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The fuel consumption effect of prolonged port stays

Hans-Jørgen Jøssund and Silje Helene Johnsen

Supervisors: Roar Os Ådland and Phuong Ho

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Abstract

Optimizing fuel efficiency on marine vessels reduces both the fuel cost and the emission of greenhouse gasses. One way of optimizing fuel efficiency is through periodical hull treatments due to hull deterioration and hull fouling. Hull fouling occurs to a larger extent during idle periods and in tropical waters. This thesis develops a model using difference-in-differences to estimate the causal effect of prolonged port stays, and prolonged tropical port stays, on fuel consumption. The estimates of change in fuel consumption after being exposed to prolonged port stays in certain ports can be used by shipowners to optimize the time interval between hull treatments to reduce fuel cost and emission of greenhouse gasses. The data included in this thesis comprises noon report data from eight Panamax vessels from two different vessel classes. The noon reports are supplied with AIS-data, port coordinates data, and third-party weather data. The results correspond with the expectation of prolonged tropical port stays leading to an increase in fuel consumption only for one of the vessel classes, and only when considering prolonged port stays as idle periods of 10 days or more. All other results contradict with the expectations of increased fuel consumption after prolonged port stays and suggest a reduction in fuel consumption after being exposed to prolonged port stays. Finally, ways to improve the method and the design of its covariates are identified.

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Hans-Jørgen Jøssund Silje Helene Johnsen

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1. Introduction

The maritime shipping industry plays a central part in the global economy, transporting over 80 percent of the world's trade by volume (UNCTAD, 2021). While utilization of the world's oceangoing vessels remains the most fuel-and cost-efficient way of transporting goods and commodities across the globe, the industry's activity is still responsible for around 2.9 percent of global greenhouse gas emissions (International Maritime Organization, 2021). Fuel is not only the main driver for emissions but also a major cost driver in international shipping, accounting for 50-70% of a ship's total running costs (Rehmatulla & Smith, 2015). Hence, increasing the fuel efficiency of a ship can have positive impacts both economically and on the environment.

There are many ways to increase fuel efficiency, including measures regarding ship design- and -specifications, fuel types, and ship energy efficiency (Balcombe et al., 2019; Xing et al., 2020). Optimized ship designs, new fuel types, and technical measures for energy efficiency all have substantial potential for increased fuel efficiency. However, these measures are in many cases also associated with capital-intensive investments and immature technologies reliant on abilities and ambitions on many levels. The levels range from shipowners, charterers and customers to the port infrastructures across the globe, as well as the policies and regulations to support them (Baldasso et al., 2020; Bouman et al., 2017; Xing et al., 2020).

Furthermore, over the recent decades, there has been an increasing focus on energy-efficient ship operation, where regulation has been the main driver, along with increasing fuel costs (Jensen et al., 2018). The significance of operational efficiency measures was formalized with the introduction of the Ship Energy Efficiency Management Plan (SEEMP) by the International Maritime Organization (IMO), assigning every shipowner to set up a formal system for management and optimization of ship and fleet performance (Farkas et al., 2021).

The most important operational measures related to fuel efficiency include speed reduction, weather routing, and periodical cleaning of ship hull and screw propeller (Adland et al., 2018). Whereas speed reduction and weather routing are measures that are highly related to external factors, periodical cleaning and removal of biofouling is something shipowners to a large degree can control. That is, even though the rate of biofouling on the ships' hull and propeller is mostly exogenous, the shipowner can decide the quality and frequency of different cleaning procedures (Adland et al., 2018). There are still many factors that are influenced by this decision, including the ships' trading program, cleaning costs, port or yard capacity, antifoulant paint quality, and the risk of spreading invasive species (Inglis et al., 2012; International Maritime Organization, 2021; Oliveira, 2019). Consequently, background knowledge and analysis on this topic are important for shipping companies as a basis for optimizing the intervals of different hull cleaning procedures.

In this thesis we use data and information from G2Ocean, a shipping company operating in the global dry bulk segment, along with third-party weather data and vessel position data to support an analysis related to the current literature on the topic of hull cleaning interval optimization.

G2Oceans' vessels carry products like wood, pulp, and paper, making time spent in port sensitive to the weather conditions. This implies that exposure to bad weather during port stay may cause prolonged port operations. Prolonged idle periods may also result in increased hull fouling, especially in tropical ports (Kovanen, 2012). Due to climate change and an increase in extreme weather and heavy precipitation (IPCC, 2022), the relevance of investigating the effect of prolonged port stays has increased.

The main objective of this thesis is to estimate the fuel consumption effect of prolonged port stays. The second objective is to estimate the fuel consumption effect of prolonged tropical and non-tropical port stays. The information gained from such estimates can be valuable for shipowners' decisions on when to perform cleaning procedures exceeding the mandatory maintenance schemes.

The methodology used for this thesis applies a purely data-driven empirical analysis based on fleet performance data. This includes noon reports extracted for a fleet of eight Panamax bulk carriers, provided by G2Ocean. In addition, we utilize AIS data and third-party weather data to supplement the noon reports, which further increases the quality and scope of our dataset. As the final dataset used for the analysis contains variables related to only eight vessels of two different ship classes of similar size and segment, the results cannot be interpreted as representative of the entire commercial fleet, though the methods are more widely applicable. Also, it is not within the scope of this thesis to conduct any detailed economic analysis of the impact of prolonged idle periods. Such analysis would require extensive consideration of a range of economic factors, such as maintenance costs, bunker fuel price and its volatility, vessel activity, chartering conditions, and constraints due to trade patterns (Oliveira, 2019; Pagoropoulos et al., 2018; Stopford, 2009).

The contributions of this work are threefold. Firstly, we show that the improved availability of fleet performance data and AIS data can be utilized to analyse the effect of prolonged port stays on fuel consumption. Secondly, we show that taking advantage of third-party weather data enables us to analyse prolonged idle periods in tropical and non-tropical ports and the effect this has on fuel consumption. Thirdly, in the process of writing this thesis, the continuous dialogue with the weather data provider, Copernicus Marine Service, has encouraged the development of a new web application as a response to our and other similar requests. The application is to be published to the Copernicus Marine Service website and will make weather data more accessible for similar purposes in the future (Copernicus Marine Service, n.d.).

The rest of the paper is structured as follows. Section 2 will present background information and motives for the thesis, along with an overview of existing literature related to the topic of hull fouling, periodical hull cleaning and prolonged idle periods. Section 3 covers the theoretical aspect of fuel consumption and resistance, which are relevant factors for the empirical analysis. Section 4 describes the data sources, assumptions, sample transformation and methodology used to retrieve the results. In section 5 the results are presented and discussed before section 6 concludes with a summary of our results, limitations of our study and propose future areas of research.

2. Background and literature review

The main motives for fuel-efficiency measures in shipping are related to emission reduction and cost-saving. The International Maritime Organization (IMO) states in its fourth greenhouse gas study that the emissions from international shipping are projected to increase by 90-130% of 2008 levels within 2050 for a range of plausible long-term economic and energy scenarios (International Maritime Organization, 2021). To avoid such pathways and further mitigate environmental pollution and climate change, numerous national, regional, and international organizations have set clear ambitions to reduce emissions from international shipping. Currently, the ambitions are being translated into measurable and reportable targets and regulations, based both on well-established frameworks and new objectives.

With the intention to reduce emissions from international shipping and to stay compliant with important regulatory institutions, it is essential for ship-owners to reduce emissions related to the fuel consumption of their vessels. There are many ways to achieve this, including measures regarding ship design and -specifics, fuel types, and ship energy efficiency (Balcombe et al., 2019; Xing et al., 2020). While optimization of ship design and technicalities for vessel newbuilds, or retrofit installations for existing ships, have a proven potential for fuel efficiency, these are in many cases also associated with capital intensive investments and immature technologies (Bouman et al., 2017). Examples are renewable energy installations with wind, solar or fuel cell technologies (Xing et al., 2020). The same goes for the transition to alternative fuel types, which in addition is reliant on many external factors such as policies, accessibility, and infrastructure. Consequently, for the time being, the maritime transport industry has mostly ignored the application of alternative fuel and propulsion systems and has mainly focused on measures for ship energy efficiency (Rehmatulla & Smith, 2015).

Ship energy efficiency measures can be divided into two main categories, i.e., technical, and operational measures. Technical measures are related to upgrades and installations of energy-saving devices for reduced ship resistance and increased propulsion efficiency (Xing et al., 2020). While many of the technical measures are effective and cost-beneficial, optimal implementation can be demanding, especially for technologies that are in the early stage of their application (Bouman et al., 2017). Operational measures include speed optimization, voyage planning, fleet management, and onboard energy management (Xing et al., 2020).

The significance of these operational of measures was formalized with the introduction of the previously mentioned SEEMP by IMO, assigning every ship operator/owner to set up a formal system for management and optimization of ship and fleet performance (Farkas et al., 2021). More specifically, the most important operational measures for energy efficiency are speed reduction, weather routing, and periodical cleaning of ship hull and screw propeller (Adland et al., 2018).

General speed reduction is a well-recognized operational measure that reduces fuel consumption and leads to a significant decrease in carbon emissions (Corbett et al., 2009). However, slow steaming lengthens round trip time by 10-20% depending on the service route and port times (Lee et al., 2015). Rehmatulla & Smith (2015) discusses that this can cause a problem of “split incentives”, as the savings in fuel costs and costs for a longer voyage may be allocated to different agents. With this, shipping companies tend to reduce speed only if there is low demand in the market, low freight rates, overcapacity, or high fuel prices (Finnsgård et al., 2020). Furthermore, weather routing is an important measure as it has the potential to reduce fuel consumption while also increasing the safety of the voyage. With the use of position data and software tools, ship operators can, in collaboration with the crew and third-party software solutions, select the most efficient route to the next port. However, weather conditions are exogenous, and exposure to bad sailing conditions can often only be minimized at the expense of increased voyage time (Adland et al., 2018). Also, weather predictions may have uncertainties that can reduce the accuracy of the alternative voyage routes (Dickson et al., 2019). While speed reduction and weather routing are measures that are highly related to external factors, periodical cleaning, and removal of biofouling on a ship’s hull and propeller is something shipowners to a large degree can control, without external interference. Even though the rate of biofouling on the ship hull and propeller is mostly exogenous, the shipowner can decide the quality, frequency, and timing to clean the hull or propeller (Adland et al., 2018).

Biofouling is a common term for marine growth on a vessel’s hull and ranges from the adhesion of organic molecules and particles on a micro level to organisms of increasing complexity on a macro level, like barnacles (Dürr & Thomason, 2009). The occurrence of biofouling increases as a ship remains in one location for a prolonged period of time, whether docked at port or at anchor in a harbour (Zargiel & Swain, 2014). In addition to long idle periods, low activity due to frequent port stays, and the seawater characteristics such as high temperature and salinity levels in these areas can increase the growth rate (Boyd et al., 2013; Edmiston et al., 2021). Nevertheless, both Edmiston et al. (2021) and Boyd et al. (2013) found that extremely high temperatures resulted in a decrease in growth rate i.e., above 25-30ºC, depending on the species. Also, Madin et al. (2009) found that the rate of growth of biofouling increase significantly when salinity levels increase, comparing dry-season with high salinity levels and wet-season with low salinity levels. However, Han & Lee (2020) discovered a decrease in growth when salinity levels exceeded certain levels. Furthermore, factors like propagule availability in the water, such as light, pollution, and hydrodynamic stress also determine fouling growth (Woods Hole Oceanografic Institute, 1952).

Moreover, the build-up of hull fouling results in excess fuel use at a maintained speed or speed loss at a maintained engine power (Kane, 2012). Excess fuel use means higher fuel costs, and Munk et al. (2009) found in their study that the fuel cost of ships increases at least 10% on average when the ship hull is lightly fouled, and up to 35% when the ship hull is heavily fouled. Olmer et al. (2017) found that the hull fouling factor increased the main engine power demand by 7% on average, ranging from 2-11% depending on each individual ship's age and maintenance schedule (International Maritime Organization, 2021). This has also been confirmed in several studies utilizing computational fluid dynamics (CFD) simulations for various fouling conditions on the hull and propeller. For example, Owen et al. (2018) found that fouling on a ship's propeller resulted in 11-30% energy loss, and Song et al. (2019) observed up to 47% increase in nominal wake fraction due to hull fouling, and up to 93% increase in ship frictional resistance due to barnacle fouling. The CFD simulation method for increased resistance due to fouling has later been validated by (Song et al., 2020). Uzun et al., 2019 used a different method with a time-dependent growth model for predicting the effects of biofouling on ship resistance and powering. They found that resistance increased up to 32% for a tanker over a one-year period, and up to 25% for a crude carrier over a three-year period.

There are today various methods and measures to reduce or remove biofouling. Oliveira (2019) has reviewed both passive and active methods for the reduction of biofouling, along with the advantages and disadvantages of the methods. He describes that passive and preventative methods include periodical treatment in drydock, where the vessel's hull is sand- or hydro-blasted and re-coated with a biofouling control coating. The active methods include in-water hull cleaning, used as a relative approach against a certain level of fouling or propulsion penalty, and in-water hull grooming suggested as a proactive approach consisting of gentle and frequent cleaning events (Tribou & Swain, 2015). Adland et al. (2018) have investigated the impact of such methods and found that periodic hull cleaning leads to a significant reduction in the daily fuel consumption. They also found that and that drydocking leads to greater reductions in fuel consumption than underwater hull cleaning, with an effect of -17% and -9% respectively. Besides drydocking, cleaning, and grooming, other active methods have been proven to be effective to a certain degree, including prevention of fouling using ultrasound transducers (Park & Lee, 2018), aeration (Menesses et al., 2017), and heat treatment (Inglis et al., 2012).

There are some risks and obstacles involved in the process of reducing the biofouling levels with the above-mentioned methods. Firstly, the state of the underwater hull is most commonly assessed by visual inspection. However, fouling may not be uniform in coverage over the hull surface and heavy fouling may not be visibly seen from above-water inspection (Oliveira, 2019). To account for this, diving contractors are often hired for inspection, which can be costly and might not be available in all preferred ports. With new technology, sensor devices are an option to monitor the build-up of fouling, as well as sea-water conditions, but this is dependent on reliable data collection, as well as correctly calibrated sensors, which can be difficult to maintain. Secondly, if it is decided that an underwater hull cleaning should be concluded, this might not either be possible in all preferred ports, due to the vessel's trading program, cost, capacity, or restrictions against contamination of the sea environment in that area. Thirdly, dependent on the roughness of the brushes used for hull cleaning or grooming, there is a risk of damage to the antifouling paint on the hull, which may give a counter-effect and lead to faster development of fouling after cleaning (Oliveira, 2019). With this in mind, it is anticipated that shipowners can benefit from obtaining more knowledge about the fuel consumption effect of prolonged port stays due to the accumulation of biofouling. This information can help shipowners to optimize hull cleaning intervals.

With insight from the current literature, it is clear that hull fouling is influenced by seawater temperature and salinity levels. In addition, studies show that time spent in port also has an effect on hull fouling. Furthermore, increased hull fouling leads to increased resistance which in turn affects the engine power and fuel consumption, and thereby fuel costs and emissions.

3. Theory of fuel consumption and resistance

A ship's fuel consumption is influenced by several factors in addition to biofouling. These include vessel speed, draft, and trim, in addition to environmental conditions such as wind, waves and sea currents (Song et al., 2019; Wang et al., 2018). All these factors represent a variety of resistance components. The fundamental theory of many studies regarding vessel performance often consists of variants of a total resistance equation, making it possible to isolate the resistance caused by the hull. In addition to the above factors MAN Diesel & Turbo (2010) and MAN Energy Solutions (2018) address the hull's shape and design as a significant factor for resistance. According to Meng et al. (2016), MAN Diesel & Turbo (2010) and MAN Energy Solutions (2018) speed V impacts the fuel consumption by increasing the right side of the following equation:

$$P_E = V * R_T \quad (1)$$

where P_E denotes the power necessary to move the ship, V denotes the velocity, and R_T denotes the total resistance, which is given by the equation:

$$R_T = R_F + R_R + R_A \quad (2)$$

Here, R_F denotes the frictional resistance, R_R denotes residual resistance and R_A denotes air resistance. According to MAN Diesel & Turbo (2010) and MAN Energy Solutions (2018), frictional resistance R_F accounts for between 70%-90% of the total resistance on slow-moving ships such as tankers and bulk carriers. R_F includes friction caused by the roughness of a ship's wetted surface and the wetted area of the hull. The authors also point out that the design of the hull and draft influence the frictional resistance as well as hull fouling due to the growth of algae, seagrass and barnacles (MAN Diesel & Turbo, 2010). Meng et al., (2016) also specify the importance of periodically hull coating and hull cleaning to lower the frictional resistance. Residual resistance R_R on the other hand is explained as eddy resistance and wave resistance. According to both Meng et al. (2016) and MAN Diesel & Turbo (2010) the residual resistance is mainly caused by waves. With regard to the wave resistance, the two authors are not consistent with each other. Whereas MAN Diesel & Turbo (2010) and MAN Energy Solutions (2018) explains wave resistance as resistance from waves caused by the ship's propulsion through water, Meng et al. (2016) describe waves as the joint effect of swell and local surface waves. Air resistance R_A is caused by wind and ship size (MAN Diesel & Turbo, 2010; MAN

Energy Solutions, 2018; Meng et al., 2016). Even though currents have little effect on the total resistance, it influences the ship’s speed over ground (Abebe et al., 2020).

When fuel consumption, speed, air resistance and residual resistance are observable, the effect of frictional resistance caused by the hull roughness can be isolated. By isolating this effect, we can determine the hull fouling’s effect on fuel consumption.

4. Data and methodology

4.1 Noon reports and AIS

The main source of data in this study is extracted from vessel noon reports. A noon report is a data sheet prepared once every day by the ship's crew to provide information on e.g., a vessel's position, speed, draft, and environmental forces to assess the ship's performance (Anish, 2021). Because the noon reports are manually prepared, they are exposed to human errors such as rounding, misinterpreting output readings and partially or fully failing to deliver complete reports. The noon reports in this study are provided by G2Ocean and contain noon reports from two different vessel classes, which typically trade in a pattern between South America and Europe, and South America and the Far East. The 6^{th} Generation class, being built between 2009 and 2011 reigns as the oldest class of sister ships. The Flexi-III class as the youngest, was built between 2013 and 2014. Both classes are similar in size but are different in shapes and qualities. A full description of the class specifications can be found in APPENDIX A.

All vessels from the 6^{th} Generation class and four of the Flexi-III vessels are included in this study, due to insufficient data on the remaining four from the Flexi-III class. The trading patterns of the included vessels are displayed in Figure 1. Figure 1 also shows that the vessels are often present in tropical areas.

The noon report variables relevant to the analyses in this thesis are listed in Table 1.

Table 1 Noon report variables included in the study

Noon report variables	
Category	**Included variables**
Vessel identification	Vessel name, vessel class
Time and location	Observation time, geographic position (latitude and longitude), time since last report (in hours), next port (abbreviation of ship's destination)
Performance	Daily average speed (in knots), daily average main engine fuel consumption (in tonnes), forward draft (in meters), after draft (in meters)
Weather	Wind direction (relative to ship's heading), wind speed (Beaufort scale), swell direction (relative to ship's heading), swell type (Douglas scale)

Figure 1 Trading pattern of vessels. Source: Data from G2Ocean and NHHs' AIS provider. N = number of observations (noon reports).

Automatic Identification System (AIS) data is an automated and autonomous system tracking and exchanging navigational information between AIS-equipped terminals in the maritime world. In 2004, IMO required all passenger's vessels and commercial vessels from 300 gross tonnage and upwards that travel internationally to carry a class A AIS transponder (IMO, n.d.)

AIS-data were retrieved though Vesseltracker and consisted of monthly files from January 1st, 2013, to July 31st, 2019. Each file consisted of hourly, vessel pooled data including up to over 10.000 ships and over 20 million observations at the most. In addition, the data was divided into two subsections covering worldwide data and Mediterranean data accumulating to approximately 0.66 terabyte (TB). From this data, data for 12 ships (4 6th Generation and 8 Flexi-III) were attempted retrieved based on IMO-numbers, in which 8 ships contained sufficient amounts of data. Hence, four 6th Generation vessels and four Flexi-III vessels were included.

The combination of noon reports and AIS-data resulted in a sample of 15,405 observations, with roughly 1,800 reports per ship. The noon reports were merged with AIS-data using the nearest neighbor method based on observation time to fill in missing coordinates if needed or possible in the noon reports. Similar for both datasets were often missing data when the ships were in port. This led to a manual insertion of coordinates for 162 of 285 ports sourced from (MarineTraffic, n.d.)

4.2 Third-party weather data

In addition to the noon reports and AIS data, we have retrieved third-party weather data from Copernicus Marine Service (CMEMS) (Copernicus Marine Service, 2022). This involves variables for seawater temperature and seawater salinity. The chosen surface level is 0.494 meters. Table 2 displays an overview of the product which these variables were extracted from.

The weather-data product used is the GLOBAL_MULTIYEAR_PHY_001_030, containing the dataset named "cmems_mod_glo_phy_my_0.083_P1-m (daily mean)" which covers the area and the time range needed to match it with the noon reports (Copernicus Marine Service, 2022). Visual examples of the variables can be found in APPENDIX D page 2-4, where layers for seawater temperature and seawater salinity have been added to a world map using QGIS.

Table 2 The extracted Copernicus dataset and variables. Source: Copernicus Marine Service

Dataset (Source)	**Temporal Resolution**	**Spatial Resolution**	**Temporal Coverage** (Period used)	**Variables Used** (Variable Identifier)	**File type** (File size)
Global Ocean Physics Reanalysis: GLOBAL_MULTIYEAR_PHY_001_030 (Copernicus Marine Service, 2022)	24 hours, daily mean	0.083°×0.083°	1993-01-01 to 2019-12-31	Seawater temperature (thetao)	NetCDF (72 GB)
			(2014-01-01 to 2019-12-31)	Seawater salinity (so)	NetCDF (72 GB)

To extract the data needed to supplement the noon reports, a Python script that reads a .csv file with the relevant dates and coordinates into a Pandas data frame has been written. Furthermore, the script downloads the requested product variables at the coordinates using the OPeNDAP API. The xarray package for Python is used to manipulate the dataset.

This process has been developed with help from the technical support team at CMEMS. Moreover, the idea from CMEMS is to utilize their Python script, which extracts weather data directly based on exact coordinates for specific dates and further develop this to a web application that will allow future users to do the same process as running the script, but via a Graphical User Interface (GUI). Such a procedure for collecting weather data will be much more efficient with the new tool, as the existing solution only provides access to download very large datasets covering variables for either too many or too few locations or dates, making the matching-process with noon reports advanced and time-consuming. The development process of the application is currently proceeding to the final tests and in parallel waiting for the backend side to be enabled for end-users. Updates regarding this process will be available at Copernicus Marine Service (n.d.) (David Bina (Copernicus Marine Service), personal communication, May 25, 20222), (Technical Support Copernicus Marine Service, personal communication, March 4, 2022).

The extracted weather data were finally merged into the sample of noon report and AIS data using spreadsheet functions for lookup values and arrays.

4.3 Sample cleaning

The following process was applied for the cleaning of the initial 15,405 noon reports supplied with AIS and weather data. First, duplicated observations, grouped by vessel and observation time, with the highest number of missing data were discarded (1995 observations). Secondly, observations with missing speed data were discarded (2673 observations). Reports filed less than 18 hours after the previous report was discarded, assuming that they might not represent open water sailing (959 observations). Note that all reports filed later than 18 hours after the previous report are kept because these are likely to represent the first noon report after a port stay. Reports containing higher speeds than 16 knots or lower speed than 8 knots (1385 observations) were discarded based on their limited ability to resemble regular open water sailing. Reports with missing fuel consumption (111 observations) and missing forward draft (38 observations) were removed. Further, observations with missing weather data (wind direction, wind speed, swell type, and swell direction) were removed (182 observations). In addition, the top and bottom 0.5% percentile were discarded to trim the data for outliers (83 observations). A total of 7979 Noon reports were included in the final sample.

4.4 Descriptive statistics and assumptions for regression analysis

4.4.1 Fuel consumption statistics

Figure 2 shows the daily average fuel consumption over time for both the 6th Generation class and the Flexi-III class, respectively. Whilst the fuel consumption has remained stable for the 6th Generation vessels, the Flexi-III class shows a large increase in the period after G2Ocean started operating the fleet in mid-2017. The increase in fuel consumption in tonnes, to maintain certain speeds seems to be related to the change of ownership.

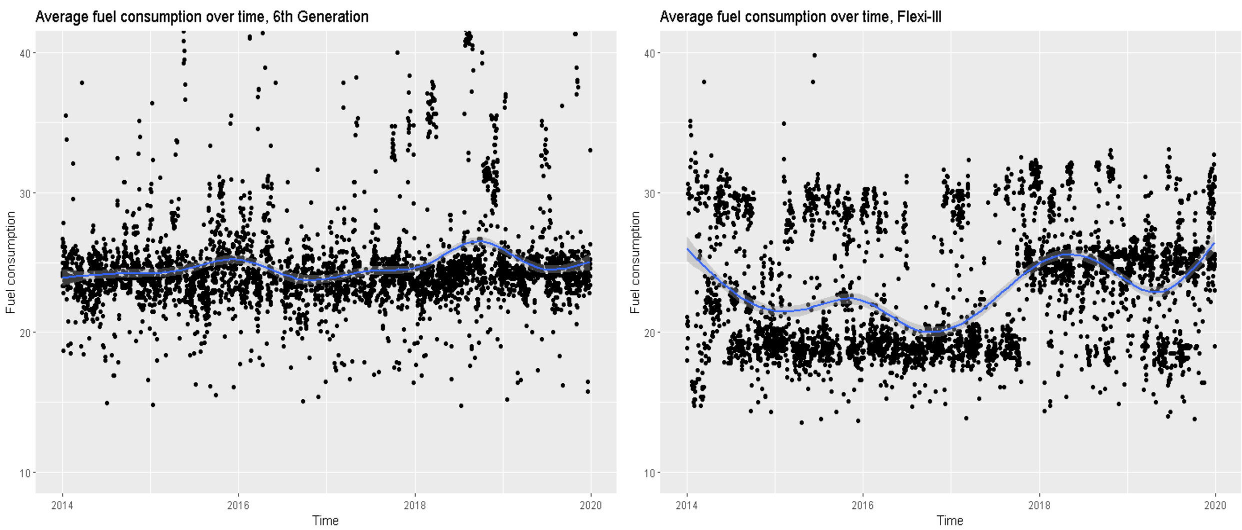

Figure 2 Average fuel consumption over time

Figure 3 shows fuel consumption in relation to GPS speed in knots for the two vessel classes. The figures are consistent with information provided by G2Ocean (G2Ocean, personal communication, 02.12.2021) in that their fleets actively seek to maintain a given fuel consumption when sailing in open waters. Applying a simplified quadratic function of the relationship between speed and fuel consumption found by Bialystocki & Konovessis (2016), Figure 3 suggest a convex relationship. Weather conditions and currents and other external factors explain the vessels' ability to maintain the same fuel consumption at different speeds and explains the heterogeneity in fuel consumption at a given speed.

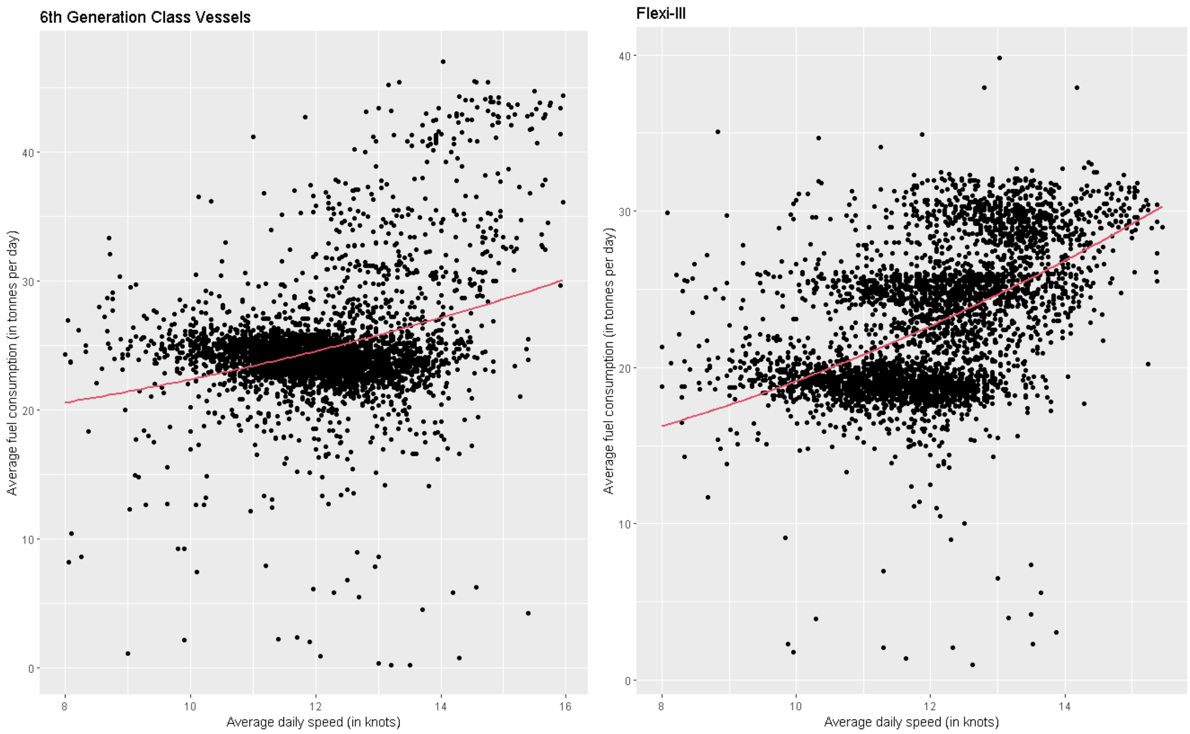

Figure 3 Fuel consumption and vessel speed

4.4.2 Defining time spent in port

In the period before mid-2017 the only measure of a port stay was the lack of noon reports during the transition of a ship changing its destination. The last noon report of a voyage leg is therefore considered the end-of-sea passage (EOSP). Because daily average speeds below 2 knots typically represent waiting or idle time, noon reports prior to the last observation containing such values were included as time spent in port. The time between the last noon report, and the first noon report of the following voyage leg were then added to calculate the full time spent in port. From mid-2017, EOSP reports were included leaving no reason to consider the last noon report as EOSP. With more complete AIS-data, it would have been possible to define the time spent in port more accurate. For instance, by extracting specific observations where a vessel reduces its speeds to approximately zero, and by defining an area considered in port by looking at a ships distance from port coordinates in nautical miles.

4.4.3 Descriptive statistics

Table 3 presents descriptive statistics of variables comprised in the study to explain the change in fuel consumption. The first set of variables included are assessed from the noon reports and can all be implemented as friction variables in equation (1) for fuel consumption previously introduced in section 3. The average daily speed variable provides GPS speed over land. Forward draft is measured in meters and explain how high or deep in the sea the vessel operates. With data for after draft missing 1677 observations, a trim variable was not generated even though it has proven to have a strong relation to the fuel consumption (Abouelfadl & Abdelraouf, 2016; Putra et al., 2017).

External, weather specific data such as wind speed and wave type are measured in Beaufort scale (0-12) and Douglas Sea State (0-9), respectively. Wind types are divided into three categories, Gentle breeze and below (0-3), Moderate to strong breeze (4-6), Near gale and upwards (7-12). Wave types were also divided into three categories with *small* representing wave types including no swell, very low and low (0-2). *Medium* being light, moderate, and moderate rough (3-5), and *large* including all categories above rough (6-9).

The wind and wave directions were transformed into *wind facing bow, wind facing stern, wind facing side, swell facing bow, swell facing stern and swell facing side* as depictured in figure 4.

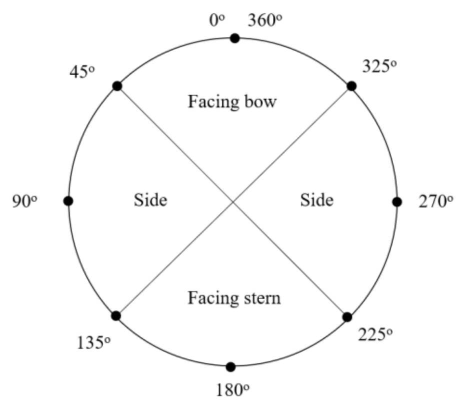

Figure 4 Transformation of directional variables

The median of 3.167 days, and the mean of 4.948 days spent in port represent normal port stays, resulting in the limit for a prolonged stay being any number of days spent in port more than 5 days. Tropical ports are defined as having a sea temperature above 25°C based on previous considerations of tropical waters (i.e., Muñoz et al., 2004) where increased growth in algae's is found (Boyd et al., 2013) and correspondingly increased hull fouling (Edmiston et al., 2021).

Table 3 Descriptive statistics, open water sailing

Variable	(1) All	(2) 6th Generation	(3) Flexi-III
Fuel Consumption in tonnes per day (log)	3.157	3.220	3.281
Daily average speed (log)	2.483	2.487	2.530
Forward draft (log)	2.391	2.427	2.390
Wind facing bow	0.541	0.502	0.618
Wind facing side	0.063	0.058	0.070
Wind facing stern	0.396	0.439	0.310
Wind type: Gentle breeze and below	0.176	0.160	0.174
Wind type: Moderate to strong breeze	0.781	0.799	0.773
Wind type: Near gale and upwards	0.043	0.040	0.052
Swell facing bow	0.479	0.502	0.492
Swell facing side	0.076	0.058	0.070
Swell facing stern	0.445	0.439	0.436
Swell type: small (no waves or short waves)	0.264	0.223	0.142
Swell type: medium	0.718	0.400	0.366
Swell type: large	0.018	0.246	0.310
Drydock	0.023	0.022	0.024

Table 4 present the descriptive statistics of port characteristics where the vessels have stayed for more than 5 days. The high standard deviations show that the vessels are exposed to prolonged stays in ports with a range of salinity and temperature characteristics. A table showing the descriptive statistics including only port stays of 10 days and more can be found in APPENDIX B. Furthermore, the timeline of each vessel and its corresponding prolonged, and prolonged tropical port stays, can be found in APPENDIX C. All vessels are exposed to prolonged port stays, and all except one vessel in the 6th Generation class is exposed to prolonged stays in tropical ports.

Table 4 Descriptive statistics, ports with prolonged port stays > 5 days

Variable	6th Generation			
	Mean	Std. dev.	Min	Max
Port temperature in °C	16.444	9.028	-1.689	32.610
Port salinity in ppt	23.519	14.23	0.000	39.540
Number of prolonged stays	91			
Number of prolonged tropical stays	16			
Variable	**Flexi-III**			
	Mean	Std. dev.	Min	Max
Port temperature in °C	17.570	8.154	0.000	33.290
Port salinity in ppt	25.410	13.73	0.000	39.190
Number of prolonged stays	155			
Number of prolonged tropical stays	32			

Table 5 present an explanation of the relationship between the logarithm of fuel consumption and the explanatory variables logarithm of speed, logarithm of forward draft, weather conditions, treatment related to dry docking and vessel fixed effects. The coefficients in columns 1 and 3 are all statistically significant and in line with the expectations of increasing speed leading to increased fuel consumption. The elasticity for fuel consumption in respect to speed of 0.441 for the 6th Generation class, and 1.051 for the Flexi-III class is much lower than suggested by Adland et al. (2018), Bialystocki & Konovessis (2016) and Psaraftis & Kontovas (2013), suggesting an elastic relationship with coefficients ranging from 1.72 to 3. In addition, the draft coefficients show that an increase in draft of 1% increases the fuel consumption by 1.22% (0.122/100) for the 6th Generation class, and 1.99% for the Flexi-III class. When accounting for weather variables in column 2 and 4, almost all coefficients are highly significant for both vessels and correspond with the expectations. The only exception is wind facing stern, moderate to strong breeze and swells facing the vessels bow. Here, the coefficients for the 6th Generation class are insignificant, whilst they are significant for the Flexi-III class.

The coefficients related to wind and wave direction and their strength and size are in line the expectations as shown in column 4. For the Flexi-III vessels, when the wind faces the vessels' bow, it increases the fuel consumption with 2.8% ($e^{0.028}$-1 = 0.028) when compared to wind from the sides. Fuel consumption is reduced by 6.4% when the wind faces the stern, also compared to wind from the sides. The coefficients also show increasing fuel consumption when wind strength and wave size increase. For instance, vessels operating in medium swells result in an increase of 9.6% compared to when operating in small swells. The effect also increases when vessels are operating in large swells (18.4%). The estimates show the importance of distinguishing between the two vessel classes because the size and shape of the two classes are affected differently by the variables. When taking weather into account, R^2 increases dramatically for both classes as expected, with 10.2 percentage points and 16.4 percentage points, respectively.

Table 5 Estimates of fuel consumptions (in tonnes per day)

Variable	6th Generation		Flexi-III	
	(1)	(2)	(3)	(4)
Daily average speed (log)	0.441*** (0.036)	0.695*** (0.039)	1.051*** (0.030)	1.315*** (0.028)
Forward draft (log)	0.122*** (0.011)	0.117*** (0.012)	0.199*** (0.010)	0.224*** (0.009)
Wind facing bow (ref: wind side)		0.026*** (0.007)		0.028** (0.008)
Wind facing stern		-0.001 (0.007)		-0.067*** 0.008)
Wind type: Moderate to strong breeze (ref: Gentle breeze and below)		0.0001 (0.005)		0.023*** (0.005)
Wind type: Near gale and upwards		0.094*** (0.012)		0.121*** (0.016)
Swell facing bow (ref: Swell side)		-0.001 (0.007)		0.025** (0.008)
Swell facing stern		-0.031*** 0.007)		-0.017* (0.012)
Swell type: medium (ref: small)		0.057*** (0.005)		0.092*** (0.005)
Swell type: large		0.128*** (0.021)		0.169*** (0.022)
After drydocking (45 days)	-0.044*** (0.011)	-0.030** (0.011)	-0.048*** (0.012)	-0.036*** 0.012)
Constant	1.794*** (0.109)	0.986*** (0.121)	0.048 (0.089)	-0.769*** (0.084)
VESSEL FIXED EFFECTS	YES	YES	YES	YES
Number of observations	3977	3977	4002	4002
R^2	0.102	0.204	0.334	0.498

Significance levels are 1% (***), 5% (**) and 10% (*).

4.5 Empirical method

The paper aims to identify the causal effect of undergoing prolonged port stays on fuel consumption. In addition, distinguishing between tropical and non-tropical port stays enables to find whether there is a difference between the two. This section explains the identification strategies to obtain these effects. Similar studies have been carried out earlier, where researchers have studied the effect before and after several treatments over a period of time. The approach is an offspring of the fixed effects model (Angrist & Pischke, 2009), called the difference-in-differences method. It is an appropriate approach to identify the causal effect of a treatment, which in this case are ships being exposed to prolonged port stays. Difference-in-differences estimation is most appropriate when the treatment is random and as in this case, when observable characteristics such as environmental variables can be controlled for. We assume the prolonged port stays to be random as all vessels within the same class are exposed to approximately the same number of treatments. We also assume it to be random because the reason for prolonged port stays can be caused by external factors such as weather, queues, waiting time for barges and tugboats, and other port operations. In addition, the method relies on an examination of the effect of a treatment group, relative to a non-treatment group, controlling for any trend in changes in fuel consumption not caused by the treatment.

The methodological framework that follows was developed by Adland et al. (2018). The same approach is used and adapted to this thesis.

Let $\ln C_{vt}$ denote the change in fuel consumption for vessel v at time t, where $v = 1, \dots, V$ and $t = 1, \dots, T$ whereas the t represent one observation[1]. Fuel consumption is expected to vary due to resistance made by different conditions. These sailing conditions include factors such as wind and swell direction, wind force and swell type, speed, and draft. We denote these characteristics X_{vt}. As a subscript, $k(v)$ denotes any treatment in form of a prolonged port stay. The effect on fuel consumption is observed during the period from one treatment until the next treatment, $t_{k(v)} \leq t < t_{k(v)+1}$. k is dependent on v since treatments at given times is specific to each vessel. Using $t_{k(v)}$ with $v = 1, \dots, V$ and $k(v) = 1, \dots, K(v)$, we can estimate two estimators around $t_{k(v)}$ to gather information about the change in fuel consumption in the period of a treatment. Let w represent the time window in which we examine the levels of fuel consumption around a prolonged port stay $k(v)$. Let $t_{k(v)}^{-w} = t_{k(v)} - w$ be the window before a prolonged port stay and let $t_{k(v)}^{+w} = t_{k(v)} + w$ be the window after a prolonged port stay. The two estimators $t_{k(v)}^{-w} \leq t < t_{k(v)}$ and $t_{k(v)} \leq t < t_{k(v)}^{+w}$ enables a comparison between fuel consumption before and after a prolonged port stay $t_{k(v)}$. $D_{vt}^{AFTER_w}$ is a dummy variable equal to 0 if the time is before a prolonged port stay ($t_{k(v)}^{-w} \leq t < t_{k(v)}$) and equal to 1 if the time is after a prolonged port stay ($t_{k(v)} \leq t < t_{k(v)}^{+w}$). A dummy U_{vt} is also added to control for the dry docking and its significant negative reduction in fuel consumption suggested by Adland et al. (2018), where $U_{vt} = 1$ in a 45-day window following the launch after a dry docking. The dependent variable, change in fuel consumption, is a continuous variable. This is a key

[1] t could represent 1 day to be more consistent. Due to the inconstancy of the noon reports, we applied number of observations instead. This can arguably be applied because it is normally 24 hours between the noon reports.

assumption when estimating the before-after estimator using Ordinary Least Square on the dataset where the vessels are pooled, such as:

$$\mathrm{lnC_{vt}} = \delta_w D_{vt}^{AFTER_w} + \beta X_{vt} + \varphi U_{vt} + \vartheta_v + \epsilon_{vt} \tag{3}$$

where δ_w is the parameter related to the before-after port stay estimator, β represent the various coefficients related to the numerous explanatory variables X_{vt} such as waves and wind, φ is the coefficient related to the estimator of dry docking U_{vt}, ϑ_v represent the vessel fixed effects, and ϵ_{vt} is the residual error with respect to perturbation such that $E(\epsilon_{vt}) = 0$ and $Var(\epsilon_{vt}) = \sigma^2$. The vessel fixed effects ϑ_v is implemented in the model to control for any other vessel specific measures that is not already accounted for.

Equation (3) can be modified to account for the believed to be different effect between undergoing a prolonged stay in a tropical, and in a non-tropical port. To do so, two dummies $D_{vt}^{AFTER_{w}tropical}$ and $D_{vt}^{AFTER_{w}non-tropical}$ are added such that:

$$\mathrm{lnC_{vt}} = \delta_w^{tropical} D_{vt}^{AFTER_{w}tropical} + \delta_w^{non-tropical} D_{vt}^{AFTER_{w}non-tropical} + \beta X_{vt} + \varphi U_{vt} + \vartheta_v + \epsilon_{vt} \tag{4}$$

To investigate the effect of an increase of days spent in port, the method is applied to two cases. In the first case, prolonged port stays are considered 6 days or longer. In the second case, prolonged port stays are considered 10 days or longer. A Wald test is used to investigate weather tropical and non-tropical ports have the same effect on fuel consumption with the null hypothesis being $H_0 = \delta_w^{tropical} = \delta_w^{non-tropical}$. Additionally, a time linear trend is applied to equation (4) to control for the assumed decreasingly effect due to sailing in open waters where friction from moving through water and the anti-fouling coating's abilities.

Continuing, the same approach as Adland et al. (2018) is implemented to estimate the difference-in differences estimator of prolonged port stays by supplementing equation (4). The treatment group includes any vessel that has stayed in a port within $[t_{k(v)}^{-w}; t_{kv}^{+w}]$. The treatment group is then compared to the control group which represent the counterfactual to the treated vessel. The counterfactual is never observed (Scott Cunningham, n.d.) but by observing sister ships with the same shape and size within the same period that have not been treated, one can assume they converges towards the counterfactual. Thus, a differentiation between vessel classes is also made when performing the difference-in-differences model. Conditions such as weather, draft and speed variations are controlled for by implementing X_{vt} in the model. The same fictious shock is also applied to the control vessels at time $t_{k(v)}$ to make the control group simulate the counterfactual.

The control group is first set to include all vessels within the time frame $[t_{k(v)}^{-w}; t_{kv}^{+w}]$. Further, the vessels v in this interval that also has been treated is excluded from the control groups as shown in Figure 5.

The model's design is constructed such that any vessel v can be included in both the treatment group and the control group, but not in the same period. This implies that if vessel 1 is treated during the time window $[t_{k(v)}^{-w}; t_{kv}^{+w}]$, then the control group includes any vessel $v \neq 1$ and in addition has not been treated during the interval. Furthermore, if vessel 1 did not undergo a prolonged port stay during the time window applied to any treatment of any other vessel ($v \neq 1$), vessel 1 will be included in the control group instead.

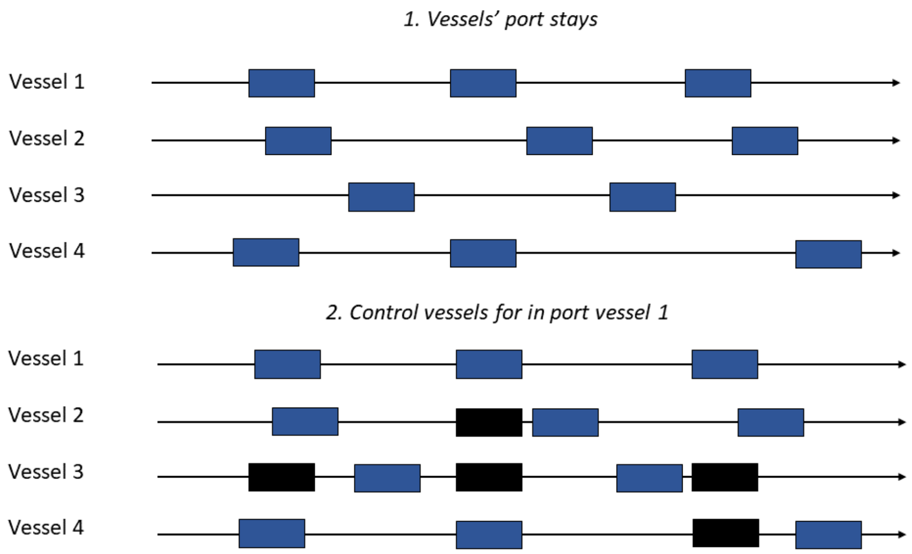

Figure 5 The blue boxes indicate the before and after time window a vessel is idle in in port. The black boxes indicate the before and after time interval of control vessels

Applying the dummy variable P_{vt} for treated vessels into the model makes it possible to obtain the difference-in-differences estimator

$$\hat{\theta}_{vt} = \left(lnC_{vt,after,treated} - lnC_{vt,after,control}\right) - \left(lnC_{vt,before,treated} - lnC_{vt,before,control}\right) \qquad (5)$$

and applying the estimator to the model:

$$\mathrm{lnC_{vt}} = \gamma_{vt}P_{vt} + \delta_w D_{vt}^{AFTER_w} + \theta_{vt}D_{vt}^{AFTER_w}P_{vt} + \beta X_{vt} + \varphi U_{vt} + \vartheta_v + \epsilon_{vt} \qquad (6)$$

The coefficient of interest, θ_{vt} then obtains an indication of the causal effect on fuel consumption regarding the treated vessels compared to non-treated vessels. γ_{vt} is the coefficient related to the treated vessels P_{vt}. δ_{vt} is related to effect at after the discontinuity $D_{vt}^{AFTER_w}$. φ is the coefficient related to the estimator of dry docking U_{vt}. Because the regression inherits a variety of vessel fixed effects ϑ_{vt}, it is important to point out that since a ship can appear both in the treated and the control group, but not at the same time, γ_{vt} is identified.

As implemented in equation (4), the distinction between tropical and non-tropical ports is included by adding the port specific dummies $D_{vt}^{AFTER_w^{non-tropical}}$ and $D_{vt}^{AFTER_w^{tropical}}$ and their belonging interaction terms $D_{vt}^{AFTER_w^{non-tropical}}P_{vt}$ and $D_{vt}^{AFTER_w^{tropical}}P_{vt}$:

$$\begin{aligned}\mathrm{lnC_{vt}} = \gamma_{vt}P_{vt} &+ \delta_w^{non-tropical}D_{vt}^{AFTER_w^{non-tropical}} + \theta_{vt}^{non-tropical}{}_{vt}D_{vt}^{AFTER_w^{non-tropical}}P_{vt} \\ &+ \delta_w^{tropical}D_{vt}^{AFTER_w^{tropical}} + \theta_{vt}^{tropical}D_{vt}^{AFTER_w^{tropical}}P_{vt} \\ &+ \beta X_{vt} + \varphi U_{vt} + \vartheta_v + \epsilon_{vt}\end{aligned} \qquad (7)$$

4.5.1 Deciding time window

To assess the optimal time window w, the minimum and maximum number of observations between treatments $(t_{k(v)})$ should be considered. In this analysis, the decision is based on port stays exceeding 5 days. To include every treatment $(t_{k(v)})$, the time window w should be set to the minimum. This approach is not very valuable in this study because there can be several other factors influencing the two observations closest to the treatment $(t_{k(v)})$, such as traffic in and out of ports and weather. Using the maximal number of observations between treatments lead to exclusion of all treatments where another treatment occurs within $[t_{k(v)}^{-w}; t_{k(v)}^{+w}]$.

As the median number of observations between prolonged port stays is 28 days, this led to further investigation of time windows from $w = 5\ to\ w = 40$ with increments of 5 days. Using time window $w = 5$ limits the number of relevant observations before and after a treatment $(t_{k(v)})$ that provide data on the various effects on fuel consumption and makes it difficult to capture any effect. Another downside of using time window $w = 5$ is that an abnormal observation will have a larger impact on the result than when using larger time windows. A total of 181 (71 for the 6th Generation class, 110 for the Flexi-III class) prolonged port stays is included when $w = 5$ is applied. Using time window $w = 40$ increases the observations within the interval $[t_{k(v)}^{-w}; t_{k(v)}^{+w}]$ but reduces the total number of prolonged port stays possible to use to 23 (9 for the 6th Generation class and 17 for the Flexi-III class) due to exclusion of treatment overlapping.

5. Results

All results presented below includes vessel fixed effects in addition to the control variable for drydocking. Common for all results is the drastic increase in degree of explanation when including weather factors in the model, such as wind direction, wind strength, swell direction, and swell size.

Table 6 presents the estimated effect of prolonged port stays on fuel consumption at the discontinuity with time window $w = 10$. Here, prolonged port stays are considered as more than 5 days. Panel A1, corresponding with equation (3), suggest a negative and significant relation between fuel consumption and prolonged port stays for the 6th generation vessels. The model suggests a reduction in fuel consumption of 4.2% ($e^{-0.043}$-1 = 0.042) after a prolonged stay when controlling for weather. No significant effect is found in the Flexi-III class when controlling for the weather. Additionally, controlling for weather data result in an increase in the R^2 value for both the 6th Generation vessels and the Flexi-III vessels from 18.3% to 25.8% and 33% to 48.8% respectively. Panel A2 includes the linear time trend which result in a slight increase in both the magnitude of the estimates and the degree of explanation.

Panel B1 in Table 6, corresponding with equation (4) provides an overview of the difference between tropical and non-tropical ports, and their effect on fuel consumption. Distinguishing between the two results in an increase in R^2 from panel A1 to panel B1 of 2.5 (28.3 - 25.8 = 2.5) percentage points for the 6th Generation class. When controlling for the weather, the coefficients suggest a slight decrease in fuel consumption for the 6th Generation class of almost 5.0% after prolonged tropical port stays and 4.5% for non-tropical port stays. The null hypothesis $H_0 = \delta_w^{tropical} = \delta_w^{non-tropical}$ is not rejected by the Wald test, meaning there is no significant difference between the two types of port stays. For the Flexi-III class, the result shows a slight significant decrease in fuel consumption of 2.3% after undergoing a prolonged tropical stay. A non-tropical port stay has no significant effect on fuel consumption. Here, the null hypothesis $H_0 = \delta_w^{tropical} = \delta_w^{non-tropical}$ is also not rejected by the Wald test, meaning there is no significant difference between the two types of port stays.

Table 6 Estimates at the discontinuity (w = 10) (idle time > 5 days)

Variable	6th Generation		Flexi-III	
	(1)	(2)	(3)	(4)
Panel A1 – no time trend				
Prolonged stay	-0.042*** (0.006)	-0.043*** (0.006)	-0.020*** (0.006)	-0.011 (0.006)
Weather	NO	YES	NO	YES
Number of observations	1418	1418	2080	2080
R^2	0.183	0.258	0.330	0.488
Panel A2 – linear time trend				
Prolonged stay	-0.046*** (0.0.14)	-0.044*** (0.013)	-0.009 (0.015)	-0.003 (0.013)
Weather	NO	YES	NO	YES
Number of observations	1418	1418	2080	2080
R^2	0.188	0.267	0.332	0.493
Panel B1 – no time trend				
Tropical stay	-0.067*** (0.011)	-0.052*** (0.011)	-0.012 (0.011)	-0.024* (0.011)
Non-tropical stay	-0.043*** (0.009)	-0.047*** (0.009)	-0.024*** (0.009)	-0.010 (0.006)
Weather	NO	YES	NO	YES
Number of observations	1418	1418	2080	2080
R^2	0.209	0.283	0.330	0.489
Panel B2 – linear time trend				
Tropical stay	-0.058*** (0.017)	-0.035* (0.016)	-0.006 (0.016)	-0.022 (0.015)
Non-tropical stay	-0.037** (0.016)	-0.034* (0.016)	-0.018 (0.014)	-0.007 (0.013)
Weather	NO	YES	NO	YES
Number of observations	1418	1418	2080	2080
R^2	0.215	0.294	0.332	0.494

Significance levels are 1% (***), 5% (**) and 10% (*).

Table 7 Estimates at the discontinuity (w = 10) (idle time > 9 days)

Variable	6th Generation		Flexi-III	
	(1)	(2)	(3)	(4)
Panel A1 – no time trend				
Prolonged stay	-0.043*** (0.008)	-0.043*** (0.008)	0.020** (0.008)	0.019** (0.007)
Weather	NO	YES	NO	YES
Number of observations	975	975	1417	1417
R^2	0.208	0.298	0.318	0.470
Panel A2 – linear time trend				
Prolonged stay	-0.073*** (0.019)	-0.063*** (0.18)	-0.017 (0.018)	-0.006 (0.016)
Weather	NO	YES	NO	YES
Number of observations	975	975	1417	1417
R^2	0.212	0.303	0.328	0.484
Panel B1 – no time trend				
Tropical stay	-0.063*** (0.014)	-0.057*** (0.014)	0.060*** (0.013)	0.036** (0.012)
Non-tropical stay	-0.026 (0.016)	-0.019 (0.007)	0.005 (0.008)	0.013 (0.008)
Weather	NO	YES	NO	YES
Number of observations	975	975	1417	1417
R^2	0.310	0.396	0.324	0.471
Panel B2 – linear time trend				
Tropical stay	-0.092*** (0.024)	-0.066** (0.024)	0.020 (0.018)	0.010 (0.017)
Non-tropical stay	-0.056* (0.025)	-0.033 (0.024)	-0.031* (0.015)	-0.007 (0.014)
Weather	NO	YES	NO	YES
Number of observations	975	975	1417	1417
R^2	0.315	0.404	0.335	0.484

Significance levels are 1% (***), 5% (**) and 10% (*).

The results in Table *7* are also based on equation (3) and equation (4) but consider idle time in ports for more than 9 days to be prolonged. For the 6th Generation class, the results are consistent with the results from Table 6 and show that prolonged port stays, and prolonged tropical port stays, indicate a decrease in fuel consumption. However, the magnitude of the effect differs slightly both without and with a linear time trend. Additionally, undergoing a prolonged non-tropical port stay has no significant effect. On the other hand, the results for the Flexi-III vessels have changed drastically. Having no statistically significant results in panel A1 in Table 6, the result now suggests an increase in fuel consumption of 1.9% in panel A1. With no linear time trend accounted for in B1, the results show an increase of 3.6% after prolonged tropical port stay. No significant effect is found for prolonged non-tropical stays in the Flexi-III class when controlling for weather factors.

Figure 6 and Figure 7 illustrates the sensitivity to the use of different time windows for both the 6th Generation class and the Flexi-III class, respectively. The top part of the figures being prolonged port stays exceeding 5 days, and the bottom part exceeding 9 days. A notable observation in the upper part of Figure 6, covering the 6th Generation class, is the indication of a reduction in fuel consumption after any prolonged stay when using time windows below 25 days. When undergoing a prolonged tropical port stay, the marginal effect ranges from -5.10% to 5.99% where the largest effect is found in time window $w = 35$. The missing bar in time window $w = 40$ show that there are no cases where the 6th Generation class has undergone a prolonged tropical port stay without being exposed to another prolonged port stay within the time window. In the case of non-tropical port stays, the marginal effects are similar to the tropical port stays, suggesting a reduction in fuel consumption when using time window $w = 25$ and below. Here the marginal effect ranges between -4.59% and 4.33%. In the bottom part of the figure, when defining prolonged port stays as idle time exceeding 9 days, the effect of tropical stays differs from non-tropical stays for time windows $w \leq 30$. The marginal effect ranges from -6.8% to 4.6% in tropical ports and -1.9% to 3.4% in non-tropical ports.

In the case of the Flexi-III vessels in Figure 7, the marginal effect in tropical ports ranges from -4.97% to 3.56% and the largest marginal effect is found in time window $w = 20$ and $w = 25$ when using idle periods longer than 5 days. For non-tropical prolonged stays, the marginal effect ranges between -1.61% and 7.74%. The largest marginal effect is here found in time window $w = 40$. When considering port stays of more than 9 days only, the results show a corresponding effect of increased fuel consumption both for tropical and non-tropical ports.

The marginal effect here ranges from 0.9% to 4.2% in tropical ports and 0.0% to 5.2% in non-tropical ports. For the tropical ports, the largest marginal effect is found in time window $w = 10$ and $w = 40$, whereas in non-tropical ports this occurs in time window $w = 40$.

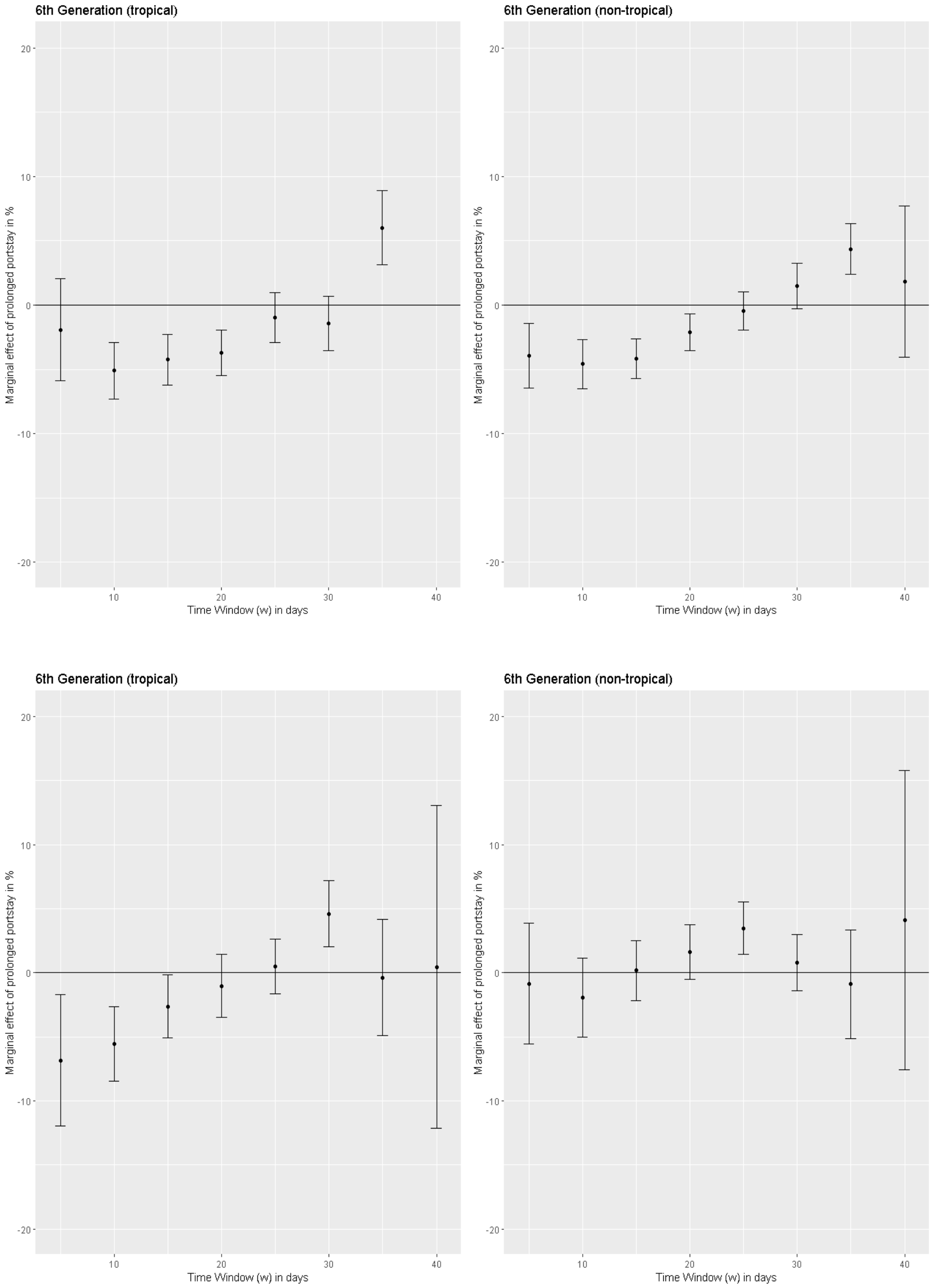

Figure 6 Estimates of fuel consumption at the discontinuity and the sensitivity to time windows for 6th generation vessels. A is when considering port stays longer than 5 days. B consider stays longer than 9 days

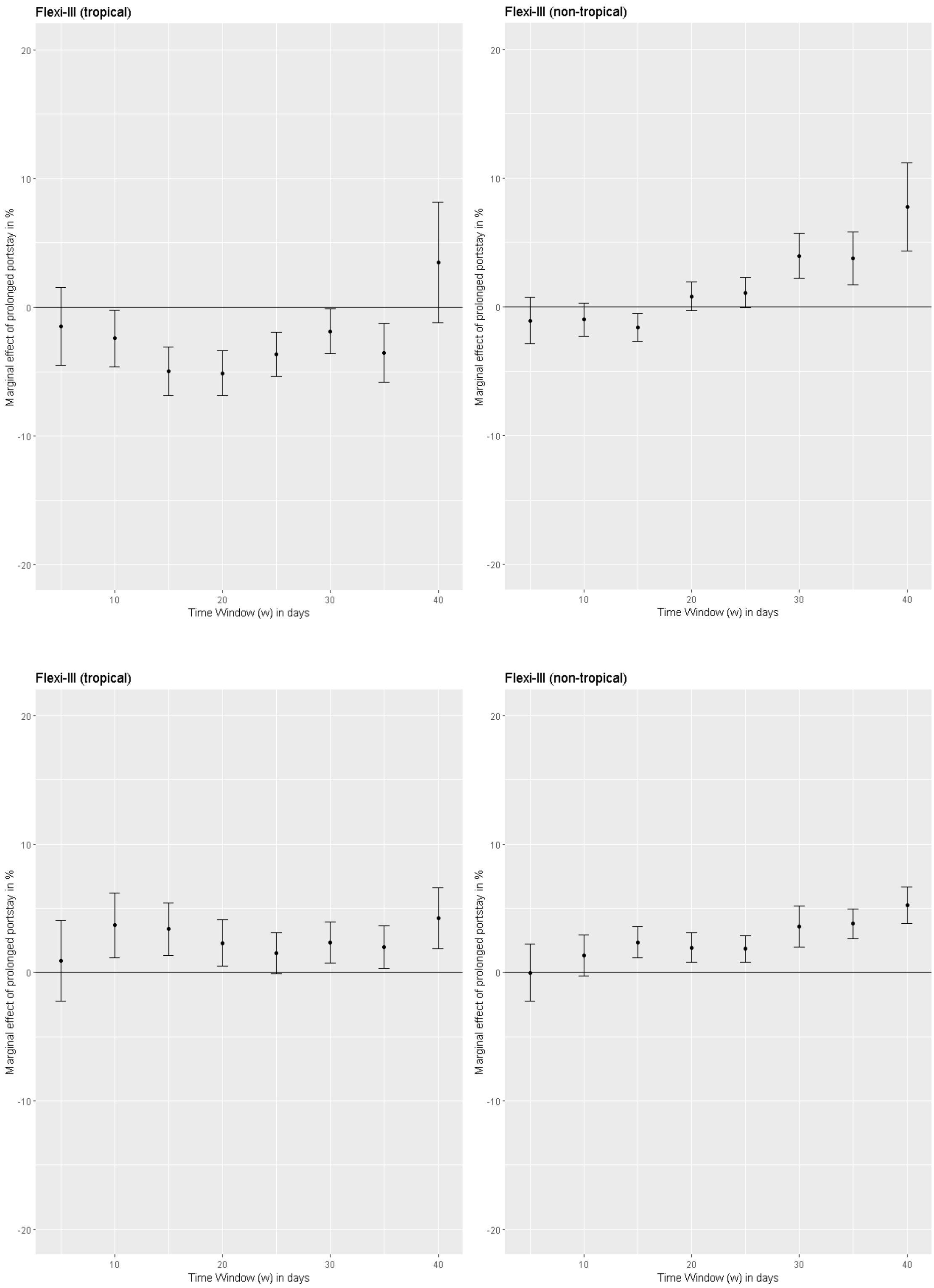

Figure 7 Estimates of fuel consumption at the discontinuity and the sensitivity to time windows for Flexi-III vessels. A is when considering port stays longer than 5 days. B consider stays longer than 9 days.

The results using difference-in-difference follows in this section. When considering prolonged port stays as idle periods exceeding 5 days, all vessels within the same class are treated approximately the same number of times and are also included in the control group. When considering port stays exceeding 9 days, the number of treatments is reduced, but remains approximately equally distributed for vessels within the same class. The exception is a vessel named Corella Arrow which does not undergo any prolonged stay in a tropical port. A visualisation of fuel consumption over time and the treatments for each vessel can be found in APPENDIX C.

The results using the difference-in-difference estimator is also divided into prolonged port stays with more than 5 days in Table 8, and more than 9 days in Table 9. Panel A in Table 8 show a statistically significant negative relationship regarding fuel consumption after prolonged stays for both ship classes when not controlling for weather factors. The result remains significant only for the 6^{th} generation class when controlling for the weather and shows a reduction in fuel consumption of 3.8%.

Column 1 and 2 in Panel B in Table 8, representing the 6^{th} Generation class, suggest a statistically significant and reducing effect on fuel consumption after the discontinuity of staying in a tropical port. Controlling for weather, the result of prolonged idle time in tropical ports lead to a reduction in fuel consumption of 5.7%. Undergoing a prolonged non-tropical stay show a significant, but less negative effect on fuel consumption, with a reduction of 2.7%. The results of Flexi-III vessel, find no significant effect of undergoing a prolonged tropical port stay, when controlling for weather. However, the effect of having undergone a non-tropical stay show a decrease in fuel consumption of 2.1% when controlling for weather factors.

When only considering the effect of port stays lasting more than 9 days in Table 9, the 6^{th} Generation class continue to indicate a reduction in fuel consumption in panel A. Now, the reduction in fuel consumption is 3.1% which is less than the result in table 8 (3.8%) when including weather factors. For the Flexi-III class the results remain insignificant.

In panel B in Table 9, the result for 6^{th} Generation vessels shows no significant effect of non-tropical port stays. However, the effect of prolonged tropical port stays remains negative (6.0%). Noteworthy is the Flexi-III vessels result in panel B. The effect of being idle for more than 9 days in tropical ports now show a significant increase in fuel consumption of 3.7%. In addition, the effect of a prolonged non-tropical port stay has no significant effect.

Table 8 Difference-in-differences estimator at the discontinuity (w=10) (idle time > 5 days)

	6th Generation		Flexi-III	
	(1)	(2)	(3)	(4)
Panel A				
Treated	0.010 (0.007)	0.010 (0.006)	-0.014 (0.008)	-0.020*** (0.007)
Prolonged	-0.006 (0.006)	-0.002 (0.006)	0.017* (0.008)	0.000 (0.007)
Prolonged x treated	-0.035*** (0.009)	-0.039*** (0.009)	-0.037*** (0.010)	-0.010 (0.009)
Weather	NO	YES	NO	YES
Number of observations	2581	2581	2652	2652
R^2	0.137	0.226	0.325	0.487
Panel B				
Treated	0.005 (0.010)	0.005 (0.009)	-0.013 (0.008)	-0.019** (0.007)
Tropical	-0.007 (0.013)	0.011 (0.013)	-0.029* (0.014)	-0.038*** (0.012)
Non-tropical	-0.018 (0.010)	-0.014 (0.010)	0.031*** (0.008)	0.013 (0.007)
Tropical x treated	-0.073*** (0.018)	-0.059*** (0.015)	0.018 (0.018)	0.013 (0.017)
Non-tropical x treated	-0.023*** (0.014)	-0.028* (0.013)	-0.055*** (0.013)	-0.022** (0.009)
Weather	NO	YES	NO	YES
Number of observations	2581	2581	2652	2652
R^2	0.187	0.260	0.329	0.490

Significance levels are 0.1% (***), 1% (**) and 5% (*).

Table 9 Difference-in-differences estimator at the discontinuity (w=10) (idle time > 9 days)

	6th Generation		Flexi-III	
	(1)	(2)	(3)	(4)
Panel A – no time trend				
Treated	0.034*** (0.008)	0.034*** (0.008)	-0.024** (0.009)	-0.027*** (0.007)
Prolonged	-0.011 (0.007)	-0.003 (0.007)	0.008 (0.008)	-0.001 (0.007)
Prolonged x treated	-0.032*** (0.011)	-0.039***(0.011)	0.011	0.017 (0.010
Weather	NO	YES	NO	YES
Number of observations	1846	1846	2652	2652
R^2	0.144	0.233	0.299	0.472
Panel B – no time trend				
Treated	0.048*** (0.012)	0.048*** (0.012)	-0.023** (0.009)	-0.026*** (0.007)
Tropical	-0.021 (0.022)	0.007 (0.023)	0.013 (0.011)	-0.014 (0.010)
Non-tropical	-0.001 (0.011)	0.004 (0.011)	0.004 (0.009)	0.005 (0.008)
Tropical x treated	-0.041 (0.027)	-0.062** (0.027)	0.035* (0.017)	0.037** (0.016)
Non-tropical x treated	-0.028 (0.019)	-0.028 (0.019)	0.003 (0.013)	0.008 (0.011)
Weather	NO	YES	NO	YES
Number of observations	1846	1846	2652	2652
R^2	0.246	0.320	0.301	0.473

Significance levels are 1% (***), 5% (**) and 10% (*).

The results from the models led to further investigation of other factors that could have influenced the results. Figure 8 show the correlation between salinity levels and temperature in ports where ships have spent more than 5 days idle in port. The correlation show that salinity levels tend to increase with increasing temperatures, with a Pearson correlation coefficient of 0.380, with a significance level of 1%.

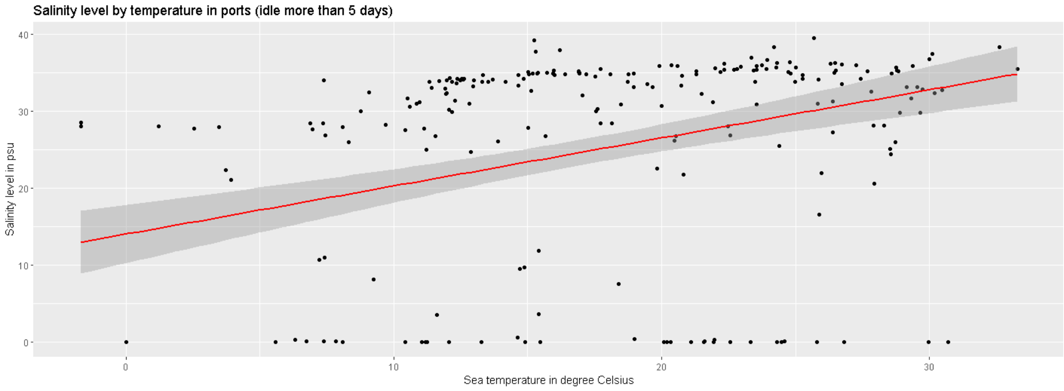

Figure 8 Correlation between salinity level and temperature in port with idle time exceeding 5 days

Salinity levels close to 0 can occur as well as temperatures surrounding 0ºC. As figure 8 shows, there are some observations with both salinity levels equal to 0psu and temperature equal to 0ºC. These observations were included in the sample because they fulfil the qualifications for estimating the effect of prolonged port stays. However, they influence the results of distinguishing between tropical and non-tropical ports because they provide no information on the port characteristics. Figure 9 show the correlation when the observations with temperature and salinity levels equal to zero are omitted. It still shows a positive correlation but with a correlation coefficient of 0.180 with a significance level of 5%. An overview of the ports with missing salinity levels and temperatures can be found in APPENDIX D.

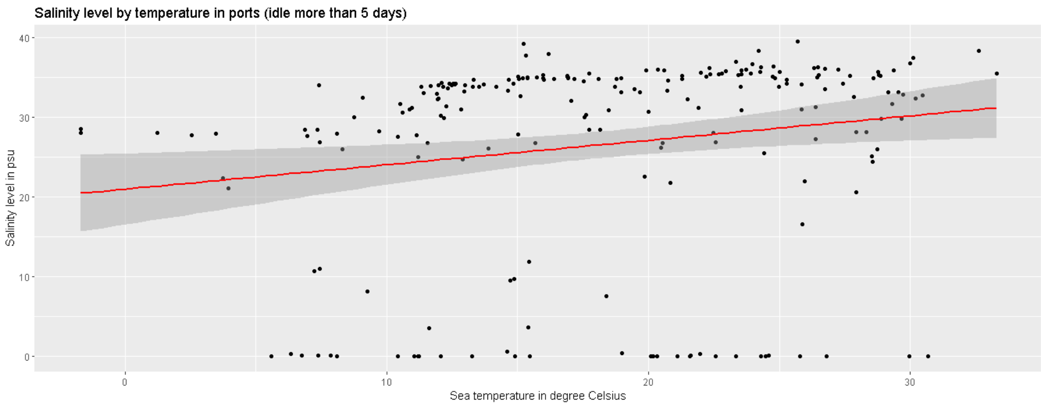

Figure 9 Correlation between salinity level and temperature in port with idle time exceeding 5 days, values with both temperature and salinity equal to 0 being omitted

6. Concluding remarks

In this thesis, we propose a data-driven framework to estimate the fuel consumption effect of prolonged port stays. The purpose of the study is to utilize noon reports, supplied with third-party data for locations and weather, to analyse if prolonged port stays, and prolonged port stays in tropical waters, has an effect on vessels fuel consumption. We explain that the main motives for fuel efficiency in shipping are related to emission reduction and fuel cost saving, and that there are multiple measures shipowners can implement to reduce the fuel consumption of their ships. In accordance with recent studies, we explain that periodical hull cleaning is one of the measures shipowners can implement to reduce fuel consumption, and that it is one of few measures shipowners to a large degree can control without external interference. Information about the effect of hull fouling due to prolonged port stays on fuel consumption can help the decision process to optimize the hull cleaning intervals. We explain that biofouling increases with temperature and salinity levels in accordance with recent studies, and therefore we also analyse the effect of prolonged tropical port stays on fuel consumption.

The main data source in this thesis comprises noon reports received from G2Ocean. We use a sample of 8 Panamax vessels, grouped in two vessel classes. The vessels operate in global trading patterns and are often present in tropical waters. By only including sister ships of the same shape, size, and age in the same samples, it enables the isolation of hull fouling (hull roughness) in the R_f factor in the total resistance equation (2) in section 3. Moreover, being able to control for air resistance and residual resistance enables the isolation of hull fouling in the total resistance in equation (1). Only including sister ships also enables the control group to converge towards the true counterfactual in the estimation using difference-in-differences.

Common for all regressions provided in this thesis is the low R^2. Considering that the variables included cover many of the factors in the fuel consumption equation (1) in section 3, the degree of explanation is expected to be higher. This can arguably be explained by the daily average speed data being provided in GPS speed over land, thus not considering the currents. In addition, the noon reports are dependent on human involvement, making them exposed to human errors. Since the noon reports are the main source of data, the data can therefore be unreliable to some extent, which can also be a part of the explanation of the low R^2 values. R^2 also differs between the two vessel classes and could have been influenced by the difference in crew filing the reports, and lastly, the different age of the two vessel classes. The two classes may also have different anti-fouling coatings.

The overall findings of prolonged port stays exceeding 5 days contradicts with the expectation of prolonged port stays resulting in increased fuel consumption. Both when looking at the first difference, and difference-in-difference estimator. Instead, the results show that prolonged port stays result in reductions in fuel consumption in the period after a port stay using time window $w = 10$. The exception is when controlling for weather in the Flexi-III class, leaving no significant result. These findings raise the question whether tropical ports might tend to be close to river outlets where salinity levels are typically lower, making hull fouling less likely. The Pearson correlation test show that the tropical ports tend to have higher salinity levels. Hence, the idea of low salinity levels being the reason for the reduction in fuel consumption is discarded. Furthermore, for the 6th Generation class, the estimated effect at the discontinuity of tropical port stays lasting 10 days or more, are similar to the ones using port stays exceeding 5 days. It showed a statistically significant reduction in fuel consumption at the discontinuity for both prolonged and for prolonged tropical stays, whereas no significant effect was found after non-tropical port stays. Even though Figure 7 shows few ports with extreme temperatures, studies show that some species decrease their growth when temperatures exceed 25^{o}C. This reduction in growth can explain some of the negative relationship we see in both the estimates at the discontinuity and the difference-in-differences estimates. Future studies should therefore investigate which species grow in different ports and their effect on hull fouling.

The results using 10 days or more in port for the Flexi-III class, suggest an increase in fuel consumption both for prolonged and prolonged tropical port stays, which is in line with the expectations. The change from a negative to a positive relationship raise questions regarding the increase in number of days spent in port. Instead of defining limits to what a prolonged port stay is, future studies could implement the change in days spent in port as a part of the model.

The Wald tests confirming no significant difference between tropical and non-tropical port stays also contradict with the expectations of tropical ports having a higher effect of increased fuel consumption. As this study only contains temperature in port at a specific day, there is no way of calculating the temperature on days with missing noon reports or AIS-data. This means the temperature in the port could have been higher or lower than the value assigned to the port during the whole idle period. There is therefore an unreliability regarding the consideration of whether a port is defined as tropical or not in the model. This should be considered in future studies.

A disadvantage with the model is not controlling for currents when daily average speed is provided in GPS speed over land rather than speed through water. This can be a possible explanation of the effect of reduced fuel consumption, since ships leaving tropical ports might tend to have currents going in the same direction as the ship. Another weakness is the construction of time windows. As viewed in Table 6 and Table 7, one would expect the panel to be balanced. The covariate of time windows is constructed in a way of not allowing a treatment to be within the time window of another treatment. However, this construction allows overlapping time windows. The overlap results in the overlapping observations only being included in the window after the first treatment $[t_{k(v)}: t_{k(v)}^{+w}]$ and excluded from the time before the following treatment $[t_{k(v)}^{-w}: t_{k+1(v)}]$. The defining of the before- and after- time windows also exceed the minimum days between prolonged ports, which allows other non-prolonged port stays to influence the effects within the time window w. Moreover, the model does not account for port stays lasting 5 days or less which occurs within the interval $[t_{k(v)}^{-w}: t_{kv}^{+w}]$.

When defining time spent in port before mid-2017 we include the prior noon reports with speeds less than 2 knots. This also includes reports with missing speed data. The chance of including noon reports with non-reliable data is therefore higher. Furthermore, because of the lack of data in both the noon reports and the AIS data, port coordinates from Marine Traffic were used to assess location of port and thereby assuming the vessels' location, making the weather data from those port stays unreliable.

The inclusion of some port stays with zero input in salinity levels and seawater temperature in the sample works only when investigating the effect of prolonged stays. However, when dividing prolonged port stays into tropical and non-tropical, these values affect the results. This is because some of these ports could be tropical but are considered non-tropical.

To conclude, we have estimated the fuel consumption effect of prolonged port stays. In addition, we have estimated the different effects of prolonged port stays in tropical ports and non-tropical ports. The results are mostly statistically significant and tend to contradict with our expectations and show an effect of reduced fuel consumption. The only exception being the Flexi-III vessels with idle periods in tropical ports exceeding 9 days. Due to the many weaknesses in our model, we will not put too much value into the results, and we suggest improving both the model and the design of covariates such as time spent in port, and time windows for more accurate results in future studies. To do so, the AIS-data retrieved should cover all days during a port stay so that weather data for the entire idle period can be included. In addition, overlapping time windows could be excluded. Despite flaws in this thesis, we suggest applying the same methodology in future studies because of the ability to isolate the causal effect of hull fouling due to prolonged port stays. As our model shows, it is easy to extend the scope of a similar study by adding the aspect of tropical and non-tropical ports. The results in an improved analysis can provide more accurate measures of prolonged port stays and its effect on fuel consumption. Moreover, such results can be used to optimize the time interval between hull cleaning procedures, which in turn can reduce fuel consumption, fuel costs, and emissions.

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Appendices

APPENDIX A

Vessel specifications	Flexi-III Class	6^{th} Generation Class
Number of vessels in class	9 vessels	4 vessels
Build period	2012-2014	2009-2011*
Overall length (LOA)	210 m	225 m
Breadth	36 m	32 m
Deadweight summer	73,000 mt	72,800 mt
Draft summer	13,8 m	14,4 m
Gross ton	46,000	44,700
Net ton	22,000	22,100
Bale capacity	87,000 cbm	85,086 cbm
Number of holds	8	8
Number of tween decks	0	0
Under deck capacity	4,073 m^2	4,324 m^2
Weather deck	4,074 m^2	4,324 m^2
Container intake	358 teu	445 teu
Australia fitted	YES	YES
IMO fitted	YES	YES
CO_2 sprinkler in holds	YES	YES
Full speed (loaded/ballast)	ABT 13.5 kn/14.2 kn	ABT 15.0 kn/15.5 kn
Eco speed (loaded/ballast)	ABT 12.2 kn/13.4 kn	ABT 13.0 kn/13.3 kn
Super eco speed (loaded/ballast)	ABT 11.8 kn/12.8 kn	-
Number of gantry cranes	0	2
Number of jib cranes	4	0
Safe working load (SWL)	45 mt	70 mt

Source: g2ocean.com *The vessel year of build listed on https://www.g2ocean.com/project/6th-generation-class/ differs from the fleet list in G2Oceans annual report 2021. Hence, annual report figures are used in the thesis text.

APPENDIX B

Port characteristics of port stays exceeding 9 days

Variable	6^{th} Generation			
	Mean	Std. dev.	Min	Max
Port temperature in °C	16.011	9.809	-1.680	32.610
Port salinity in ppt	20.965	15.211	0.000	38.340
Number of prolonged stays	36			
Number of prolonged tropical stays	6			

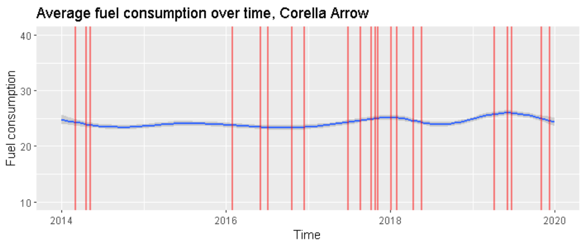
Variable	Flexi-III			
	Mean	Std. dev.	Min	Max
Port temperature in °C	19.480	7.753	0.000	33.290
Port salinity in ppt	28.560	11.569	0.000	38.280
Number of prolonged stays	74			
Number of prolonged tropical stays	20			

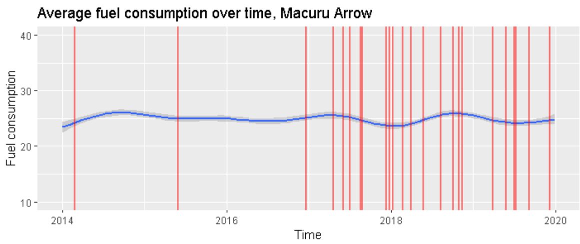
APPENDIX C

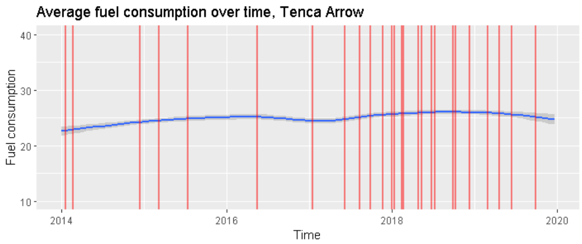
Fuel consumption over time per vessel, with prolonged and prolonged tropical port stays (page 1/4)

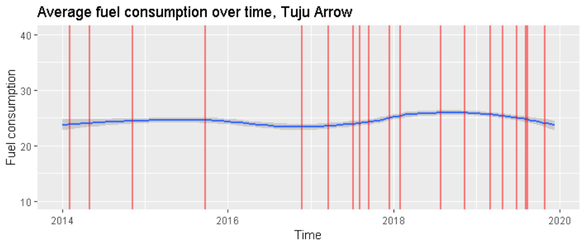
Prolonged port stays exceeding <u>5 days</u>:

6th Generation:

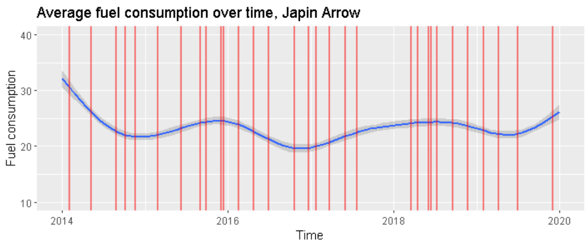


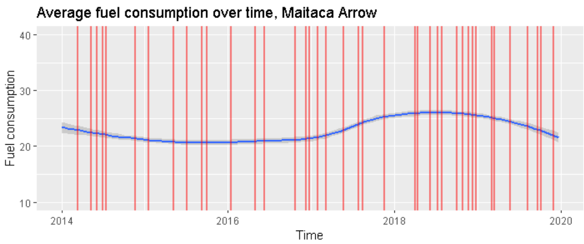


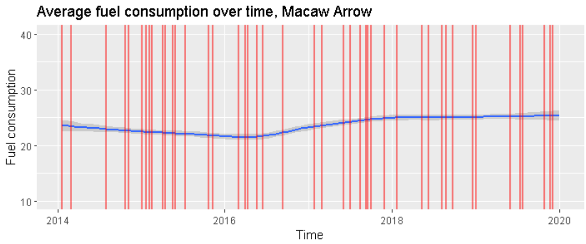


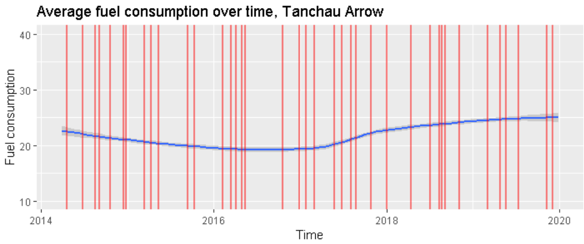


Flexi-III:







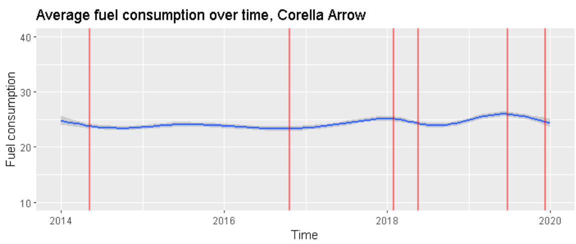


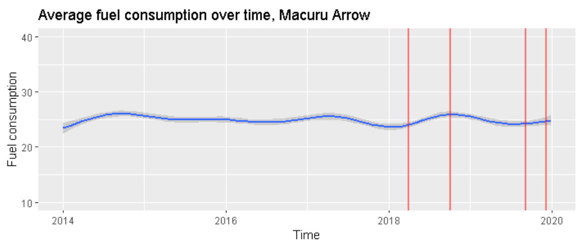
APPENDIC C

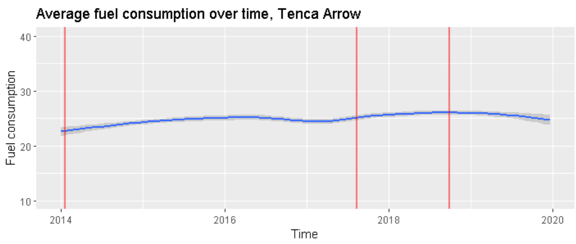
Fuel consumption over time per vessel, with prolonged and prolonged tropical stays (page 2/4)

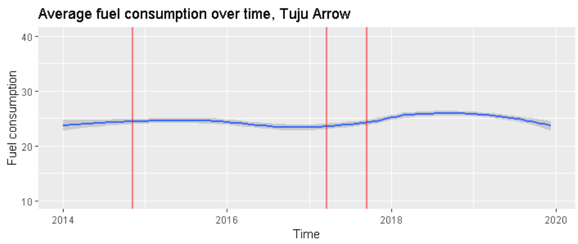
Prolonged *tropical* port stays exceeding <u>5 days</u>:

6th Generation:

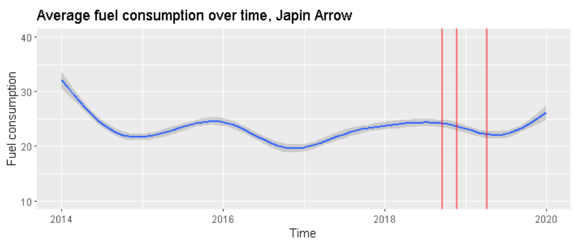


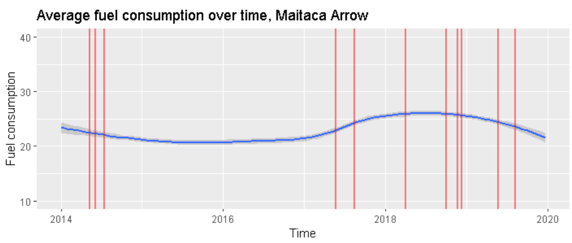


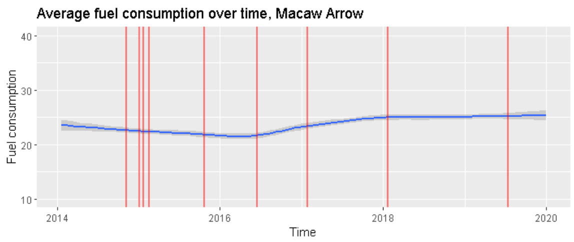


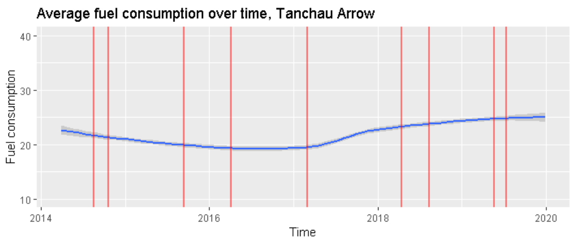


Flexi-III:







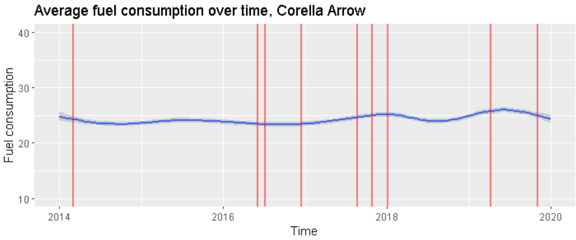


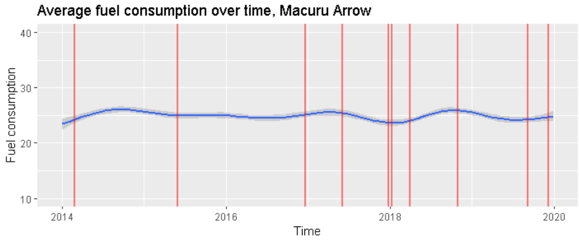
APPENDIX C

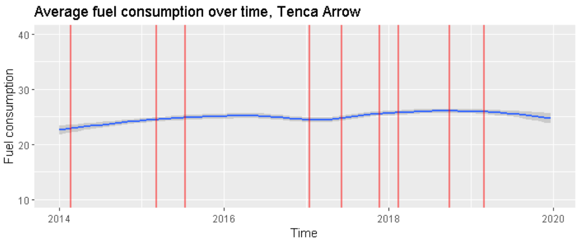
Fuel consumption over time per vessel, with prolonged and prolonged tropical stays (page 3/4)

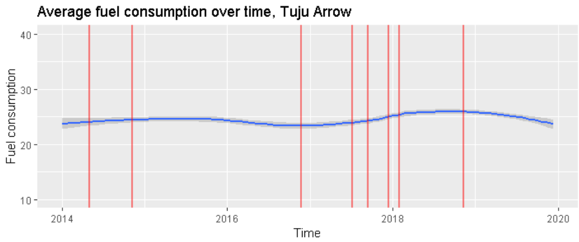
Prolonged port stays exceeding <u>9 days</u>:

6th Generation:

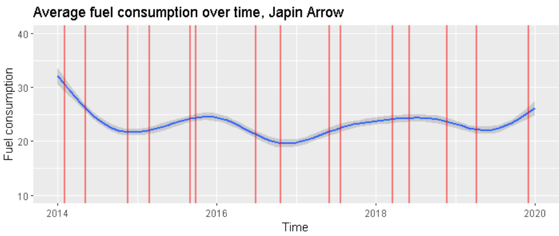


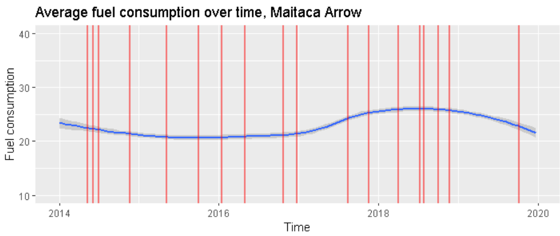


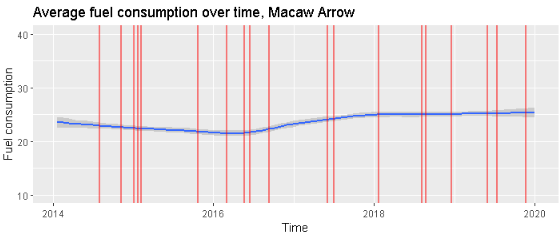


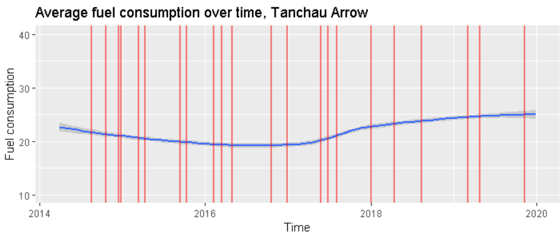


Flexi-III:







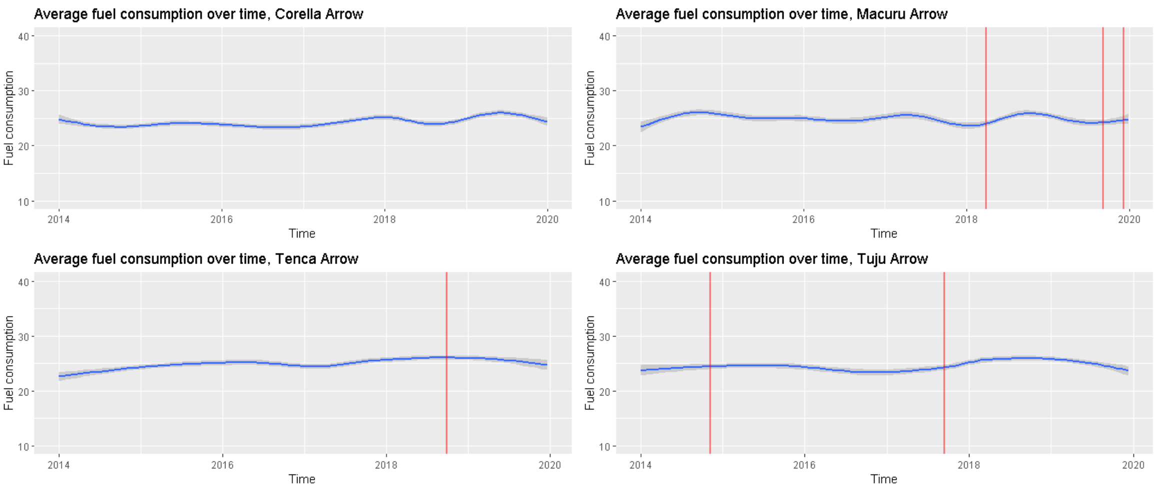


APPENDIC C

Fuel consumption over time per vessel, with prolonged and prolonged tropical stays (page 4/4)

Prolonged *tropical* port stays exceeding <u>9 days:</u>

6th Generation:



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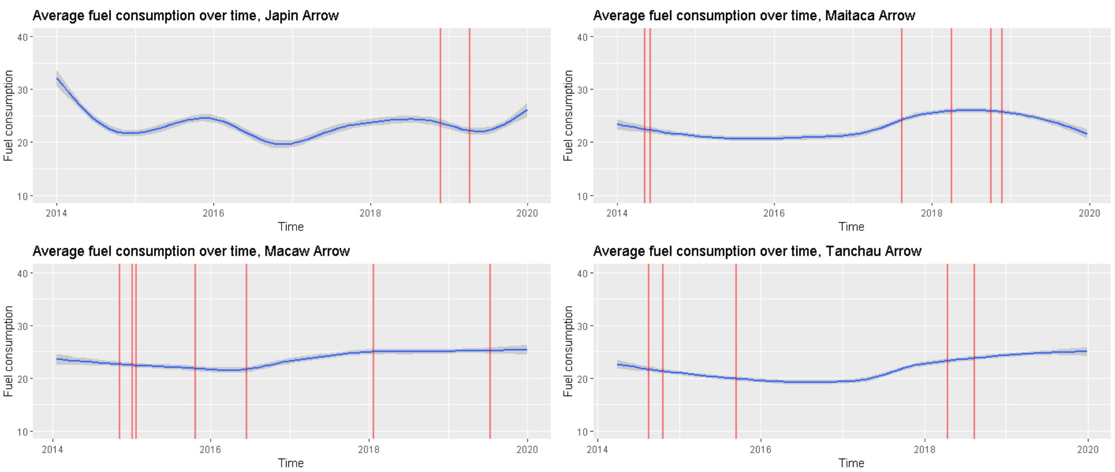


APPENDIX D

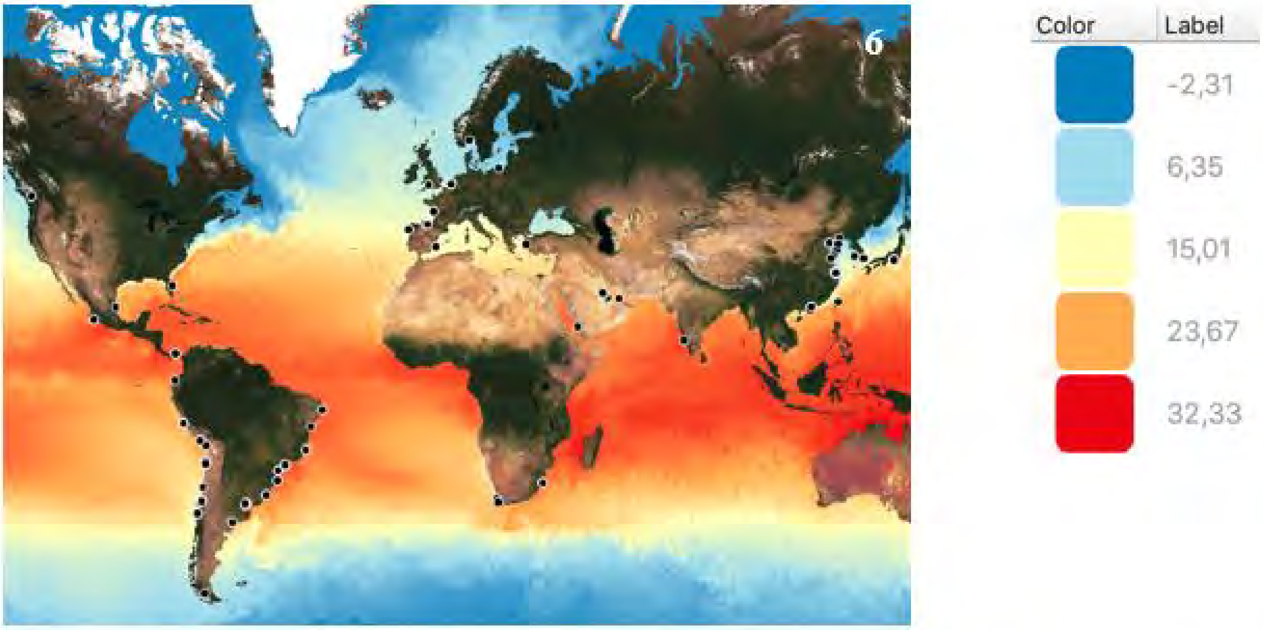
Vessel positions in ports with missing weather data (page 1 /4)

The above picture (1) shows vessel positions in ports (black circles) from our dataset with missing weather data. 216 in total.

The above pictures (2-5) show zoomed versions of picture 1. These are examples of why weather data (seawater temperature and salinity level) is missing: the vessel's position appears to be on land or at an unrealistic position outside the grid, due to a source of error. The examples are from Doha (2), a sailboat/yacht marina in Vigo, Spain (3), Rizhao (4), and Buenos Aires (5).

APPENDIX D

Vessel positions with missing weather data (2/4) – examples with with weather data layers

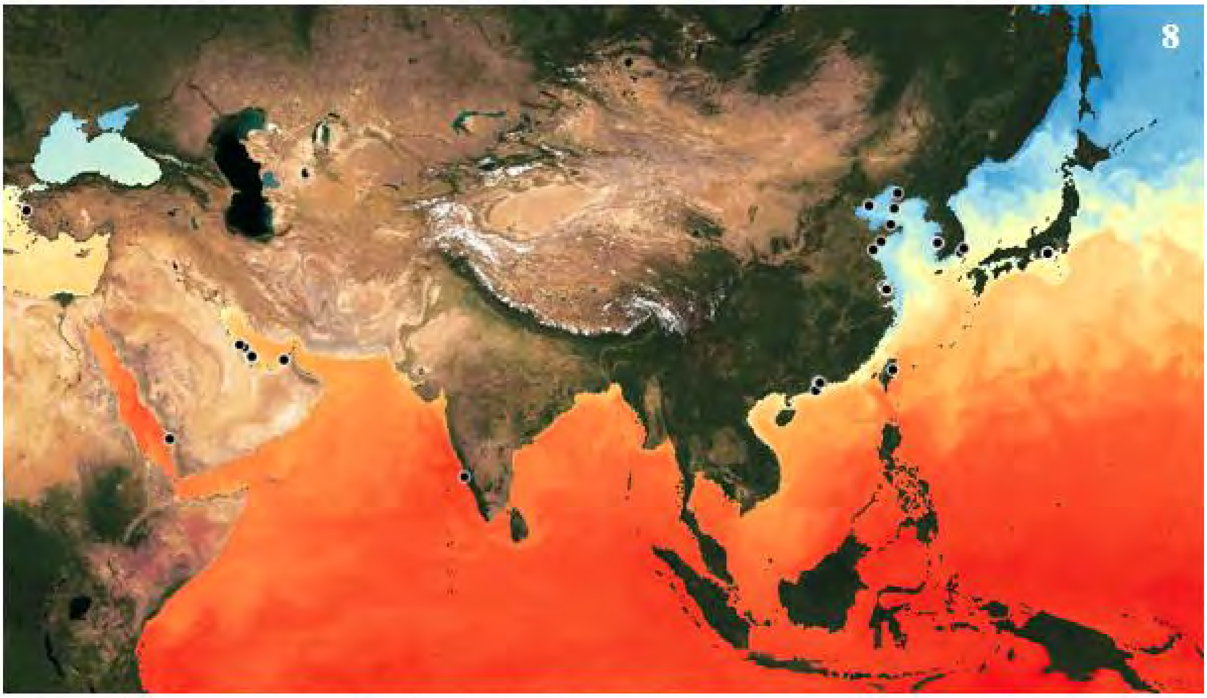


The above picture (6) shows the same world map and vessel positions as picture 1, with an added layer of seawater temperature data (layer "*thetao*" from the netCDF-file of product "*cmems_mod_glo_phy_my_0.083_P1D-m*" from Copernicus Marine Service (2022). In this example, the extracted data represents the daily mean temperatures in the time frame 1st to 2nd of January 2014. The "label" column in the legend to the right represents the colour scale in degrees Celsius at a surface debt 0.5 meters. This picture visualizes the temperature data omitted from the analysis, which if included could have impacted the results.

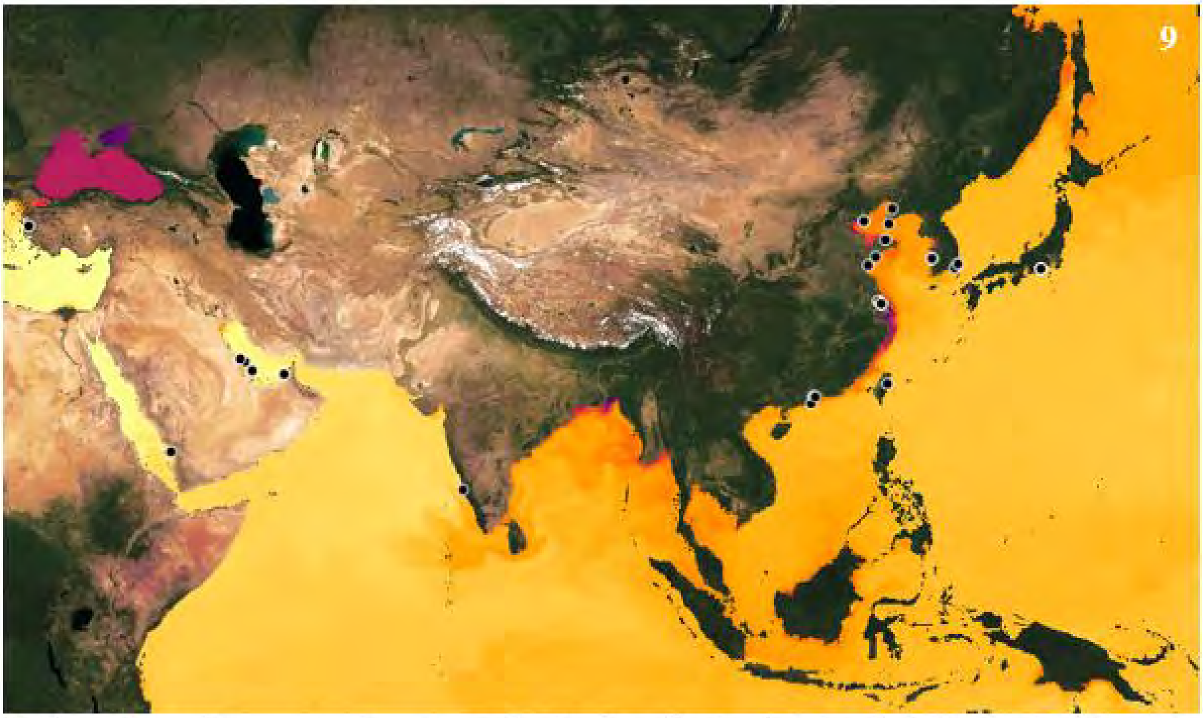
The above picture (7) shows the same world map and vessel positions as picture 1, with an added layer of seawater salinity data (layer "*so*" from the netCDF-file of product "*cmems_mod_glo_phy_my_0.083_P1D-m*" from Copernicus Marine Service (2022). In this example, the extracted data represents the daily mean salinity in the time frame 1st to 2nd of January 2014. The "label" column in the legend to the right represents the colour scale in units 1e3 at a surface debt 0.5 meters. This picture visualizes the salinity data omitted from the analysis, which if included could have impacted the result.

APPENDIX D

Vessel positions in ports with missing weather data (3/4) – Examples from Far East

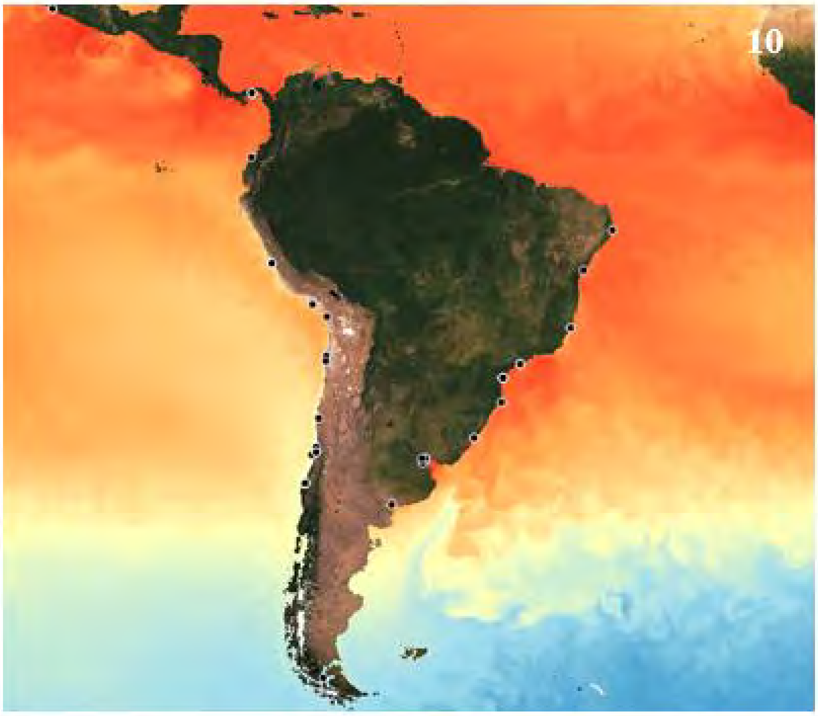


The above picture (8) shows a zoomed version of picture 6 to better display temperature data for the Far East from the example netCDF-file covering the first day of January 2014. The legend from picture 6 is applicable.

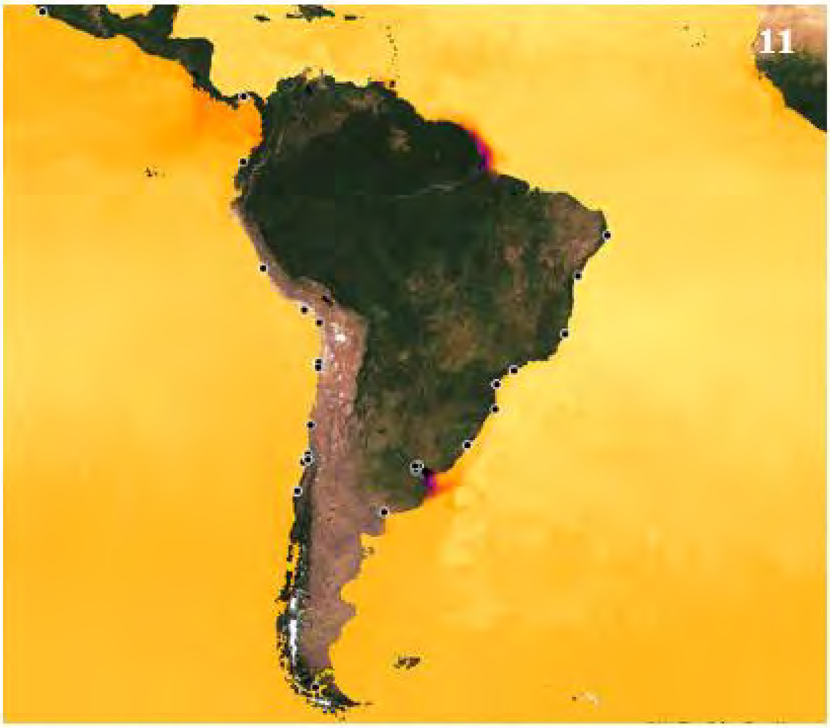


The above picture (9) shows a zoomed version of picture 7 to better display salinity data for the Far East from the example netCDF-file covering the first day of January 2014. The legend from picture 7 is applicable.

APPENDIX D
Vessel positions with missing weather data (4/4) – Examples from South America



The above picture (10) shows a zoomed version of picture 6 to better display temperature data for South America from the example netCDF-file covering the first day of January 2014. The legend from picture 6 is applicable.



The above picture (11) shows a zoomed version of picture 7 to better display salinity data for South America from the example netCDF-file covering the first day of January 2014. The legend from picture 7 is applicable.