 2008 financial crisis, more specifically in the outer limits of the port of Singapore. This has driven the question of how prevalent stationary ships have been during the pandemic, not only on the British coast but all around the world. Leading ultimately to the research presented in the last chapter.

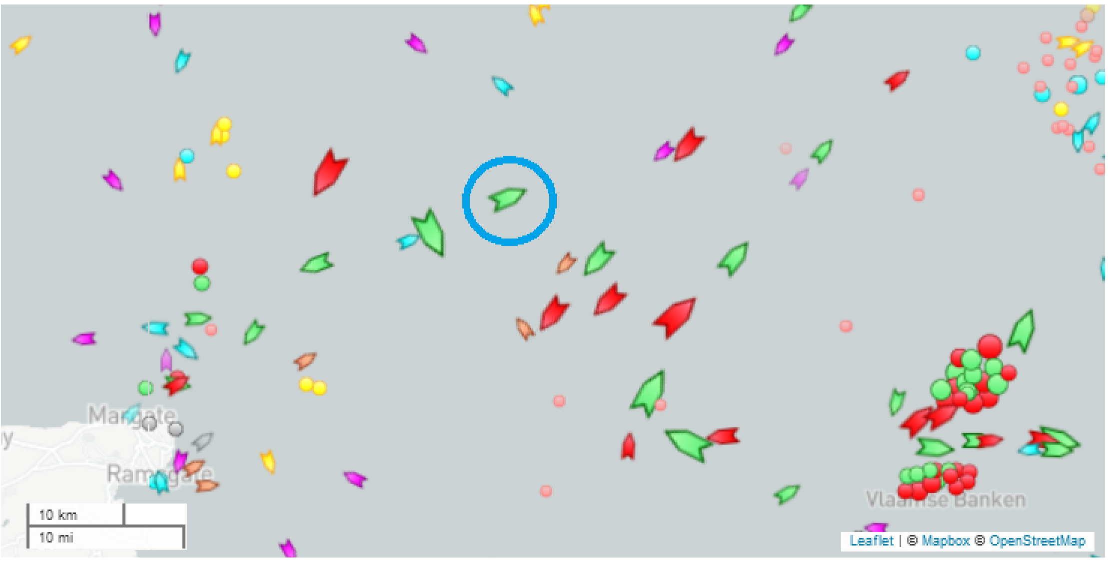

Figure 21: AIS offers a real-time view of the ocean; the image was taken on the 5th of September 2023 on the website Marine Traffic and showed a cutout of the English Channel. Ships are represented by the arrowhead shapes and colors delineating their classification. Stationary obstacles, like buoys and windpower stations or anchored ships, are depicted as dots, again with color giving an indication of their nature. In the blue circle the vessel starting this train of thought, the Pauline, can be found on her current regular trips between London and Zeebrugge.(Müller and Peters, 2024)

But the potential gains do not end there. The positional data would also have allowed for different research and a more "personal" connected story to be followed. The vessels that became stationary on the British Coast do have names, Pauline and Alfa Italia. To follow just one of them, the Pauline is a so so-called "Roll-on-Roll-of" vessel, meaning it transports mainly automobile vehicles. The AIS data lets us also follow the story of this single vessel, where it has been, and for how long.
The Pauline is currently observed to service a regular travel schedule between Felixstowe and Zeebrugge. These travels can be followed on public websites (for example, marine traffic), even after they have left the coast and "vanished" over the horizon or from the detection range of radar installations. The quantitative approach could also have been to follow the path of the Pauline and other vessels that have become immobile during the pandemic, looking for their properties and asking the question of what has made them the ones that got disrupted in their regular operations. This way, the worlds of the ocean become knowable in previously impossible ways (Ducruet, 2020), allowing us to not only reflect on the economic dynamics of layup but also see patterns and trends over time in this phenomenon.
Viewing the ocean through the lense of AIS challenges the established notion of a space void of life, instead the ocean shelters a continous population. While central within the human geographies of the sea, shipping is just one of its areas of concern (an important one, though) (Borovnik, 2012; Cresswell and Martin, 2012; Hasty and Peters, 2012; Peters and Squire, 2019). From the insights of shipping, do follow related questions:

- How big is the population of these “ocean residents”?
- How long do they stay where they are?
- How do the conditions of waiting differ between different kinds of shipping?

Shipping has been a useful area to demonstrate potential benefits of widening the scope of study and it invites discussion on how closely related topical areas could also benefit from these insights. Thinking about the unsteady residents of the sea is just the start, as connected issues can also benefit from insights gained through AIS.
To illustrate this, periods of long-term immobility and especially layup are related to efforts to save on maintenance, eroding paints, fouling, and prolonged human habitation in one spot. All of these are connected with an increase in local oceanic pollution and damage to the ecosystem. Linking up with AIS data allows ecologists and marine protection advocates to check the waters of layup areas for contamination with oil, the residue of anti-fouling agents, and dumped waste (Parks et al., 2019). The local ecosystem that is in danger from the pollution might also be vital as a food source for the coastal population, finding immobilized vessels will allow for the detection of communities that are most affected.
The legacy and establishment of empire and colonialism in the present moment are central issues within ocean humanities (Belhabib, 2021; Davies, 2022; Fawcett et al., 2022). The question is how power dynamics play out in the real world.

Utilizing AIS might provide an insight to the processes of port development in Global South countries. Generating positional datasets from smaller vessels before and after establishing new ports will help recognize the displacement of Indigenous interests. Quantifiable data and effects are often at the core of policy-related action; being able to engage on this level will assist in demonstrating the influence increased shipping has on traditional livelihoods to make the case for change.
To reflect, the impacts of a widening scope of methodology are not only that quantitative analysis offers an overview, and qualitative data deepens it. Findings from AIS may also allow us to deepen the questions we ask about water worlds(Anderson and Peters, 2016).

4.4 Discussion AIS

This chapter has followed the more applied one before by providing background and reasoning for the application of AIS in research. Especially in those fields that are currently qualitative in methodology and, therefore, do not engage with large-scale numerical data. After introducing where AIS data is currently utilized, and where its limitations are, I have made a case for extending AIS and the connected quantitative methodology to the fields of mobilities and the human geographies of the sea.
I am motivated by Sibilia's qualitative analysis of layups that connects well with Ducruet's quantitative analysis of shipping networks and ports (Ducruet, 2020, 2017) and human ocean geography's treasure of work, treats broader patterns and trends at sea with care(Peters and Squire, 2019). AIS is showcased as a tool for deepening analysis and raising further questions for the fields to explore (Müller and Peters, 2024).
In the revision of current publications, I found that AIS is employed by a broad spectrum of fields that deal with the ocean; they have been separated into six categories: ship navigation, the network of ships, transportation, environmental impact of ships, marine governance and technical development & reviews. For the mobilities of shipping, this gives us some insights that have not been captured in the first chapter. Strong motivating and inhibiting factors are produced by collision prevention; the emergence of the AIS itself attributes to this fact. It also underlines the import of traffic management or VTS, organizing the flow of ship traffic in straits. This is closely linked to marine governance, while the ocean is perceived as free of barriers some areas are prohibited to shipping. This can be connected to conflicting ocean use assignments (wind parks, for example, are off-limits) or bound to restrictions based on the pollution of vessels. The prevention of pollution might prevent ships from entering population centers or force vessels to undertake detours.
Then limitations to the technology have been introduced, from the errors in the system itself over intentional meddling to the political problems involved in working with AIS data. AIS provides us with information on the movement of ships, which closes the gap between what happens on board and the networked perspectives of ocean space. However, additional information is needed to generate information on these other areas. Large parts of the humanities scientific com-

munity view quantitative data like this with skepticism. This has its roots in the past when modernist thinkers reduced the exploration of the world to a matter of measurements and numbers. This trend has been abandoned, and the focus has shifted towards more experience- and people-driven approaches. My goal is not to turn back the clock to positivism.

The danger that is arising anew is the over-claiming of findings, as shown in an academic exchange through publications between McDonald et al. (2021) and Swartz et al. (2021). McDonald et al. have made the claim that they can identify illegal fishing and human rights violations based on AIS data. Their analysis is based on a couple of base assumptions that need to be verified further before going public with their findings, as Swartz et al. point out. The problem is the missing fusion between the strengths of qualitative and quantitative research methods. Instead, there need to be compromises from both sides for this kind of exploration to work. Positional data and models need to be understood as useful but flawed. The search for and identification of greater or repeating patterns is the strength of large datasets, but this is only one side of the equation. The step of making reason of what is discovered may be the point where a more qualitative approach will be at its best. The other way it does also work, as I have shown in the example of the layup, a qualitative description can provide a great reason and starting point to shape a search within the vast amounts of data that are accumulating today.

The possibilities opened up by AIS challenge the oceans' 'unknowable' status, bringing insight to those areas not available to classical research and methodology(Peters, 2010; Psuty et al., 2004). Once understood as the 'empty spaces' between metropolitan centers (Steinberg, 2001), positioning technologies like AIS allow us to see oceans for what they are: full of life and activity, shaped by natural forces and constructed in shared understanding.

Breaking down the boundaries between fields is a worthwhile endeavor, but it is not an easy process. The fields develop different languages and tools to serve their core interest. This necessitates more contextual information when making connections. An interesting case for those insights that might be lost at field boundaries has been the publication of the maps in section 3.4. For me, working within the data, the maps have originally been more of a curiosity or byproduct, the original goal being just a show of the data extends in the set. Only after a discussion of the maps with people who are not regularly working with AIS data to this extent did we start to see features that, in turn, raised an increased interest and the question of what can be found in the maps just by looking at them.

Becoming proficient in the language of data will empower human geographers of the sea and mobilities scholars in striving to influence policymakers. Politics tends to speak a language of numbers, indicators, and measured performance goals. This does not mean that the existing traditions need to be shed, but that formulating appeals and criticisms in a way understandable to the policymakers has the potential to engage them more effectively. Modern times do produce increasing amounts of data, being open minded and learning what big data methodologies could offer is an investment for the future(Manderscheid, 2016).

I want to restate that an emphasis on quantitative methods is not meant as a way to replace the current ideas circulating in the field of human geographies of the sea. The gain is in engaging the methods in dialog. Describing a qualitative

phenomenon, then try to identify its spread and position out on the ocean. It has the goal to give back this information to the qualitative side, supporting the shared quest to illuminate worlds out at sea.
To provide the mobilities that are generated by the human element of the ship in a way different to the human geogarpies of the sea would necessitate the research i have been calling for in this chapter. As it is thin at best, I want to keep it more general and base it further on the literature. Traditions, information, feelings, intuitions, and experience can drive the navigation on the bridge of a vessel. Crews are taught not to become over-reliant on their Electronic Chart Display and Information System (ECDIS) support but to remain vigilant to their environment(Kristić et al., 2021). As long as the automation is not developed further, it will be a human that figuratively turns the steering wheel to set the ship's course.

5 The Mobilities of Ships

This work has introduced the perspectives different fields have on ships. Based on the knowledge gained, I want to make a limited model of the mobilities surrounding a ship. After introducing the necessary geographical frameworks for a discussion of this interdisciplinary work, I have first focussed on the networked view predominant in transport geography. The ship here is understood as part of a network of flow, its movements based on the profits made from fulfilling the need for transportation. To make the following research understandable, I have introduced some basics and concepts from network science. This has led to the presentation of my first project, the modeling of reorganizations to the global shipping network as a consequence of changes to the available shipping routes. This contains two steps: the first is the determination of the changed distances as a consequence of change routes, and the second is the application of a flow model to check how ship traffic reorganizes in reaction to the changed distances. The scenarios that have been tested were either an opening of the Arctic or a closure of the major shipping canals in Panama or Suez. For the accessible Arctic, four different scenarios have been defined: complete ice freeness, an opening of the northern sea route or the northwest passage, and a scenario where both passages are open.
The results for the changing shipping distances have shown that an opening of the Arctic would result in a major shortening of shipping routes, whilst a closure of the canals leads to significant increases in the distances. The main benefactors of an opening Arctic are located in the global north and connect the Atlantic ports of the United States and Europe to East and Southeast Asia/ Oceania. In my observation, the difference between the Arctic scenarios for distance gain is marginal. The greatest increases in the case of the closure of canals are experienced by those ports close to the location of the canals.
To get to the changes in route utilization a radiation model for the prediction of flow has been utilized. This shows that an opening of the Arctic would lead to traffic similar to that experienced by the canals in the current scenario. Consequently, traffic through the canals is significantly diminished in open Arctic scenarios. To visualize the results maps have been created that show the abundance of flow as well as the differences between scenarios of shipping. Closing the canals reduces overall trans-oceanic flow. Interestingly, closing only the Suez leads to an increase in the Panama Canal utilization as it becomes a new, shorter route between Europe and Asia.
My results have shown four main impacts on the macro mobility of ships. Profit and cost of operation, conceptualized as opportunity and distance in the radiation model, are the main modeled mobilities. However, I also inferred the economy of scales and insurance from my results. The economy of scales means that shipowners are willing to pay the extra cost in the distance for building ships too big for the shipping canals. The existence of Suezmax+ and Panamax+ vessels illustrates well that distance as a cost factor can be accounted for by reducing per unit shipping cost to the point that longer routes retain competitive margins of profit. The influence of insurance also becomes apparent from the results. Insurance represents the main reason for the hesitance to utilize the northern routes, even though

the passages have been open multiple times in the last decade. The same is true for the avoidance of the red sea in winter 2023, the dangers to the vessels caused ships to take the long way around the cape of good hope even though the attacks on shipping where limited in number and no vessels where lost(Notteboom et al., 2024). Uncertainty for ships is expressed in insurance premiums for journeys, the sheer value of a laden container vessel could if lost and not insured destroy a shipping company.

While this perspective on shipping unveils major mobilities, it can not relate to the mobilities of individual vessels. To gain a better understanding I have introduced the Automatic Identification System, short AIS, as a source on the movement of single vessels. To illustrate how this data can be used to explore mobilities, I have applied it in my second project to find the patterns of stationarity of ships in the waters of the United States of America over the years 2018-2021. From the mobilites perspective, stationarity is a state where factors constraining movement overpower those that motivate movement. With the COVID-19 pandemic happening in the middle of the studied time frame, I did look for insight into both the patterns of immobility under normal circumstances and under the disturbance brought by the pandemic. The results have shown two major outcomes. The first is that stationarity has its own regular patterns throughout the year. This trend is driven mainly by tankers, while cargo transport immobility is less pronounced, running more smoothly with irregular shorter stays.

The regular trends in stationarity are then broken by the pandemic. Against initial expectations regarding the behavior of the shipping system under pandemic conditions, the disruption manifests in a reduction of stationarity. This means that over the pandemic, fewer vessels have become stationary in US Waters. The location of stationary vessels corresponds with those ports in the study area that have the greatest centrality in the context of the global network of shipping. An initial trial of linking oil price to the number of stationary vessels has not produced definite results. Possible influences to explain the encountered pattern of immobility have been discussed, such as the role of US ports in the global economy and a linkage to more central ports as the driver of pandemic immobility.

The chapter closed with an observation of the richness of oceanic activity that can be identified from AIS data. The unfiltered data was processed onto a grid to create an impression of the areas covered by the US dataset. In it, features such as shipping lanes and tourist areas become visible, but also legislative boundaries and ocean currents. This opened the question to the extent of insight that can be gained from AIS.

That observation started the third main chapter of this work. I introduced how AIS is currently used by researchers from different fields and the limitations to its utilization. The insight that emerges from summarising current research is that while most fields with a topical link to ships and shipping have embraced AIS, the researchers focusing on the human elements of shipping are not engaging with this data. The mobilities of the ship have been expanded to include collision prevention, traffic management and zoning in the context of marine governance.

A disinterest in quantitative methodology has been a historical development for the human geographies of the sea and, to an extent, also mobilities. In the interest of widening the remit of the fields and gaining deeper insight into the human elements of ship mobilities, I make a case for an extended methodology that engages quantitative methodology in dialogue. The quantitative methods have the ability to recognize patterns within the phenomena described by qualitative research. From the general advantages, I close the chapter by engaging with the potential gains on the topics that have been central to this work. Potential applications that combine AIS and current questions within the human geographies of the sea. The goal of this work has been to follow ships and understand what shapes their movements from the perspective of different fields and methods. In the next section, I want to summarize the mobilities that have been identified, focusing on the enabling or inhibiting forces and motivations that cause the movements observed in the data.

The main motivation for building a ship is to supply the demand for transportation. That means especially for the sector of privately owned commercial shipping they need to operate in a profitable manner, selling their transport capacity. Ports are the point between which the demand for transportation emerges. They are the interface between ships and land and provide infrastructure from handling containers, bunkering fuel and exchanging crew to drydock services allowing for extensive repairs.

Ships are built for a purpose: container vessels, gas tankers, ferries, or recreational craft, meaning one central mobility is built into the hull. We have seen this manifest in the different patterns of immobility between transport sectors like dry cargo and tankers. And this mobility is also deliberate when it comes to scale. A large vessel will have problems traversing shallower waters, for example, serving small ports, but they can be the best value for money investment on long-distance inter-hub and inter-ocean travel. This becomes apparent in the building of vessels that are too big for the shipping canals but still operate competitively even while having to take significantly longer routes. This is possible due to the economies of scale, making bigger ships relatively more efficient when it comes to maintenance.

A ship needs constant maintenance. This can be conceptualized as the cost of going from one port to another. It includes the fuel that is burned, components that need to be renewed and the hull that needs to be protected from the corrosive oceanic environment. But it also includes the crew that needs to be rotated over time, their wages and sustenance. In this work, these have been conceptualized as the distance a ship has to overcome in order to reach a prospective next destination or as the losses that made layup a viable strategy when freight rates deteriorate too much.

A central mobility is the avoidance of risk, as laden ships are very valuable objects. This manifests on a macro scale through insurance premiums. These keep ships from taking the shorter routes through the Arctic and avoid more risky passages even though they are more maintenance intensive. On a medium scale this is done through the implementation of VTS and pilots that orchestrate ship traffic in dense or difficult to traverse areas. For the ship itself, AIS has been developed alongside ECDIS to give the crew the best opportunities to avoid potential collision or beaching. While the ocean is regularly conceptualized as a free and empty space, the last decades have seen a rise in more stringent zoning that impedes ships' freedom of movement. Traffic separation zones have been defined close to the shores, guaranteeing a water depth and ensuring no other ocean use gets in the way of transport. These areas impose rules similar to roads, forcing ship movement into defined corridors. Traffic separation zones are also often the first object that is introduced to any spatial plan of ocean space, and they are coordinated internationally. Other ocean areas exclude transport shipping, environmental protection areas, aquaculture, or wind parks. Ships have to plan their movement in order to comply with these regulations.

Seafaring is also a practice with a long tradition and a degree of autonomy for the captain and crew; their experience and decisions shape the movement of the vessel. While the macro decision for movement will be taken on an operational level, the form this movement takes will be shaped on board. The decisions on the specific route a vessel takes can be influenced by the crew, for example, reacting to weather conditions or utilizing currents to save on cost. To dive deeper into this topic, it would be of great interest to combine AIS and qualitative research.

The movement of any given ship will be influenced by a combination of these factors. This list is not exhaustive, but I have not engaged deeper with the strategies of shipping companies in assigning journeys or delved deeper into cultural preferences and behavior. Some influences will be marginal or only occur in special circumstances, but overall, these are the major mobilities I have encountered in my work.

The goal has been to contribute to the body of research that protects the ocean by utilizing a lens that makes visible the networks and activities that humans undertake on the ocean. Only by including the perspectives of those who rely on the sea for their livelihood can we create regulation that is not only effective in theory but that can also be put into action and enforced for the good of our global ocean. The work with ships is a reminder that the ocean is not just an empty place between remote centers of population. It is often viewed as the border to where human activity ends. Instead, it should be seen as being inhabited by thousands of people, from sailors and fishers to officers and migrants. It provides nourishment and jobs to whole communities. The space is dense with activity, so dense in fact that technology needed to be invented to prevent disastrous collisions. All of this activity is undertaken by applying swimming vessels in the form of ships or boats. This has lead to ships being a part of culture as well as economy.

This work contributes to a more integrated view of ocean space. Shipping is at the heart of the global economy, and understanding how the field reacts to challenges and crises will provide a better basis for addressing the challenges of the 21st century. Being a significant contributor to growth and pollution, cultural exchange, and colonialism, the sector touches society on all sides. Working from the sea and back to the land, the traditional landed approach to creating maps has been subverted, just as the traditional silos the fields I combined find themselves in.

I started this work by pointing out the ocean's emptiness next to the vibrant continents. I want to offer you a new alternative color scheme utilizing our new insight into the mobilities of ships at sea.

5.1 Outlook

The concept of mobility is not limited to movements through space but also seeks to understand the influences that shape an actor through time(Cresswell, 2010). Curiosity is, I would argue, the central mobility for research over time. With my work I wanted to arouse curiosity for ships, but also for the way that they are thought about. The next section will be a suggestion on where the curiosity will lead the research that follows after this work.
To do this, I will first return to my applied chapters, the prediction of shipping routes and the identification of marine immobilities, to see where they can be picked up, tested further, and modified. Then, I want to look at the more general implications that follow from my work and consider the applications and limitations that come with it.
For the future of the work on predicting shipping lanes, I think it could be good to look at a more granular dataset. This would include not only more recent flows of shipping and separations by sector but also extended information on the ports. We find in the literature and also my own research in chapter two that differing sectors within shipping follow their own patterns(Ducruet, 2013); this has so far been less of a concern. The finer differentiation could also be extended to the ports, first by their purpose, as they mirror the specialization of the ships themselves and, therefore, are limited in interaction. But also within the identified categories. To model the shape of the system more closely, it could be interesting to separate out the hub and spoke ports. In the literature, the systems are described as local clusters of densely connected ports with only one or two acting as hubs and facilitating most of the long-distance connections(Ducruet, 2020). This sounds like a good case for the application of network science to identify a port's identity. In doing so, the longer-distance flow models could be both simplified and improved by cutting at the number of possible connectors and reducing short-distance connectors that are less influenced by global change but can skew the results of models. The differentiation will unveil the mobilities of the sectors. But to connect to the other parts of this thesis they might also uncover small connections of flows between remote ports that warrant a more qualitative attention. For applications that exceed the current one to the Arctic and canals, it is interesting to think about what the methodology for determining distance allows us to do. This is to make predictions on the impact that the establishment of marine protected areas, so zones where shipping is not allowed would have on the sector. If it is feasible to run significantly longer routes by building larger and more efficient ships, smaller detours to protect the ocean seem a viable proposition.
The search into the patterns of immobility is currently mainly held back by scope. While the method does work to identify immobility, more areas need to be covered to reach deeper systemic understandings. Ships are roughly a conserved measure. With the pandemic having been identified with a slowdown in shipping, the vessels missing from the US must have ended up somewhere. To move from the inferences that have been made so far to a more conclusive picture, a dataset covering more areas will be necessary. Seeing the system-wide patterns will be more expressive for the mobilities and where they are overcome by immobility to create stationarity. Interest could be in following up on the role of betweenness

centrality as a determinator for stationarity or the search for areas of true layup or long-term stationarity.
The regular and irregular patterns of immobility are also a further point to follow up on with future research. Examples here would be the "waves" of immobility that propagate from disruptive events as vessels are first held up and then rush to fulfill their obligations, clogging the system downstream. Or the different regular immobilities between different types of shipping.
I have spent a chapter arguing for better integration of quantitative work into the fields of mobilities and the human geographies of the sea, and I am excited about the possibilities that this opens. Especially for the mobilities of single vessels, it would be interesting to use AIS data to identify unusual ships and examine what makes them special. But partly, this will also be a matter of engagement; it will take scholars who are open to charting the new waters that are opened up here. This work is not the first call for a reconnection between the different fields(Ducruet and Beauguitte, 2014; Ng et al., 2014; Ducruet, 2020; Manderscheid, 2016; Peters and Squire, 2019), so far broader shared projects have not emerged at scale. The strength of recognizing patterns will be a great aid in the development of coasts and environmental protection areas. Quantitative methods might help uncover the relations that these features create with the coastal communities.
The challenge society and science will have to deal with for the foreseeable future is finding a way forward that combines protection with the use of the ocean(Peters, 2020b). To do this, it is important to understand what changes and challenges will do to the current system. The projects that contributed to this work share that goal; new opportunities are on the horizon on the topic of arctic shipping, and at the same time, the tense political and vulnerable environmental situation around the area mandates an approach that unifies these concerns. The same calculations become more and more interesting in the regional conflicts surrounding the Red Sea. The initial idea to deal with the closure of Suez has been in connection with the 2021 Evergreen blockage, but the same calculations apply to the more recent situation surrounding attacks on shipping in the so-called Gate of Tears at the southern entrance to the Red Sea. For future work, it could be interesting to look at the other set of mobilities I have mentioned here, those that shape development through time. What causes determine the course of shipping: Economic developments? Political change?Technological progress? Scarcity of resources? or societal concern? Most likely, all of these and more. To figure out where the system is going, it will again be interesting to study how common new qualitative phenomena are in a global context.
The ocean is a multi-layered environment that is difficult to understand in just one dimension; neither a purely physical nor biological nor a purely societal and cultural perspective manages to damm it in. Without looking for broader perspectives on the shipping system and the central role shipping plays in the modern world, it will not be possible to reach the long-term goal of finding sustainable ways to live together with the ocean.

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6 Appendix

Connection	Current	Ice Free	Passages	NSR	NWP	No Canals	No Suez
Europe to East Asia	19130	13090	14420	14350	14790	25290	24660
Europe to US West	14850	11870	13230	13150	13550	25090	14850
Europe to Gulf of Mexico	9060	9060	9060	9060	9060	9060	9060
East Asia to US West	9910	9910	9910	9910	9910	9910	9910
East Asia to Gulf of Mexico	18540	17340	17360	18540	17360	27760	18537
US West to Gulf of Mexico	8730	8730	8730	8730	8730	25150	8730

Table 4: Full table of shipping distances between different regions over the Scenarios that have been introduced. The distances are measured in Kilometers and represent the shortest path between the two ports that stand as representatives for their region.

Connection	Current	Ice Free	Passages	NSR	NWP	No Canals	No Suez
Suez Canal	48116	26070	40165	40548	40320	0	0
Panama Canal	28691	25959	26143	26503	26176	0	36125
Bering Strait	0	15119	10836	9887	10199	0	0
Cape of Good Hope	7224	7177	7170	7179	7186	41382	17858
Magellan Strait	258	238	215	215	215	3689	286

Table 5: Full table of shipping flows on defined representative connectors in the scenarios that have been introduced. The numbers represent the expected number of ships traveling on the passage, they represent the flow along all port shortest paths.

7 Eidesstattliche Erklärung

Hiermit versichere ich, dass ich diese Dissertation selbstständig verfasst habe und nur die hier angegebenen Hilfsmittel und Quellen benutzt habe. Zudem versichere ich, dass diese Dissertation weder in ihrer Gesamtheit noch in Teilen einer anderen Hochschule zur Begutachtung in einem Promotionsverfahren vorliegt oder vorgelegen hat. Bis auf die angegebenen Publikationen, ist diese Arbeit noch nicht veröffentlicht worden. Die Leitlinien guter wissenschaftlicher Praxis an der Carl von Ossietzky Universität Oldenburg wurden befolgt. Für dieses Promotionsvorhaben wurden keine kommerziellen Vermittlungs- oder Beratungsdienste in Anspruch genommen.

Ole Jörg Müller, Oldenburg