NTNU – Trondheim
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Weather Routing of Supply Vessels in the North Sea

Solving the Supply Vessel Weather Routing Problem

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MASTER THESIS IN MARINE CYBERNETICS

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FOR

STUD. TECH. Joakim Kjølleberg

Weather Routing for Offshore Vessels in the North Sea

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Background

As marine operations increases in numbers and complexity in harsher environments, smarter tools for planning and execution are sought. There has been done a lot of research on the topic of deep-sea voyage planning, and several commercial software suites for weather routing exist. These are generally aimed at voyages and not operations or short transits. A few papers exists on the topic of short sea routing.

Work description

This master thesis will try to address frontiers where improvements are still obtainable. Improvements concerning weather optimal routing is sought. The thesis should propose a generic vessel resistance model, based on known parameters and vessel data. A medium-term planner will find an optimal route based on waypoints, the vessel model, charts, weather information, etc.

The aim will be to solve the supply vessel weather routing problem, in order to find the cost optimal route for a supply vessel servicing offshore installations.

Scope of work

- Review relevant literature and current software and clients for voyage planning. Briefly review planner-applications for other means of transportation (e.g. sail yachts).
- Define requirements and functionality for an operation planner.
- Develop a MATLAB based voyage planner (proof of concept). The program is to be made up by designated modules for vessel resistance modelling and weather forecasts extraction.
- Assess and discuss the results and the potential and future of a voyage planner.

Modus operandi

The report shall be written in English and edited as a research report, including literature survey, description of mathematical models, description of optimisation algorithms, test results, discussion and a conclusion including recommendations for further work. Source code will be made available online. It is supposed that Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work. The thesis is to be submitted digitally within June 10th.

Co-supervisors:	Ivar Ihle	(Rolls-Royce Marine)
	Vahid Hassani	(MARINTEK)

Professor Asgeir J. Sørensen
Supervisor

Preface

When I once sailed the English Channel, I noticed the large container vessels would pass by in an orderly manner - aligned to the turns of the tide. They would 'hit' the peak tidal currents time and time again, boosted toward their destinations. The concept of merchant vessel routing was introduced and it sparked curiosity for the field. The same sail trip lasted a year, and the number of weather forecasts studied and analysed during that year was countless. For the record, we were never hit by anything exceeding gale-force winds.

This is the final thesis for my Master's degree at Norwegian University of Science and Technology, Department of Marine Technology. This work is done in cooperation with Rolls-Royce Marine. The thesis is the result of the efforts lain down during the spring of 2015. It is to be noted that the project thesis - the pre-project, handled a completely different topic. This work is written only by the author, but would have been even harder without the help of the following:

First off, I'd like to thank Ivar Ihle for initially pitching the idea of weather routing, and then for answering all the questions I'd might have (and often answering e-mails within 10 minutes!) I'd like to thank Eirik Bøckmann for invaluable input on vessel modelling, for general guidance and brain storming. I am thankful to Vahid Hassani, for his help towards expressing the problem and how to solve it. Last out I'd like to thank Asgeir Sørensen, for his insight and passion for the bigger picture.

Joakim Kjølleberg

Joakim Kjølleberg

Trondheim, June 10, 2015

Abstract

This thesis is concerned with defining and solving the supply vessel weather routing problem. The particular problem in focus will be Statoil's supply circuit in the middle North Sea, including the Johan Sverdrup oil field. The thesis considers a single platform supply vessel doing a single trip to supply a given number of platforms. The goal is to find the cost optimal route. The approach will use standard weather forecasts and ship resistance models to calculate the cost for each candidate route.

The supplying of offshore installations are done with platform supply vessels. Today, these PSVs follow a weekly schedule in order to supply the installations and do not automatically account for severe weather. This can cause unwanted delays, extra vessel days, and in worst case installations shutting down production due to lack of supplies.

The main objective of this master thesis is to explore the topic of weather routing for supply vessels. The approach is to develop and document a 'proof-of-concept' MATLAB program, attempting to solve the supply vessel weather routing problem.

The core part of the program is the *cost function*, which can be tow energy, brake energy, fuel consumption, CO2-emissions or operational costs for the supply vessel. This function is subject to be minimised in order to find the cost optimal route. Some restrictions apply: Crane operations on rigs are subject to wave height limitations, typically 4 meters. Cranes stop due to severe weather and nightly close-downs (of crane operations) introduce *dynamic time windows*.

The only routing done is changing the order in which the installations are visited, and each unique sequence is a *candidate route*. Every installation is to be visited once, each for a specified duration of time - a *service time*. The fleet size and mix vessel routing problem is assumed to be solved, so that a single vessel, single voyage needs to be optimised. It is assumed that the total demand does not exceed the vessel capacity, and that the supply allocation problem is solved. The speed between installations is governed by a *reduced speed* algorithm or a *constant speed* algorithm. The speed is reduced due to environmental loads, by keeping the propulsion power constant.

The results deem weather routing to be possible and feasible. For small waves (less than three meter significant wave height) the typical savings are <5%, which is not significant due to model- and forecast uncertainties. For borderline weather and complex time windows, savings has been observed in the 20%-range - by just changing the order of visiting installation.

The field of short sea weather routing is ripe for more research. Routing of wellboats and windmill service vessels, and life cycle simulations of supply vessels for future designs are other applications available through the presented program.

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Nomenclature

DP **D**ynamic **P**ositioning

DSS **D**ecision **S**upport **S**ystem

ECDIS **E**lectronic **C**harts **D**isplay and **I**nformation **S**ystem

ECMWF The **E**uropean **C**entre for **M**edium-range **W**eather **F**orecasts

FSMVRP **F**leet **S**ize and **M**ix **V**ehicle **R**outing **P**roblem

GFS **G**lobal **F**orecast **S**ystem

GRIB **GRI**dded **B**inary

MIPP **M**ixed **I**nteger **P**rogramming **P**roblem

NCEP **N**ational **C**enters for **E**nvironmental **P**rediction

NCS **N**orwegian **C**ontinental **S**helf

PSV **P**latform **S**upply **V**essel

SFC **S**pecific **F**uel **C**onsumption

SVWRP **S**upply **V**essel **W**eather **R**outing **P**roblem

TSP **T**ravelling **S**alesman **P**roblem

TSPTW **T**ravelling **S**alesman **P**roblem with **T**ime **W**indows

VRP **V**ehicle **R**outing **P**roblem

VRPTW **V**ehicle **R**outing **P**roblem with **T**ime **W**indows

VRPPD **V**ehicle **R**outing **P**roblem with **P**ick-up and **D**elivery

VTMIS **V**essel **T**raffic **M**onitoring and **I**nformation **S**ystem

WOW **W**aiting **O**n **W**eather

Note: Variables are described where they appear.

1: Introduction

Since the 1960's, the North Sea has been the epicentre of Norwegian oil extraction. The era is predicted to last for another lifetime, with an increasing complexity to exploit the oil reserves. The common denominator of all Norwegian oil exploration is that it is located offshore at the Norwegian Continental Shelf shown in Figure 1.1. In order to ensure safe and continuous production, the installations need supplies from onshore bases.

Figure 1.1: The Norwegian Continental Shelf. Illustration courtesy of The Norwegian Petrolium Directorate

The offshore industry can be divided into two main areas, with respect to logistics: Upstream and downstream. The downstream segment is to get the oil and gas from the well to the end-user. The upstream segment is the process to get to the bottom of the well, and keep the oil streaming. Within the upstream segment, one of the major costs is the operation of supply vessels. These have traditionally been operated with little concern of optimal operation - as long as they kept the uptime of the installations high. Because the main focus of the operators has been the oil, the topic of optimal supplying has been more or less neglected. In times of cutting costs, expenses further down on the list are brought under the spotlight.

The workhorses of the Norwegian oil era are the Platform Supply Vessels (PSV). They are typically rugged and advanced vessels, tailor made for goods deliveries to offshore installations. PSV's are often equipped with dynamic positioning systems (DP), fire fighting (FiFi) and oil recovery (OilRec) equipment and are practically multi-purpose vessels. Oil companies charter these vessel to serve their offshore installations.

The field operators charter vessels on long term contracts, and plan supply routes for weeks at a time, in order to meet requested demands. Fluctuations in the demand is met by chartering vessel on short term contracts, from the spot marked for PSVs. Some research is done in order to achieve optimal fleet sizing and vessel routing, and this work is used by the operators (i.e. Fagerholt and Lindstad (2000)). These papers solves the Vehicle Routing Problem (VRP) for a vessel or multiple vessels (see Table 1.1) in order to create weekly schedules.

Overall, the Marine Transport Planning Problem has seen relatively little attention in literature and Christiansen et al. (2007) have highlighted a few reasons why the marine sector has relatively little research:

Less Visible - Ships are rarely seen in operations, and thus easily forgotten.

Less Structure - The planning problems faced by ship owners are highly variable, where the schedules are subject to frequent changes. The shipping business has less structure than i.e. airliners and railways.

More Uncertainty - The weather impact on ships is an uncertainty hard to include in models.

More Fragmentation - With a long history, strong traditions and many players, the ways of operations are hard to change to the more optimal ways.

The supply vessel planning procedures currently in use are long term optimisations, planning weekly schedules, and deal with discrepancies as they appear. The current methods of handling weather are based on experience and 'manual' decisions. Planning tools such as the one presented in Halvorsen-Weare et al. (2012) introduce slack in the time schedule in order to make room for slow-downs caused by weather.

Borderline weather, where wave heights are in the vicinity of the allowed boundaries, is identified as a big challenge to the current system. This state is where weather routing is believed to be the most applicable.

The problem addressed in this master thesis is trying to overcome one of the shortcomings in the optimisation of supply vessel routing. Several papers focus on the fleet management and routing of supply vessels. However, little or no research has explored the direct effects of weather in this context. Finding the optimal route with regards to real-time forecasts has not yet been done (atleast not described in academic papers known to the author). The weather impact on the vessel schedules can be severe. Due to the nature of the North Sea weather, the structure of the upstream operations is robust. But is it optimal?

This thesis will attack the routing problem in a new, 'low-level' approach termed *the supply vessel weather routing problem* (SVWRP). The idea is to evaluate every valid route, and calculate the cost function associated with the path travelled. The possible synergy effect of this approach, coupled with that of a more high-level fleet mix and planning solver, could render a more robust solution to the overall supply problem, being more certain the closer the events are in time. The strength of this approach is the ablility to analyse the feasibility of a route schedule and prove the best way to solve the route, given the forecasted weather situation. This approach can easily accommodate more complex cost computation algorithms, and could ultimately feature a complete router. Figure 1.2 is a graphical representation of the program, visualising the different stages of the process.

1.1 Objective

The aim of this thesis is primarily to develop a 'proof-of-concept' software suite, and do a literature study exploring the possibilities within the field of weather routing for supply vessels and short sea shipping. A lot of research has been done within deep-sea routing from A to B, and fleet- and fleet optimisation has been the topic of quite a few papers (Christiansen et al., 2004). But to the author's knowledge, there is limited research done on deterministic weather routing for PSVs or other types of short sea shipping.

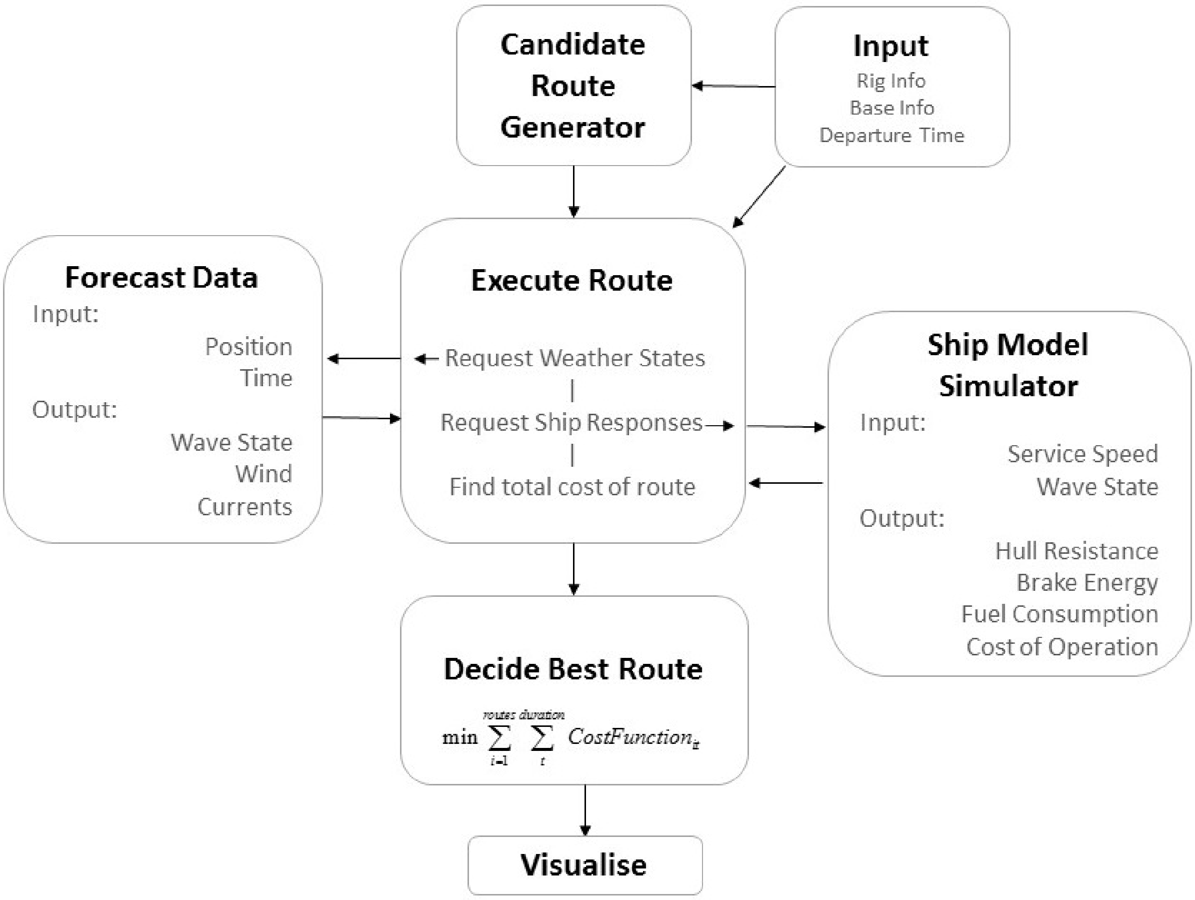


Figure 1.2: Program Build-up Illustration

The advances of IT is rapidly affecting all fields of industry and transportation as well as the many other aspects of life, and according to DNVGL's Bjørn K. Haugland, IT will be the main technology driver for the future maritime sector (Haugland, 2015). Weather forecasts are becoming more accurate and more accessible, and they are a vital part of the digital infrastructure. Better forecasts can predict the weather effect on voyages and marine operations to foretell unsafe conditions and ultimately save money on optimised marine operations.

The objective is to calculate candidate routes by using forecast (or hindcast) data and ship resistance models to predict the cost optimal route under given conditions and constraints (see Figure 1.2). The information can be used in on-board Decision Support Systems (DSS) and at the operation centrals managing the vessels.

The candidate routes are calculated and evaluated as Travelling Salesman Problems (TSP), which are considered sub-problems of the VRP. The TSP pursues the optimal route in which to visit a number of cities with the minimum travelling distance (minimum cost). In this case cost between each installation is dependant on the distance, speed and the weather condition.

1.2 Limitations

The thesis and the program is subject to the following limitations:

- The method does not properly model DP.
- The method is limited to the operation of a single trip for one vessel.
- The vessel model is limited to the quality of its inputs.
- The program does not distinguish between land and sea.

1.3 Previous Work

This section will introduce the reader to existing literature relevant to this thesis. Section 1.3.1 is the main topic, describing literature regarding supply vessel routing and scheduling, as well as a comparison of methods. Due to the fact that the outcome of this thesis can be used as decision support, section 1.3.2 will briefly describe some literature on DSS.

1.3.1 Supply Vessel Routing

The governing problem to be addressed, is a part of the upstream logistics problem; to provide the installations with the needed goods at the right time to the lowest price. The work of Aas et al. (2009) addresses the critical role of the PSV in upstream logistics, and states that this field has not been subject to much research. In terms of possible improvements, failing to deliver due to bad weather is concluded to be one of the biggest bottleneck for the logistics problem.

Recent research presented in this section, and the papers summarised in Table 1.1 all attack the routing problem in different ways. The categories are explained in the successive subsections.

Supply Vessels	*Weather Dependent*	*Level of Operation*	*Number of Vessels*	*Optimisation Problem*	*Short Sea*	*Time Dependency*	*Load Dependent*
This thesis	Yes	Low	Single	TSPTW	Yes	Yes	No
Halvorsen-Weare et al. (2012)	Slack	High	Multiple	VRPTW	Yes	Yes	No
Aas et al. (2007)	No	High	Single	VRPPD	Yes	No	Yes
Gribkovskaia et al. (2008)	No	High	Single	VRPPD	Yes	No	Yes
Fagerholt and Lindstad (2000)	Slack	High	Multiple	VRPTW	Yes	Yes	No
Other Types of Vessels							
Overdal and Tveit (2013)	N/A	High	Multiple	VRPTW	Yes	Yes	Yes

Table 1.1: Literature Review on Supply Vessel Routing (abbreviations: TSP = Travelling Salesman Problem, VRP = Vehicle Routing Problem, TW = with Time Windows, PD = with Pickup and Delivery, N/A = Not Applicable)

Weather Dependence

As it is observed in Aas et al. (2009) and Halvorsen-Weare (2012), weather conditions play a crucial role in the punctuality of offshore supply services. Especially in the prevailing conditions during winter season of the North Sea. In Halvorsen-Weare et al. (2012) the sailing speed is set, and different fuel consumption rates are given for transit and station keeping. In this paper, along with Fagerholt and Lindstad (2000), robust schedules are introduced by assigning slack for each trip, which means that the schedule has a minimum number of hours between ending one trip, and starting a new. None of the other papers explicitly address the uncertainty of the weather in their models.

Level of Operation

The level of operation reflects how the algorithm attacks the vessel routing problem. Much of the available research within vessel routing is what this thesis characterises as high-level. The high-level approaches consider the fleet's, or the individual vessel's main strategy – the governing time schedule in order to sufficiently service the installations. A low-level approach aims to optimise an individual trip, based on more detailed information retrieved closer to departure. Basically a high-level solver solves a version of the VRP, where as the low-level solves a version of the TSP. A low-level approach is probably most useful coupled with a high-level model. All of the papers reviewed are high-level approaches to their respective vessel routing problems; I.e. Fagerholt and Lindstad (2000) consider a planning horizon of one week for a demand scenario in order to service a geographical area with installations. The algorithm finds the optimal fleet and vessel routes for the given scenario. Aas et al. (2007) address one vessel that serves ten installations, in several trips, with a schedule updated weekly.

Optimisation Problem

Gribkovskaia et al. (2008) uses *single vehicle routing problem with deliveries and selective pickups* (SVRPDSP) where the delivery and pickup can be done in two separate visits for one or two installations. This modelled heuristics is proved to be more advantageous than a Hamiltonian cycle (one stop per installation). Aas et al. (2007) is a VRPPD where they introduce limited free storage, meaning that the sum of delivery and pick-up goods cannot exceed the total free storage space on the vessel and installation combined. In order to simplify the problem it is expressed as a mixed integer programming problem (MIPP). Fagerholt and Lindstad (2000) initially solves the fleet size and mix vehicle routing problem (FSMVRP) modelled as an integer programming model. The individual vessel trips are then optimised by means of a TSP. Due to the small size of the TSP, it is implemented as a exhaustive search, evaluating every possibility. Also Halvorsen-Weare et al. (2012) consider a FSMVRP to service a number of installations on a weekly schedule. When the candidate voyages (that fulfil the constraints) are generated, the TSP with multiple time windows is utilised to find the cost optimal voyage plan.

Number of Vessels

Fagerholt and Lindstad (2000) and Halvorsen-Weare et al. (2012) consider the fleet size and mix vehicle routing problem. Overdal and Tveit (2013) consider a fleet of small tankers to accommodate the fuel demand of ships in a harbor area. They do a version of the FSMVRP where the allocation of different goods is considered. Aas et al. (2007) and Gribkovskaia et al. (2008) simplify their models to optimise the route for a single vessel.

Short Sea

All the papers considered here deal with short sea shipping. The key point is that transit times are relatively small compared to loading time and transit between installations. Deep-sea shipping is the crossing of oceans, from continent to continent, where the path between the waypoints are of importance. In short sea shipping, transits have a smaller effect on the overall cost, and thus the sequence of stops is an increasingly important factor.

Time Dependency

Opening hours of the customer is regarded as time dependency. Fagerholt and Lindstad (2000) concludes that a scheme with rigs open around the clock is the most cost effective for vessels – after simulating multiple time windows. Also Halvorsen-Weare et al. (2012) models multiple time windows in the TSP part of the solver.

Load Dependency

Load dependency is whether or not the computer model allocates supplies and capacity. A version of the capacitated vehicle routing problem (CVRP) is solved in Gribkovskaia et al. (2008). In Aas et al. (2007) a sufficient free space constraint is introduced to model the limited deck space on rig and vessel. Fagerholt and Lindstad (2000) models a frequency of visits that will take care of 150% of the average demand, but does not include supply capacity in the model.

1.3.2 Decision Support Systems

The topic of decision support is increasingly relevant with the swift technological advances we see today. Two areas of commercial DSS are considered:

- **Short-term support:** Predicts current-, and near-future events (from seconds to a few hours). Assesses the current sea state in order to predict hazards and critical situations in due time to start countermeasures. On-board advisory systems like ABB's OCTOPUS and AWT's Enroute Live predicts the chance of slamming, damage on cargo etc. based on estimations and forecasts of the current sea state. (Nielsen and Jensen, 2011)
- **Medium-term support:** Proposes optimised routes for the next 8-15 days. Based on relevant information like weather data, ice coverage and ship data. Commercial deep

sea routing suites like AWT's BonVoyage and Jeppesen's VVOS are compared in Walther et al. (2014). Some resent research include: Avgouleas (2008); Hinnenthal (2007); Shao et al. (2012)

Within yacht sailing, user friendly and intuitive 'apps' are becoming popular. A great example is the 'Weather4D Pro', using GRIB-files for weather forecasts and computes routing with the isochrome method seen in Figure 1.3 (the blue lines are the isochromes). The point is that an intuitive user interface increases the chance of the product being used frequently. This is by no means an exception for a commercial product.

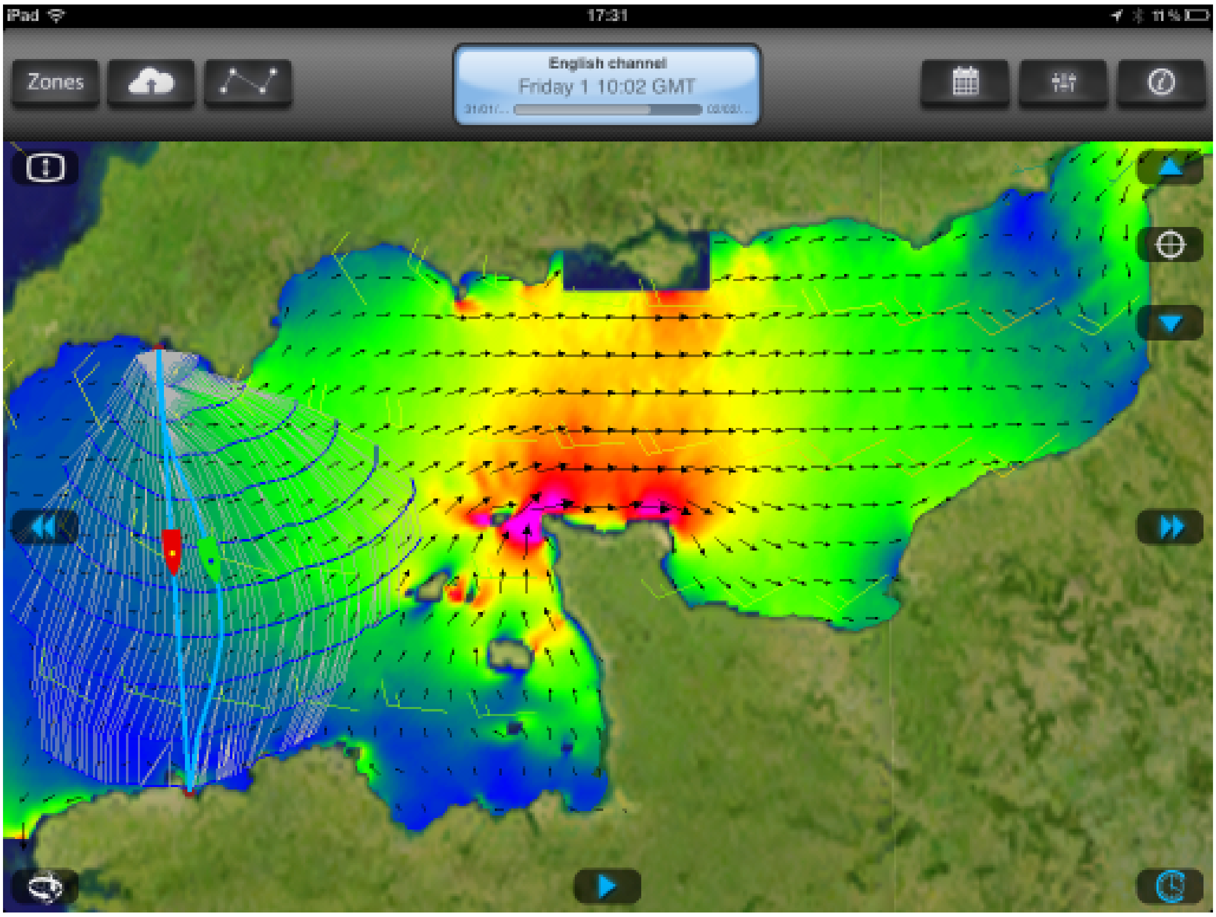
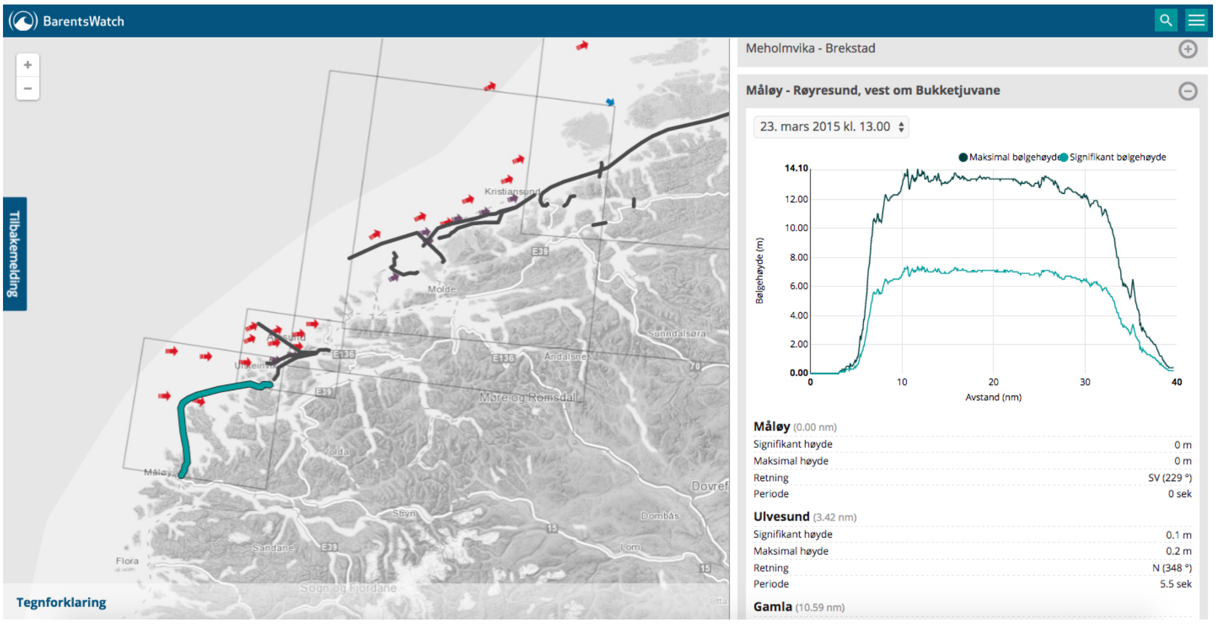


Figure 1.3: Weather4D - Passage Router. By courtesy of Bouyssou (2015)

Some DSS are basically a refined forecast. The newly released "Wave forecast for fairways in Norway" (Figure 1.4) is a brilliant example of utilising weather forecasts to display useful information for decision support. The forecast displays popular fairways along the coast of Norway and displays intuitive information about the wave height along each point of interest.



Måløy (0.00 nm)

Signifikant høyde	0 m
Maksimal høyde	0 m
Retning	SV (229 °)
Periode	0 sek

Ulvesund (3.42 nm)

Signifikant høyde	0.1 m
Maksimal høyde	0.2 m
Retning	N (348 °)
Periode	5.5 sek

Gamla (10.59 nm)

Figure 1.4: Forecast Refinement: Wave forecast by BarentsWatch. By courtesy of (BarentsWatch, 2015)

1.4 Contributions

The primary contribution from this work is the framework in which to solve the supply vessel weather routing problem. The program can simulate arbitrary supply routes for any vessel with any forecast of choice. This work is hoped to serve as an inspiration towards the possibilities of weather routing for short sea shipping:

Chapter 2 defines the supply vessel weather routing problem. This issue has not been regarded in any academic work known to the author.

Chapter 4 describes how the problem is implemented in a MATLAB program.

Chapter 5 will reveal the tools of the trade in which vessel routing can be computed. The performance of the 'reduced speed'-method is studied.

Chapter 6 studies routing for nightly closed installations. Ensemble forecasts' impact on routing is explored. The alternative 'constant speed' is evaluated. Thoughts on the MasterPlanner is presented to encourage further studies.

Chapter 7 states the status quo of short sea weather routing, and proposes topics for further work.

Appendix C presents an animation in book format(!)

1.5 Outline of the Thesis

The objective of this thesis is primarily to develop a proof-of-concept program to solve the supply vessel weather routing problem in MATLAB. The program can serve as platform to further explore the feasibility and the impact of weather routing. The ultimate goal is to shed light on the potential of weather routing in short sea shipping.

Chapter 2 contains a more detailed problem description, due to the novelty of the approach. In order to express the problem as a computer program, a mathematical model is derived from the problem description. The case study, to be evaluated in this thesis, is presented.

Chapter 3 presents the underlying theory and the modelling of the cost function. The parts of the cost function is explained. Weather forecasts and ensembles are explained and put into context for the thesis. The reduced speed mode and the constant speed mode is defined.

Chapter 4 sheds light on how the model is implemented , along with explanations central algorithms. The forecasts used in the program are presented, and a visual comparison is given.

Chapter 5 illustrates the results extracted from the program, by describing the output graphics. The first setup that is presented as an example is using the reduced speed mode, rigs open around the clock, a deterministic ECMWF forecast and operational costs as cost function. Each figure is explained thoroughly.

Chapter 6 presents the remaining setups available in the program. Program setup figures will distinguish the different setups.

Chapter 7 states the conclusion and identifies several areas for further work.

Appendix A contains extra background information regarding PSVs and cost optimisation of the upstream supply chain.

Appendix C contains a short help to run the MATLAB-program. The last part is an animation in the form of a flip book (works best on print).

2: Problem Description and Method Approach

This chapter will define the problem that this thesis is aiming to solve, and introduce the method trying to solve it. Section 2.1 will describe the problem, the objective of the solution, and the suggested constraints. The mathematical model will be described in section 2.2, and assumptions made are covered in section 2.3. Section 2.4 will describe the method and key terminology. Section 2.5 will present the case ship and the case scenario used in this thesis.

2.1 Problem Description

The Norwegian Continental Shelf (NCS) is currently the scene for Norwegian oil activity, and can be divided into five different zones as seen in Figure 1.1. The maturity of the zones vary from the well-established North Sea, to the emerging Barents Sea. The challenges in the high north are lack of infrastructure, coldness, darkness and the risk of ice, whereas in the North Sea the operations are becoming more complex in a harsher environment. The North Sea is the busiest area at the NCS and thus the primary area for logistics optimisation.

The installations receive supplies on a weekly schedule of vessel routes. Routes start out fixed, but are frequently altered due to weather and demand changes. This causes a huge challenge in order to optimise the utilisation of the chartered PSVs.

The *supply vessel weather routing problem* is to identify the cost optimal route for a given weather condition. The weather condition is to be provided by state-of-the-art forecasts. The goal is that the calculated difference in performance between the weather-optimal and the shortest route can advise route changes in order to save fuel and money.

Rigs producing oil have a lower and more predictable need for supplies. These rigs are often closed for supplies during night time, and the PSVs are modelled in the program so they

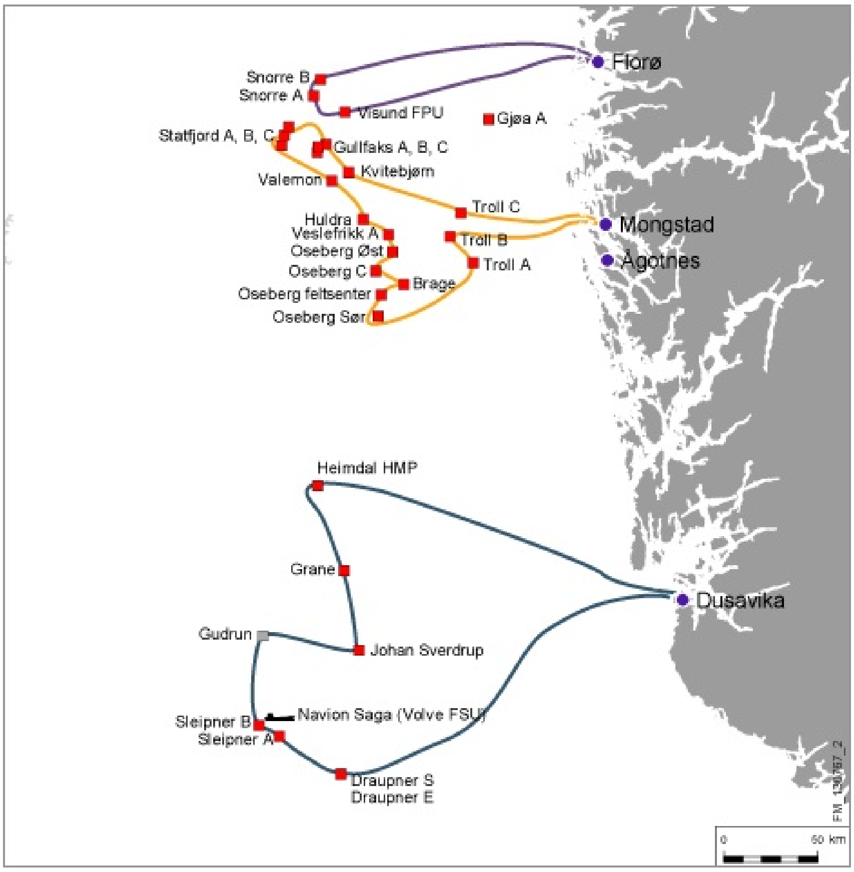


Figure 2.1: Statoil supply routes for the North Sea. By courtesy of Statoil (Statoil, 2013)

can't service the installation outside of open hours. Rig-vessel interactions such as receiving goods, are affected by waves and weather. Thus, the rigs are forced to cancel crane operations when the wave state exceeds safety limits. These factors combined introduce *dynamic time windows* and can force the vessel to wait on weather (WOW) or wait for opening hours.

2.2 Mathematical Model

In order to convert the problem into a MATLAB program, it needs to be mathematically modelled. The program will calculate the cost of each candidate route in order to decide the optimal route. The candidate routes are the n shortest routes out of the pool of possible routes. Let $\mathscr{R}$ be all candidate routes that will be calculated. $\mathscr{N}$ is the installations that are to be visited. Each route is split up into a number of time steps with an individual duration. Let $\mathscr{T}_r$ be all the time steps in route r. Increasing the number of time steps will increase the fidelity of the calculation, but also the time needed for computation. d_{rt} is given as the duration of time step t in route r. The duration is introduced to precisely calculate the route cost. C^T

is the vessel charter cost per hour. C^F_{rt} is the fuel cost per time step and is given by the ship model function for the forecasted weather condition. V_{rit} is a binomial parameter to decide if the time step is spent at installation i, out of the $\mathscr{N}$ installations. S_i is the required service time for each installation. For $r \in \mathscr{R}$ (route in the pool of candidate routes) the objective function is:

$$\min \sum_{t \in \mathscr{T}_r} \left(C^T + C^F_{rt}\right) d_{rt} \tag{2.1}$$

where

$$C^F_{rt} = \text{ShipModel}(Weather, Status) \tag{2.2}$$
$$\text{Weather} = \text{Forecast}(time, position) \tag{2.3}$$

subject to the following constraints

$$\sum_{t \in \mathscr{T}_r} V_{rit} d_{rt} \geq S_i, \qquad i \in \mathscr{N}, \tag{2.4}$$
$$d_{tr} \in \mathbb{R}^+, \qquad t \in \mathscr{T}_r, r \in \mathscr{R}. \tag{2.5}$$

Equation 2.4 ensures that each installation receives their required service time. Equation 2.5 states that the duration must be a real, positive number($\mathbb{R}^+$,).

2.3 Assumptions

It is assumed that the governing VRP is already solved, so that the only task remaining is to set the sequence in which the rigs are to be visited. The goods allocation is assumed to be solved in advance, and that the route will not supersede the capacity of the vessel. No cherry picking should be needed due to rearrangement of goods in order to accommodate the installations as planned. Cherry picking means that a container is picked up from a location on deck surrounded by cargo. This is described in G-OMO's chapter 9.11 (G-OMO Steering Group, 2013).

The problem is of a deterministic character with respect to the forecast. This means that the forecast is assumed to be the true weather state. However, when used with an ensemble forecast, the nature of the forecast is stochastic. An ensemble forecast is multiple forecasts bundled together. The different forecasts vary over the same time and location, but are perturbed and display different 'outcomes'. An ensemble forecast can represent the confidence of the forecasted weather and a small deviation over the forecasts, can be treated as a more certain forecast. Forecasts are covered in chapter 3.3.

The method is only as good as the input it gets. Thus the model assumes that the forecast, the ship resistance and the fuel consumption model correlates with actual operations.

2.4 Method

This section will explain the approach to solve the problem described, in order to give a platform for the underlying theory and modelling explained in chapter 3. The meteorological data is retrieved formatted as Gridded Binaries (GRIB) and contains a lattice or grid of points with meteorological data attached to each of these points.

The approach utilises the 'Travelling Salesman Problem with Time Windows' (TSPTW) where the start- and end nodes are set at onshore bases. The computationally heavy part is to evaluate the cost value for each candidate route and only a small number of routes can be evaluated. Suggestions for further enhancement are proposed in chapter 7.2.

The *ship model* calculates operation costs from current- wave- and wind data, and vessel speed. Information about hull resistance, propulsion coefficients and engine data is used to calculate a chosen cost function.

The *cost function* is the parameter in which the route is to be minimised for. Different parameters like tow energy, energy output from engine (brake energy), fuel consumption, CO2-emissions and operational cost can be chosen as this cost function.

Two methods will be implemented in order to calculate the cost of the route. The two methods are the *constant speed*, with slow steaming to hit time windows, and the *reduced speed* with the vessel waiting to service near installations.

2.4.1 Constant Speed

The transit time to the next way point is found as $\frac{\text{distance}}{\text{service speed}}$. If the waypoint is a rig, and the rig is available for the duration of the given service time, the speed is set. If the rig is unavailable, the speed is reduced until the vessel 'hits' an available time slot. Slow steaming towards the installation will reduce the fuel consumption.

2.4.2 Reduced Speed

The transit speed is governed by a constant propulsion power. If the environmental forces increase, the speed decreases. If the rig is unavailable upon arrival, the supply vessel will wait on site for the rig to be available.

2.5 Case Study: Far Searcher at Statoil's North Sea Circuit

The case scenario will be the PSV Far Searcher serving Statoil's supply operations in the middle North Sea. The middle North Sea has a total of 21 producing fields as of 2014. Six fields are under development and several more are being planned. Among planned fields is the Norwegian giant, Johan Sverdrup, expected to account for over a fourth of the national oil production by 2020. (The Norwegian Petroleum Directorate, 2014). The route is the lower of the circuits in Figure 2.1 on page 14.

Far Searcher is a UT 751 E design from Rolls-Royce, built in 2008. It has been going on long-term contracts for Statoil. It has two Azipull AZP120 azimuthing thrusters as main propulsion, and three tunnel thrusters for manoeuvring.

The Dusavik Supply Base is serving six fields for Statoil, as displayed in Figure 2.1. Table 2.2 lists the installations and their characteristics.

PSV Far Searcher - UT 751 E

LOA	93.2	m
Breadth	21	m
Draft	6.6	m
Deadweight	5127	mt
Deck Space	1091	m^2

DNV Class Notations

+1A1, SF, E0, Clean,DK(+), DYNPOS-AUTR
LFL*,HL(2,8), COMF-V(3), OILREC, NAUT
OSV(A), ICE-C, ESV-DP(HIL), SUPPLY VESSELl

Table 2.1: Key Facts About Far Searcher

Figure 2.2: Platform Supply Vessel - Case Ship: Far Searcher. Courtesy of Farstad

Installation	**Latitude**	**Longitude**	**Loading Time** [h]	**Service Hours**	**Wave Limit** [m]
Johan Sverdrup	N 58°49’25.26”	E 2°36’54.76”	5	0 - 24	4
Heimdal	N 59°34’26.98"	E 2°13’43.70"	5	8 - 19	4
Grane	N 59°09’54.86"	E 2°29’14.60"	5	8 - 19	4
Sleipner A	N 58°02’02.33"	E 1°54’31.01"	5	8 - 19	4
Gudrun	N 58°50’42.80"	E 1°44’ 37.40"	5	8 - 24	4
Draupner S	N 58°11’19.60"	E 2°28’21.60"	5	8 - 24	4

Table 2.2: List of Installations

3: Theory & Modelling

This chapter will state and explain the theory and models needed to approach the method outlined in section 2.4. Section 3.1 will describe the candidate route generation. Section 3.2 will explain the build-up of the cost function and how it is calculated.

3.1 The Route

The route section of the problem statement requires combinatorial theory. This section will give a brief introduction to combinatorial theory, as well as the theory behind the utilised concepts of the TSP. The calculation of arc lengths is presented, in order to find the distances between points on a globe.

Combinatorial Theory

Combinatorial optimisation is the hunt for the optimal candidate in a finite pool of possibilities. Though the number of candidates is finite, it might not be feasible to do exhaustive search, probing every combination. Some common problems utilising cominatorial optimisation is the knapsack problem and the nurse scheduling problem. An introduction to combinatorial optimisation is found in Gerdts (2009). Laporte (2007) introduces the reader to the general Vehicle Routing Problem.

The Travelling Salesman Problem

The Travelling Salesman Problem (TSP) is the problem where a salesman is to visit a number of cities once and want travel as short as possible. TSP is a NP-Hard problem, meaning that the problem is at least as hard as the hardest problem in NP (Non-deterministic polynomial time) which basically says that the verified optimal solution is hard to find. From a supply vessel perspective, the TSP is a sub-problem of the 'Vehicle Routing Problem' (VRP). The VRP regards a number of goods that is to be distributed to a number of customers with a number of vehicles. This can be regarded as the fleet optimisation part.

The Arc Distance

The shortest distance between two points on the globe is the great circle path, being the circumference of a plane that crosses the middle of the sphere. It is calculated with equation 3.1.

$$\alpha = tan^{-1}\left(\frac{\sqrt{(\cos\phi_2 \sin\Delta\lambda)^2 + (\cos\phi_1 \sin\phi_2 - \sin\phi_1 \cos\phi_2 \cos\Delta\lambda)^2}}{\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos\Delta\lambda}\right) \tag{3.1}$$

α is the arc angle, and the distance is '$R\alpha$' where R is the radius of the earth. ϕ_1 and ϕ_2 is the latitudinal position for point r_1 and point r_2. $\Delta\lambda$ is the longitudinal angle between point r_1 and point r_2

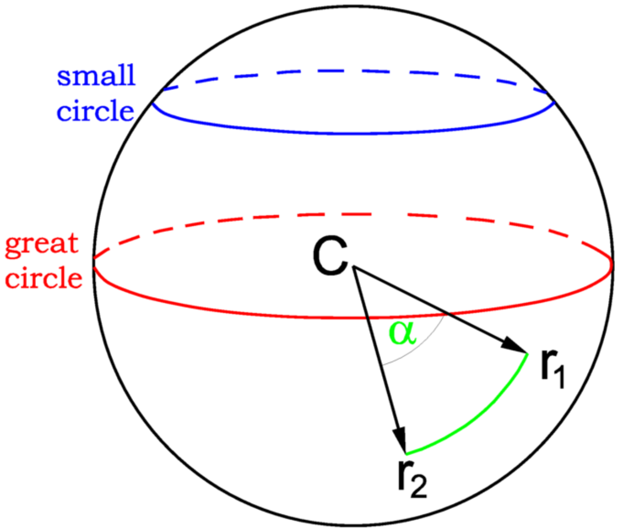


Figure 3.1: The Concept of Great Circles. By courtesy of Wikimedia Commons

3.2 The Cost Function

The core element in this method is minimising a cost function of choice. The cost function can be towing energy, brake energy, fuel consumption, CO2-emissions and operational costs. This section will explain the different elements used in the different cost functions. Each part of the function will be identified, and the current methods of acquiring the cost values will be explained.

3.2.1 Ship Resistance

The first cost function, and the elementary part, is the resistance the ship experiences at given speeds and environmental conditions. It consists of three components:

$$R_T = R_{CW} + R_{AW} + R_{AA} \qquad [N] \tag{3.2}$$

$$P_E = R_T V_S \qquad [W] \tag{3.3}$$

R_{CW} is the calm water resistance, which is mainly caused by skin friction, wave generation and creation of turbulence. It is expressed as a function of the ship's velocity. The added resistance in waves R_{AW} is the wave induced resistance, and is mostly damping forces due to extra accelerations, and absorption of wave energy. The last component, the R_{AA} is the wind resistance, which scales with the relative velocity, and roughly the size of affected surface area. The needed towing power P_E is the product of the total resistance (R_T) and the vessel speed (V_S). The following subsections explains how these resistance components were found:

Calm Water Resistance

A thorough calm water performance result can be obtained from towing tests. Preliminary values are calculated in ShipX, through a ShipX-model of the vessel of interest utilising strip theory calculations, which is explained in Faltinsen (1993). An introduction to calm water ship resistance and its components can be found in Steen and Minsaas (2013)

Added Resistance in Waves

R_{AW} is additional resistance from wave loads, expressed as a function of weather parameters and vessel speed. Weather parameters utilised are significant wave height, peak period and wave direction.

The added resistance in waves is modelled as a series of regular waves derived from a Pierson-Moskowitz wave spectrum and superpositioned to a total force (see Equation 3.7). The used method is direct pressure integration based on strip theory, calculated in ShipX VERES. How ShipX calculates added resistance is found in Fathi and Hoff (2004). Currents are added to the speed vector. The Pierson-Moskowitz wave spectrum is given by by equation 3.4 with parameters A and B given by equation 3.5 and 3.6.

$$S(\omega) = \frac{A}{\omega^5} \exp - \frac{B}{\omega^4} \tag{3.4}$$

$$A = 0.11 H_S^2 \omega_1^4 \tag{3.5}$$

$$B = 0.55 \omega_1^4 \tag{3.6}$$

$$\overline{F_i^s} = 2 \int_0^\infty S(\omega) \left(\frac{\bar{F}_i(\omega;\beta)}{\zeta_a^2} \right) d\omega \tag{3.7}$$

This version of the PM-spectrum is called the ISSC-spectrum and is a function of the significant wave height H_S and the middle frequency of the spectrum (ω_1) which is the 'centre of gravity' of the spectrum. Wave spectrums are described in the chapter 'Irregular Seas' in Pettersen (2007). Further information, and state-of-the-art research on the topic is found in Chuang (2013) for a 8000dwt tanker. The mean wave load ($\overline{F_i^s}(\omega;\beta)$) is stated in equation 3.7 (Faltinsen, 1993). The fraction part $\left(\frac{\bar{F}_i(\omega;\beta)}{\zeta_a^2} \right)$ is the calculated transfer function from ShipX-VERES, where $\bar{F}_i(\omega;\beta)$ is the wave load from a regular wave .

Wind Resistance

The wind resistance is calculated as a function of the relative wind velocity V_R, and the area of the super structure in the relevant direction, times a coefficient. For the surge direction the wind resistance is:

$$R_{AA,X} = 0.5 \rho_a V_R^2 C_X(\gamma_R) A_X \qquad [N] \tag{3.8}$$

Notice that the wind resistance can be a positive contribution. The wind resistance coefficients in $C_X(\gamma_R)$ are found in ShipX, and only the surge contribution is taken into calculation. (Fathi and Hoff, 2004). The sway and yaw components are neglected in this model, but causes substantial contributions especially in DP-mode. Section 6.2 discusses the shortcomings in this model.

Currents

Tidal currents, ocean currents and currents due to stokes drift (second order wave effects) are simply added to the velocity of the vessel, as a vector, if the current is provided by the forecast.

3.2.2 Propulsion and Operation Modes

This section will bridge the gap between the required towing effect, and the engine and its required brake effect. The underlying propulsion theory can be found in Steen (2007). The required brake power - P_B [W] is calculated from the required towing power P_E [W].

$$P_B = \frac{P_E}{\eta_D \eta_M} + P_H \tag{3.9}$$

where

$$\eta_D = \eta_0 \eta_H \eta_R \tag{3.10}$$

In equation 3.9, P_H [W] is the hotel load for the vessel, which includes all consumers that are not related to propulsion. The coefficients (the η's) are introduced in Table 3.1

Name	**Description**	**Typical Value**
η_0	Open Water	0.45 - 075 [-]
η_R	Relative Rotation	0.98 [-]
η_H	Hull	1 [-]
η_M	Mechanical	0.97 - 0.98 [-]
η_D	Propulsion	0.4 - 0.7 [-]

Table 3.1: Coefficient Description

The hull coefficient η_H and the relative rotation coefficient η_R are given in equations 3.11 and 3.12. The t is the thrust reduction number which is the additional thrust needed due to the inequality between produced thrust and the needed thrust, shown in equation 3.13. The wake factor w is the added thrust needed due to the increased water velocity observed around the aft ship, in which the propeller operates in.

$$\eta_H = \frac{1-t}{1-w} \tag{3.11}$$

$$\eta_R = \frac{Q_0}{Q} \tag{3.12}$$

$$t = \frac{T + F_S - R_T}{T} \tag{3.13}$$

Q_0 is the ideal torque, and Q is the actual torque. T is the total thrust, F_S is the line pull and R_T is the total vessel resistance. The open water coefficient (η_0) is given as:

$$\eta_0 = \frac{J}{2\pi} \frac{K_T}{K_Q} \tag{3.14}$$

where

$$J = \frac{V_A}{nD} \tag{3.15}$$

K_T and K_Q: are modelled as Wagening B propellers by coefficients given by Oosurveld and Van Oossanen (1975) as a function of the advance velocity V_A, propeller speed n (RPS), diameter D, advance number J, propeller blade area Ae, and the number of blades z. These are assumed to give a sufficiently good model of the propulsion system.

3.2.3 Engine Model and Fuel Consumption

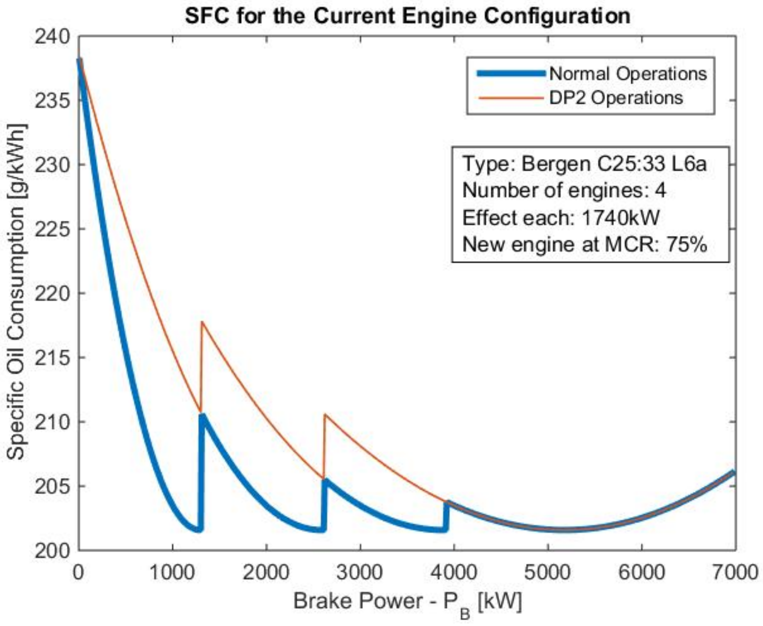


Figure 3.2: Specific Fuel Consumption Model

The engine model is based on a power per unit calculation. In order to assure redundant operations, one extra engine is required to run in DP-operations. The specific fuel consumption (SFC) [g/kWh] is found by the polynomial in equation 3.16. m is the number of engines required to run, of a total of M available engines, as given by equation 3.17. P_B is the brake power required from the generators, P_{max} is the maximum power output of the engine and $\%MCR$ is the maximum continuous running percentage the engine can maintain, used as the level for which a new engine is put on line.

$$sfc = aP_U^2 + bP_U + c \tag{3.16}$$

$$m = min(ceil(\frac{P_B}{(\%MCR)P_{max}}), M) \tag{3.17}$$

$$Pu = \frac{P_T}{mP_{max}} \tag{3.18}$$

The factors are $a = 67$, $b = -100$ and $c = 240$. These factors are arbitrarily chosen to get a decent SFC-curve. The resulting SFC plot for this setup is shown in Figure 3.2. The red DP-line in Figure 3.2 is the only difference from transit and waiting.

3.2.4 Pareto Frontier

When the cost function is calculated and the route is to be chosen, the best route with regards to duration and the cheapest route can be different ones. Trade-offs must be made. In order to display the possible trade-offs, a Pareto frontier like Figure 3.3 is calculated. A Pareto frontier displays the set of solutions that are all Pareto optimal, when dealing with multi-variable optimisation. The best solution with regards to one variable might not be the optimal solution with regards to the other variables. A Pareto frontier will visualise the possible trade-offs between the variables. The Pareto frontier will be represented in a plot of the

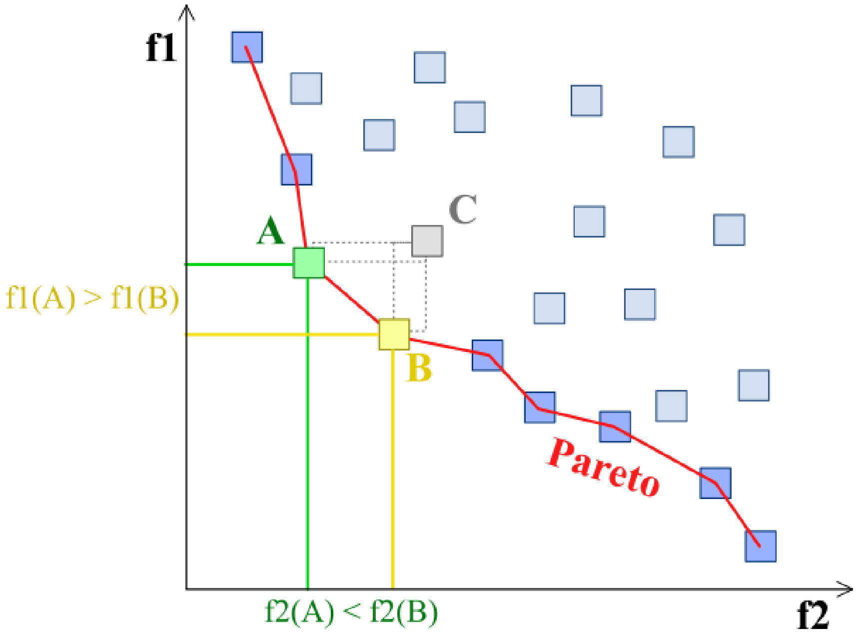


Figure 3.3: Pareto Frontier. Licensed under CC BY-SA 3.0 via Wikimedia Commons

available solutions, and the Pareto optimal set consists of the best combinations.

3.3 Weather Forecasts and Ensembles

The forecast data used is formatted as Gridded Binaries (GRIB) files. Providers of weather data is typically governmental institutions like the Norwegian Meteorological Institute (met.no), ECMWF (EU) and NOAA (USA). Forecasts are computed one to four times a day, at given times, by super computers. The amount of data and calculations required for one such run are vast. Back in 2007, 1.63×10^{15} computations and 8,906,427 assimilated data points was needed for a typical 10-days global ECMWF forecast (Trémolet, 2007). The weather is structured as a 4D grid, with time, latitude, longitude and height as the index axes. The very basics of a forecast calculation is to 'train' an atmosphere model on hindcast/analyse data and use this model to predict the future.

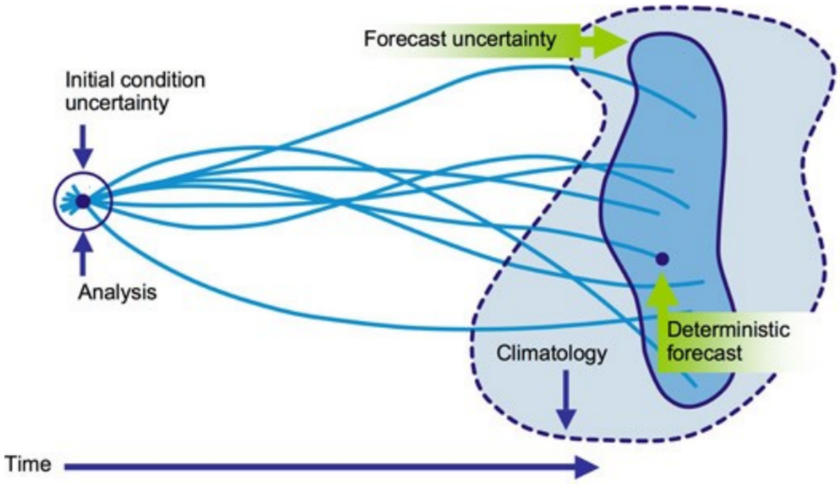


Figure 3.4: The Basics of Ensemble Forecasts. By courtesy of Peter Bauer, ECMWF (Bauer et al., 2014)

Ensemble Forecasts

Ensemble forecasts are sets of models with slightly different parameters, trained by an analysis run, predicting different weather progressions (forecast). Due to the chaotic nature of weather, slight perturbations in these parameters can ultimately lead to vastly different results (coined the butterfly effect). As pictured in Figure 3.4, these forecasts are well suited to predict the uncertainty of a forecast. By running the model for different weather scenarios, a confidence interval of the prediction can be calculated. See Krishnamurti et al. (2000) and Lorenz (1963) for more information.

4: Implementation

The means to address the problem described in chapter 2 is a MATLAB software suite named the MasterPlanner, which is presented in this chapter. The governing philosophy is to explore the possibilities presented by gridded weather forecasts. The program consists of about 50 MATLAB scrips and a few thousand lines. It is customisable with several choices given in Figure 4.1 and will be explained in the following sections.

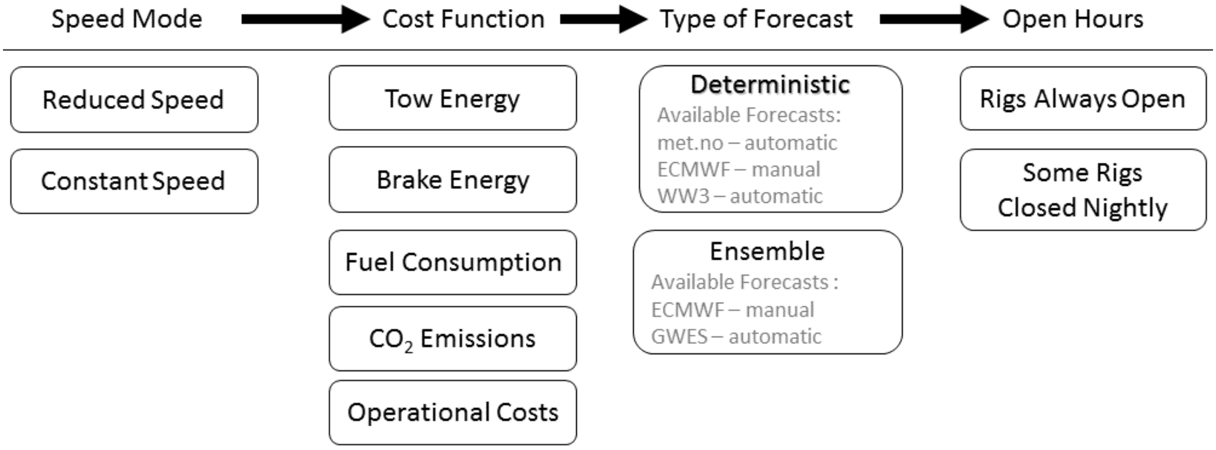


Figure 4.1: Program Choices: Each column represents a choice. These choices are covered in this chapter as well as in chapter 3. This Figure will return in chapter 5 and 6.

The function of the program can be summarised with these bullet points:

- Generate look-up tables for the current ship resistance model
- Download the GRIB-file containing the relevant meteorological data
- Generate valid candidate routes and find distances between nodes
- Evaluate time windows for the installations
- Assign vessel speed in transits
- Calculate route cost for candidate routes

- Decide the best route and visualise the results

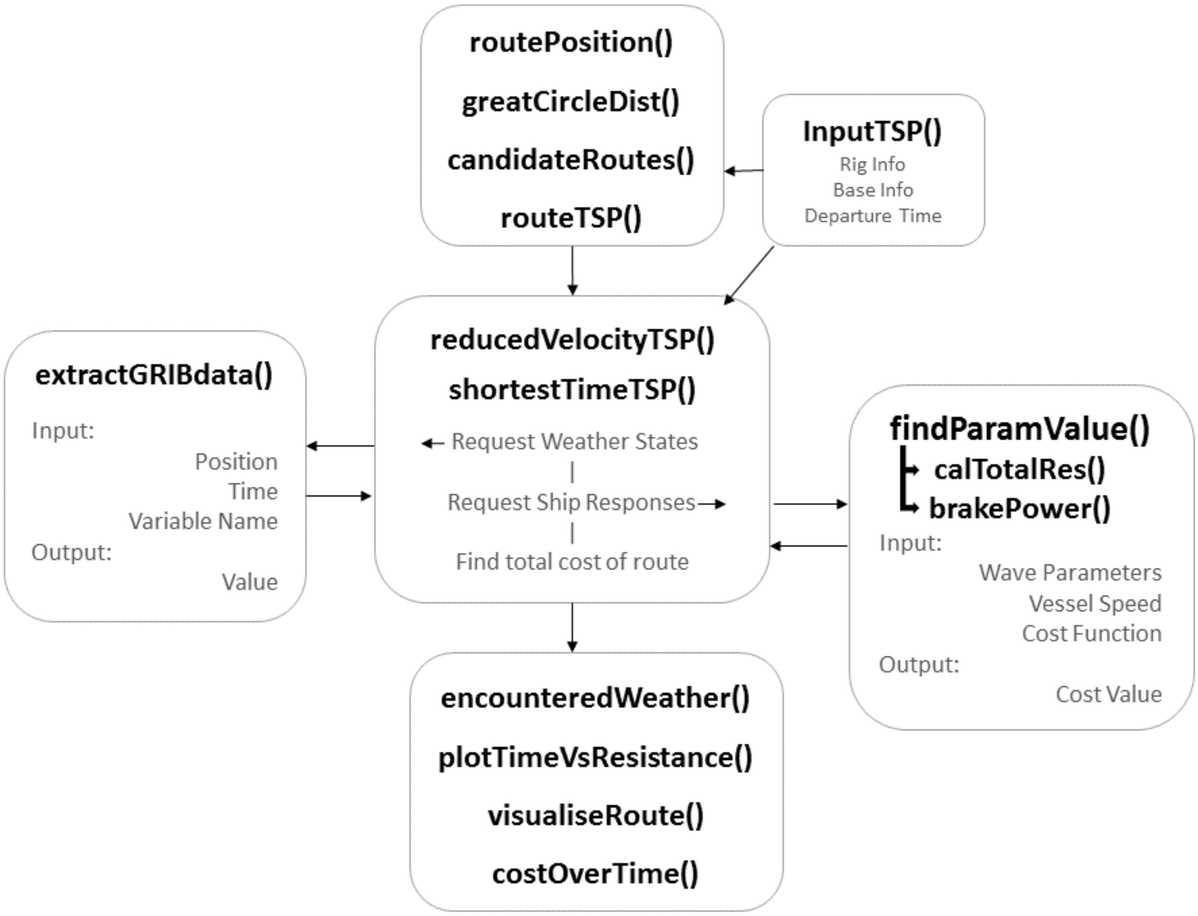


Figure 4.2: Flow chart similar to Figure 1.2 with names of functions

The structure of the program was outlined in Figure 1.2 at page 4. Figure 4.2 shows how the function calls used in the MasterPlanner are coordinated.

The program uses three external toolboxes in additions to the native MATLAB-functions:

m_map A mapping toolbox to draw world maps in MATLAB. All maps in this thesis is based on the *m_map* toolbox. In order to accommodate wave direction, the vector function in the library has been enabled to use flipped arrows. By courtesy of Rich Pawlowicz. `www.eos.ubc.ca/~rich/map.html`

NCTOOLBOX A data set toolbox that enables read-only extraction of data from common data model data sets. In this thesis GRIBs, OPeNDAPs and NetCDFs are accessed with the *NCTOOLBOX*. By courtesy of B.Schlining, A.Crosby and R.Signell. `github.com/nctoolbox/`

Pareto Front A toolbox to calculate Pareto frontiers. All the Pareto frontiers of this thesis are calculated by this library. By courtesy of Yi Cao.

`mathworks.com/matlabcentral/fileexchange/17251-pareto-front`

4.1 Forecasts

This section will summarise the forecasts implemented and displayed in Figure 4.1. The grey forecast names are also defined as automatically fetched within the program, or manually fetched and linked to within the script.

A number of forecasts are implemented to work with the MasterPlanner. The different providers uses different approaches and different means of distributing forecasts. For the interested reader, a comparison between NCEP and ECMWF (along with the Canadian MSC) is carried out in the work of Buizza et al. (2005). It is to be mentioned that the atmospheric models are compared, but the wave forecasts are derived from atmospheric data models. A visual comparison of the four providers is done in Figure 4.3

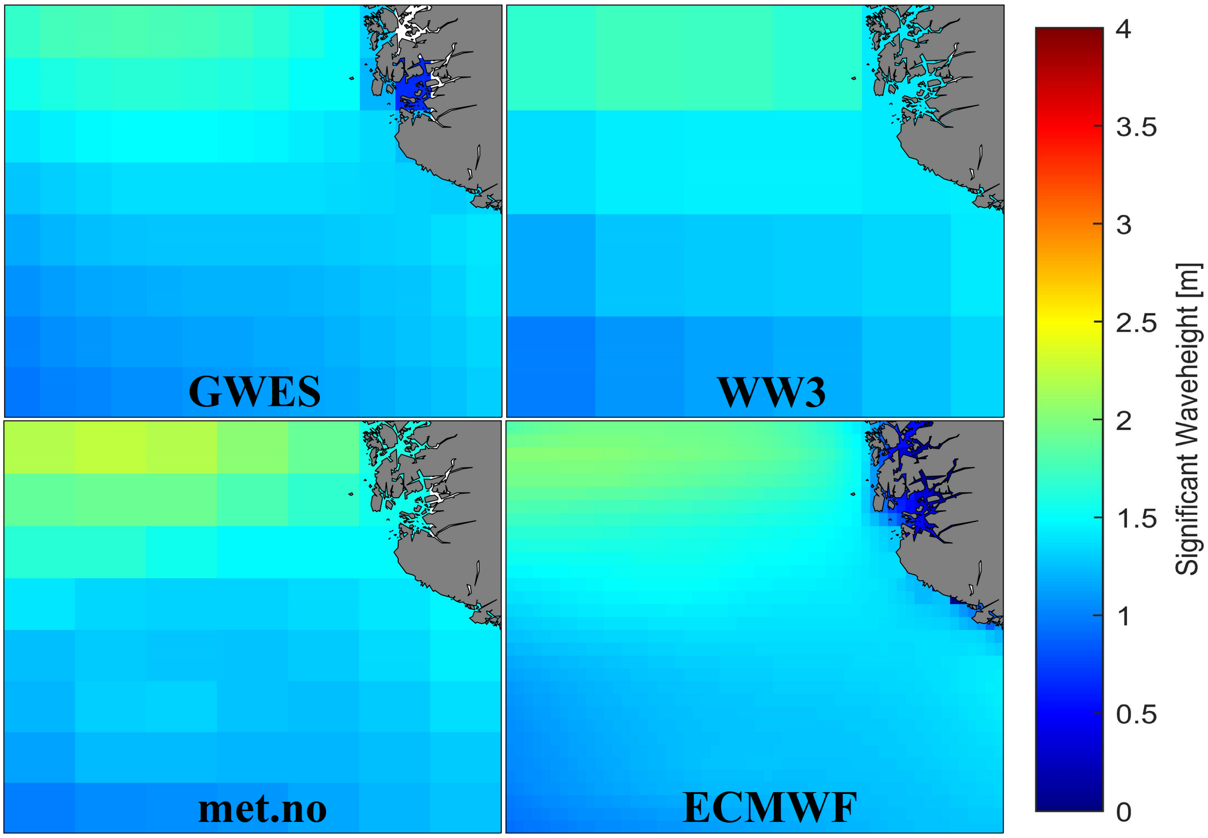


Figure 4.3: Forecast Comparison for June 4th, 2015 at 0600 UTC.

met.no

The first compatible forecast is the same as found on Yr.no. The forecast is generated by the Norwegian Meteorological Institute (met.no), made available through Yr.no. The GRIB-file is downloaded from '`http://om.yr.no/verdata/grib/`' and is available for the North Sea and the Norwegian Sea. The resolution is 1° × 0.5° (due to the curvature of the earth). This forecast is implemented to be automatically downloaded in MasterPlanner.

ECMWF

The European Centre for Medium-Range Weather Forecasts (ECMWF) offers a range of forecasting services - some available for the public, and some services are only available for member-state users. The GRIB-files are compiled in a browser-application found at: `http://apps.ecmwf.int/services/mars/catalogue/`, where area of interest, variables and resolution can be selected. Both deterministic and ensemble versions are available. A batch functionality exists, through python scripts, automating the data fetching. MasterPlanner uses manually downloaded GRIB-files with a resolution down to 0.125° × 0.125°. The ensemble consists of 50 forecasts.

WW3

The WaveWatch III is a deterministic wave model based on the winds of the Global Forecast System (GFS) and provided by the National Centers for Environmental Prediction (NCEP). A description of the method can be found in the work of Tolman et al. (2014). The resolution is 1.25° × 1°. It is available online through ftp-servers, and the fetch is done automatically in the program.

GWES

Global Wave Ensemble System is the ensemble model of the WaveWatch III, with the same characteristics and 21 ensembles. The GRIB-files for WW3 and GWES are made available at: `http://www.ftp.ncep.noaa.gov/data/nccf/com/wave/prod/`

4.2 Candidate Routes

The rigs and their positions are given as input. All the possible route combinations are generated, constrained by visiting each rig once. The start and stop can be an arbitrary location, but is usually a base. The distances between the rigs are calculated and then summed up for each route. The routes are sorted by distance, and the n shortest routes are picked for weather evaluation. The optimal route is often found among the shortest routes, so to save computational time, the longest routes are not computed.

Time Windows

Each rig can be closed due to severe weather and closed hours. The time windows for each rig are given for the duration of the input weather forecast. The time windows are evaluated and the output is an array of binomial values, as exemplified in table 4.1 - 1 for open and 0 for closed, for every hour throughout the forecast. When the program calculates the timings for arrival, it will check if the vessel is able to service the installation in one go. Splitting up the service is not modelled.

Time	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
J.Sverdrup	1	1	1	0	0	0	0	1	1	1	1	1	1	1	0	0
Sleipner	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0
Heimdal	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
Sleipner	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0

Table 4.1: Example Time Windows Array for Installations

4.3 Route Cost Calculation

The route cost calculation is the core of the program, to which all the other pieces build up to. Algorithms 1 and 2 are simplified versions of the reduced speed method and the constant speed method, that try to explain the logic and flow of the scripts. There was not developed a unique model for DP and waiting near installation. The DP and waiting modes are modelled as a 1.5[m/s] transit. This approximation is just a best guess assumption and will be one of the subjects of discussion in chapter 6.2. The starting time is arbitrary – it is a input variable that can be set to anything within the forecast range.

Algorithm 1: Reduced Speed Route Evaluation

```
input  : Rig data
output: Route cost
for $i = 1 \rightarrow$ number of routes do
    for $j = 1 \rightarrow$ number of legs do
        while Not arrived at rig do
            Set transit speed based on weather Calculate partial transit cost
        end
        if Rig is not open at arrival then
            while Rig is not open at arrival do
                Calculate waiting time cost
            end
        end
        Set arrival and next departure
        for Length of rig service time do
            Calculate partial DP cost
        end
        Leg cost = $\sum$ transit + $\sum$ DP + $\sum$ Waiting
    end
    Route cost = $\sum$ Leg cost
end
```

Algorithm 2: Constant Speed Route Evaluation

```
input  : Rig data
output: Route cost
for $i = 1 \rightarrow$ number of routes do
    for $j = 1 \rightarrow$ number of legs do
        Set transit speed Calculate ETA at destination
        if Rig is not open at ETA then
            while Rig is not open at ETA do
                Decrease speed to delay ETA
            end
        end
        Set arrival and next departure
        Set transit time
                                        /* Starts to evaluate effect of weather */
        for Length of transit time do
            Calculate partial transit cost
        end
        for Length of rig service time do
            Calculate partial DP cost
        end
        Leg cost = $\sum$ transit + $\sum$ DP
    end
    Route cost = $\sum$ Leg cost
end
```

5: Results - The MasterPlanner

This chapter will present the output from MasterPlanner (the MATLAB program). The main output is plots, but also route data are available to be extracted. The plots and visualisations will be thoroughly explained in section 5.1. The show case is the weather forecasted on March 19th, where the MasterPlanner is running in reduced speed mode. Some performance analysis is done in section 5.2. An analysis of the most important setups and methods will be continued in chapter 6.

5.1 The Output Graphs

This section will introduce the output from the MasterPlanner, by presenting an example. Figure 5.1 states the setup computed.

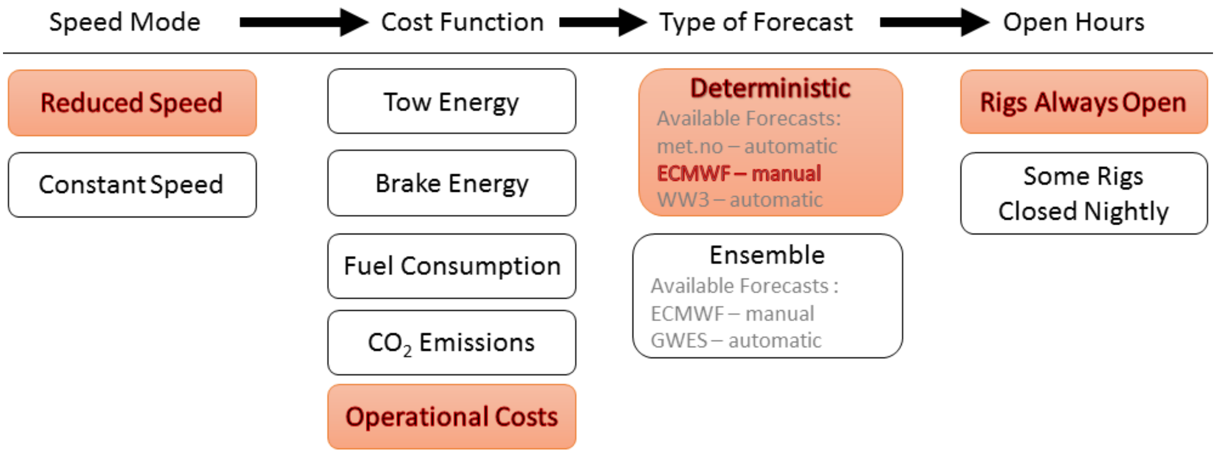


Figure 5.1: Program Setup: This setup uses the reduced speed mode where the cost function is operational cost. A deterministic ECMWF-forecast is used to compute the route with rigs open around the clock

The Scatter Plot and Pareto Frontier

The upper plot of Figure 5.2 shows the best performing routes. If there is not one route that is the fastest and the cheapest at the same time, a Pareto frontier is displayed. The Pareto frontier connects all the dots that are either fastest, cheapest, or a combination of the two. The best route is defined as the fastest route, but the Pareto front presents all the routes for consideration. I.e. if the cost is more crucial than time, another route in the Pareto front could be used. In order to display how good the best route is, all the routes are displayed in the upper plot of Figure 5.2, as a function of time and cost function. The bottom left plot is the same as the upper plot, but zoomed out in order to display the true relation between the axis as well as the relation between the calculated routes. The axes are the chosen cost function on the y-axis, and voyage duration on the x-axis. The bottom right plot is a bar graph of the cost value for all the routes in the Pareto front, coupled with their counterparts. **A counterpart** is the same route going in the opposite direction, and displaying the difference of opposite routes can highlight the importance of weather routing for the current sea state.

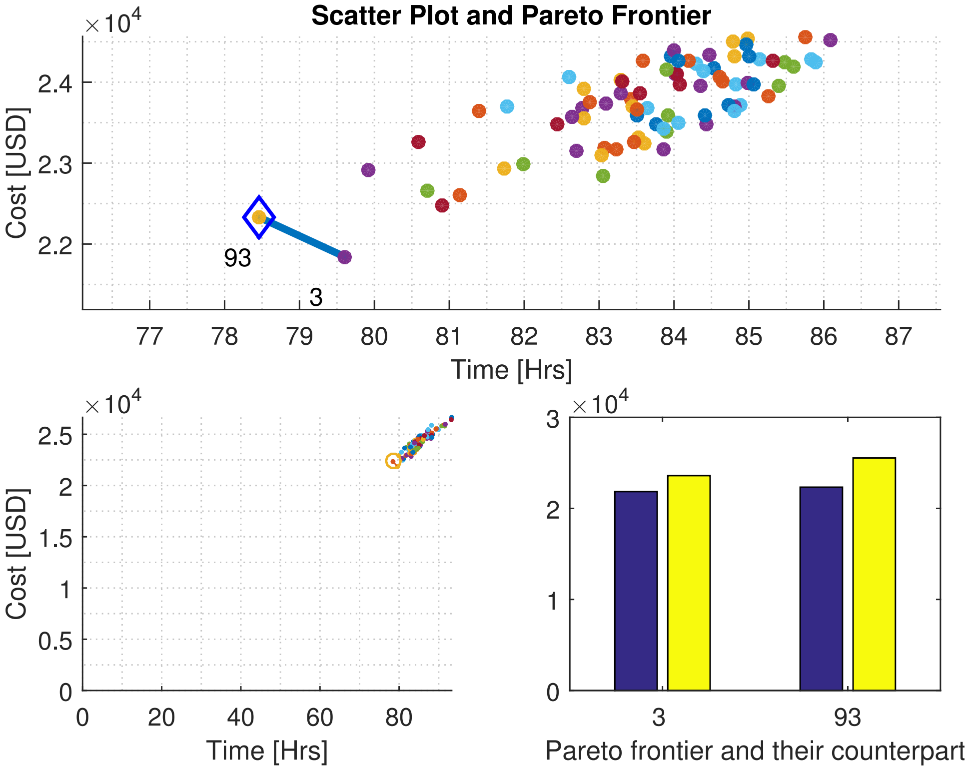


Figure 5.2: Scatter plot and Pareto frontier: **Upper**: The best performing routes - circling the best route - Pareto front if applicable (see Figure 6.12 for example). **Lower left**: Zoomed out, displaying all routes, and actual axes. **Lower right**: Bar graph of routes in the Pareto front as well as their counterparts . In this case, route 93 is the optimal route.

The WaveMap

The WaveMap graphics (Figure 5.3) represents the weather encountered for a chosen route, with the route's KPIs enlisted.

The best route is given as the route with minimum time for the given speed calculation. The key performance indices (KPIs) are given in lower right corner of the Figure, and are numbers that explain how well a route is performing. The first KPI is how much longer the best route is compared to the shortest, and this index can show that a longer route can be better overall. The next KPI is estimated saved fuel, compared to the shortest route. The third is saved time, and time can be saved by hitting time windows to lessen the environmental resistance and thus obtain higher transit speeds in 'reduced speed' mode.

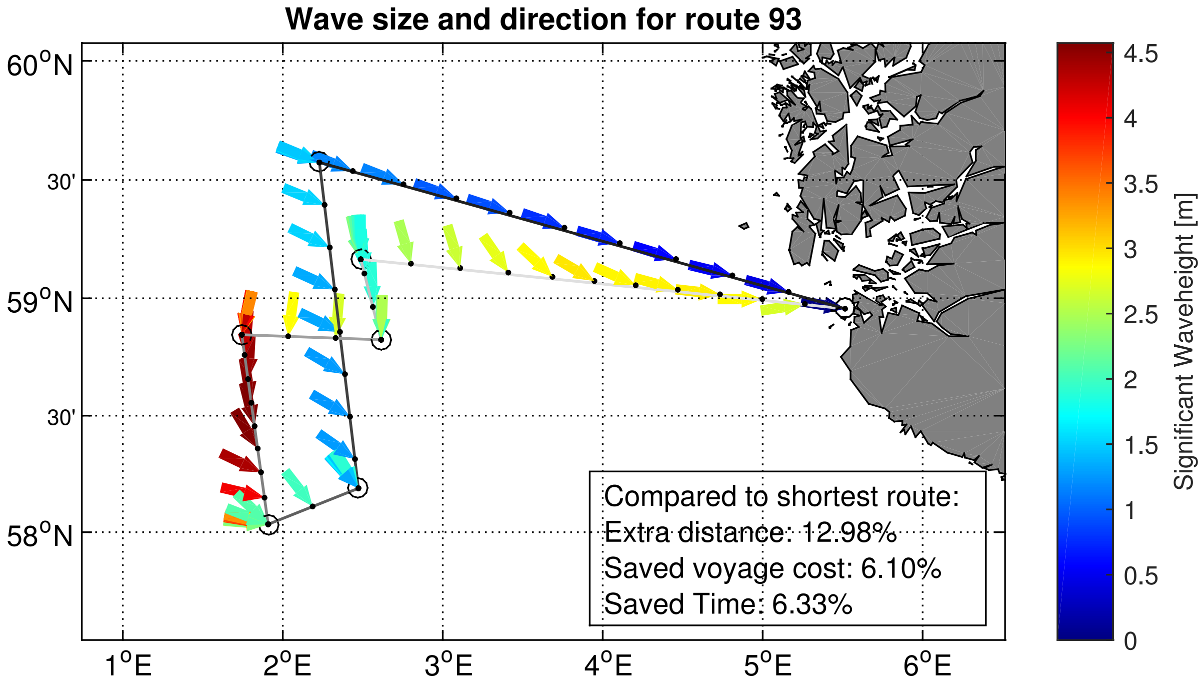


Figure 5.3: WaveMap: The optimal route is visualised with the encountered wave height and direction for the time that the vessel passes the point. The route starts as a black line, and ends white. **Route #93** is the best route in this case

The WaveMap-figure displays the wave- size and direction along the route. The wave- size and direction is given for the time that the vessel passes the point on the route. The colour of the path **starts out black and ends at white**, meaning that the first leg is coloured black.

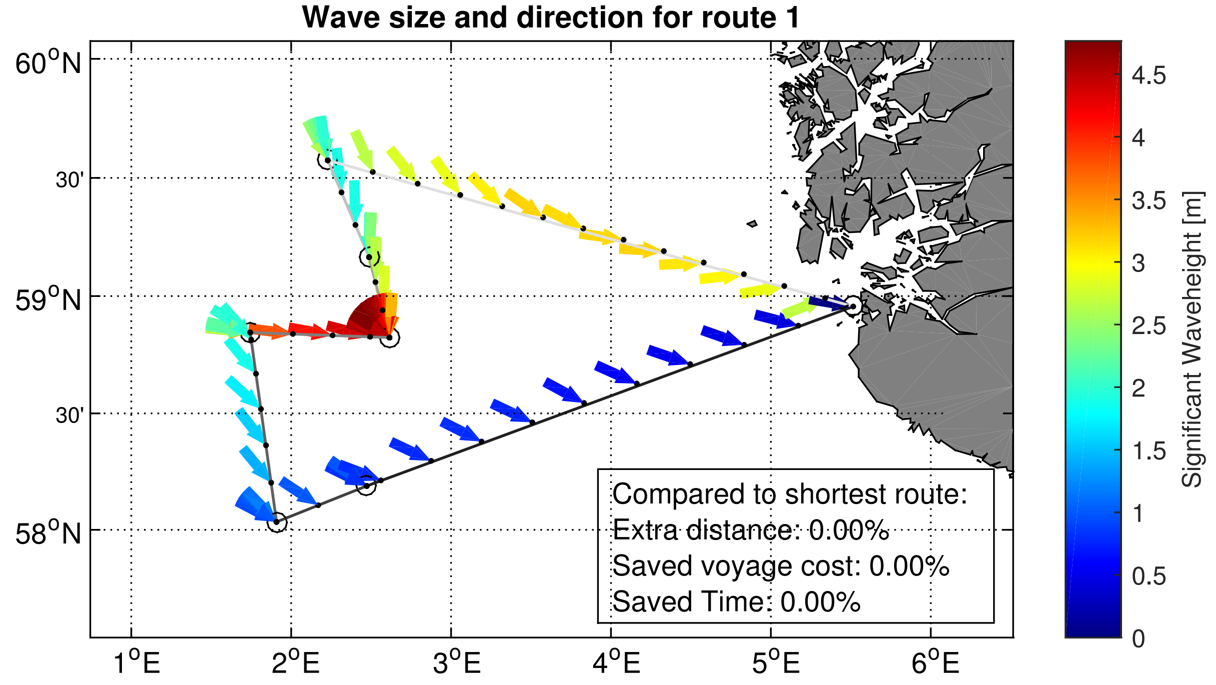


Figure 5.4: WaveMap: The shortest route. This is the same scenario as route 3 in Figure 5.3. The reason why this route performs poorer can be seen in Figure 5.5 and 5.6.

The route in Figure 5.4 is the shortest route, the KPI's are zeros because they are compared to itself.

Cost vs Wave Height vs Speed

Figure 5.5 can be 5.6 are useful plots that show the correlation between the cost function, the wave height and the vessel speed. **Red dots** are transit points, **yellow dots** are DP/servicing rig, and **purple dots** are waiting on weather or waiting for rig to be open for service. For the example in Figure 5.5 notice that the three purple points are above the 4 meter line in the second graph, which happens to be the wave limit. The speed of the vessel can be observed to correlate with the wave height.

The two plots reveals the secret to why route #93 is considered better than route #1. In plot 5.5 the vessel must wait on weather for approximately one hour (one purple dot), whereas in plot 5.6 the vessel must wait for about eight hours (nine purple dots). This extra waiting period makes route #1 slower overall.

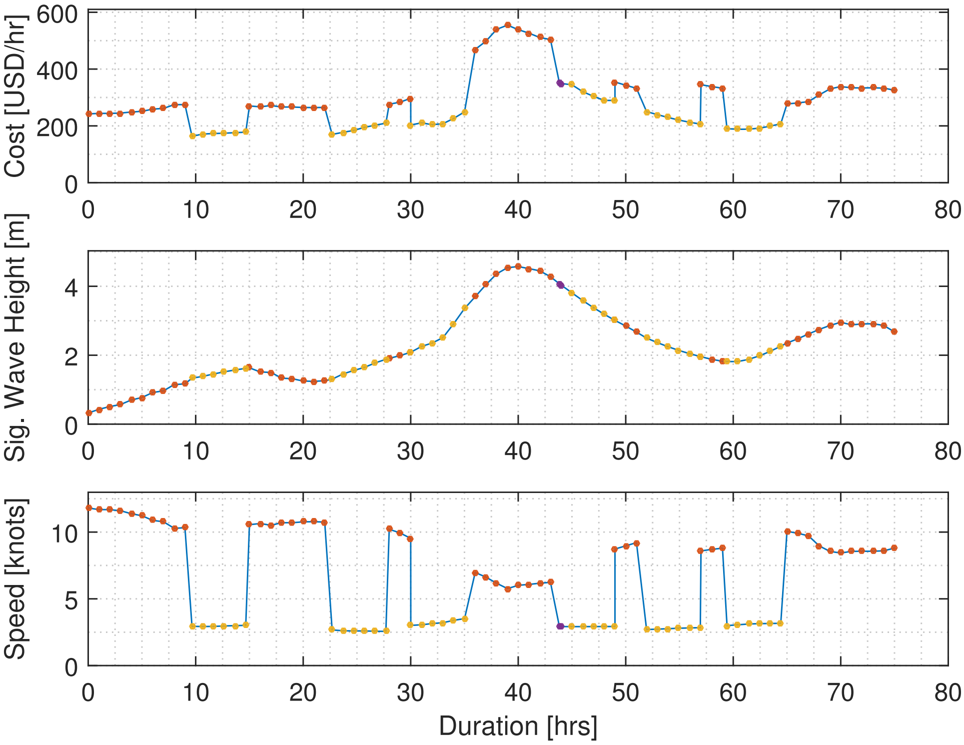


Figure 5.5: Cost per Time for route #93, the optimal route. Route #93 has only one hour of waiting.

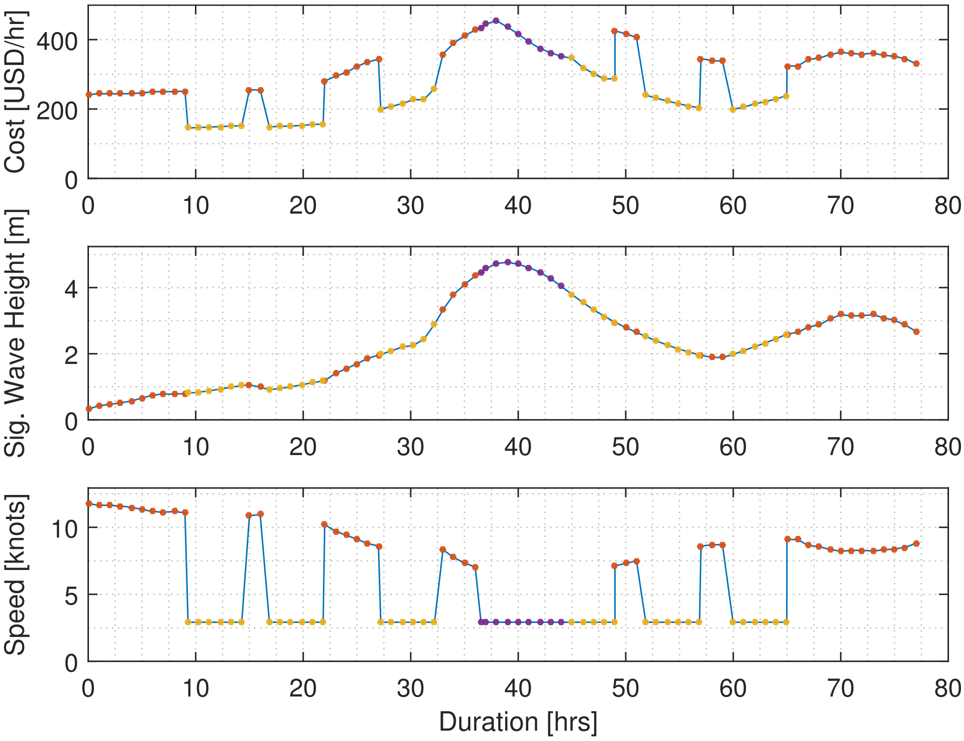


Figure 5.6: Cost per Time for route #1, the shortest route. The route has approximately 8 hours of waiting

5.1.1 Route Schedules and the Effect of Time Windows

The plots in this section are schedules for routes of interest. As decision support they show the dynamic time windows of the different rigs. In Figure 5.7 only time windows due to weather are accounted for. This setup assumes that the installations are open around the clock. The colour codes are intuitive – green is open and red is closed. Orange means warning, that the wave height is close to the wave limit. The greenest shade of orange begins at 70% of the allowed height, and continues up to allowed height in a red shade of orange.

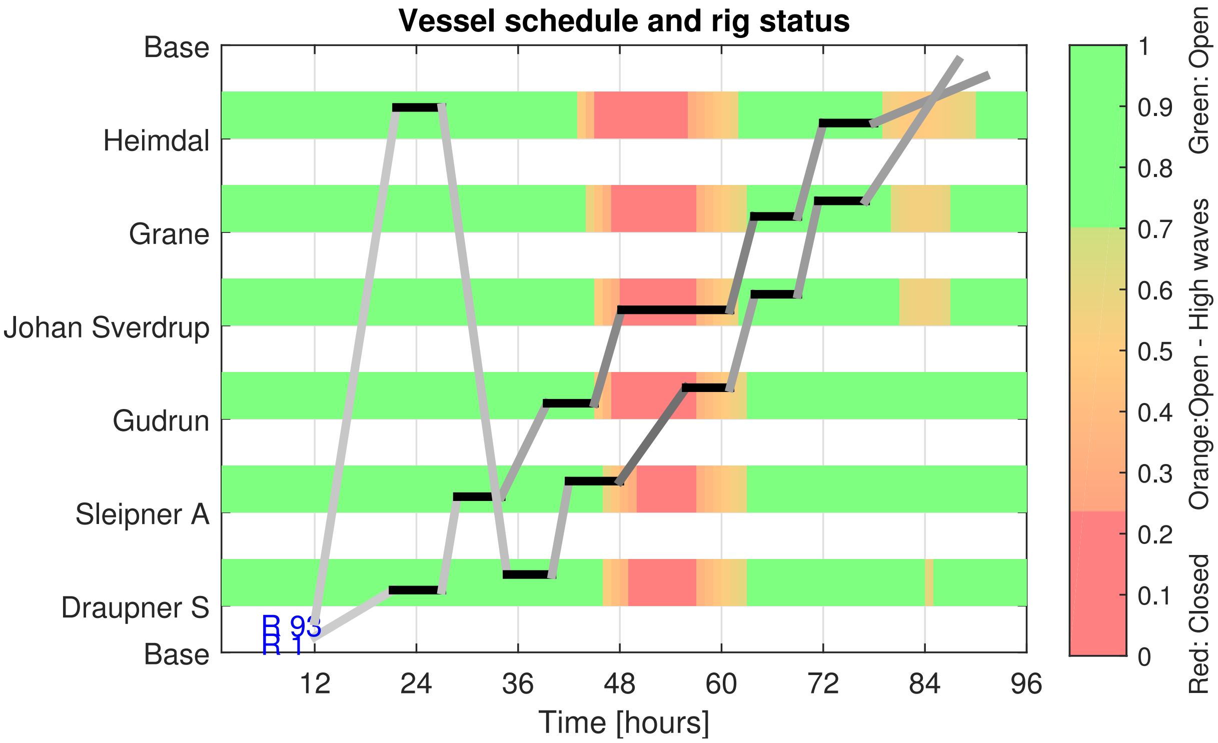


Figure 5.7: Schedule without time windows. The colour of the line represents the speed. A whiter colour is a higher speed. A detailed view of the speed is found in Figure 5.5

The line represents the vessel's route. The route number is given at the start of the line. The colour of the line represents the speed of the vessel, where a whiter speed is a faster speed. The speed can better be seen in Figure 5.5. The distances between the rigs are not equivalent to distance, but just the order of the first route. Here, the two lines are the optimal route (R93) and the shortest route (R1). The best way to distinguish the lines is to notice that route #1 is the line that keeps the lower black line in each horizontal status bar, where as route #93 is in the top part of each status bar.

Closed Hours

When introducing *open hours* the closed hours are shown as the reoccurring red bars. The sailing pattern becomes more complex and longer routes are more likely to become feasible. Figure 5.8 is not the same case as the previous figures, but uses time windows. The case with nightly closed rigs will be analysed in chapter 6.1.1. Please note that Figure 5.8 is not part of the previous case, but its purpose is to explain closed hours.

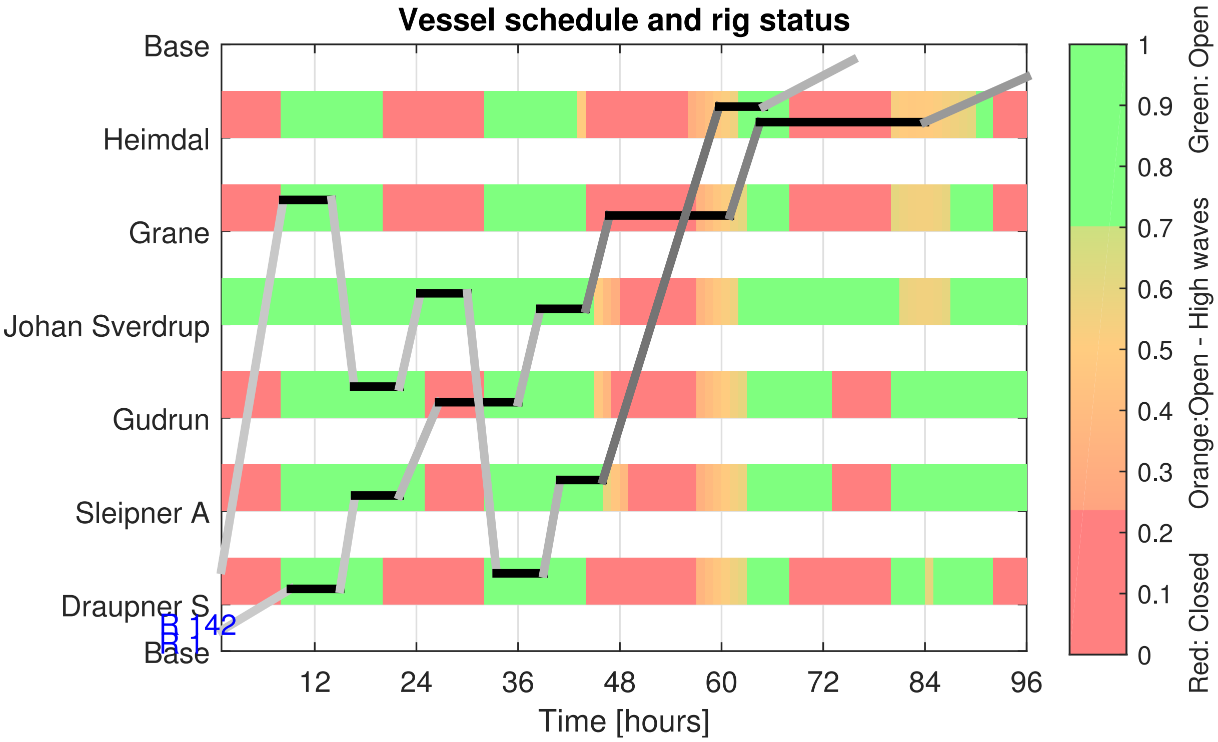


Figure 5.8: **New Case**: Route with time windows. The time windows are more complex and the best route can be a longer one.

In Figure 5.8 we see that route #142 is the best route, and finishes more than a day earlier than route #1.

5.1.2 Routing with Ensemble Forecasts

In ensemble mode many versions of a forecast are calculated in parallel. The router is calculated for each ensemble, where the durations and the costs are found. A confidence interval, with respect to the forecast, is created. The function of Figure 5.9 is explained by plots for each of the subplots, see Figure 5.10, 5.11 and 5.12 - and mind the footnotes.

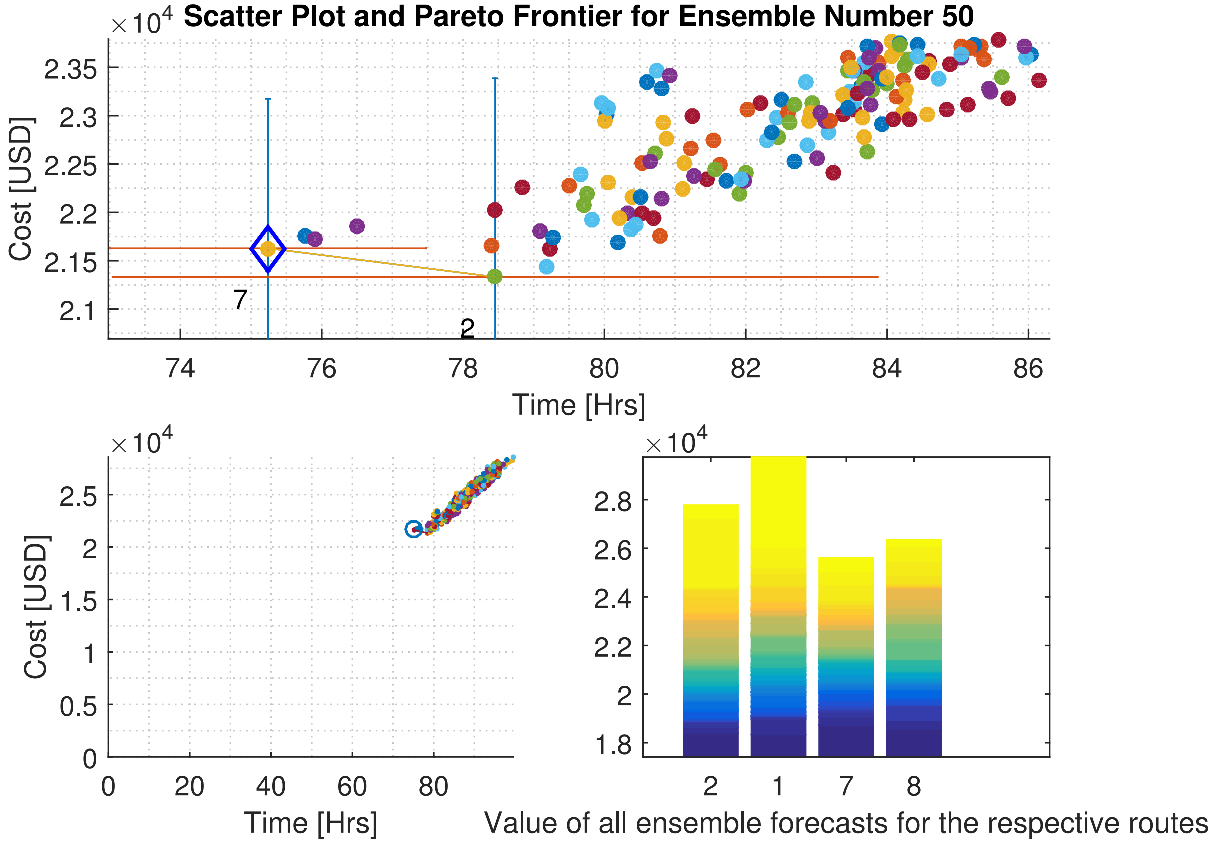


Figure 5.9: The complete ensemble scatter plot. Explanation to each subplot can be found in the following figures.

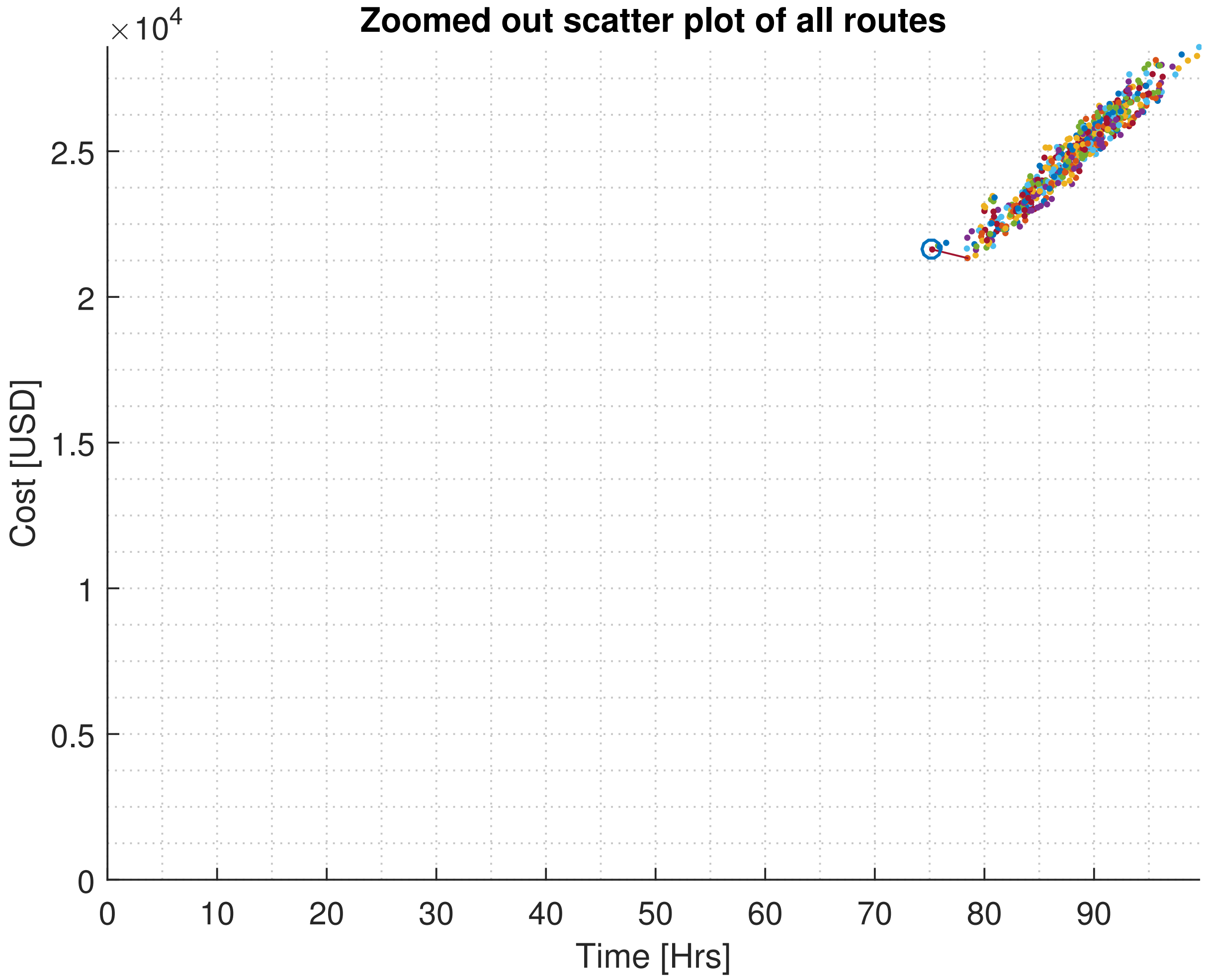


Figure 5.10: The zoomed out plot gives a perspective to the relation between the axes. The Pareto Frontier is plotted and the optimal route is circled

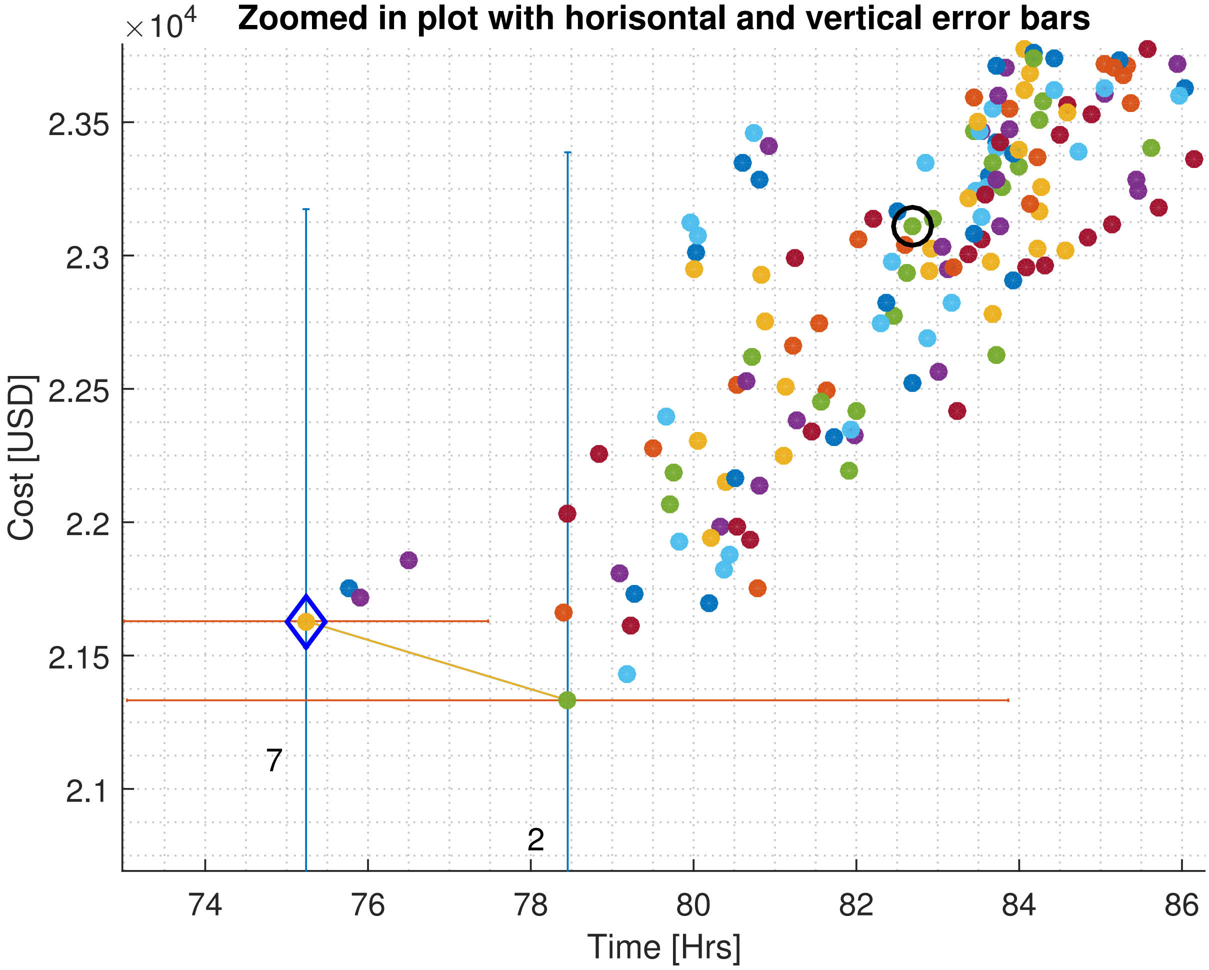


Figure 5.11: A zoomed in plot of the best routes. Each point is the mean duration and cost of each individual candidate route. The **horisontal lines** are the route duration confidence intervals. The **vertical lines** are the cost value confidence intervals - how certain the cost is. The **diagonal line** is the Pareto front of the routing case. The **blue diamond** expresses the best route (route #7), based on the route duration. The **black circle** is route #93, that was the best route of Figure 5.2

. It is interesting to notice that the best route of the deterministic forecast does poorly in the ensemble run. Each point is the mean route duration and the mean cost of the 50 ensemble forecasts.

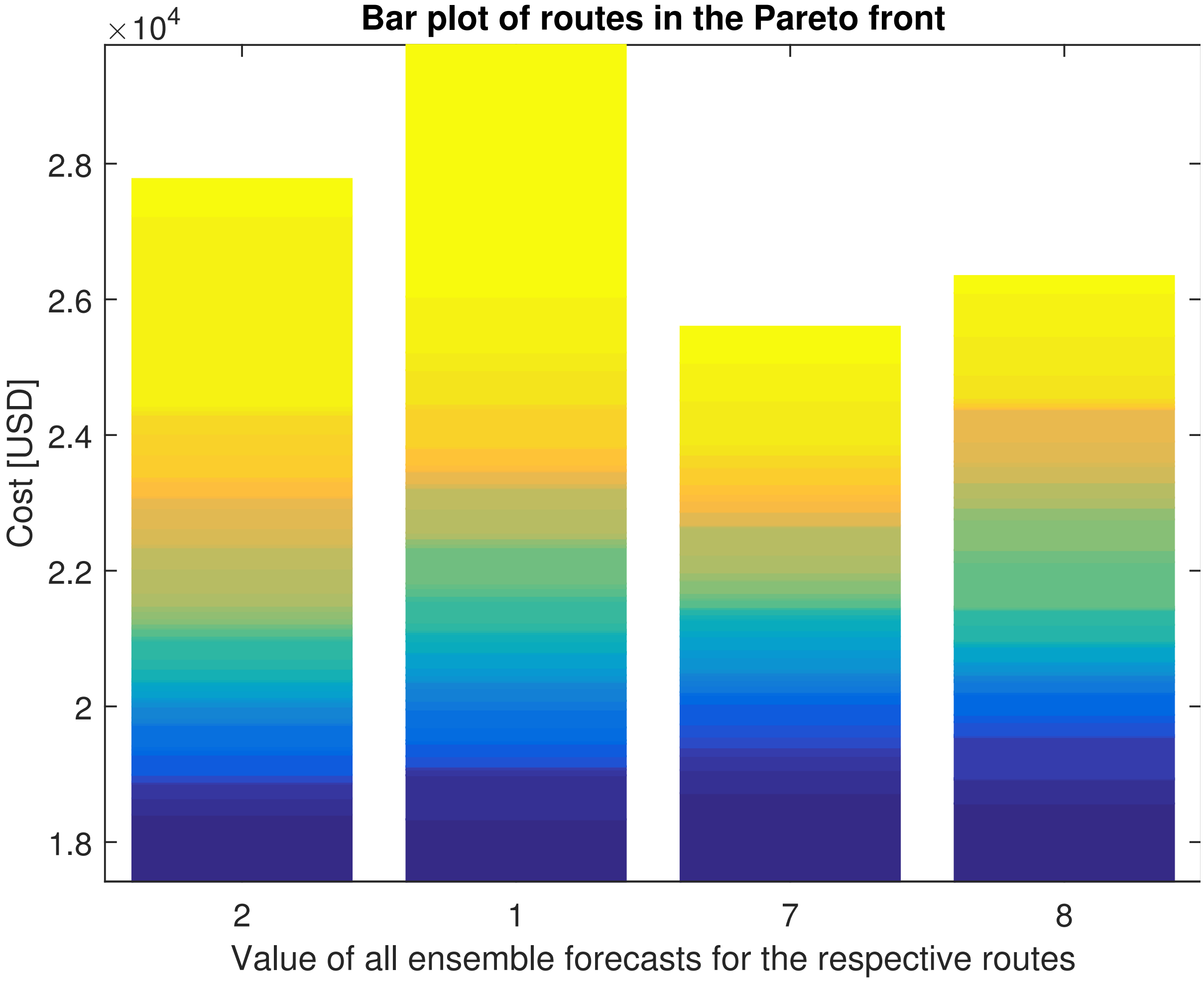


Figure 5.12: The bar graph of the routes in the Pareto Front, route #7 and #2 are plotted along with their counterparts; the routes sailing the opposite direction. All the values of the different ensemble runs are sorted and stacked - the bars consists of all the values from 50 ensemble runs. A compact bar means a more certain route cost - less variation.

5.2 Program Performance

The program is developed and executed in MATLAB version 2014b on a Dell Laptop dating back to 2010 with an Intel i5 520M processor and 8GB RAM.

Forecast	**Method**	**Type**	**Time Window**	**Routes Calculated**	**Timing**
met.no	Reduced	Deterministic	Open Nights	120	57.59s
met.no	Constant	Deterministic	Open Nights	120	45.86s
ECMWF	Reduced	Deterministic	Open Nights	120	48.26s
ECMWF	Constant	Deterministic	Open Nights	120	45.35s
ECMWF	Reduced	Deterministic	Closed Nights	120	56.05s
ECMWF	Reduced	50 Ensembles	Open Nights	720	4hrs
Initiations				-	10.41s

Table 5.1: Typical Program Performances

A few setups of the MasterPlanner is timed and the results are found in Table 5.1. Notice that most of the runs are done at 120 route calculations. The reason is that the best route is most of the time among the first and shortest routes. In order to save computation time, the number of calculated routes is reduced.

Function Name	**Calls**	**Total Time** [s]	**Self Time** [s]	**Description**
PSVrouter	1	48.257	0.002	Main program
reducedVelocityTSP	1	38.803	2.459	Method
extractGRIBdata	75287	17.149	17.149	Fetch metdata
findParamValue	10673	7.798	0.636	Vessel model
calcTotalRes	10673	5.754	5.123	Vessel resistance
encounteredWeather	1	5.241	0.066	WaveMap visualisation
m_idist	5381	4.635	3.305	Calculate arc distance
reduceSpeed	5381	3.714	2.301	Calculate speed reduction

Table 5.2: Timing of MasterPlanner: ECMWF - Reduced - Deterministic - Open Nights

The biggest time consumer is reading the metdata for each position (approx 50%). This script consists of a linear interpolation in the three dimensions; time, latitude and longitude, interpolating 8 points of data per value fetched. Another time contribution to the metdata fetch, is a work-around for the angle wrap-arounds. It is not sufficient to merely do an average of two angles, as the relevant average of 20° and 350° is 5° and not 185°. Table 5.2 shows the timings of a program execution. The visualisations (making graphs, mainly the map) are timed and contribute with approx. 10 seconds.

Provider	**Best Route**	**Time** [hrs]	**Fuel Costs** [USD]	**Saved Time**	**Saved Cost**
met.no	3	69.64	15724	0.08%	-0.90%
ECMWF	1	69.88	16720	0%	0%
WW3	5	72.37	19353	0.15%	2.06%
GWES-1	18	72.29	18100	0.63%	1.13%

Table 5.3: Comparison of Forecasts for 04.06.2015

Table 5.3 compares the different forecast providers by running the MasterPlanner for the exact same date. Notice that the WW3 and GWES-1 (one ensemble) are 2.5 hours slower than met.no and ECMWF. This is a topic to explore further, and is suggested in further work (chapter 7.2).

6: Discussion

This chapter will continue to analyse the different setups and then express some thoughts regarding the MasterPlanner. Section 6.1 will investigate the remaining modes and features in the MasterPlanner and comment on the outcome. Section 6.2 will discuss some thoughts on the achievements of MasterPlanner, but it will also cover important shortcomings. One of the really interesting applications of Masterplanner will be discussed in section 6.2.2.

Chapter 5 introduced the output from MasterPlanner, while presenting the first case. The following section will continue the presentation with the case considering nightly closed rigs. (the first figure was shown on page 39.)

6.1 Functionality Analysis

This section will explore the different functions in the program, and assess their use. The test case will be set to the forcast of March 19th, 2015 00:00, powered by ECMWF deterministic and ensemble forecasts. The cost function is operational costs without charter costs (only fuel costs), in order to make the cost function less time dependant (the charter cost is calculated per hour). Figures like 5.1 will illustrate which setup that is currently investigated. The fuel price is set to 600 USD per metric tonne.

6.1.1 Reduced Speed

The first case is using the ’reduced speed’-method. The case for open rigs around the clock was presented in chapter 5, along with the actual plots. This section will cover the case of closed hours.

Rigs closed at night

Closing hours and their implications are discussed in Fagerholt and Lindstad (2000). MasterPlanner has incorporated closing hours as being rig specific, with any combination possible. Interestingly route #142 is the optimal route. The route is 15% longer, but performs 25% better on the other KPI's. The reason can be observed in Figure 6.6 and 6.7. It can be observed that time saving routes score well, i.e. routes that does not have to wait.

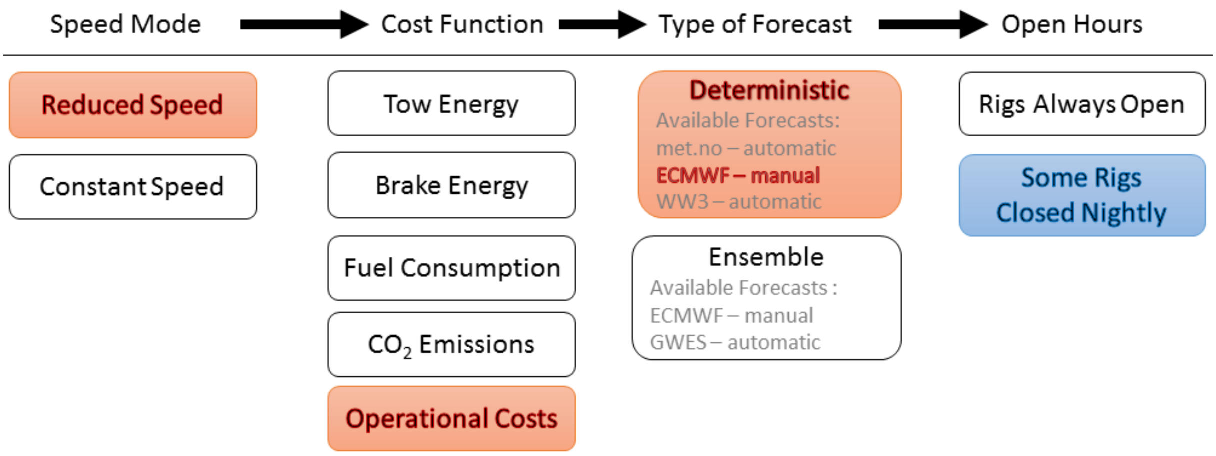


Figure 6.1: Program Setup for nightly closed rigs

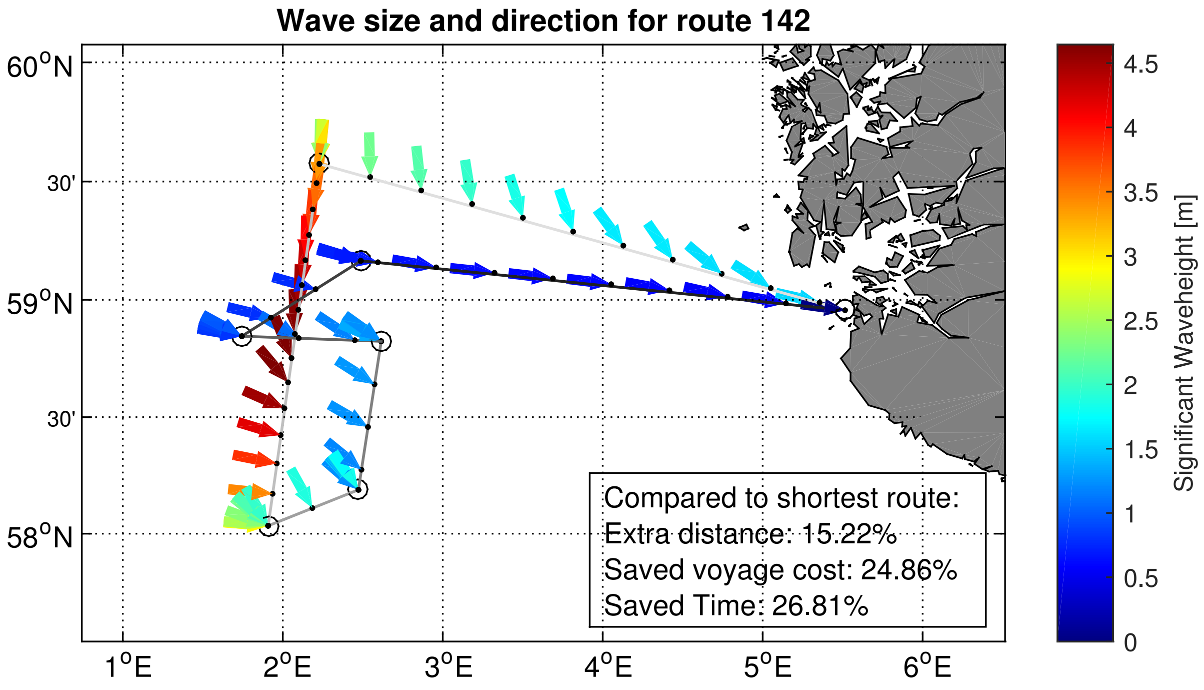


Figure 6.2: WaveMap: The optimal route is 142.

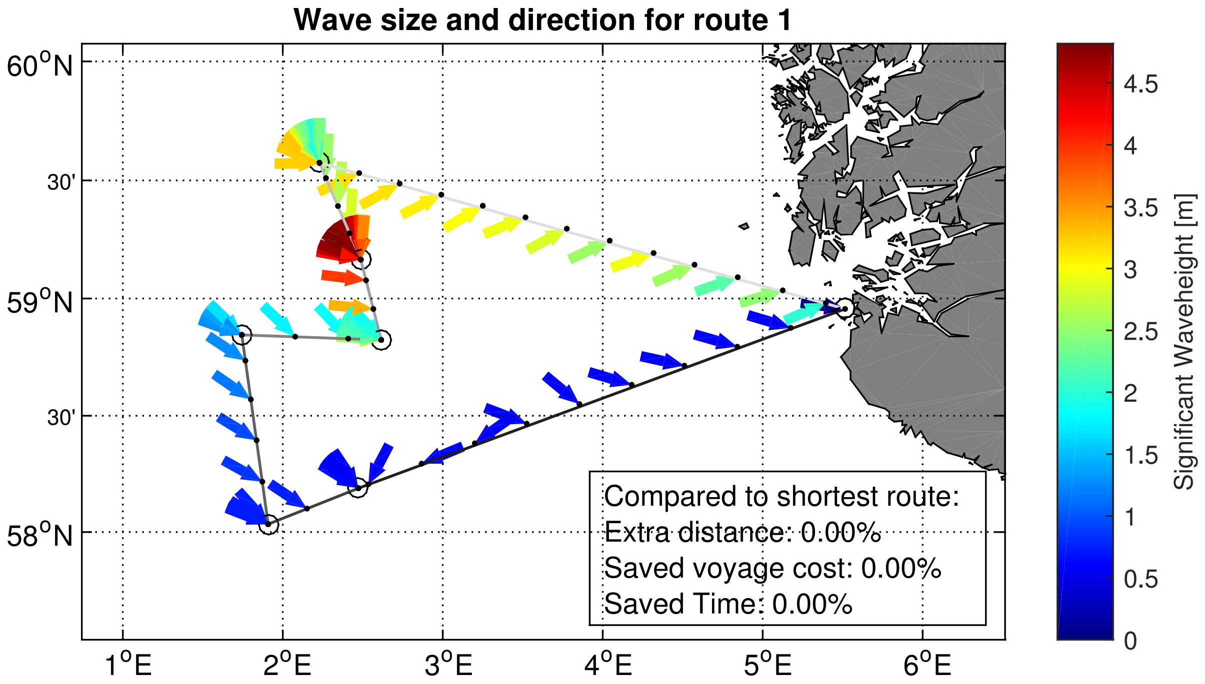


Figure 6.3: WaveMap: Shortest route for setup with time windows

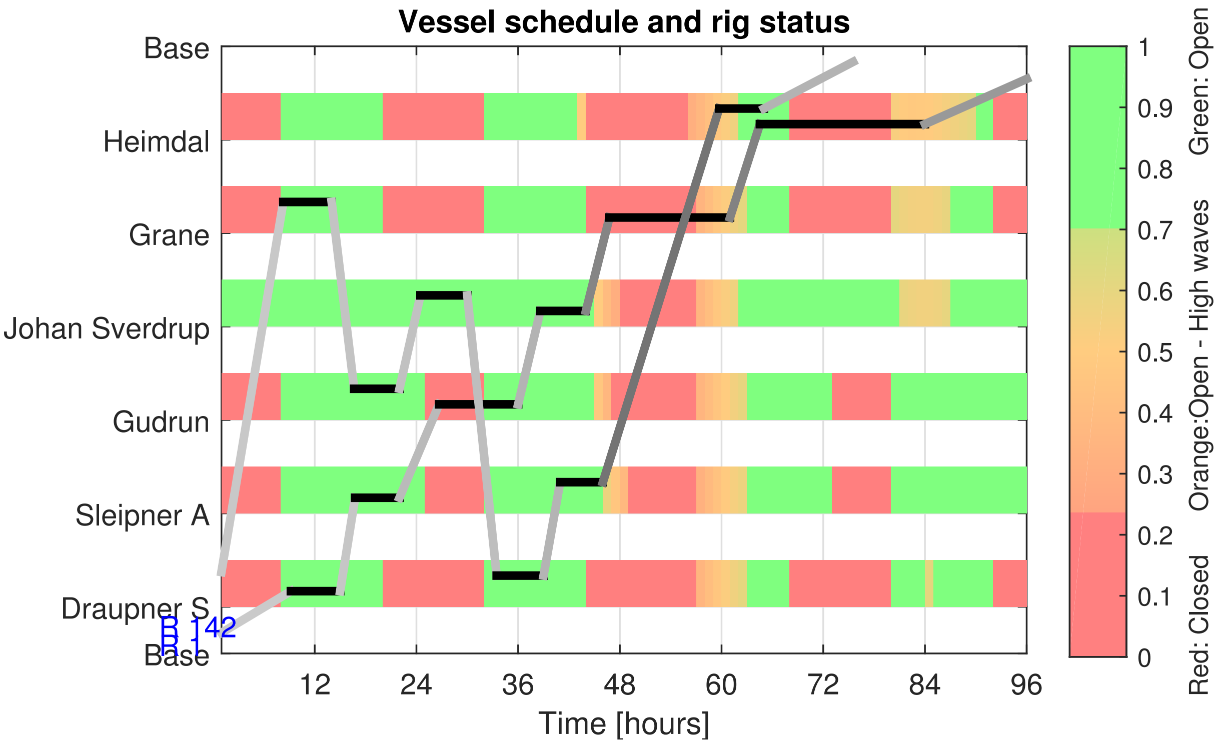


Figure 6.4: Schedule: The schedule with nightly close downs was thoroughly explained at page 39. However we see the perfect timing of the route #142, compared to route #1.

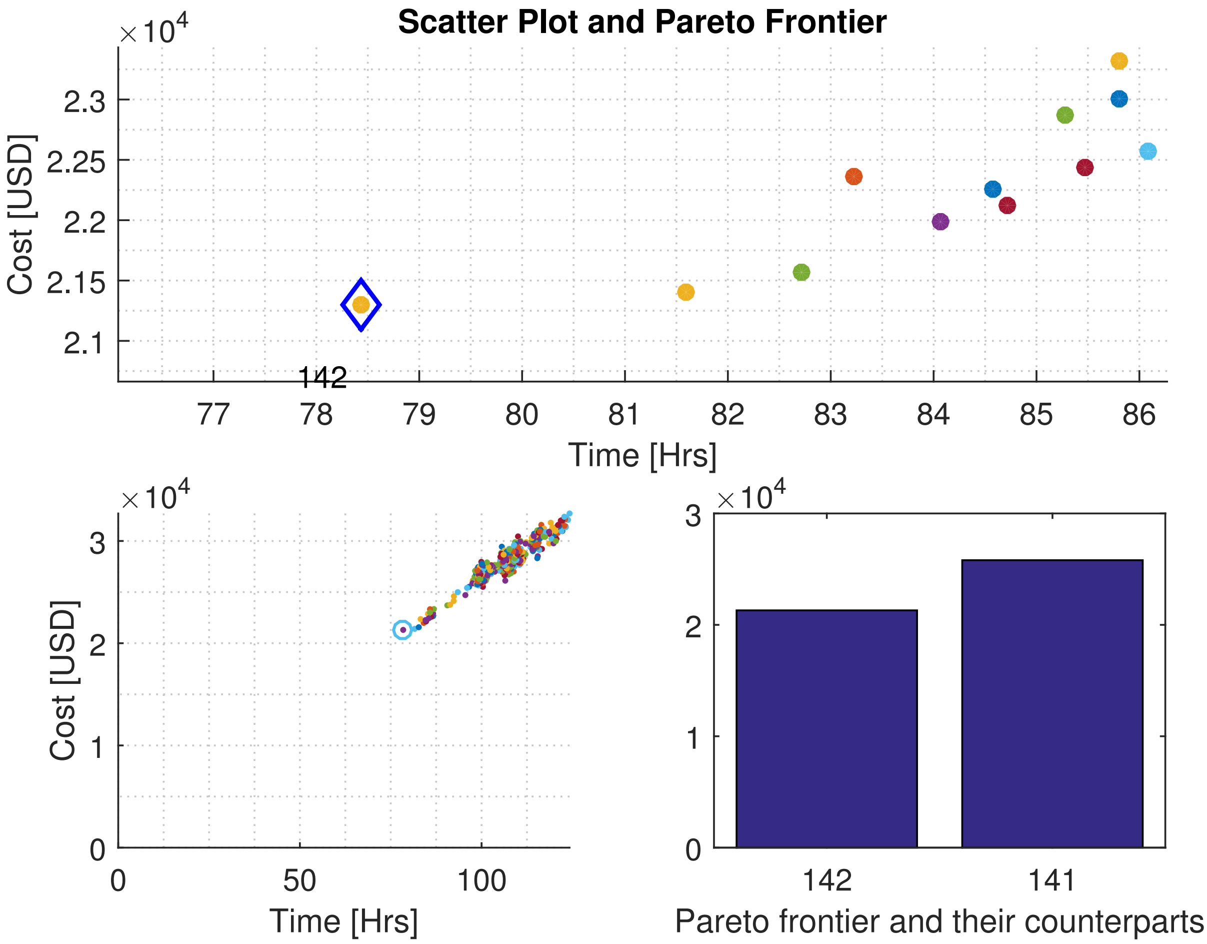


Figure 6.5: Scatter Plot: The stretch in the results is due to the complexity of the route. The optimal route (#142) is the route that best hits the windows, and minimises waiting time.

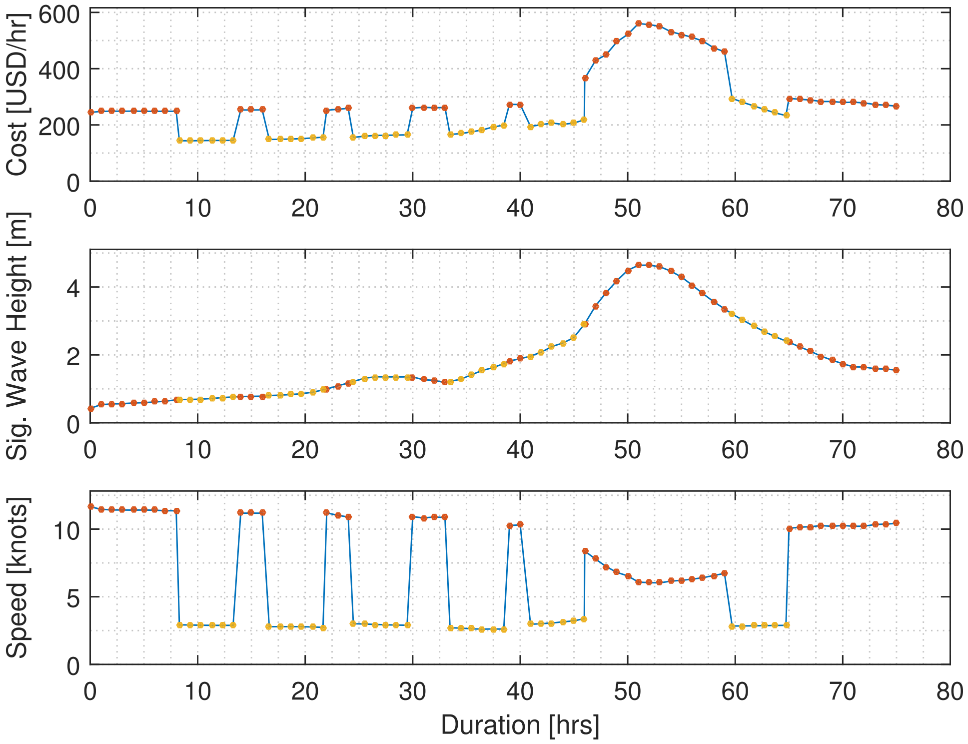


Figure 6.6: Cost vs Wave Height vs Vessel Speed: The optimal route (#142). Notice the lack of waiting periods (purple dots)

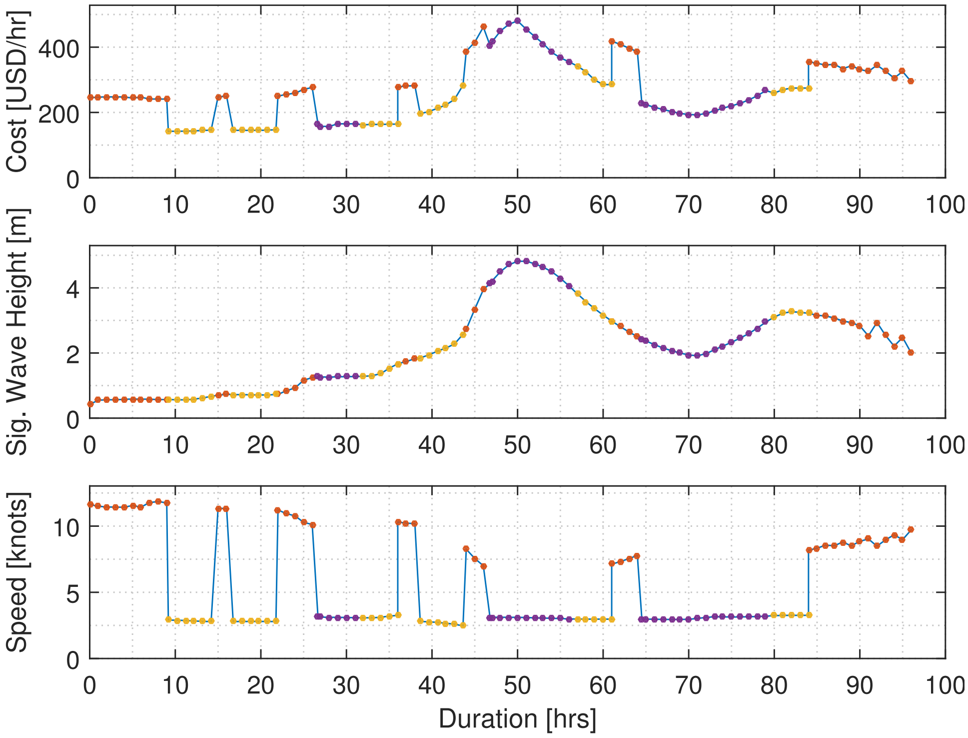


Figure 6.7: Cost vs Wave Height vs Vessel Speed: The shortest route (#1). The amount of waiting is significantly larger than in Figure 6.6

6.1.2 Ensemble Forecasts - Reduced Speed

The ensemble calculation is the same setup as seen in chapter 5 and Figure 5.2. Here the MasterPlanner is calculating routes fifty times, for fifty ensemble forecasts.

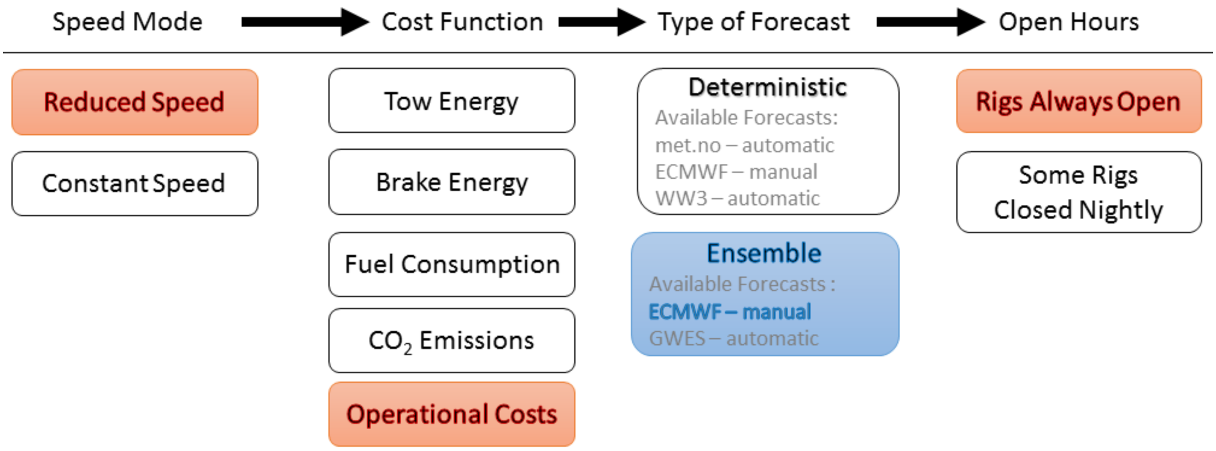


Figure 6.8: Program setup for the ensemble run

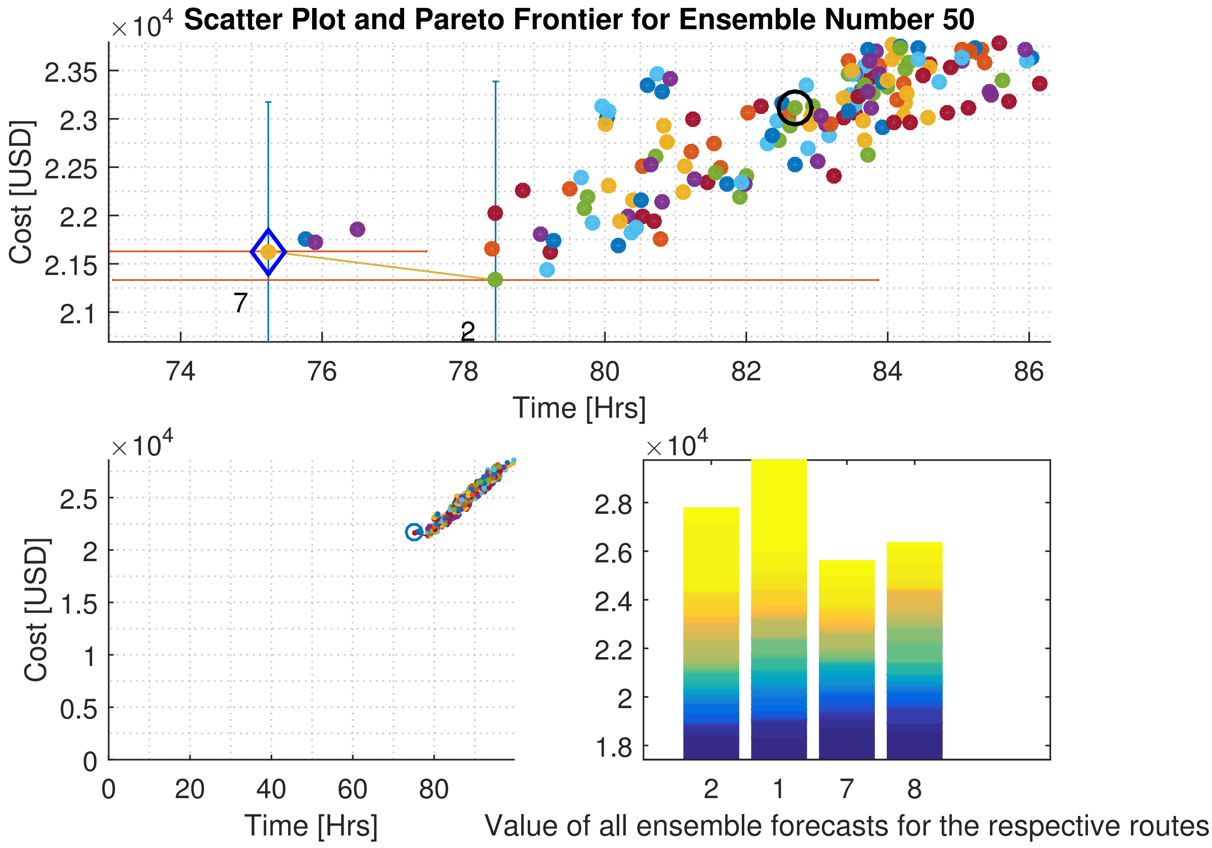


Figure 6.9: Scatter Plot: Notice the black circle highlighting route 93 - that was the best route in Figure 5.2

When 50 ensembles are calculated, the robustness of the route is determined. The variation of route 7 in Figure 6.8 are significantly smaller than the other route in the Pareto front. This means that through all the calculations, route 7 performs great overall. In addition, when we look at route 93, that was the best route in Figure 5.3, it performs mediocre in the ensemble test. In Figure 6.9 route 93 is highlighted with a black circle. Hence, the ensemble calculation is probably more useful than the deterministic forecast.

6.1.3 Constant Speed

The constant speed mode sets a fixed speed for the vessel, for the entire route. If the vessel misses a time window, the vessel is set to a slower speed in order to hit the next time window. This method was developed to offer the reduced speed method a comparison method. It can be observed that full speed in 4.5 meter waves requires a lot of fuel to maintain the speed, and is probably not plausible in a real life scenario.

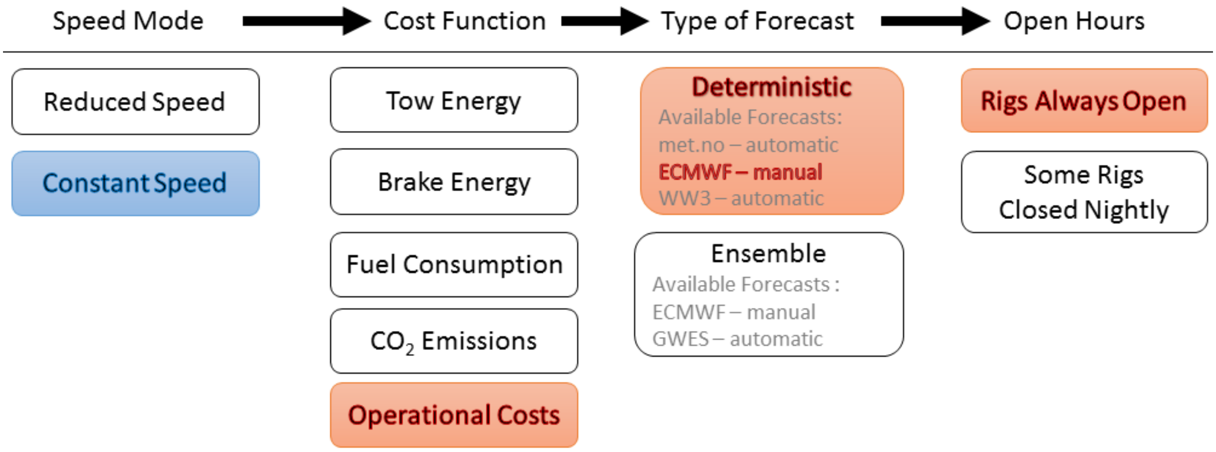


Figure 6.10: Program setup for the constant speed mode.

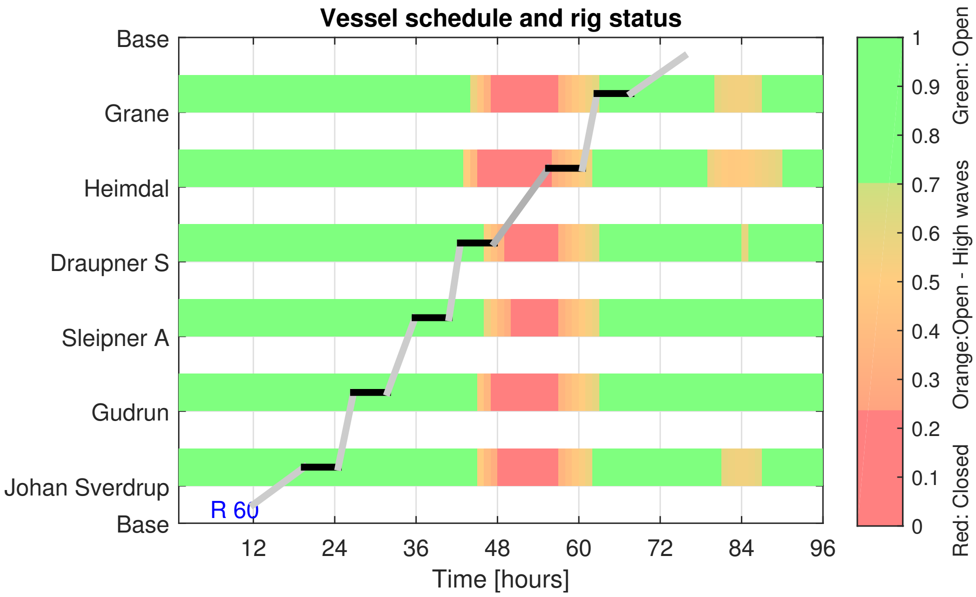


Figure 6.11: Schedule: The speed is higher throughout the route.

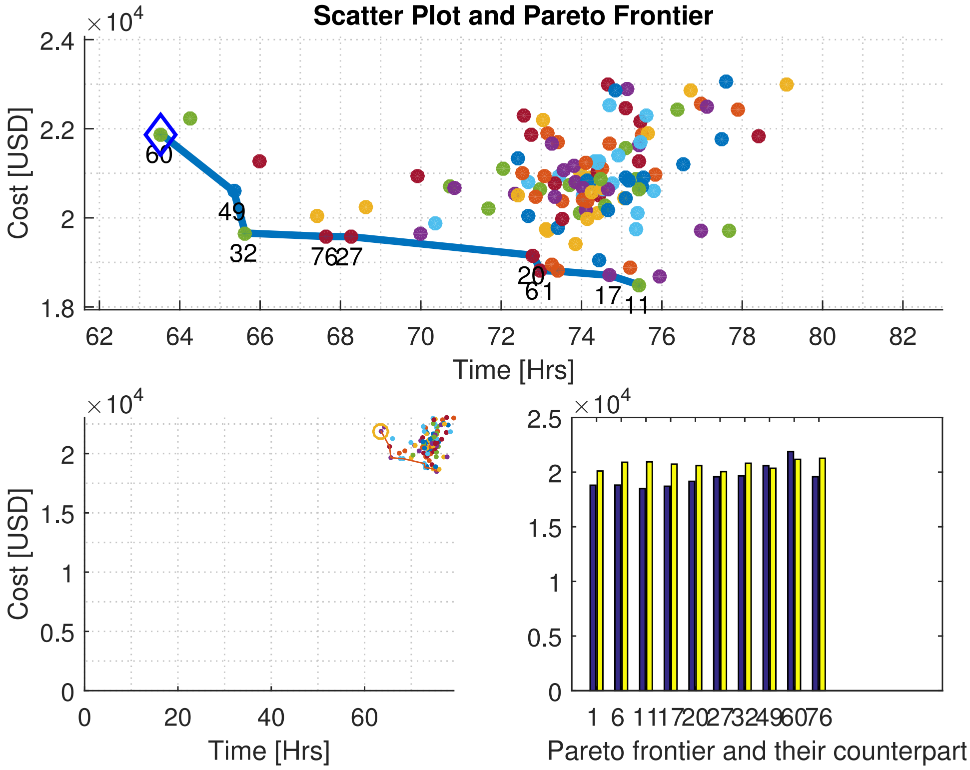


Figure 6.12: Scatter Plot: The wave-size independent speed makes more routes attractive. Interestingly, the route cost of this method is very similar to the values of the routes in Figure 5.2 at page 34.

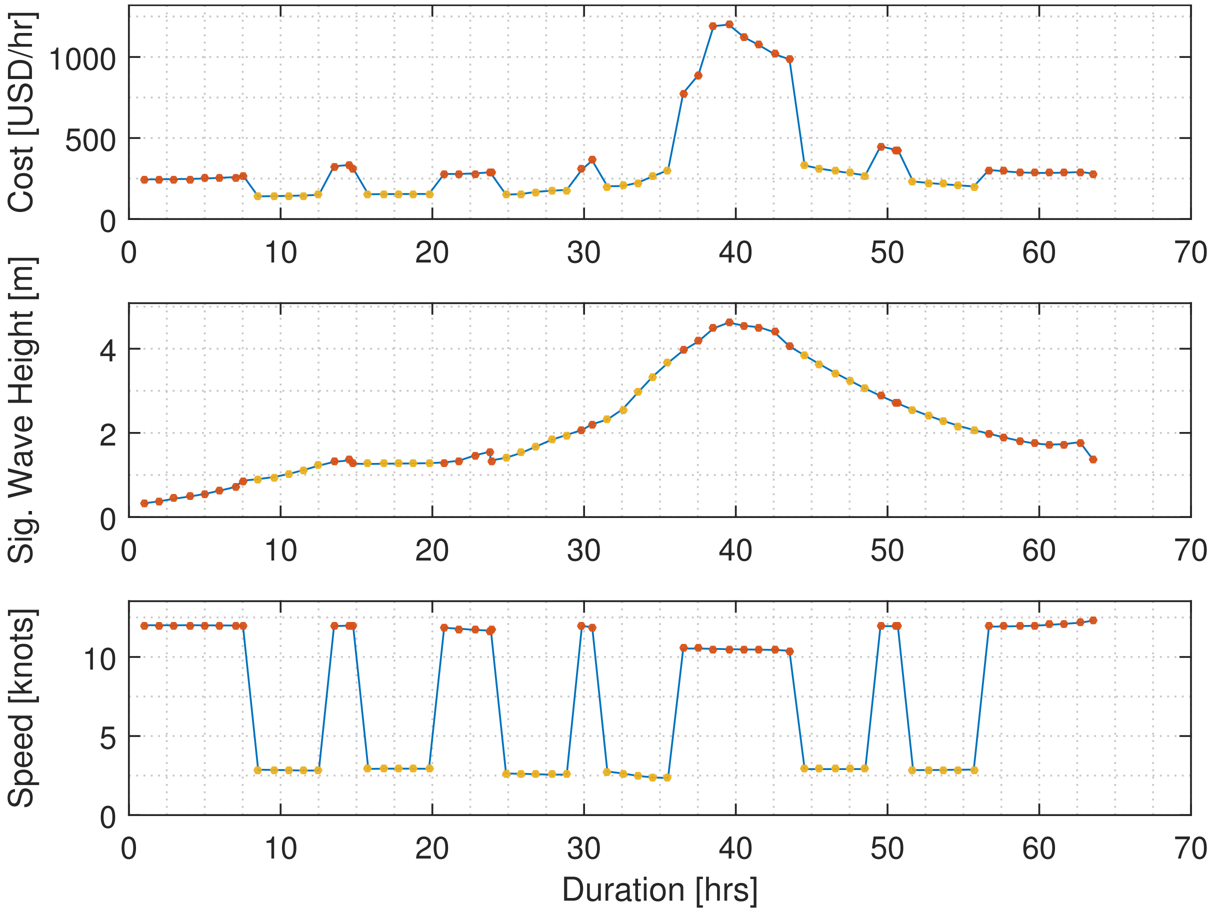


Figure 6.13: The cost comparison shows a huge peak associated with the highest wave heights.

6.1.4 Mandatory Stop

If the vessel has to be at one station at in a given time span, what is the best route? The problem was can be solved in the MasterPlanner, by using specified time windows as seen in Figure 6.14.

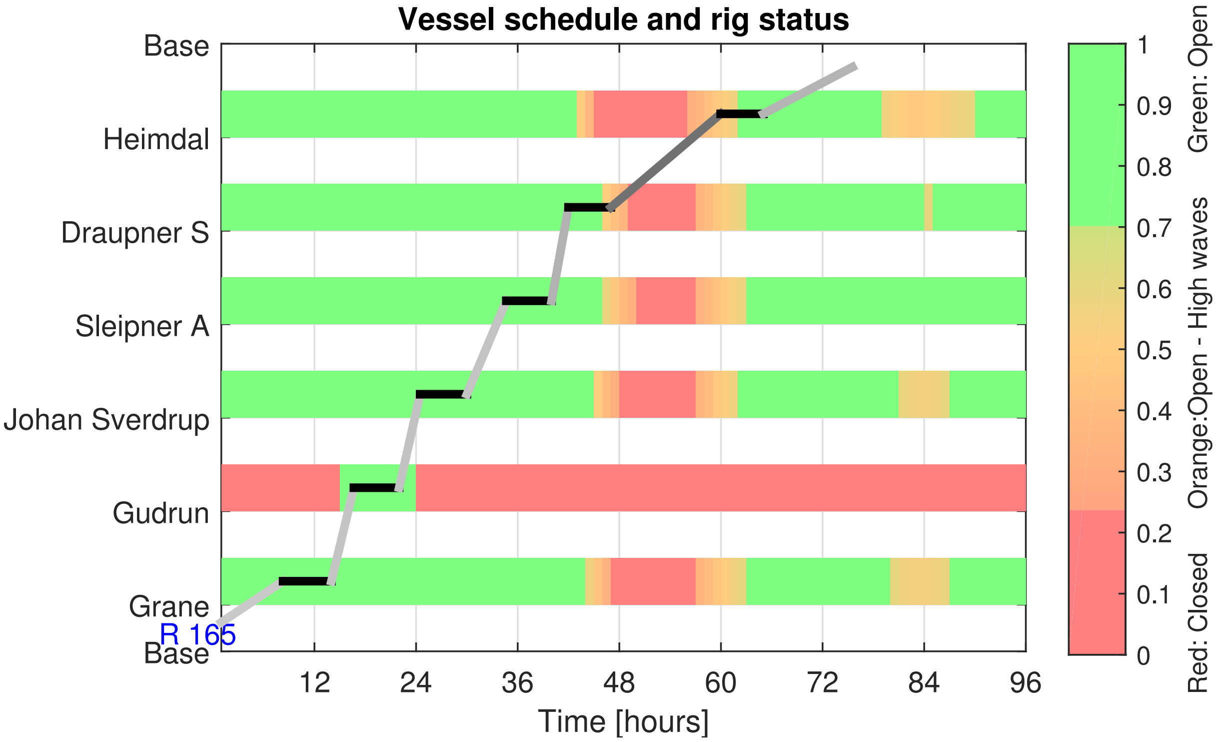


Figure 6.14: Schedule: Mandatory stop

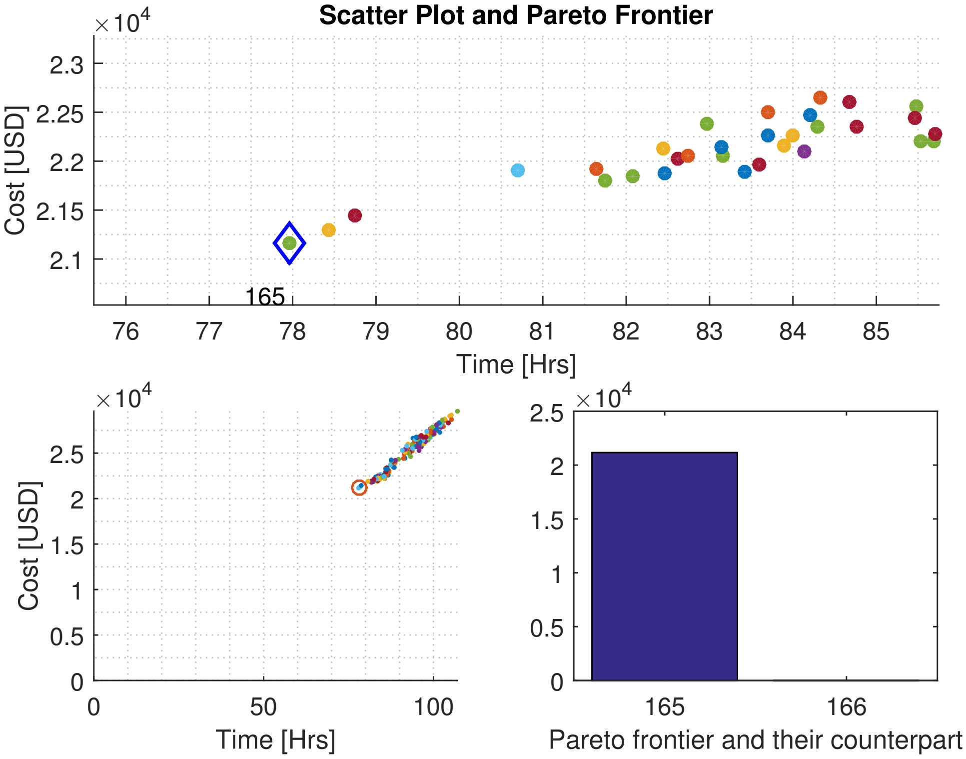


Figure 6.15: Scatter plot for mandatory stop: The number of feasible routes is drastically reduced due to the hard constraint. Notice that route #166 is not present – a route that fails to make the circuit is given as a 'nan', a fail.

6.2 Thoughts regarding the MasterPlanner

The program is developed to be as general as possible. It is to work with any route, ship model and forecast provider, as long as the format of the input is the same. The possibilities available with this problem is hardly covered in this thesis, however a flavour is revealed. Some shortcomings and drawbacks exist, and the identified ones are covered here:

Inaccurate Dynamic Positioning Model

The DP-mode is currently modelled as a transit with 1.5 [m/s]. The heading is assumed to be towards the waves. This model is far too simplified. Currents are not integrated properly. A more sophisticated DP-model is suggested as further work in section 7.2 at page 63.

Rigid departure times and rigid speeds

The time of start is set as an input, and as a consequence some longer routes become feasible, due to the perfect fit of time windows. A more robust solution, especially when encountering bad weather, would be to set the departure time as the first possible departure, and then let the program find the ideal time of departure.

The speed calculation is rigid (either set speed, or set propulsive power), and some time windows that are missed could be reached by regulating the speed in a smarter manner.

Hull Resistance

The vessel resistance in waves is calculated by the direct pressure integration-method. ShipX can also utilise the Gerritsma and Beukelman-method. The difference between the methods Gerritsma and Beukelman, and direct pressure integration is not explored, but the pressure integration method is chosen based on recommendations.

ShipX Veres uses strip theory for the hull under the waterline. The contribution over the waterline is neglected. The resistance calculation should be validated or improved before running any real-life routing.

Missed potential in weather forecasts

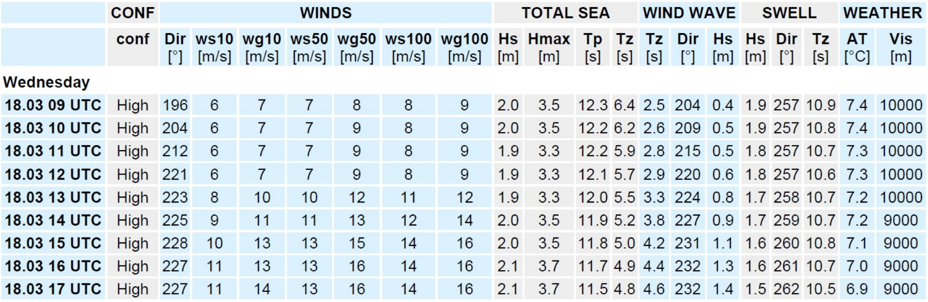
The meteorological data models used in the program contains more data than actually used. The program currently uses a total combination of all swells, whereas a superposition of the different wave components (e.g. primary-, secondary- and wind- swell) could render a more detailed simulator.

Big Savings Needed to Change Route

The parties involved in the upstream logistics are reluctant to change. If the expected improvements are in the range below 5%, the gain is probably deemed in vain. The supply plan follows a weekly schedule, thus introducing uncertainties in the delivery times can cause more hassle than the costs saved. So are the findings here really useful? It might not be, as the old habits overrides small, uncertain savings.

6.2.1 MasterPlanner as Weather Viewer

In case the weather routing is not attractive for the operators, it can serve as a weather forecast displayer. The current weather forecasts are often presented as tables of values like Figure 6.16. A more graphical weather forecast than just a table or a simple GRIB-viewer should be of interest. Recent rules requires ECMIS at the bridges of Norwegian ships over a certain length (see Appendix A.4). This means that a suitable display is already installed on vessels.



	CONF	WINDS							TOTAL SEA				WIND WAVE			SWELL			WEATHER	
	conf	Dir [°]	ws10 [m/s]	wg10 [m/s]	ws50 [m/s]	wg50 [m/s]	ws100 [m/s]	wg100 [m/s]	Hs [m]	Hmax [m]	Tp [s]	Tz [s]	Tz [s]	Dir [°]	Hs [m]	Hs [m]	Dir [°]	Tz [s]	AT [°C]	Vis [m]
Wednesday																				
18.03 09 UTC	High	196	6	7	7	8	8	9	2.0	3.5	12.3	6.4	2.5	204	0.4	1.9	257	10.9	7.4	10000
18.03 10 UTC	High	204	6	7	7	9	8	9	2.0	3.5	12.2	6.2	2.6	209	0.5	1.9	257	10.8	7.4	10000
18.03 11 UTC	High	212	6	7	7	9	8	9	1.9	3.3	12.2	5.9	2.8	215	0.5	1.8	257	10.7	7.3	10000
18.03 12 UTC	High	221	6	7	7	9	8	9	1.9	3.3	12.1	5.7	2.9	220	0.6	1.8	257	10.6	7.3	10000
18.03 13 UTC	High	223	8	10	10	12	11	12	1.9	3.3	12.0	5.5	3.3	224	0.8	1.7	258	10.7	7.2	10000
18.03 14 UTC	High	225	9	11	11	13	12	14	2.0	3.5	11.9	5.2	3.8	227	0.9	1.7	259	10.7	7.2	9000
18.03 15 UTC	High	228	10	13	13	15	14	16	2.0	3.5	11.8	5.0	4.2	231	1.1	1.6	260	10.8	7.1	9000
18.03 16 UTC	High	227	11	13	13	16	14	16	2.1	3.7	11.7	4.9	4.4	232	1.3	1.6	261	10.7	7.0	9000
18.03 17 UTC	High	227	11	14	13	16	14	16	2.1	3.7	11.5	4.8	4.6	232	1.4	1.5	262	10.5	6.9	9000

Figure 6.16: Forecast example for a location in the North Sea. Illustration by courtesy of StormGeo

6.2.2 Aid to Design Future PSVs and Logistics Chains

MasterPlanner can be used to establish typical operational profiles and life cycles in order optimise new build specifications. A hindcast study spanning over years can gather information about weather encountered and time spent in transit, waiting and DP. This information can be crucial in the process of deciding new build design criterias.

The whole problem can also be flipped upside down, from the single vessel perspective to the field life time perspective. Say an oil company wants to make sure the current configuration of vessels and upstream logistics is sufficiently optimal yet robust. A discrete event simulator simulating stochastic demands on actual hindcast meteorological data can calculate an optimal fleet composition.

7: Conclusions & Future Work

7.1 Conclusions

The objective of thesis has been to study weather routing of short sea shipping. The supply vessel weather routing problem has been introduced and the focus has been to solve this problem with a MATLAB-program, with the use of meteorological data sets and vessel resistance simulation. The program has been developed and named 'MasterPlanner' (since it is a Master's Thesis and an operation planner). The following bullet points sums up the conclusion:

- **Weather routing of supply vessels is possible and feasible.**
- Borderline weather is the most applicable scenario for weather routing
- Typical improvements for a route in light weather (ca. 3 meter max Hs) is <5%. This is not significant due to uncertainties.
- Scenarios with complex time windows can be optimised with >20% better time and cost efficiency - based on the current model.
- Accurate model inputs are crucial to the routing application.
- Constant speed rates seems to be a bad approximation/simplification.
- MasterPlanner could excel as decision support and forecast viewer.
- Weather routing in a life cycle simulator has great potential.

7.2 Further Work

The underlying idea of the thesis is ripe to be explored further. Effective use of weather forecasts in a direct way has spun off to several ideas where forecasts can be used. With the basis in the idea of MasterPlanner, some suggestions for further work follows:

Comparison study: Model data versus real data

Vessels can be equipped with an immense amount of sensors, to measure virtually all aspects of operations. A suggestion is to develop a program that systematically store data in order to build up sailed route profiles and overall resistance profiles. In order to increase the accuracy and performance of a weather router, the real data can be incorporated into the model and use some learning algorithms to find trends and patterns, or validate models.

Weather Routing for Wellboats and Windmill Service Vessels

During the last years the size and complexity has increased for vessels carrying fish from fish farms to onshore facilities. The fleet management and routing aspect, could apply to these vessels in the same way they apply to PSV’s. The emerging sector of maintenance of offshore windmills can benefit from weather routing. Further work could be to set up cases as likely scenarios and explore the effect of weather routing.

Simulating life cycles of vessels and oil fields

A weather routing software can do Monte Carlo simulation of vessels life cycles, by using hindcast and possible supply routes. Useful design criterias like time spent in DP, and an ’encountered weather profile’ , can help ship designers and to optimise future ship design.

The simulation of oil field logistics chains can be done by doing discrete event simulation. I.e. run the MasterPlanner for a year or ten, with likely voyages and evaluate the outcome. This approach can suggest whether a fleet setup is likely to work or not.

Fleet Management with Weather Data Support

Further develop the vessel voyage optimisation to include the entire fleet. Christiansen et al. (2007) states that:

> *Routing* is the assignment of a sequence of ports to a vessel. *Environmental routing* or *weather routing* is the determination of the best path in a body of water that a vessel should follow..

The suggestion is to merge the high-level routing and the low-level weather routing in order to maximise the coverage of supplies. In border-line weather or before storms, this could be a particularly useful way to meet every installation's demand.

Specialised Vessels

Aas et al. (2009) suggests looking into specialised vessels and explore their effect on the supply vessel routing problem. A more specialised vessel (e.g. bulk only) could probably be built to withstand harsher weather, and thus offer more certain deliverance.

Optimisation of Each Leg

Do dynamic programming for each leg, exploring the effects of exploiting currents, tides and local weather to reduce fuel consumption. See Hinnenthal (2007) and Avgouleas (2008).

Modelling and Optimisation of WOW and Dynamic Positioning

The current DP-model is not accurate, and a more thorough model would be advantageous toward a more accurate vessel simulator. Suggestions would be to make look-up tables or simulators with input of environmental factors that output needed break power. Another suggestion is to look into more cost optimal DP as suggested in the works of Fossen and Strand (2001) andKjerstad and Breivik (2010)

Automate Information Flow - Increase Integration

Currently we see a shift towards 'smarter' systems, where tasks are automated. I.e. information from Load Computer should be available for integration with other systems that could benefit from the data. Data concerning the journey (rig availability, priority, etc.) could automatically be integrated into the operation planner.

Autonomisation

Situation awareness for crewless vessels. Detailed routing. Development of onshore operational DSS that gives right advices in order to make the right decisions.

Increase Weather Model Fidelity

The forecasts provides a vast number of variables (see Table 7.1). The variables not used in this thesis could better describe the weather condition and improve the weather routing problem.

In Use	Available
10 metre wind direction	Air density over the oceans
10 metre wind speed	Benjamin-Feir index
Mean direction of total swell	Coefficient of drag with waves
Mean period of total swell	Free convective velocity over the oceans
Significant height of combined -wind waves and swell	Maximum individual wave height
U-component stokes drift	Mean direction of wind waves
V-component stokes drift	Mean period of wind waves
	Mean square slope of waves
	Mean wave direction
	Mean wave period
	Mean wave period based on first moment
	Mean wave period based on first moment for swell
	Mean wave period based on first moment for wind waves
	Mean wave period based on second moment
	Mean wave period based on second moment for swell
	Mean wave period based on second moment for wind waves
	Model bathymetry
	Normalised energy flux into ocean
	Normalised energy flux into waves
	Normalised stress into ocean
	Peak period of 1D spectra
	Period corresponding to maximum individual wave height
	Significant height of total swell
	Significant height of wind waves
	Wave spectral directional width
	Wave spectral directional width for swell
	Wave spectral directional width for wind waves
	Wave spectral kurtosis
	Wave spectral peakedness

Table 7.1: ECMWF Variables Available in the Ocean Wave Model

Highly Parallelisable

The program written in this project is to be considered a 'proof of concept' and is hardly written with regards to computation speed - it is written in MATLAB. However the task at hand is very well suited for efficient computation. I suggest GPU programming (i.e. with metdata stored in texture memory to make the memory operations very effective). This could make it feasible to optimise entire fleets and detailed leg optimisations.

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A: Additional Background Information

A.1 Experience from Chief Officers

I have been in contact with first mate Jostein Straume, and first mate Christian Remøy in order to get an idea of the state of the art. I will summarise their thoughs and experiences based on how a decision support system can be of help:

Forecasts Weather forecasts are rapidly improving. In the last decades the forecasts have gone from a VHF radio-message, through Telex, to special area forecasts based on global computational models.

Displaying Information The ECDIS is the main source of map information, and is prone to too much information. Crucial information can be lost in the mess.

Broadband Limit Satellite broadband is not cheap, and ship owners tend to save money where money can be saved. Nowadays 128kb/s is the de facto standard. Subject to improvement in the future.

A.2 Statoil Marine Operations

Statoil Marine Operations is an internal organ of Statoil ASA, and is responsible for all vessel traffic in the vicinity of offshore installation and all vessels in service for Statoil, upstream and downstream. MO is utilising vessel traffic monitoring and information systems (VTMIS) in order to monitor all vessel activity. They make schedules for the coming weeks, based on the need for goods on the installations. Fleet Optimisation is utilised to improve vessel efficiency. A typical trip for a PSV lasts 2-3 days and visits 2-6 installations. Loading time at each installation is typically 3-5 hours, but can be longer and shorter in duration. The typical characteristics are summarised in tablee A.2

Voyage Characteristics		
Description	**Typical Values**	
Stops	2-7	Installations
Loading time per installation	3-5	hours
Voyage Length	2-3	days
Hs Limit	4-5	meters
Visits per week	1-3	times

Table A.1: Voyage Characteristics

From informal talks with MO, they identified borderline weather conditions as the most relevant scenario for deterministic weather routing.

A.3 Ways to reduce fuel consumption for PSVs

The overall goal for the field explored in this thesis is to reduce costs, and lessen the environmental impact of ships. The bigger picture is crucial in order to pinpoint which parts of the puzzle that are prone to improvements.

Weather Routing on transit Avoid bad weather and unfavorable conditions. Could also decrease motion sickness and damage on cargo.

Speed Variations Within given constraints, reduce and increase speed to "hit" better conditions, e.g. avoiding local weather, hit favourable tides etc.

Improve Arrival Time Estimations If a supply vessel is due to load to a rig at 16:00, there is no point to be at site 5 hours in advance. Might be better to slow-steam to location.

Operation Mode Optimise the use of operation modes to the most fitting mode. I.e. with the introduction of diesel-electric propulsion, a PSV reduced fuel consumption by 50% during DP-operations.

Precision Requirement If a vessel is standing by, does it need to be within 5 meters of a setpoint?

Crew Incentives The first place to start saving fuel is to encourage the crews. Without them, all the equipment in the world count for nought. A campaign where the element of competition is introduced might spark the crew's interest. A great example is the Solstad Green Operation (Solstad, 2015) where they believe to have reduced consumption by 20% as seen in figure A.1.

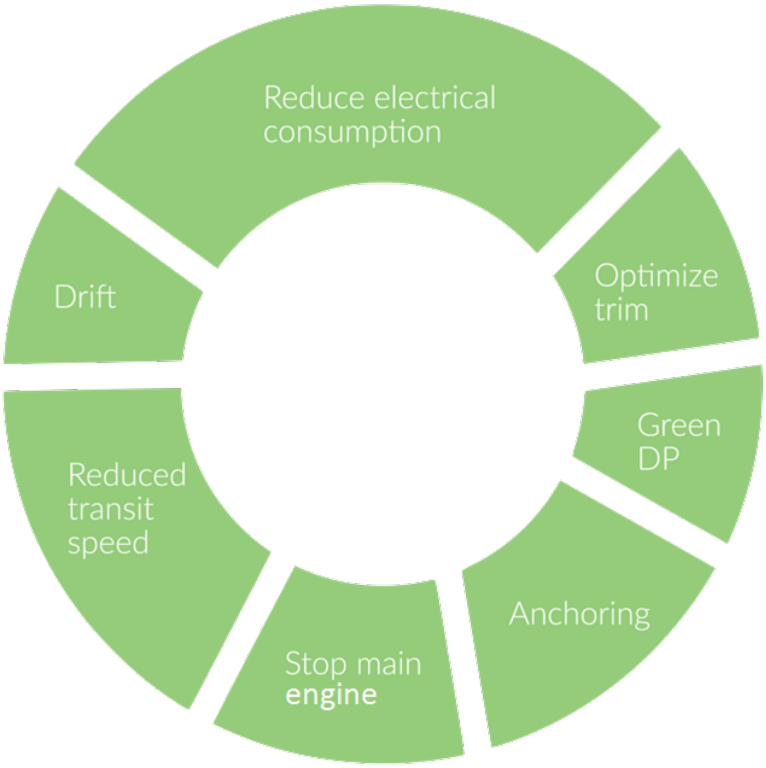

Figure A.1: Fuel Savings by category in 'Solstad Green Operations'. By Courtesy of Solstad

Clean Design DNV-GL launched in 2008 a voluntary class notation called "Clean Design", ensuring different measures for a given ship to do less of an environmental impact. The class notation has implications to emissions to air and sea, as well as structural improvements to reduce the environmental impact in case of a collision etc. The notation is often sought by oil companies, and some has 'Clean Design' as a requirement in order to contract ships.

Concluding Remarks

In the end it all comes down to money, and making it profitable to reduce fuel consumption will be the most robust way to ensure it. A few ship owners have initiated projects that aim to do greener shipping i.e. frame work and regulations that promote fuel saving.

A.4 Rules & Regulations

Guidelines for Offshore Marine Operations

G-OMO describes regulations and best practises regarding marine operations. E.g. deck- and bulk loading. The different oil companies can have additional regulations for their installations and bases.

ECDIS

Weather routing and electronic aids has become more relevant due to recent regulation updates. In 2009 SOLAS Ch.V Reg.19 (International Maritime Organization (IMO), 2015) was amended by resolution MSC.282(86) stating that :

> (2.1) All ships irrespective of size shall have: (.4) nautical charts and nautical publications to plan and display the ship's route for the intended voyage and to plot and monitor positions throughout the voyage. An electronic chart display and information system (ECDIS) is also accepted as meeting the chart carriage requirements of this subparagraph. Ships to which paragraph 2.10[1] applies shall comply with the carriage requirements for ECDIS detailed therein;

EEDI & EEOI

The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Index (EEOI) are indexes aiming to quantify vessels effectiveness. These are proposed by IMO and enforced by the class societies. They will serve as benchmarks and lower index value will be more attractive to lease by (in this case) the oil companies.

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \tag{A.1}$$

Where FC_j is the fuel consumption of the j'th fuel, and C_{Fj} is the CO2 mass conversion (the relation between fuel input and carbon emmission). m_{cargo} is the mass or quantity of cargo, and D is the distance sailed.

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[1] Paragraph 2.10 explains the phase-in regime for ECDIS for specific ships engaged in international voyages.

B: Attachments

In addition to the master's thesis, a zip-file is attached. The zip-file contains the following elements:

- Master exhibition poster. The poster is mandatory for students at Department of Marine Thechnology, NTNU.
- MasterPlanner. The MATLAB source code on which this thesis is based.

C: MasterPlanner & Animations

The MATLAB code enclosed is to be extracted to your MATLAB-folder. The ShipX data is not attached, so vessel data must be added to the 'Vessel Model'-folder. Then run 'gogoMP' and follow instructions.

The next part of the thesis is the animation. Use the book as a flip book to animate the two cases. These cases are the ones from chapter 5 and 6. Does not work for the digital version. For digital user, please visit `https://youtu.be/4s3DmO3oVoQ` for a youtube-video of an animation.

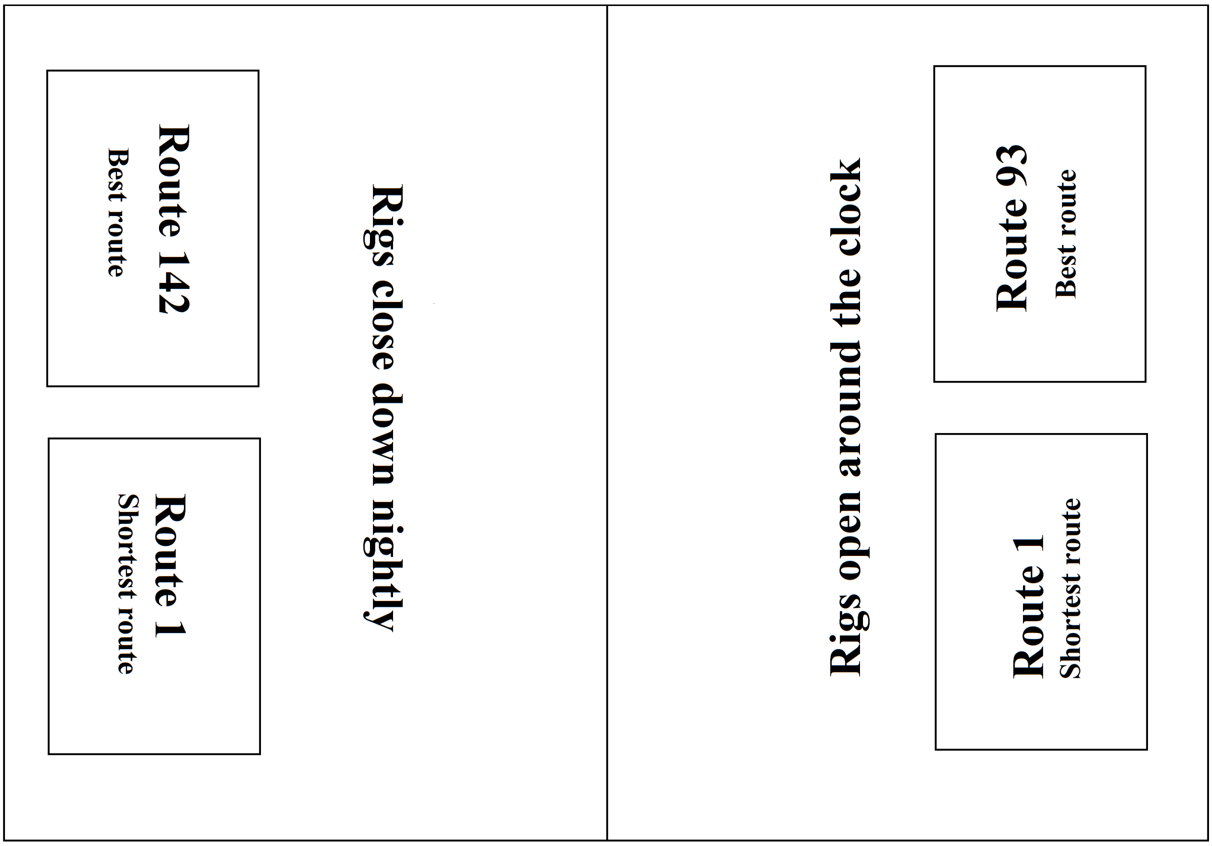
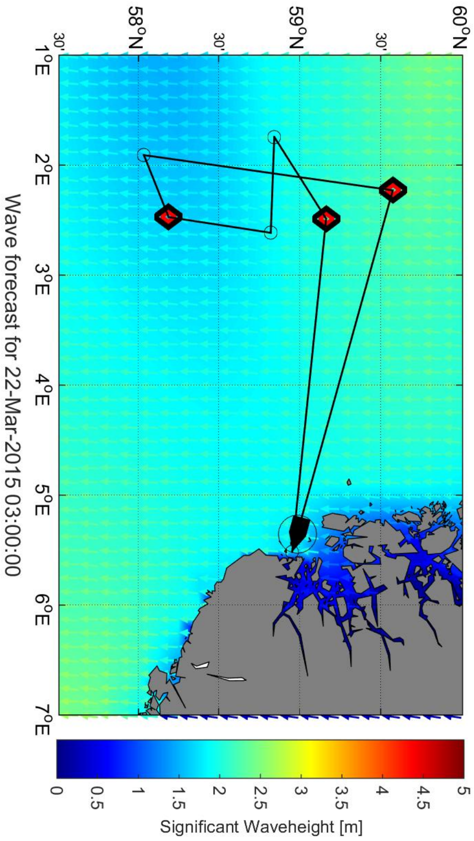


Figure C.1: Animation Description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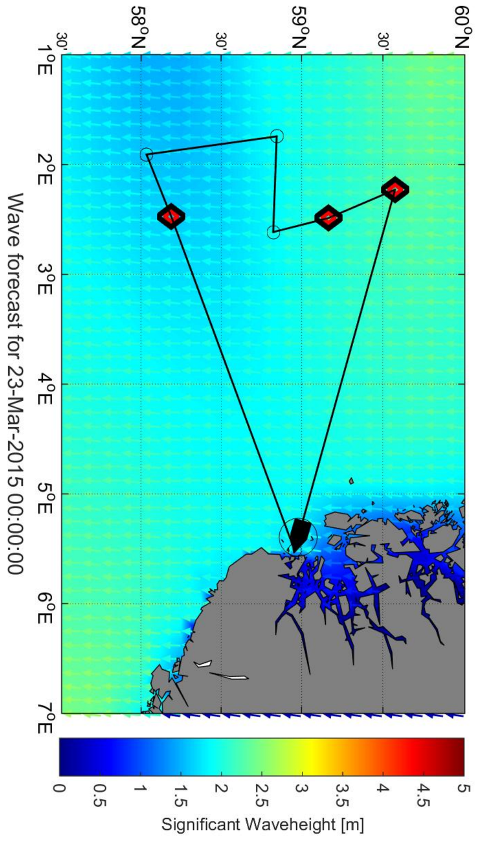
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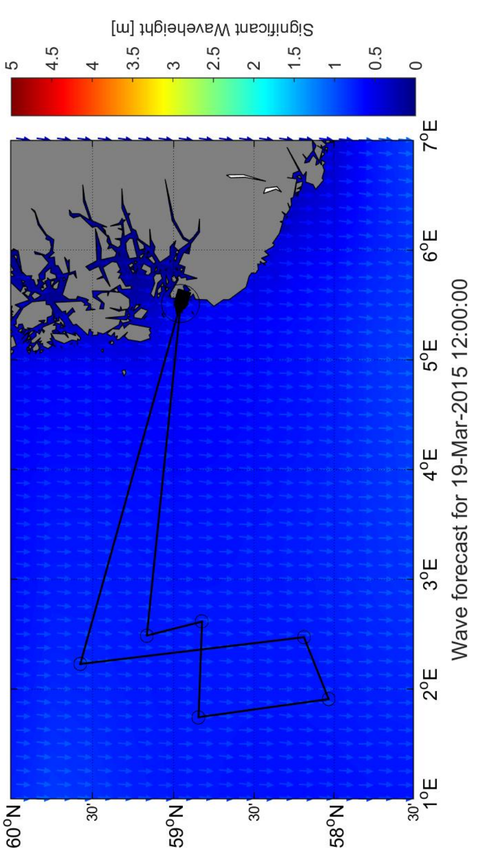
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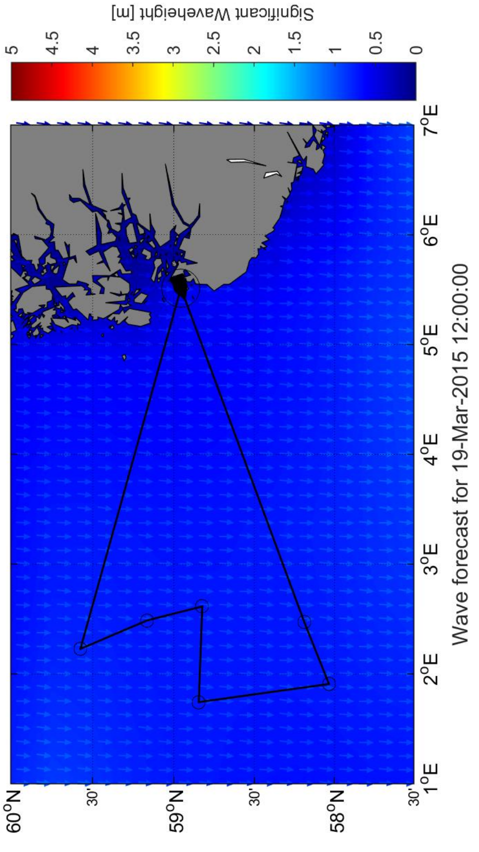
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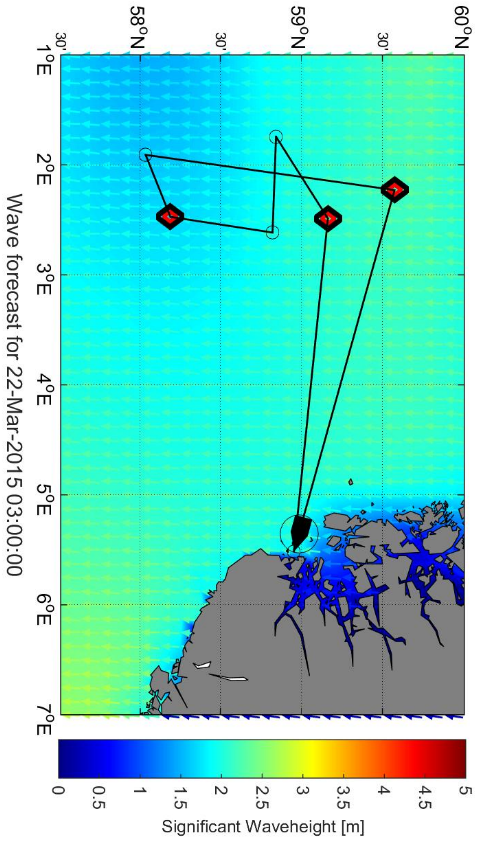
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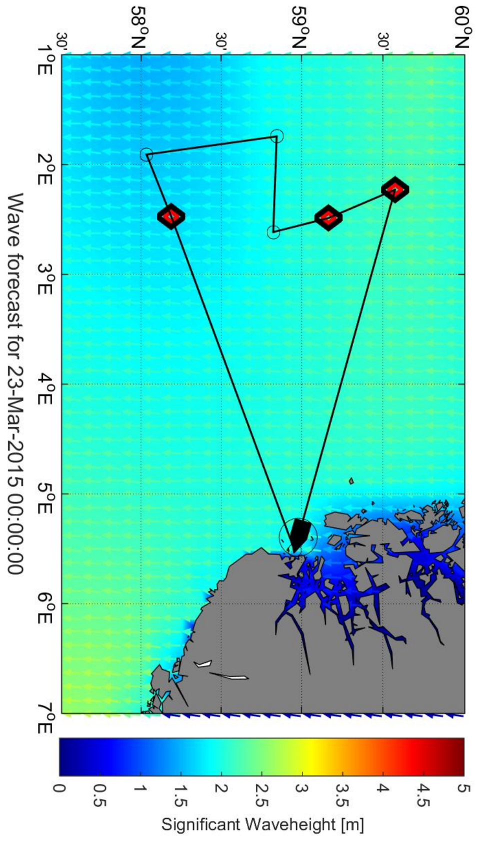
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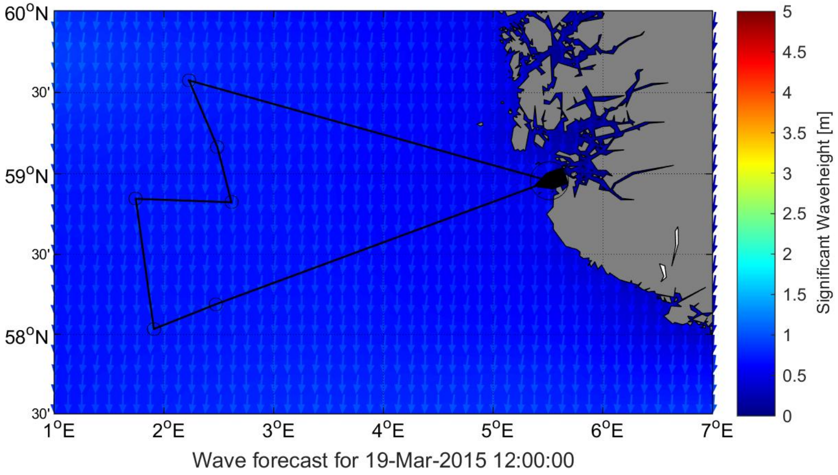
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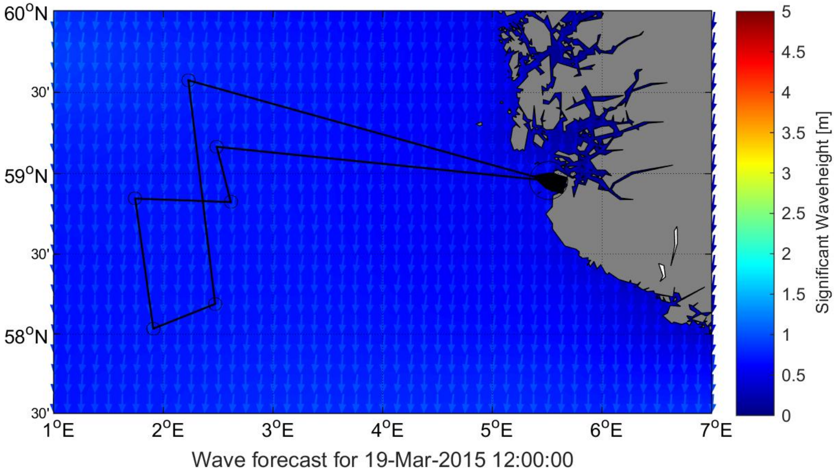
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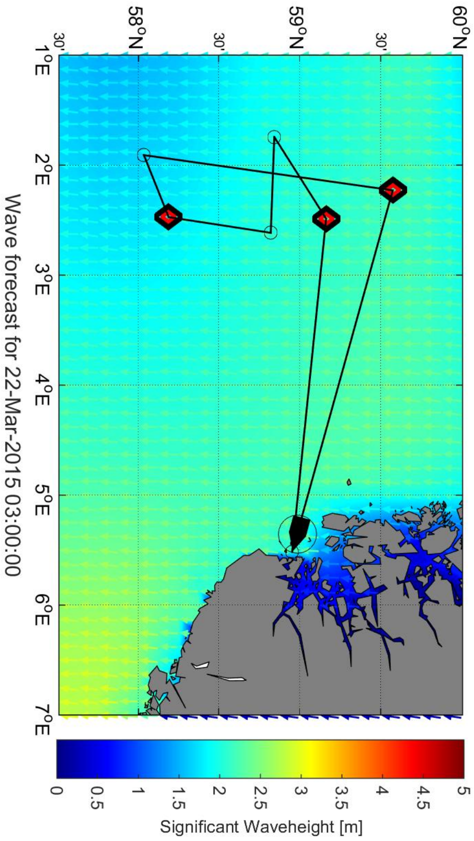
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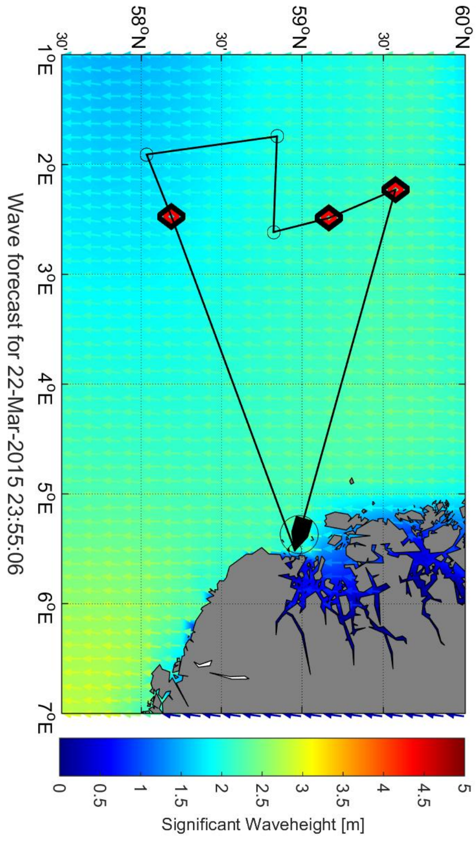
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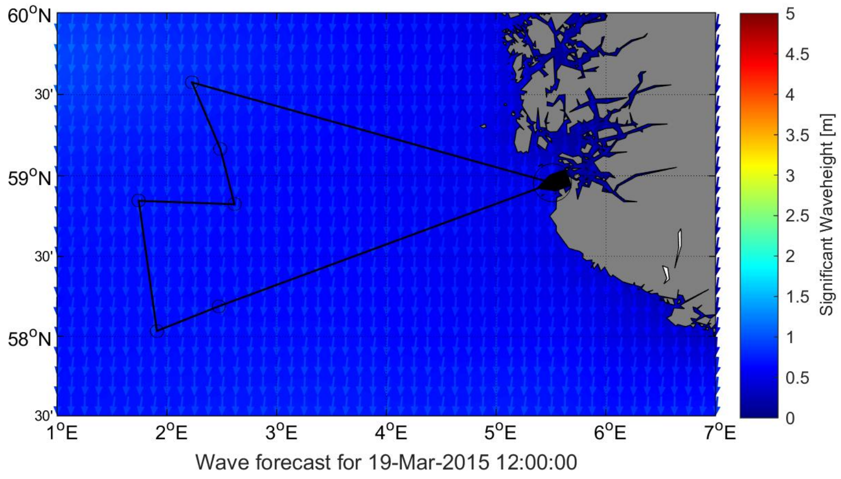
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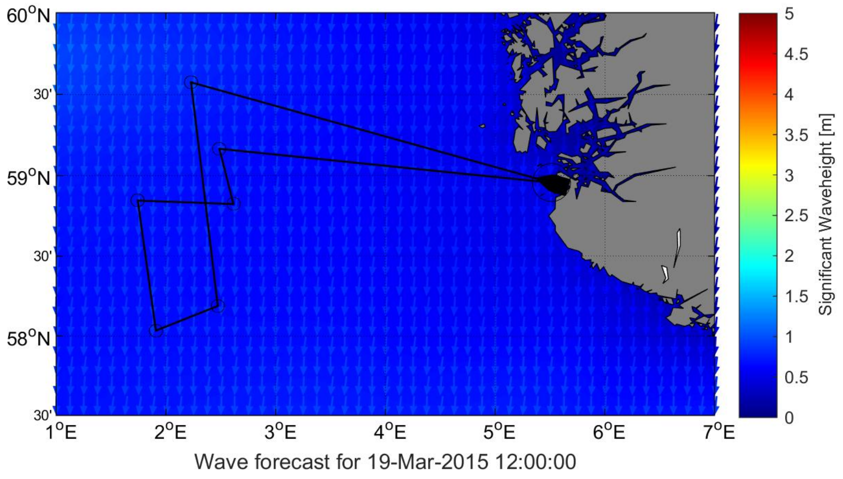
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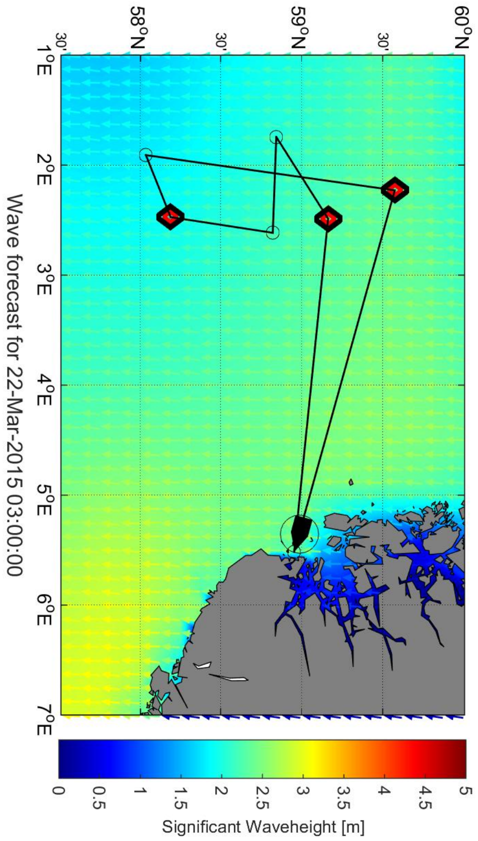
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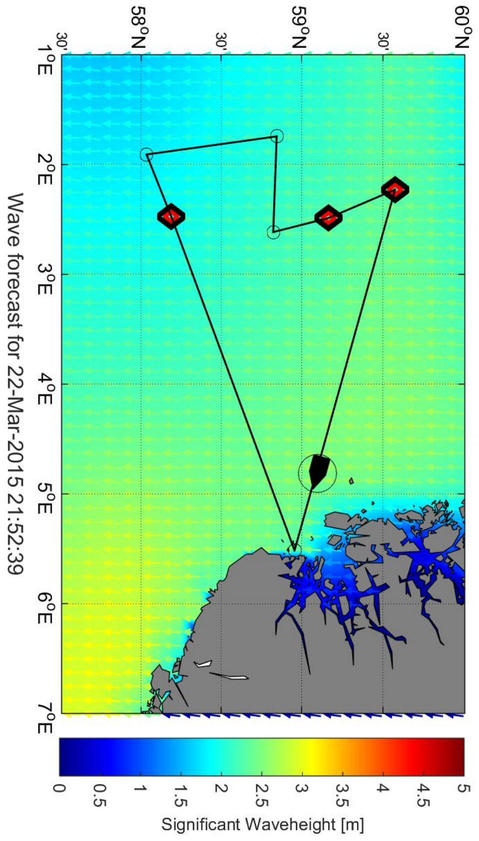
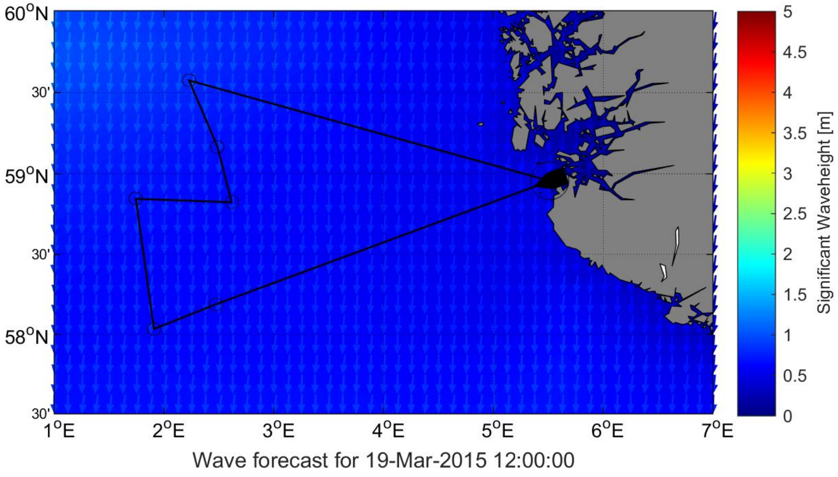
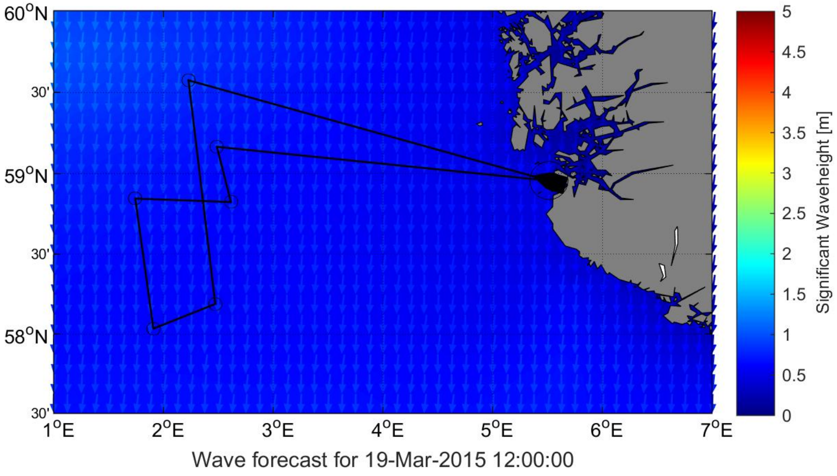
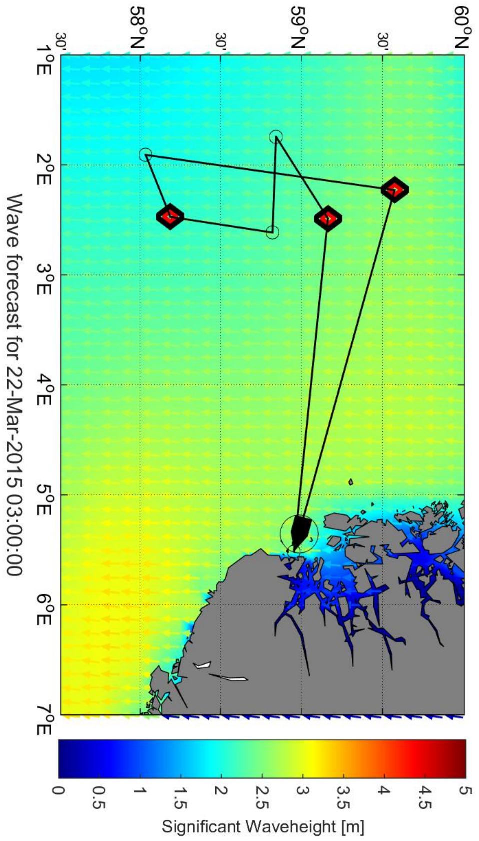
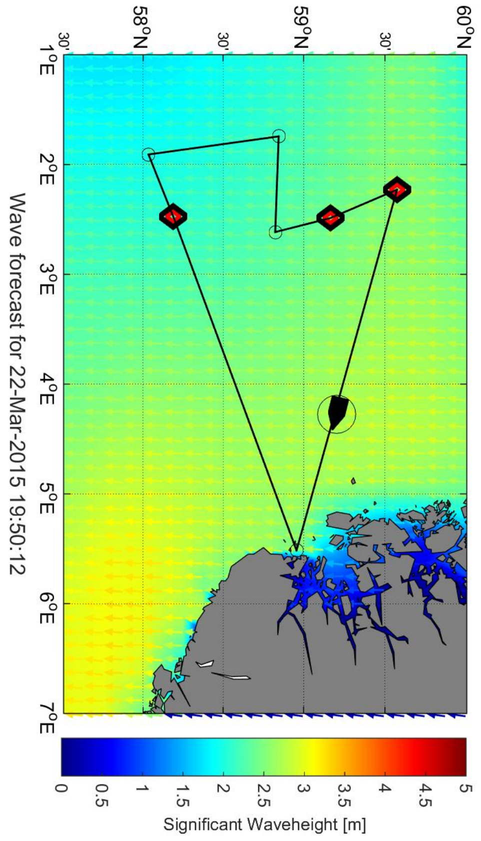
5
Significant Waveheight [m]

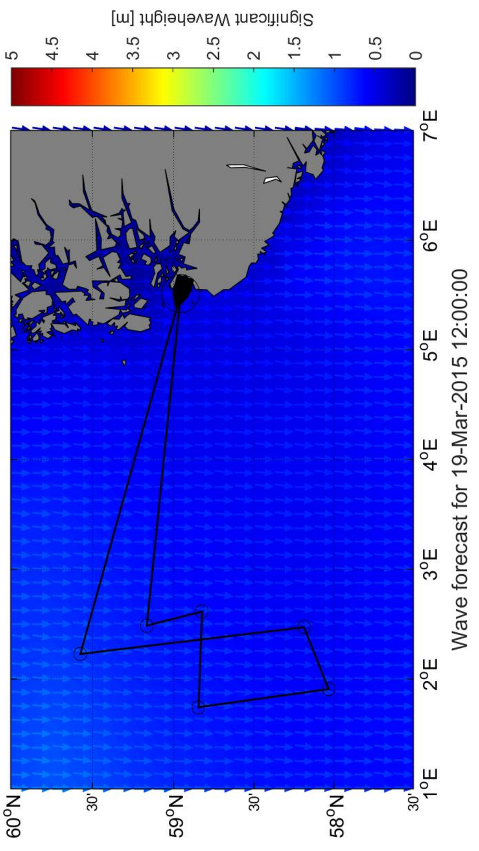

Wave forecast for 22-Mar-2015 21:52:39
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

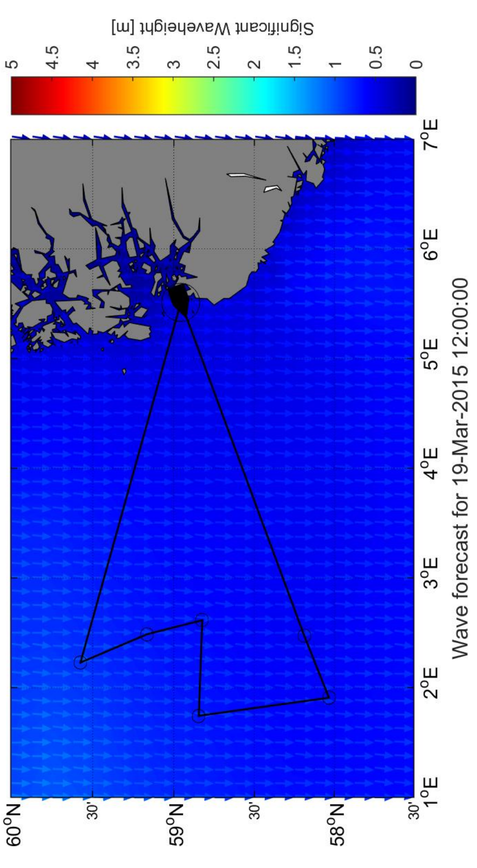

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

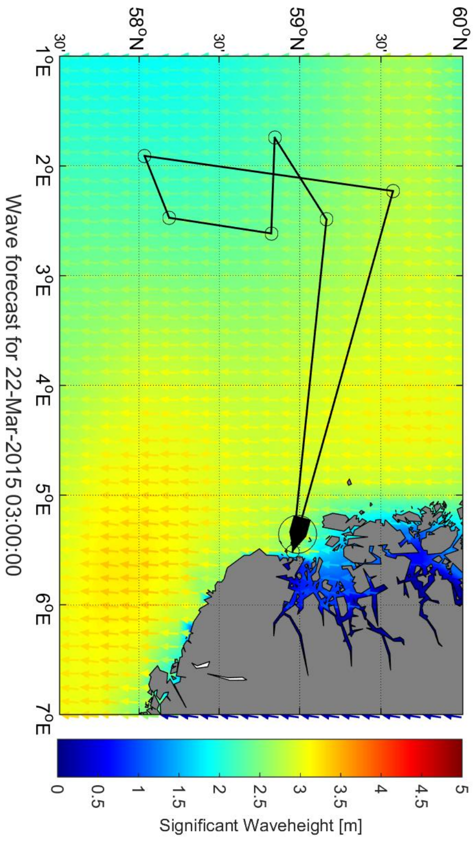

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

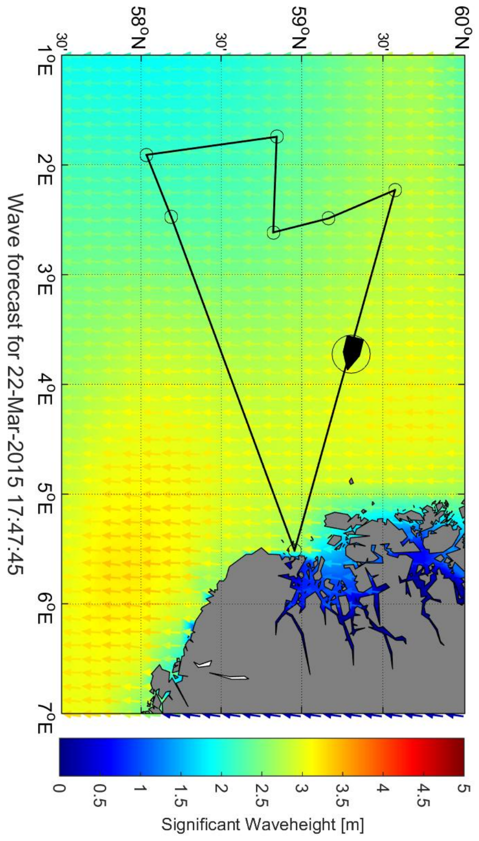

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

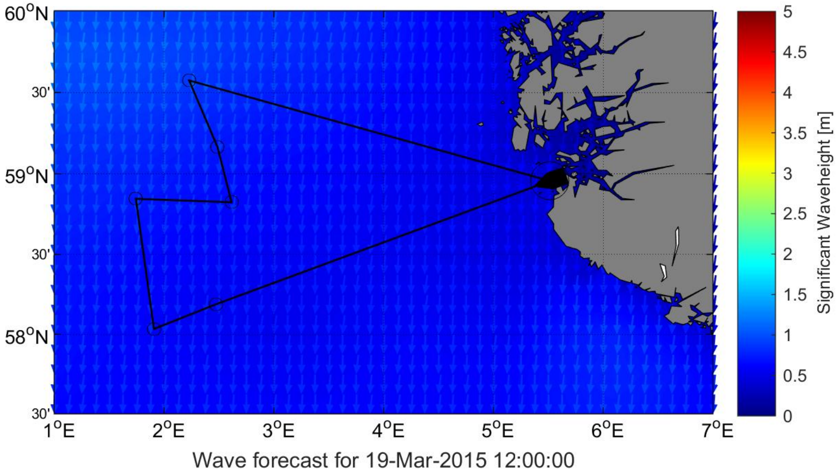

Wave forecast for 22-Mar-2015 19:50:12
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

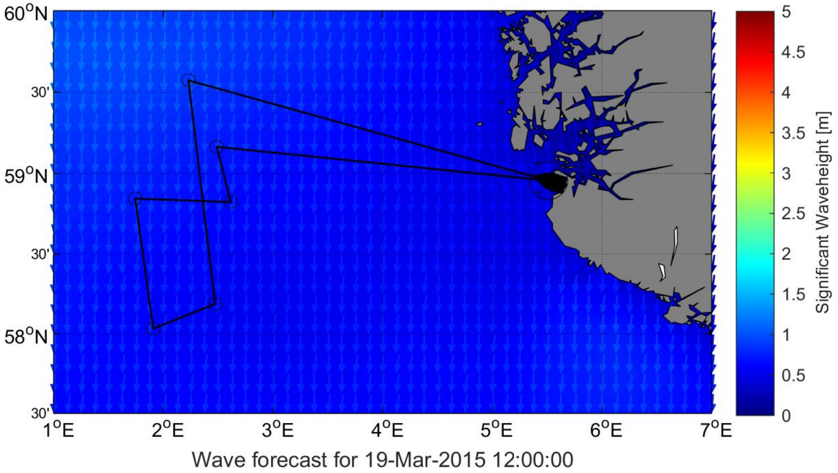

Wave forecast for 19-Mar-2015 12:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

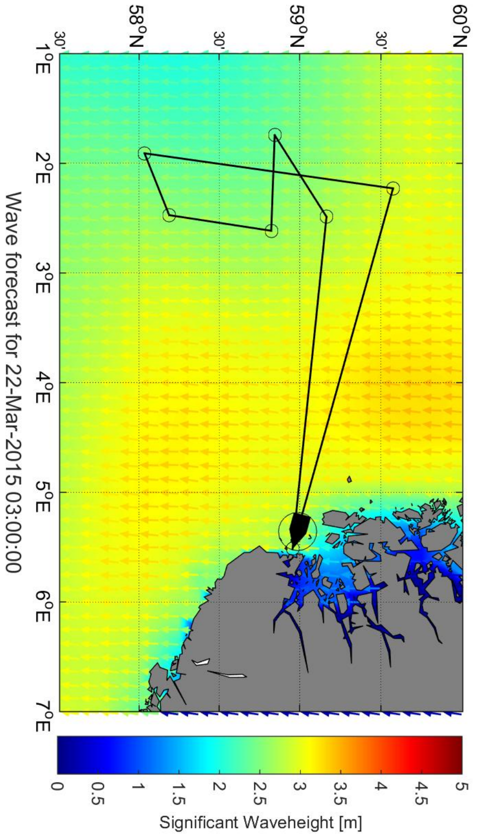

Wave forecast for 19-Mar-2015 12:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

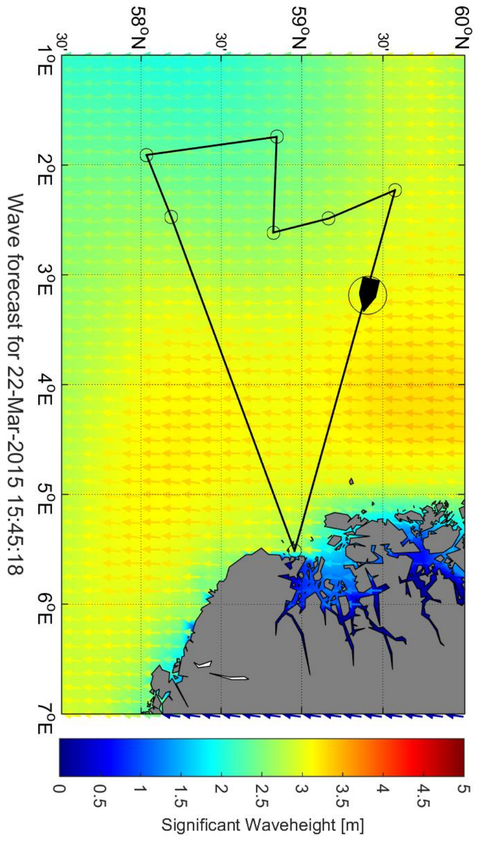

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 03:00:00
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

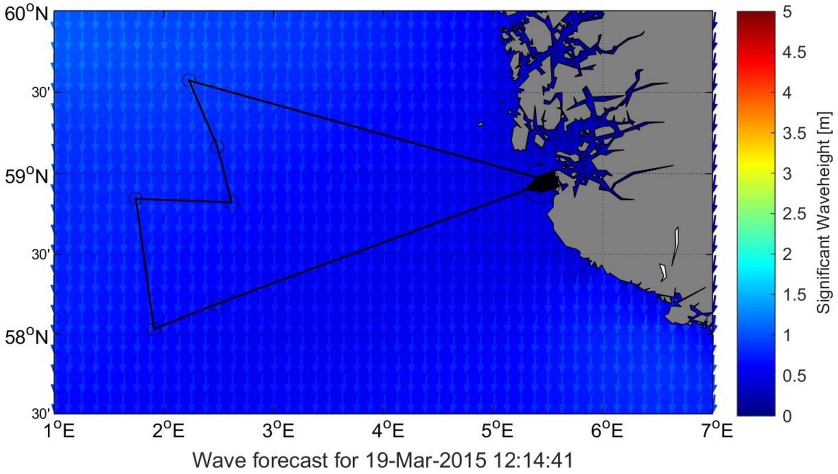

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 17:47:45
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

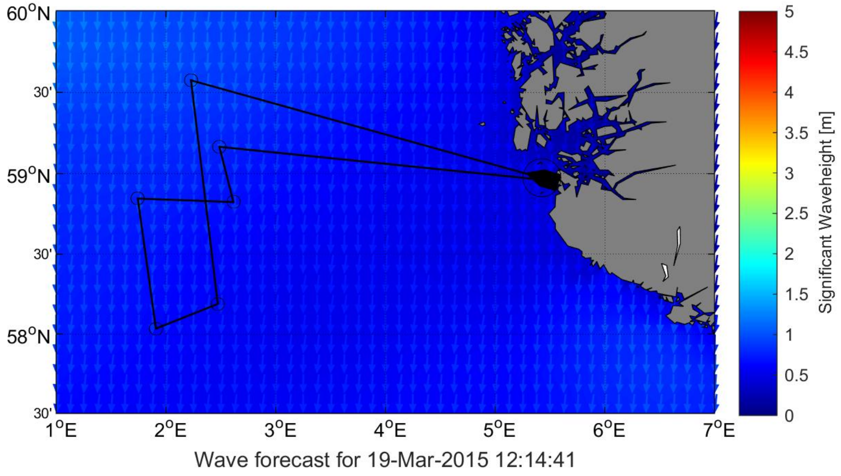

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

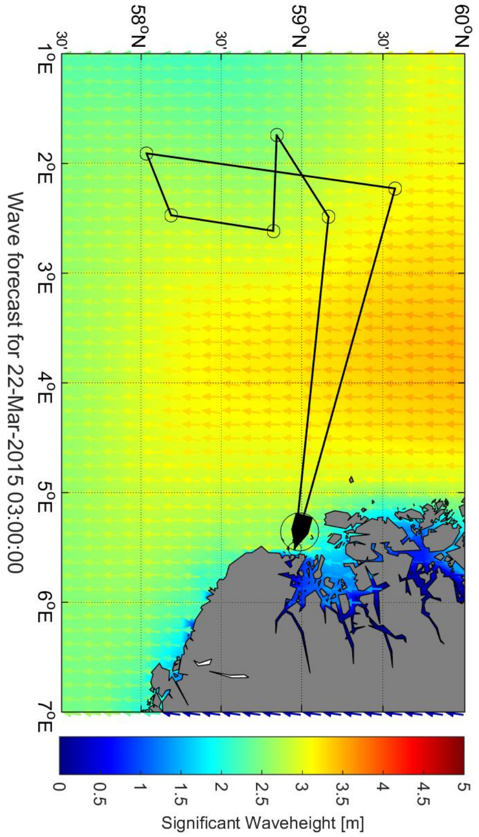

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

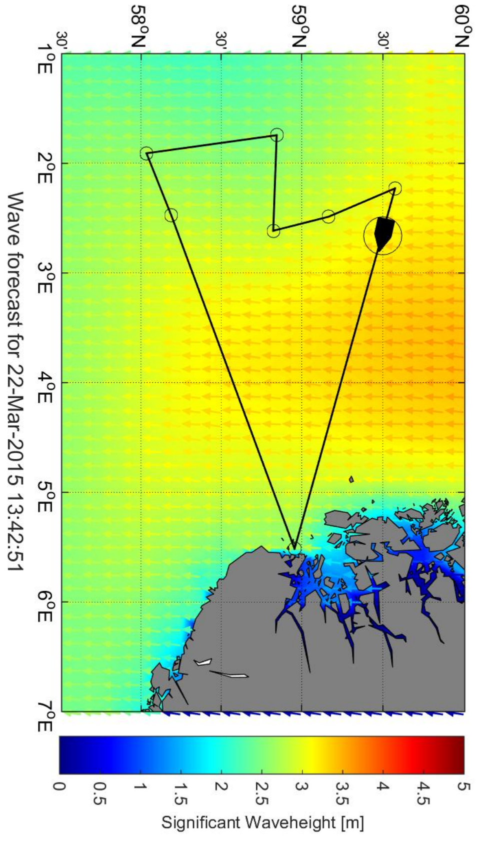

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

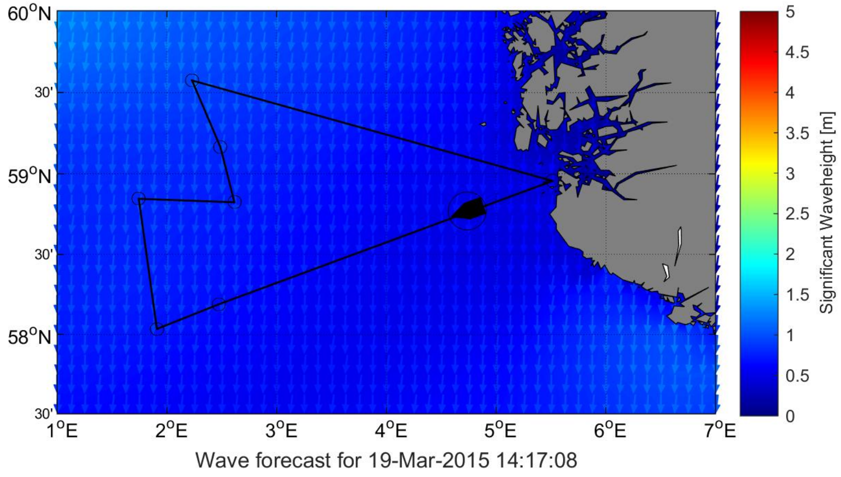

Wave forecast for 22-Mar-2015 15:45:18
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

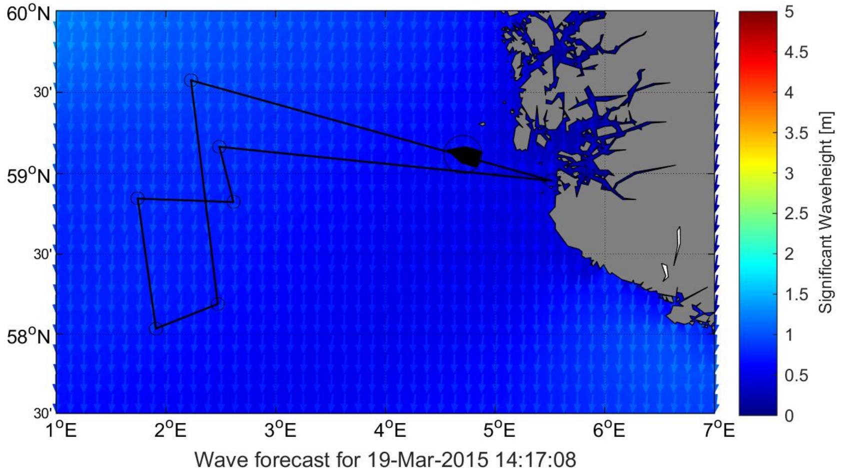

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:14:41
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

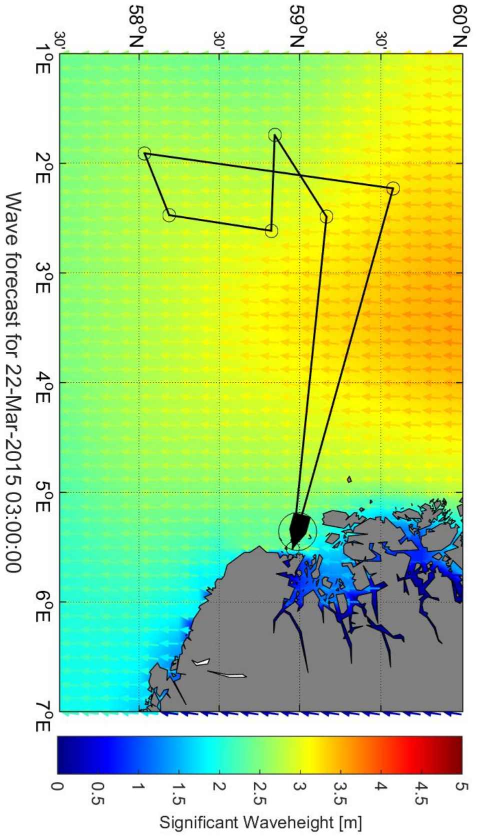

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 12:14:41
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

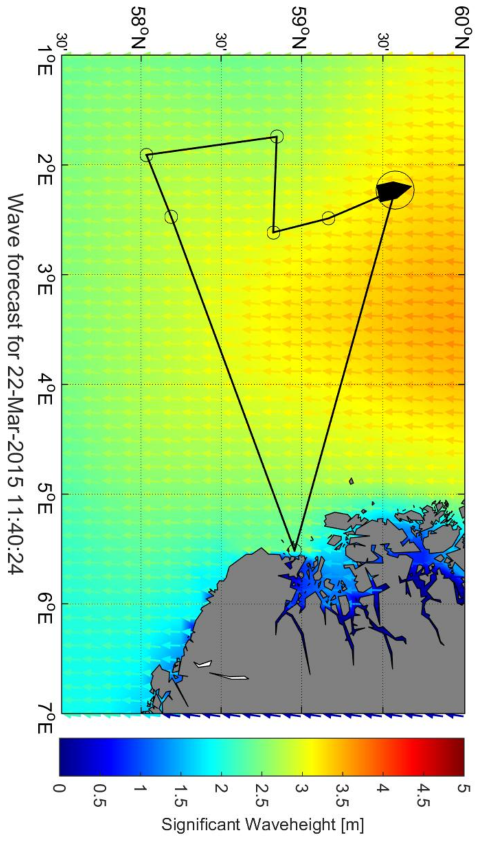

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

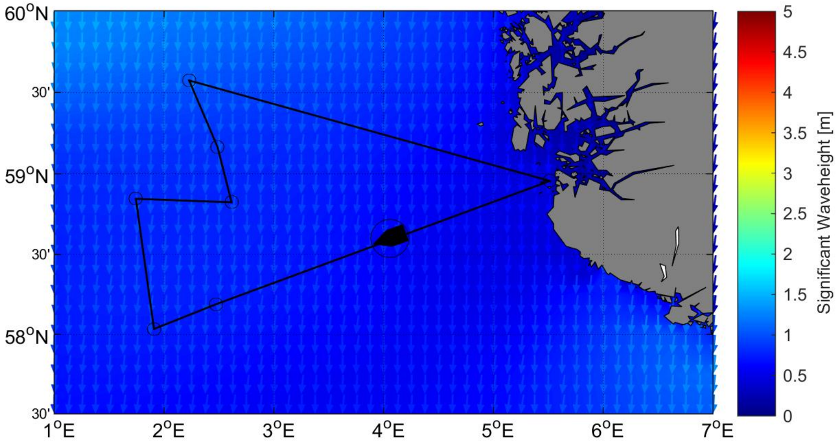

Wave forecast for 22-Mar-2015 13:42:51
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 14:17:08
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

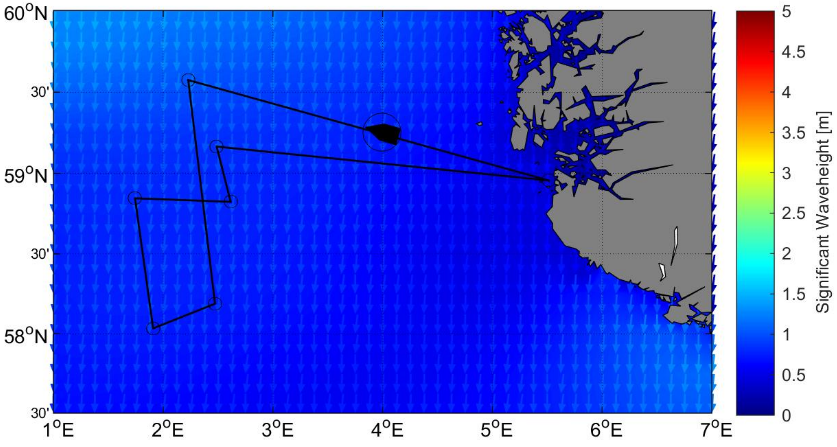

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 14:17:08
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

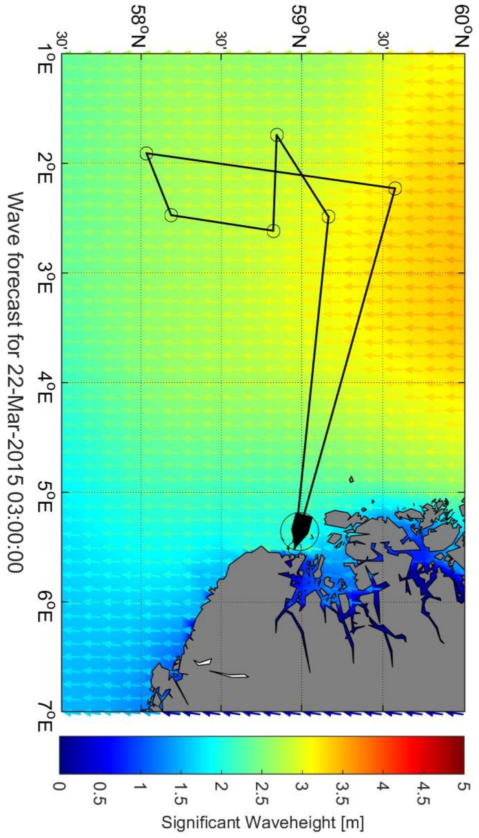

Wave forecast for 22-Mar-2015 11:40:24
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

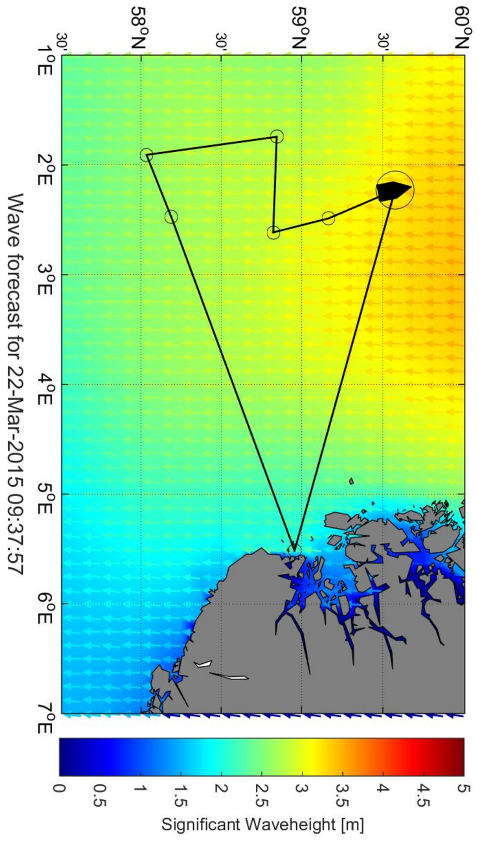


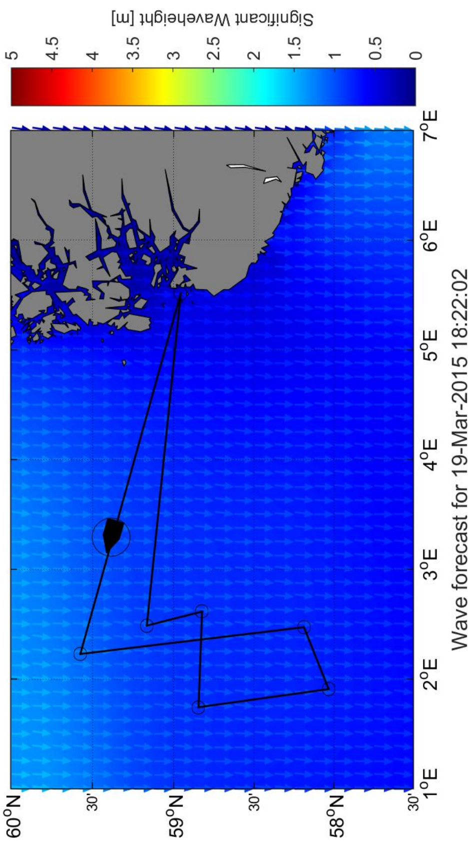
Wave forecast for 19-Mar-2015 16:19:35

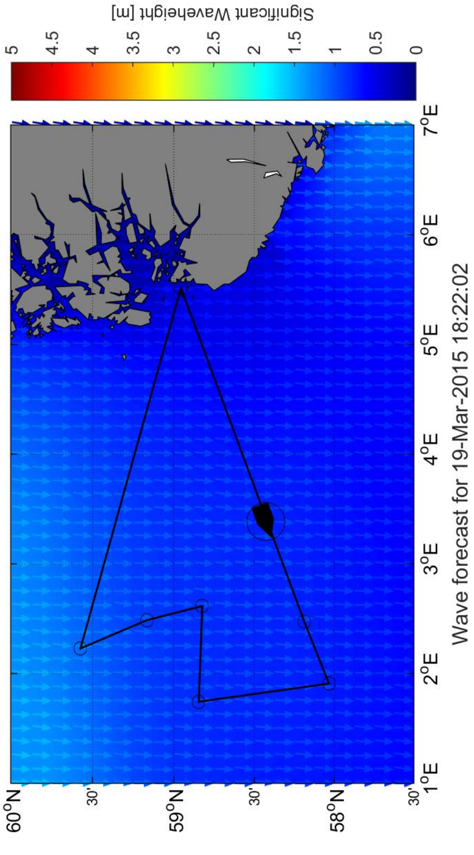


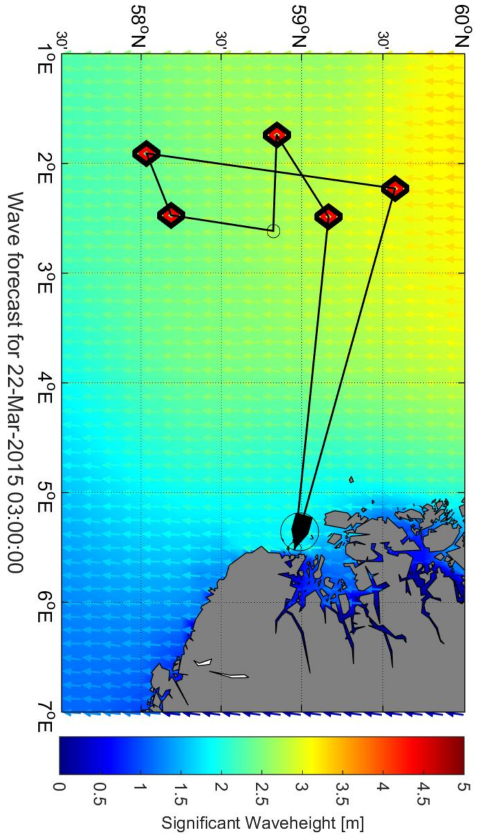
Wave forecast for 19-Mar-2015 16:19:35

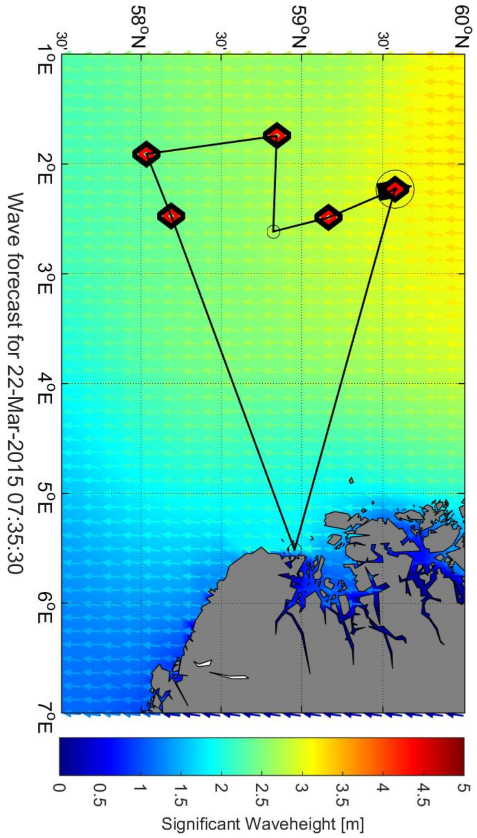

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

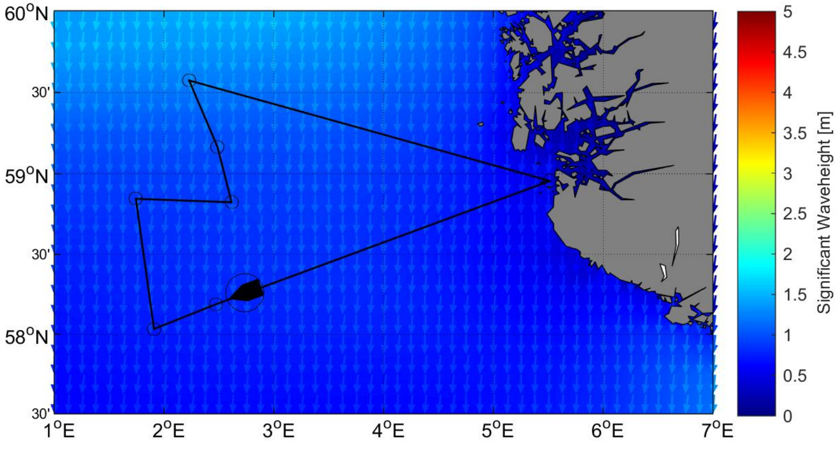

Wave forecast for 22-Mar-2015 09:37:57
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 19-Mar-2015 18:22:02
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

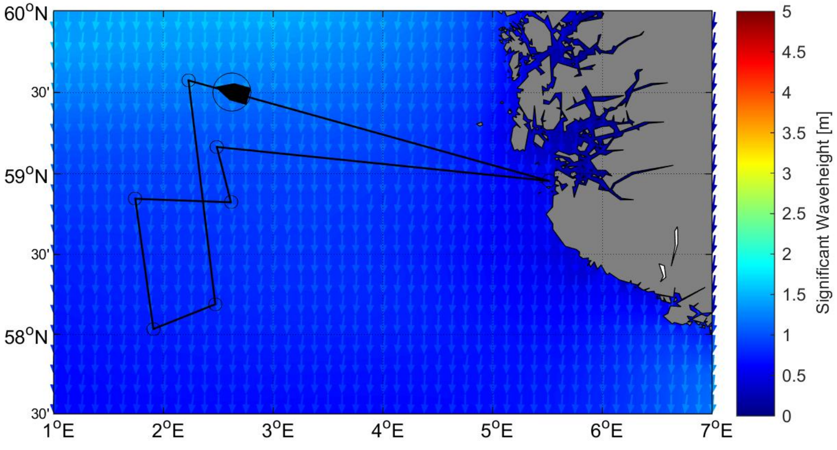

Wave forecast for 19-Mar-2015 18:22:02
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

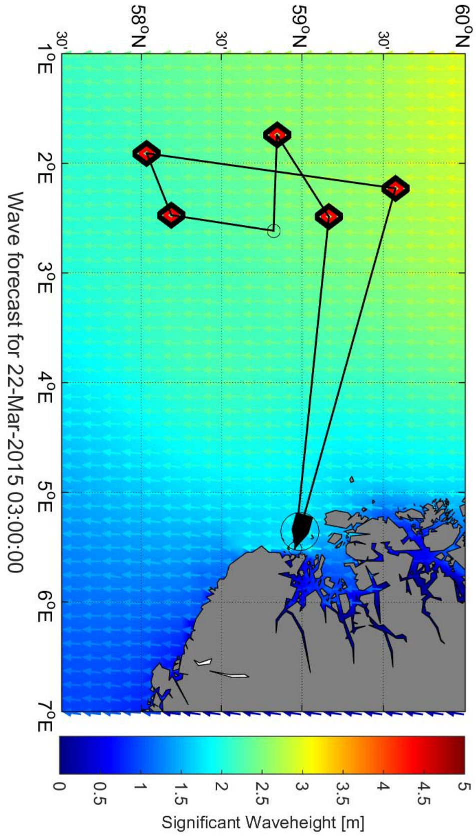

Wave forecast for 22-Mar-2015 07:35:30
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

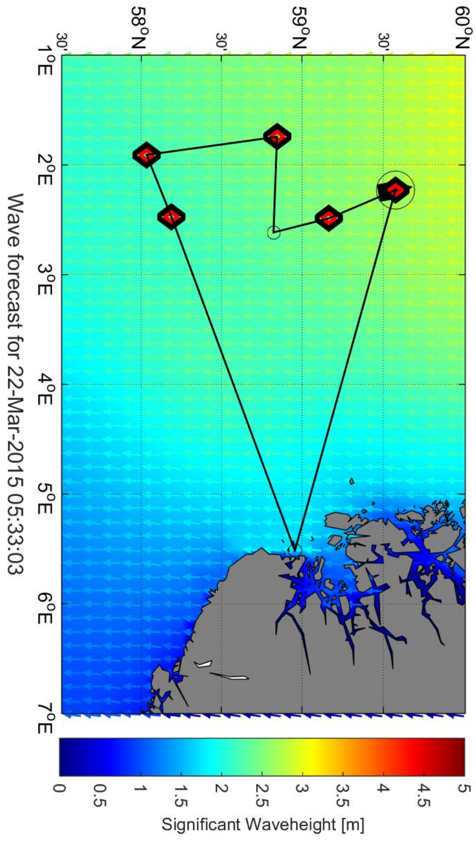


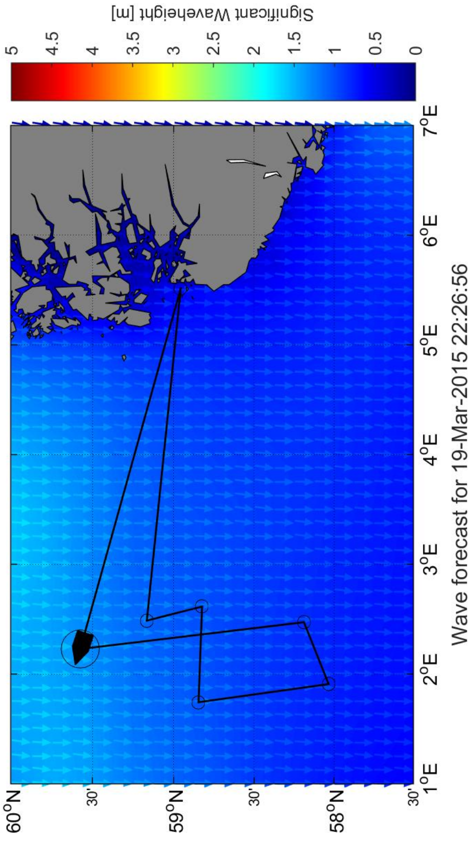
Wave forecast for 19-Mar-2015 20:24:29

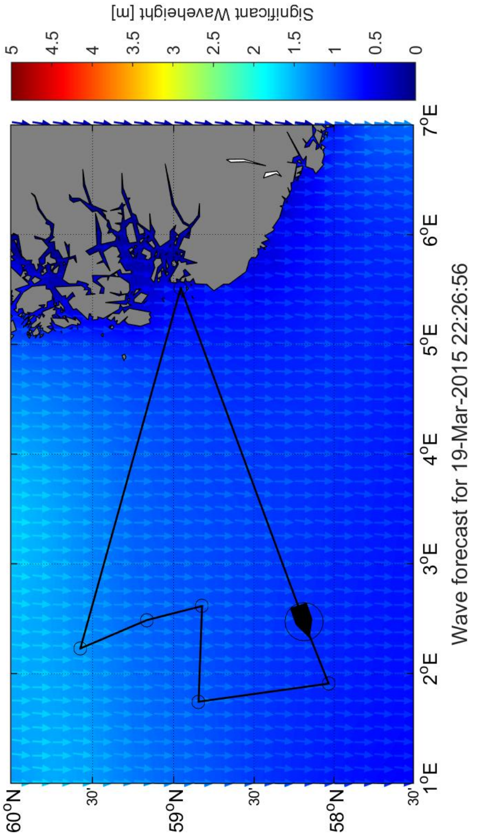


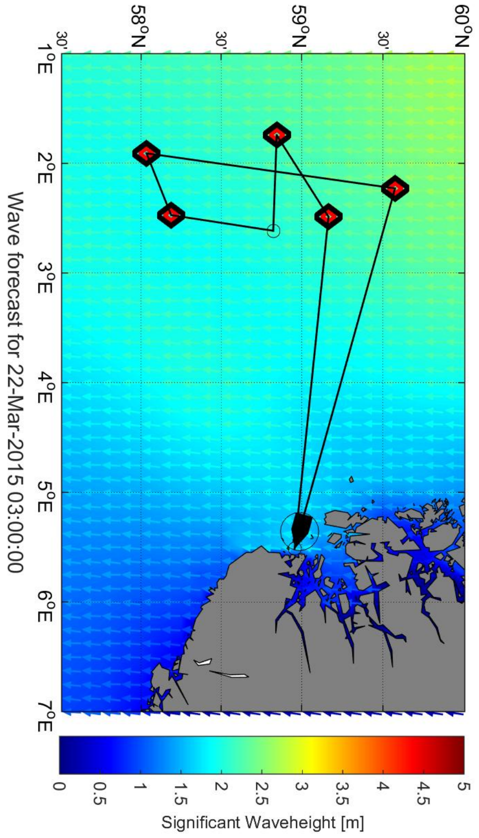
Wave forecast for 19-Mar-2015 20:24:29

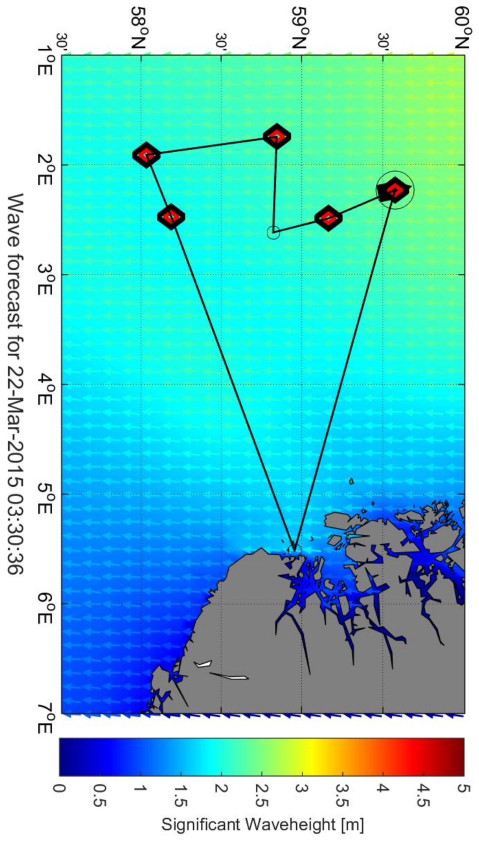

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

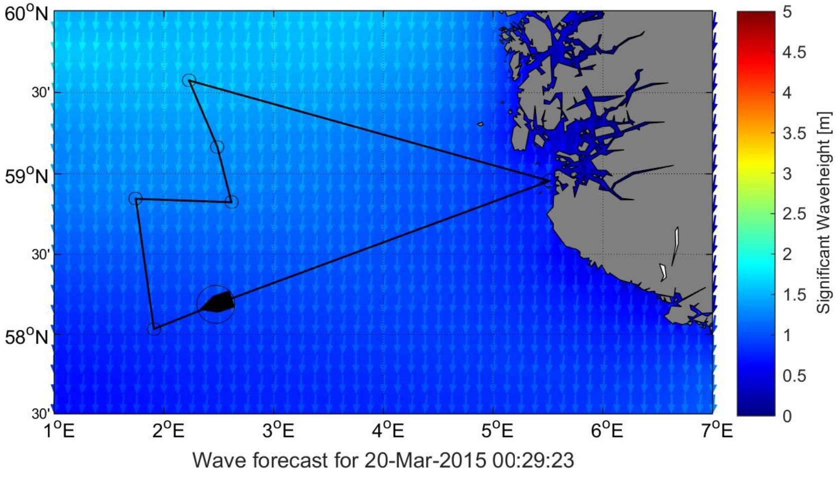

Wave forecast for 22-Mar-2015 05:33:03
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

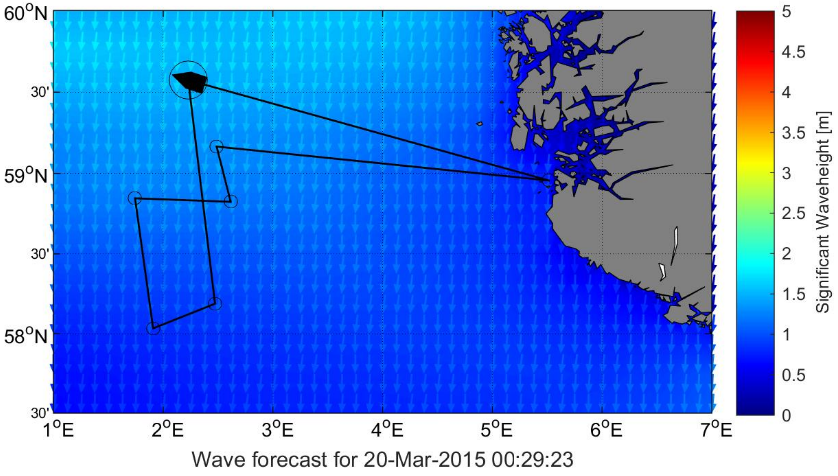

Wave forecast for 19-Mar-2015 22:26:56
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E

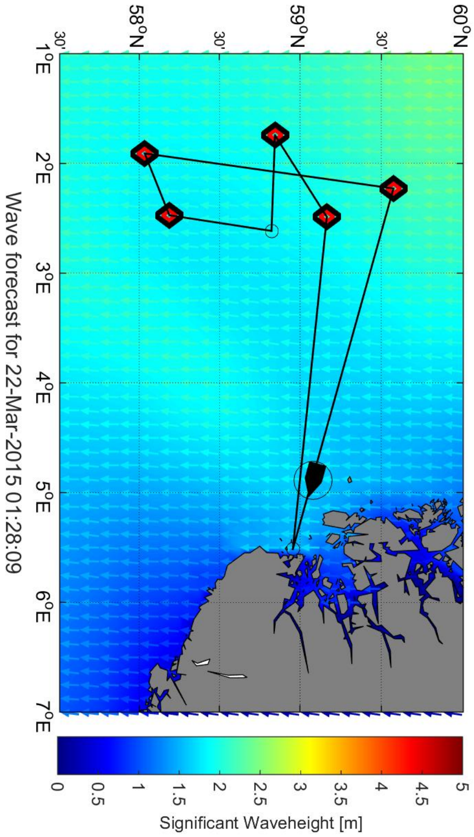

Wave forecast for 19-Mar-2015 22:26:56
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E

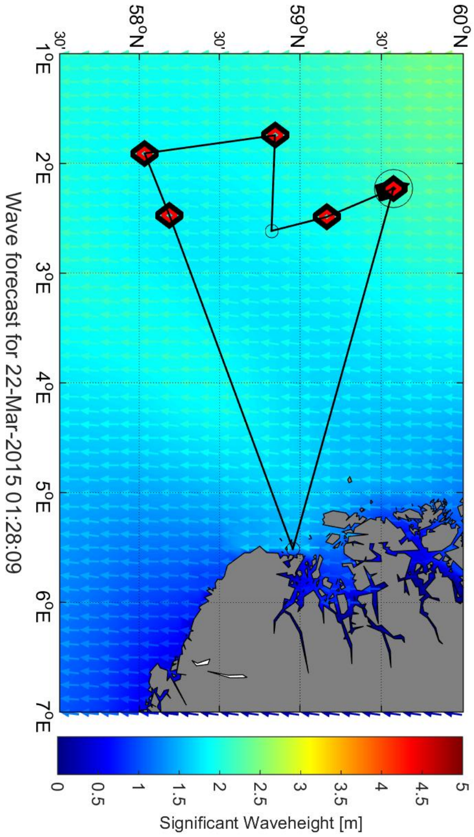

Wave forecast for 22-Mar-2015 03:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

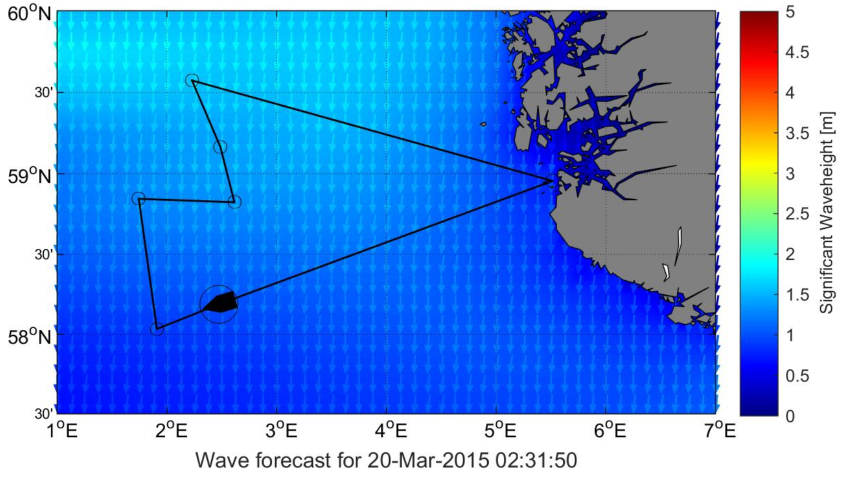

Wave forecast for 22-Mar-2015 03:30:36
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

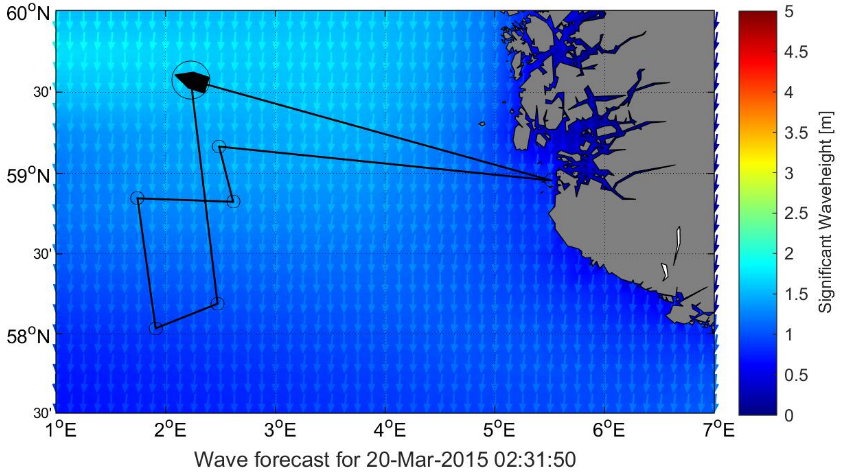

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 00:29:23
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

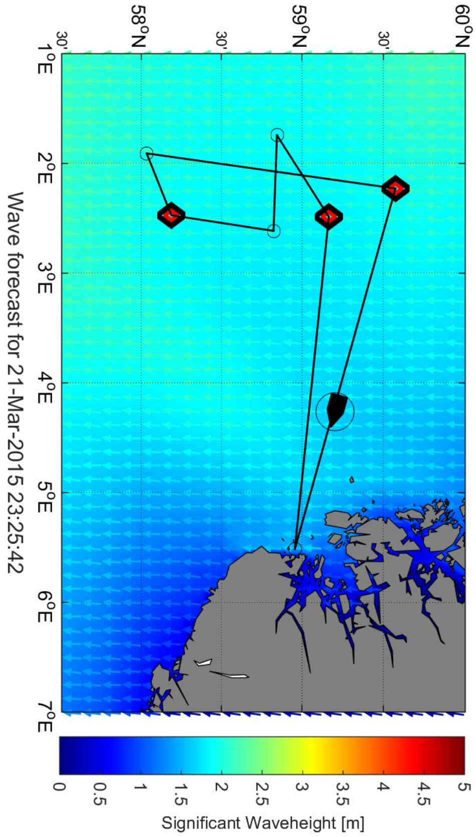

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 00:29:23
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

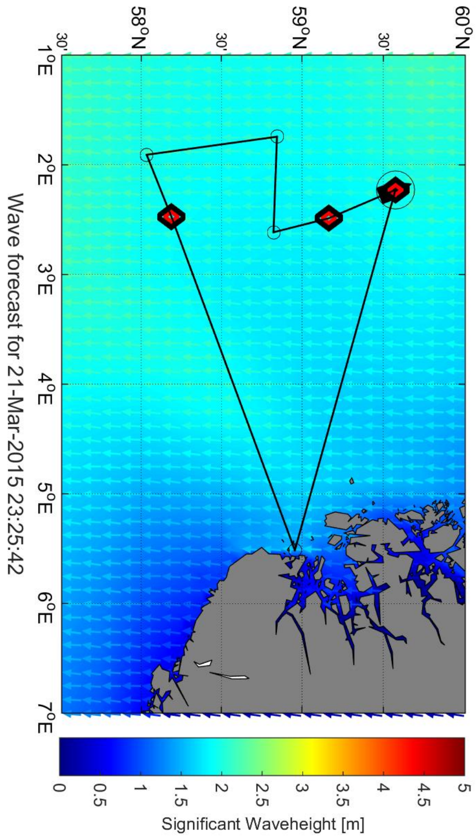

Wave forecast for 22-Mar-2015 01:28:09
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

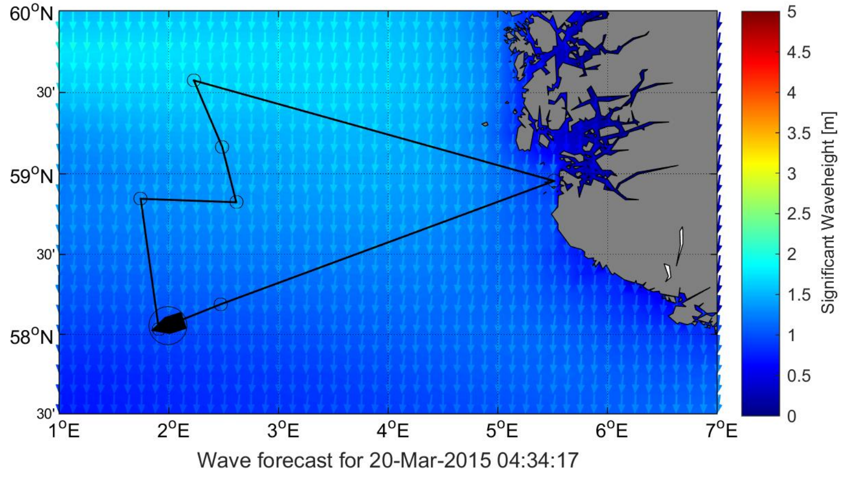

Wave forecast for 22-Mar-2015 01:28:09
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

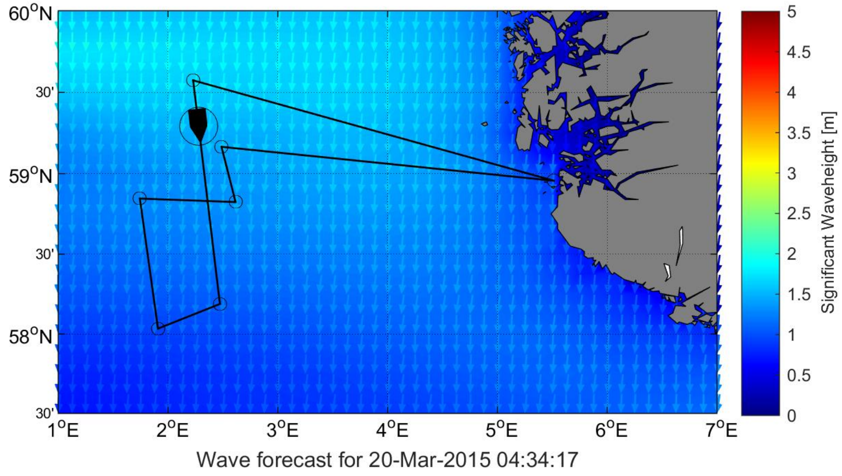

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 02:31:50
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

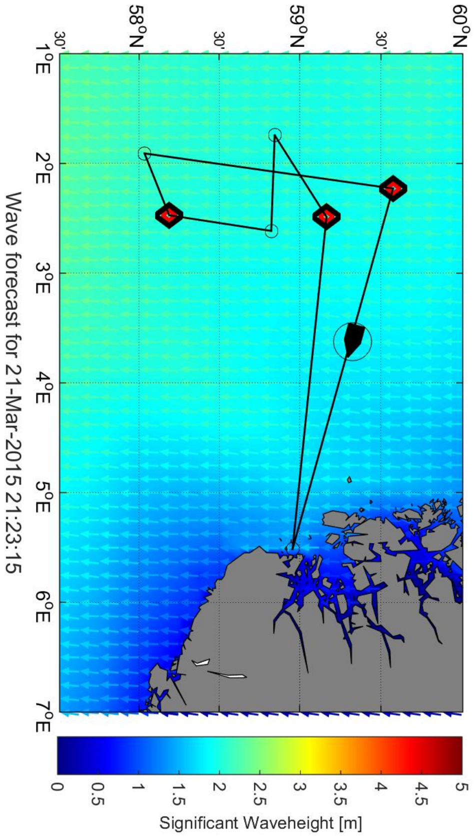

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 02:31:50
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

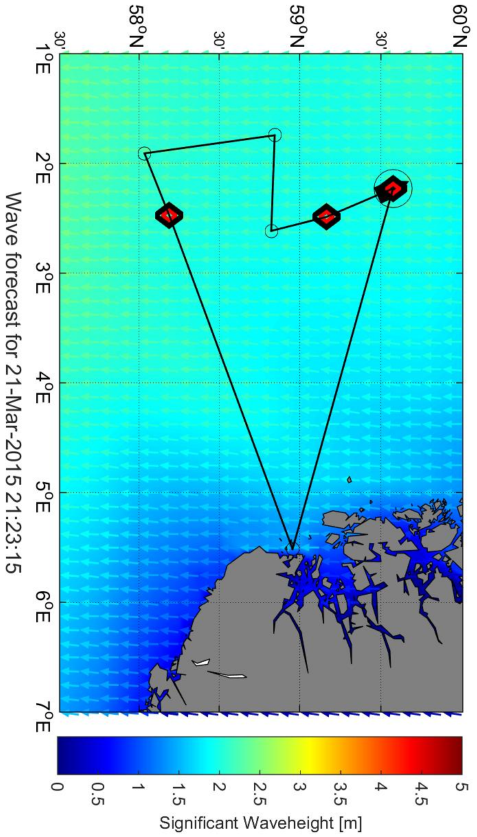

Wave forecast for 21-Mar-2015 23:25:42
1°E
2°E
3°E
4°E
5°E
6°E
7°E
30'
58°N
30'
59°N
30'
60°N
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

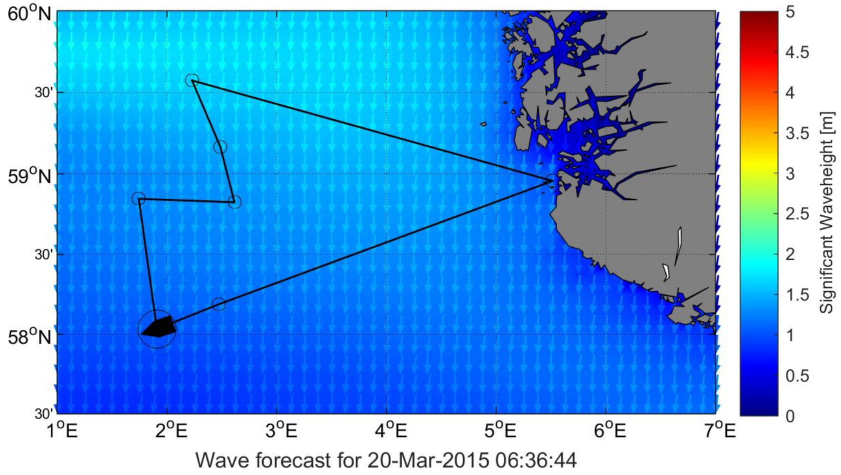

Wave forecast for 21-Mar-2015 23:25:42
1°E
2°E
3°E
4°E
5°E
6°E
7°E
30'
58°N
30'
59°N
30'
60°N
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

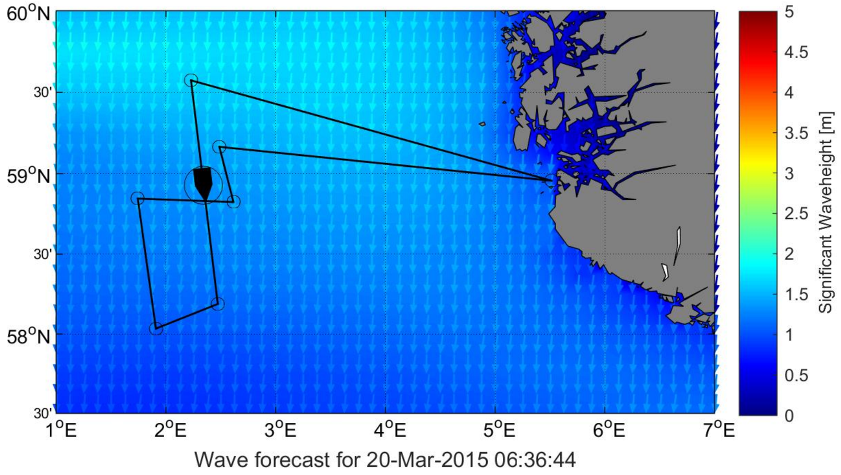

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 04:34:17
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

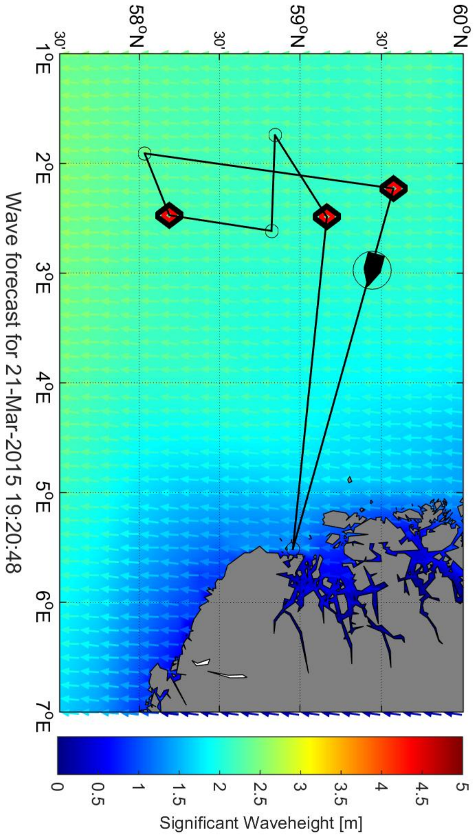

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 04:34:17
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

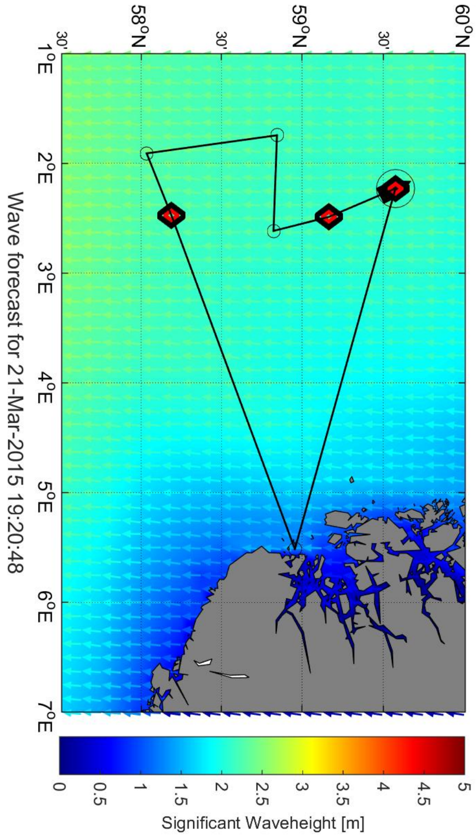

Wave forecast for 21-Mar-2015 21:23:15
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

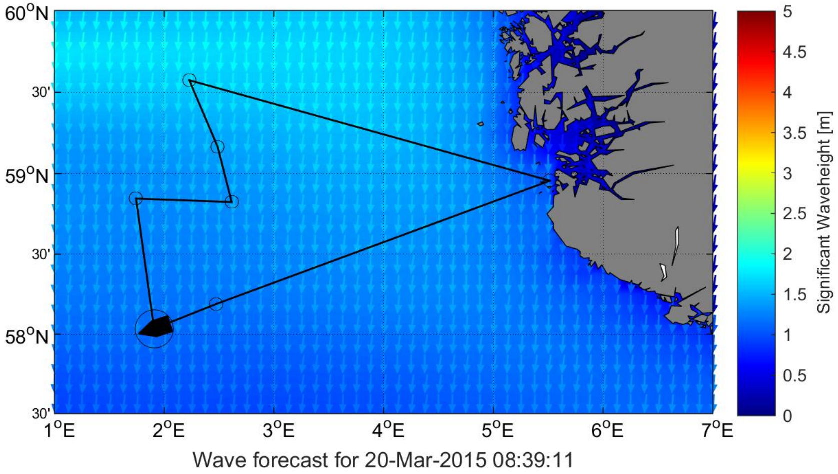

Wave forecast for 21-Mar-2015 21:23:15
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

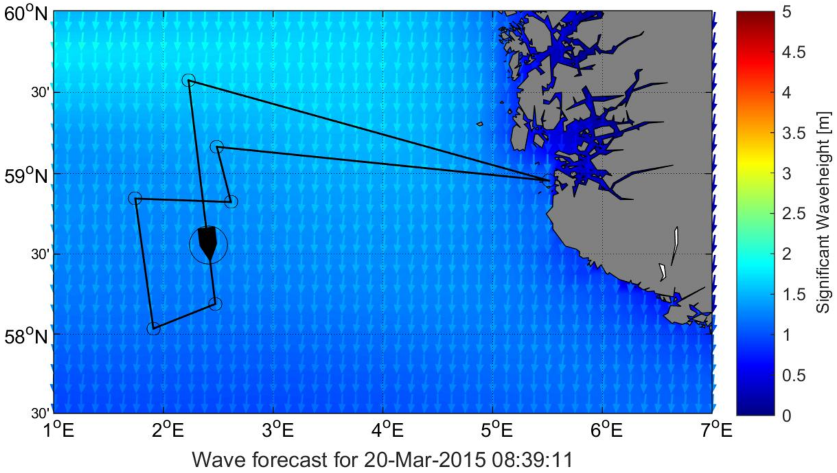

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 06:36:44
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

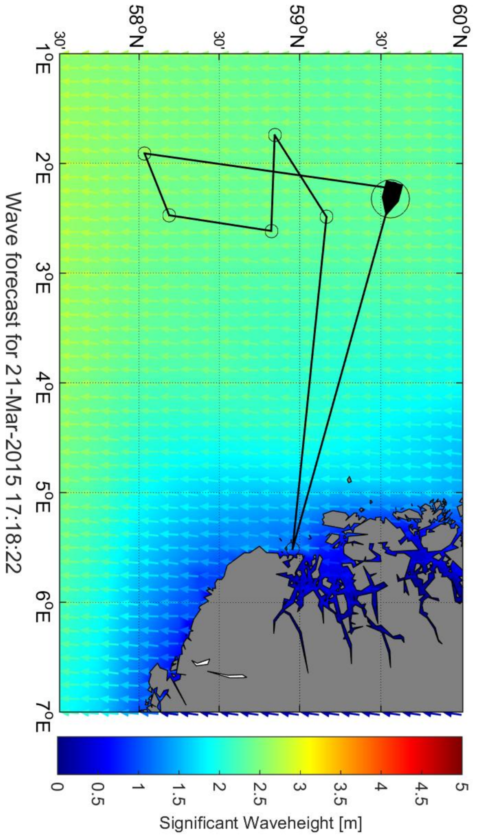

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 06:36:44
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

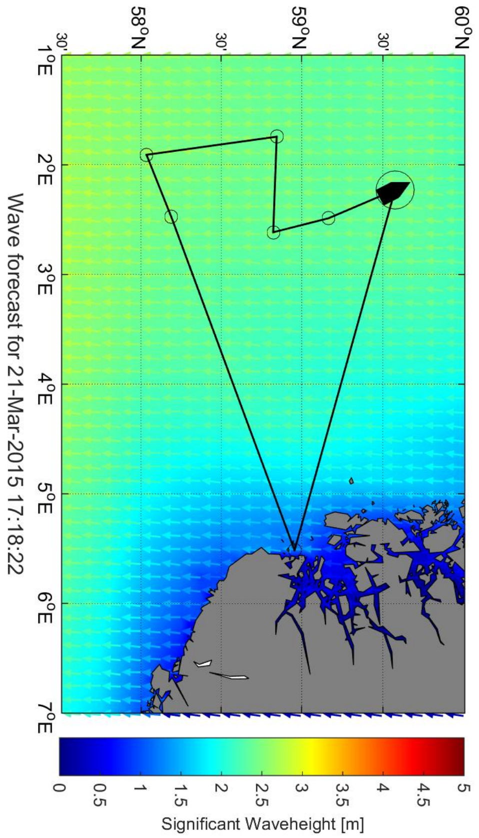

Wave forecast for 21-Mar-2015 19:20:48
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

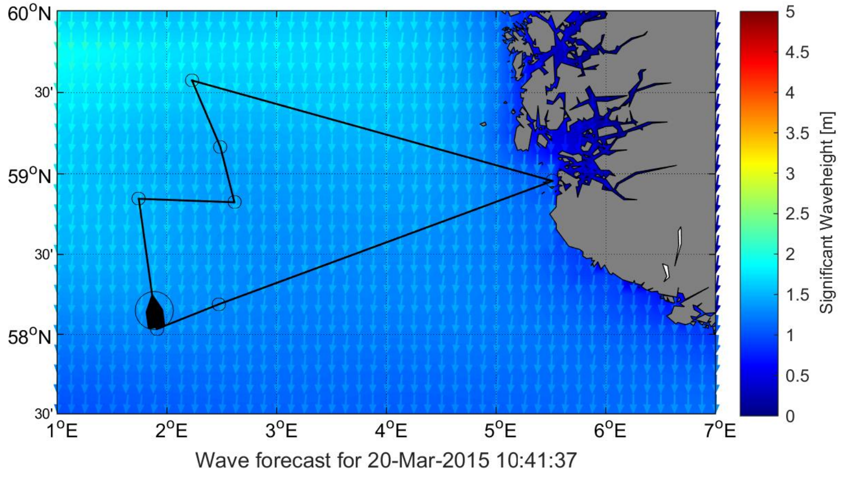

Wave forecast for 21-Mar-2015 19:20:48
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

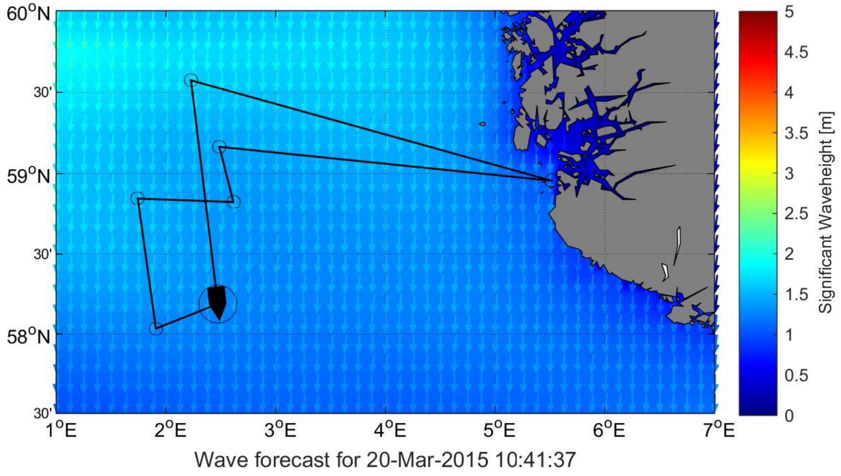

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 08:39:11
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

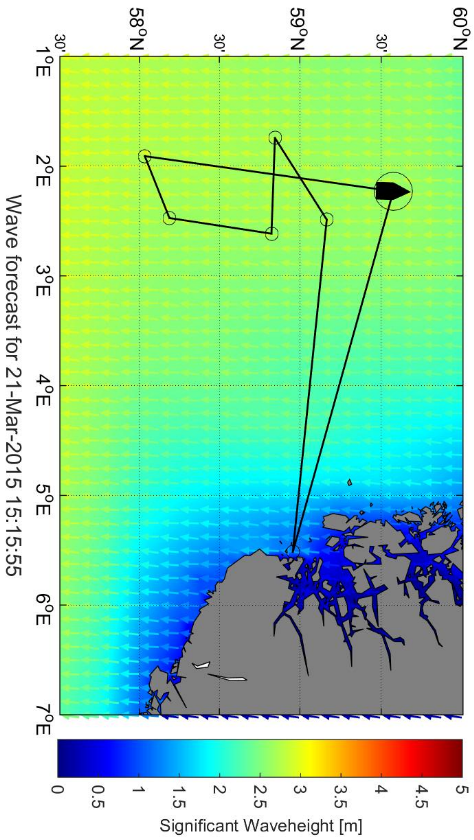

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 08:39:11
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

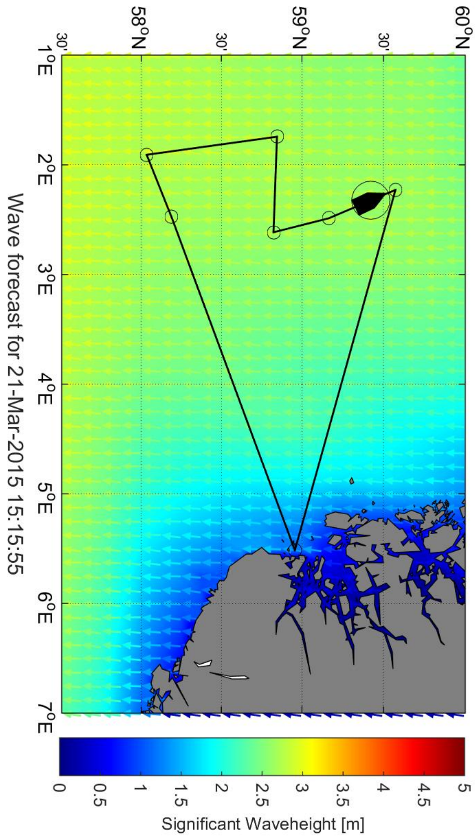

Wave forecast for 21-Mar-2015 17:18:22
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

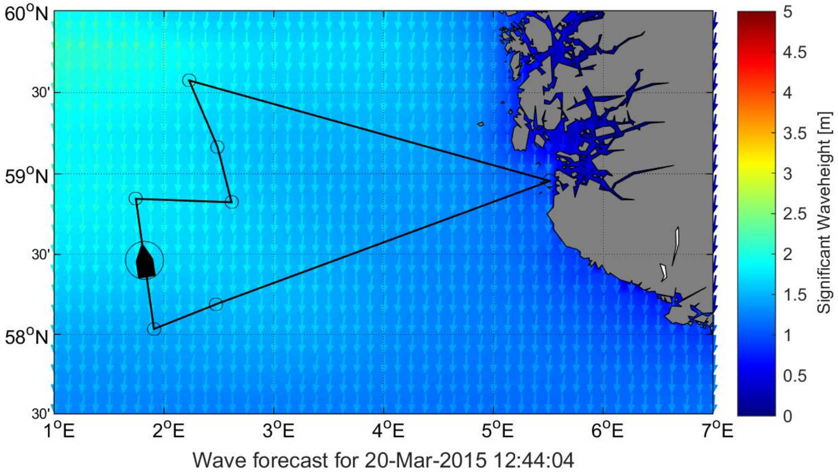

Wave forecast for 21-Mar-2015 17:18:22
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

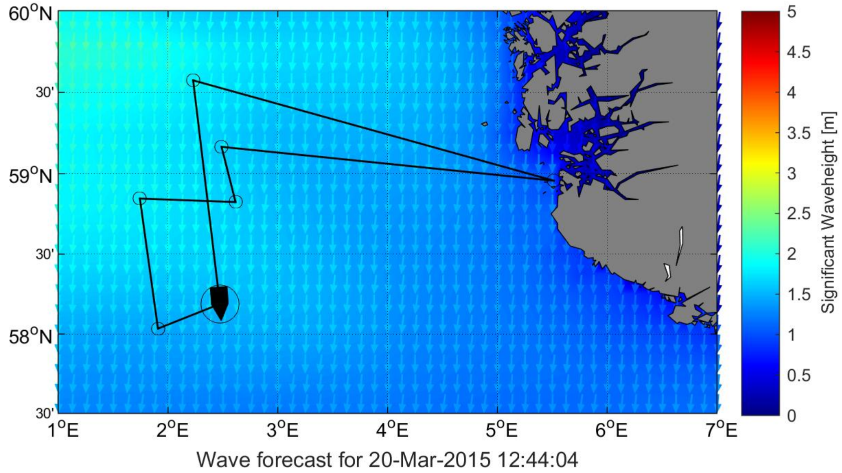

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 10:41:37
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

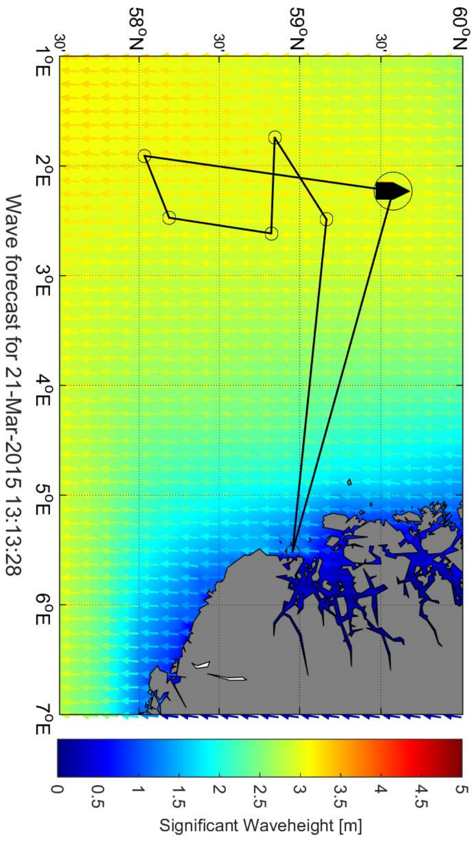

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 10:41:37
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

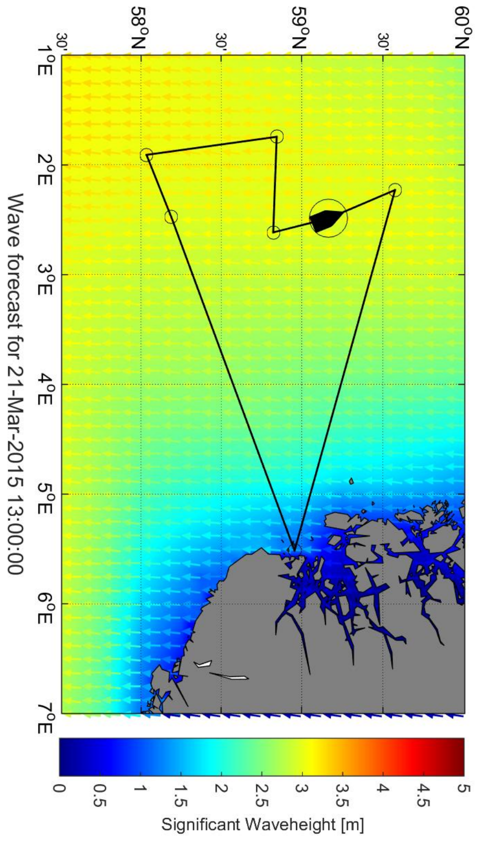

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 15:15:55
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

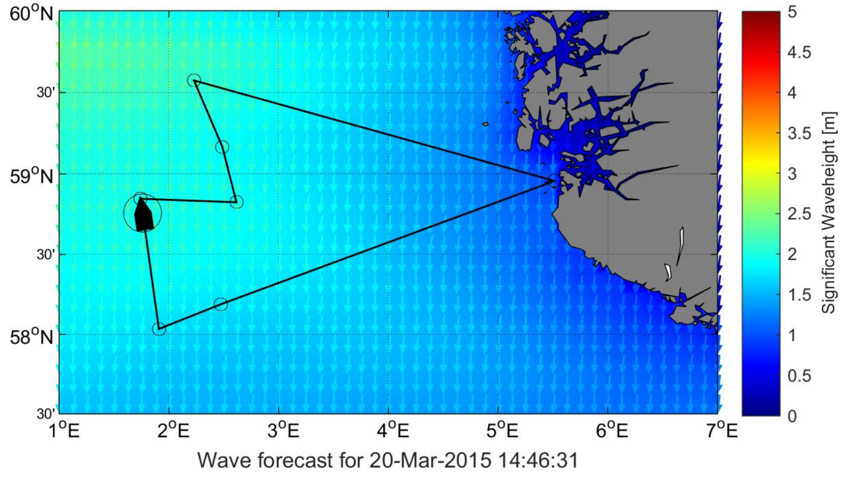

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 15:15:55
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

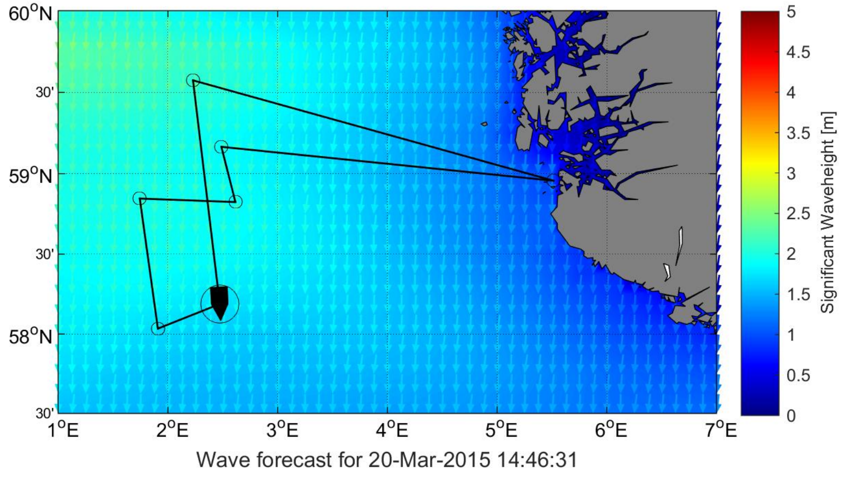

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 12:44:04
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

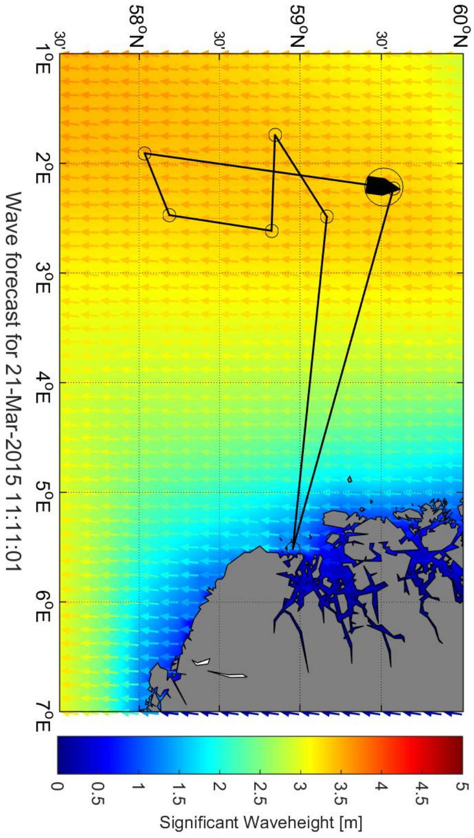

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 12:44:04
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

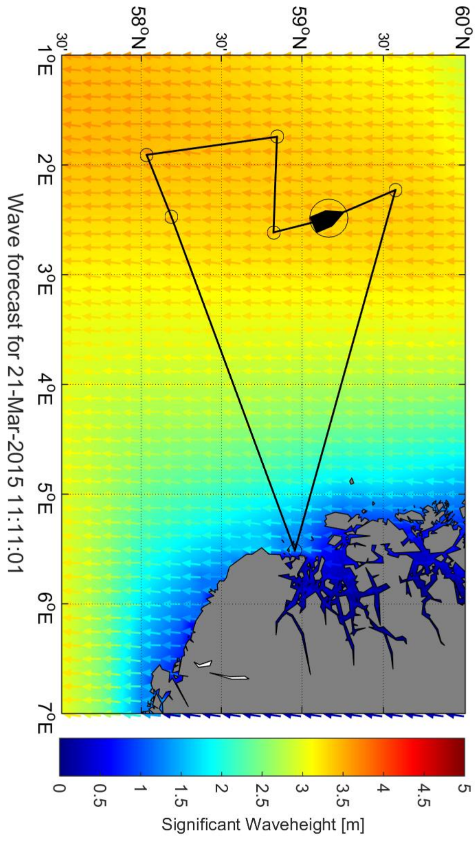

Wave forecast for 21-Mar-2015 13:13:28
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

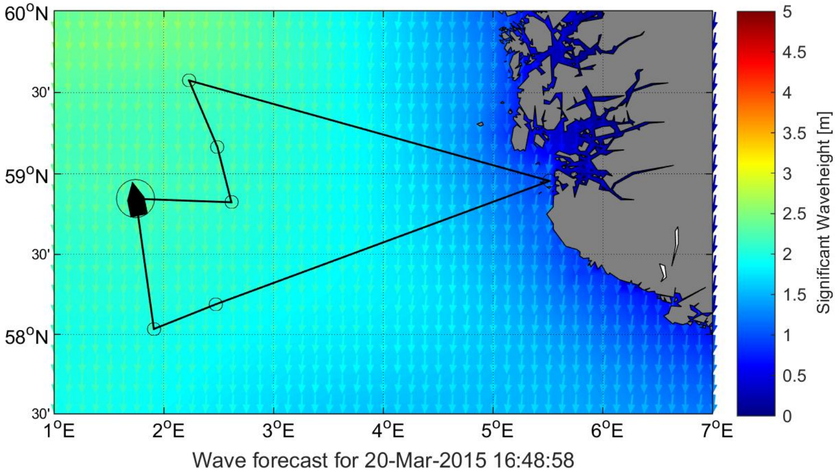

Wave forecast for 21-Mar-2015 13:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

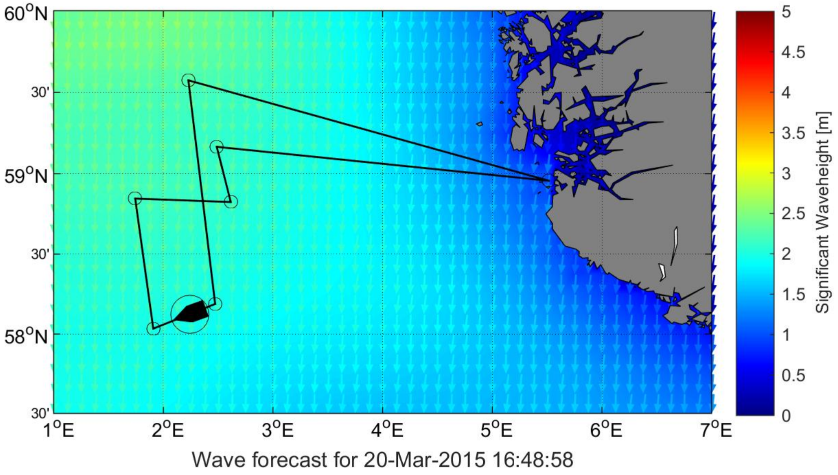

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 14:46:31
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

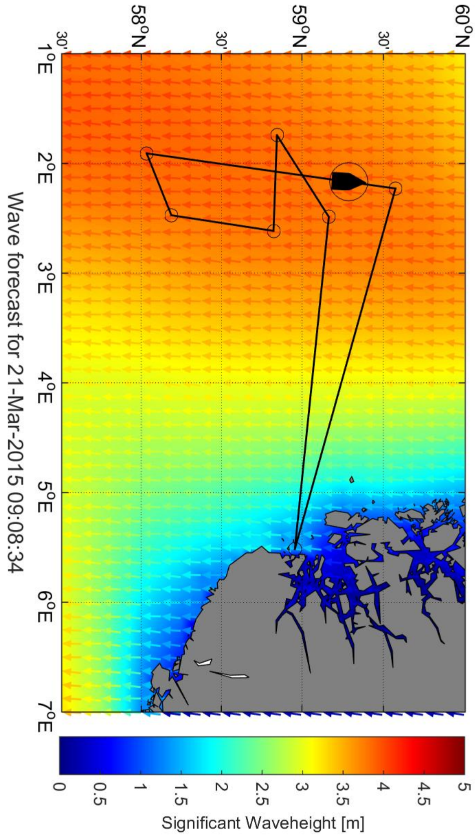

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 14:46:31
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]


Wave forecast for 21-Mar-2015 11:11:01
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 21-Mar-2015 11:11:01
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 16:48:58
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 16:48:58
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 09:08:34
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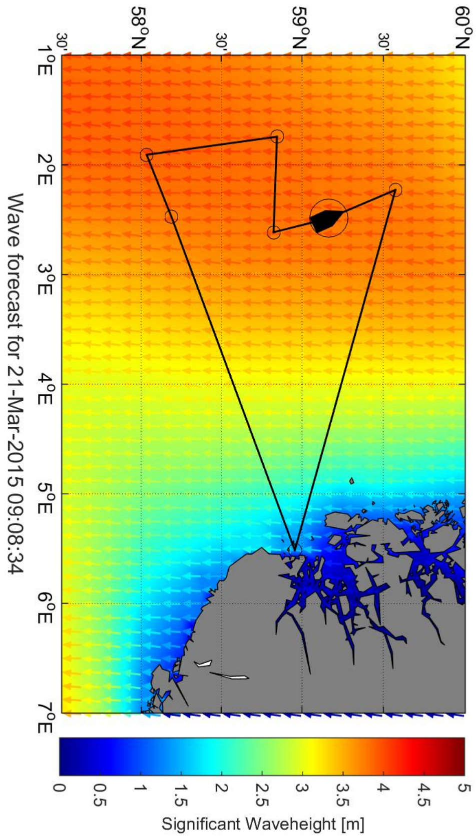
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Wave forecast for 21-Mar-2015 09:08:34
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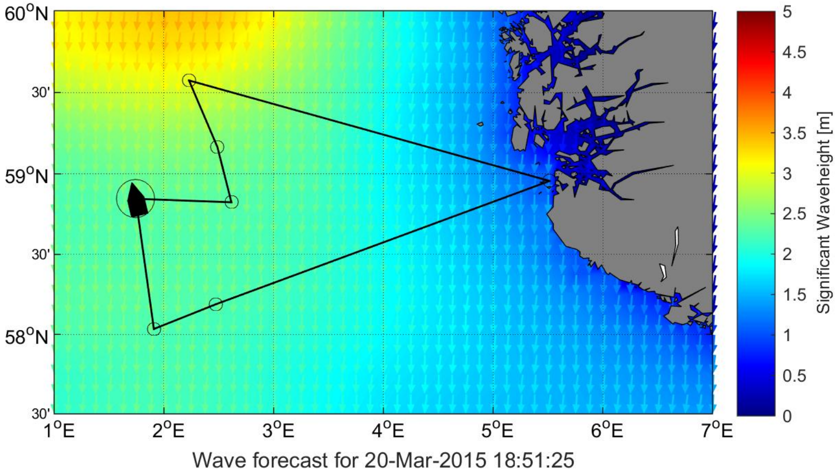
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Wave forecast for 20-Mar-2015 18:51:25
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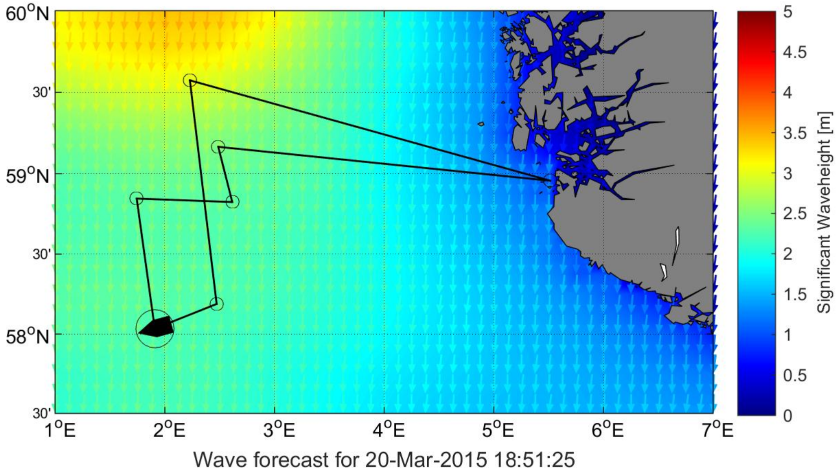
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Wave forecast for 20-Mar-2015 18:51:25
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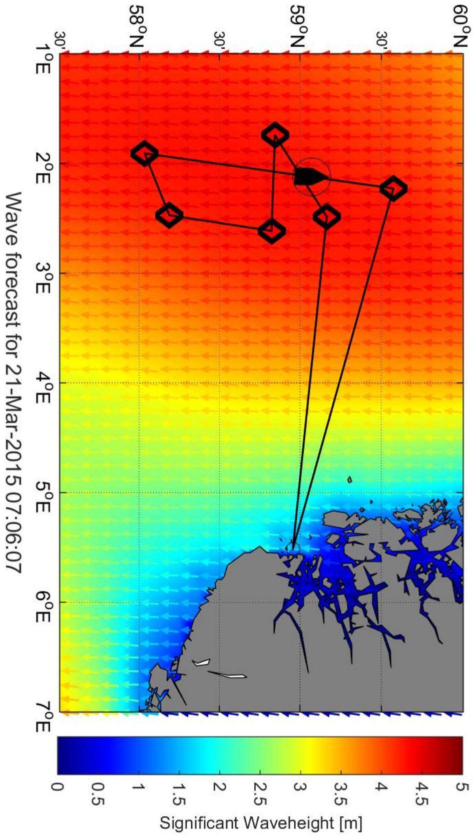
Wave forecast for 21-Mar-2015 07:06:07
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30'
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2°E
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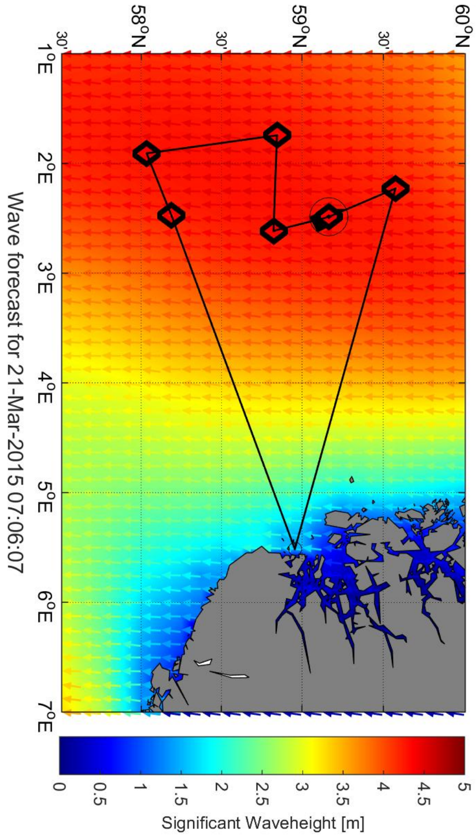
Wave forecast for 21-Mar-2015 07:06:07
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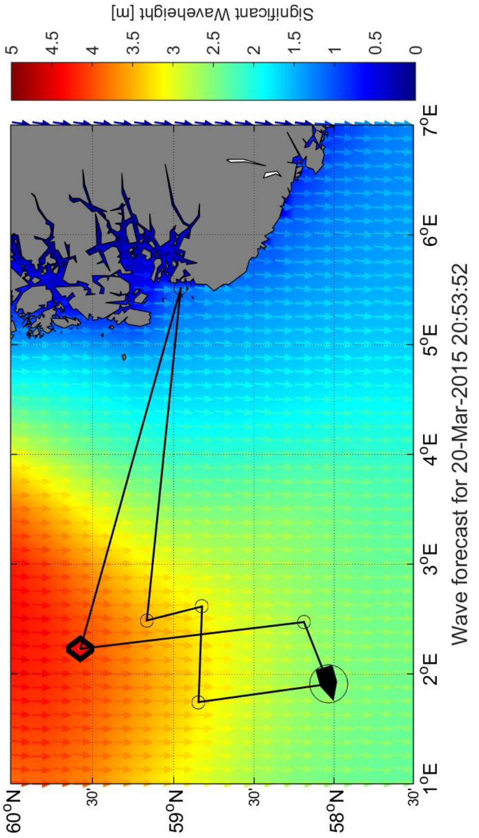
Wave forecast for 20-Mar-2015 20:53:52
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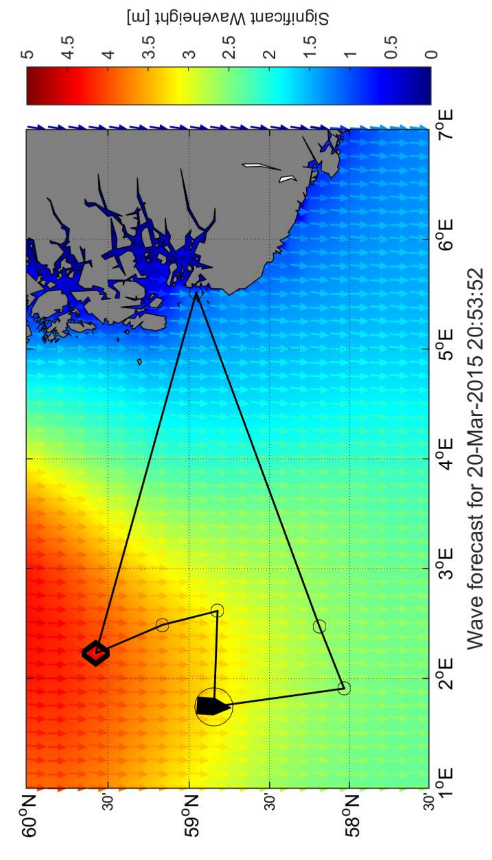
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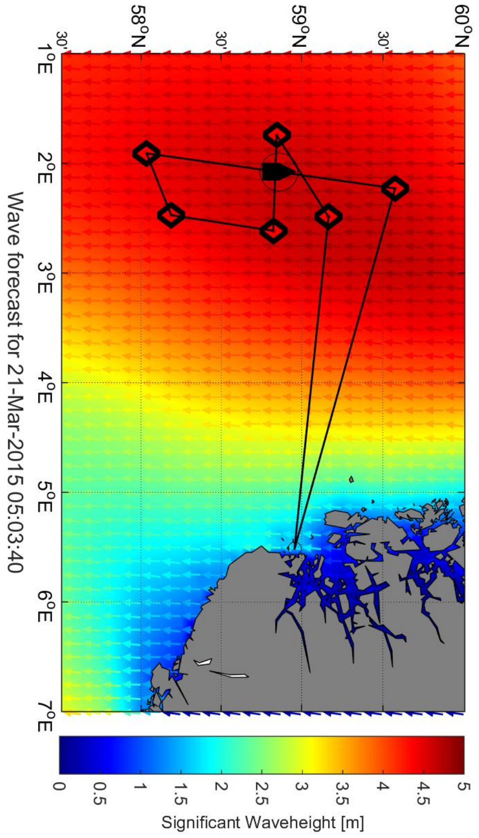
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7°E
Wave forecast for 21-Mar-2015 05:03:40
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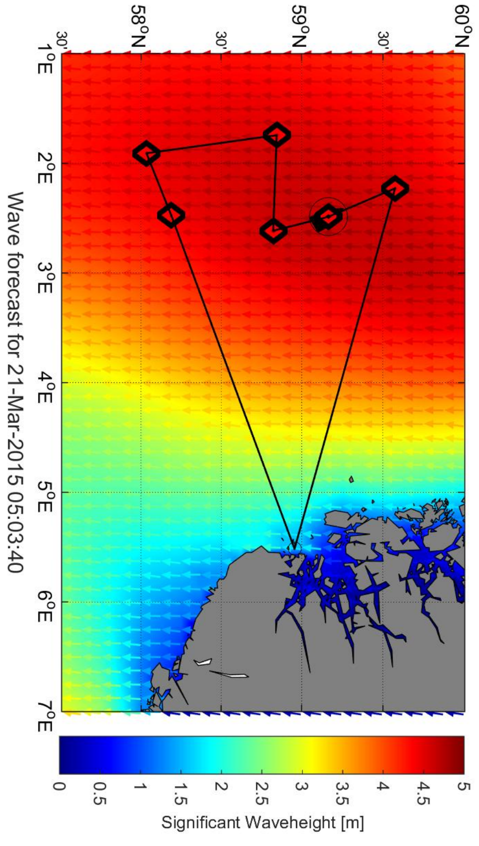
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7°E
Wave forecast for 21-Mar-2015 05:03:40
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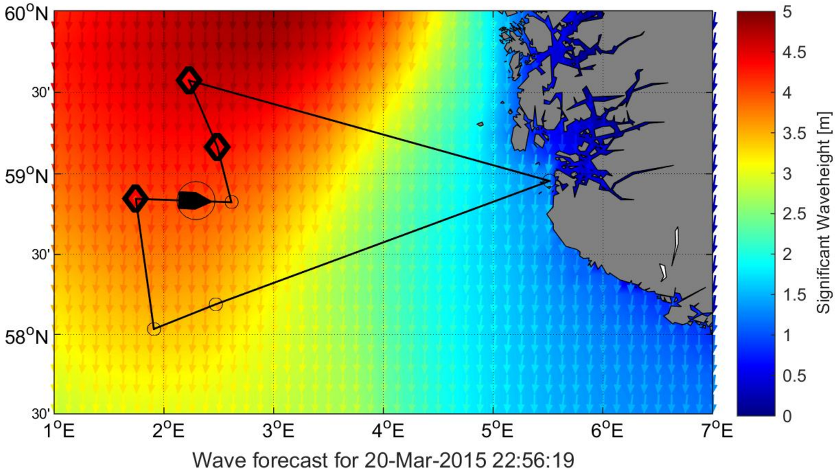
Significant Waveheight [m]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1°E
2°E
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4°E
5°E
6°E
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Wave forecast for 20-Mar-2015 22:56:19
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3.5
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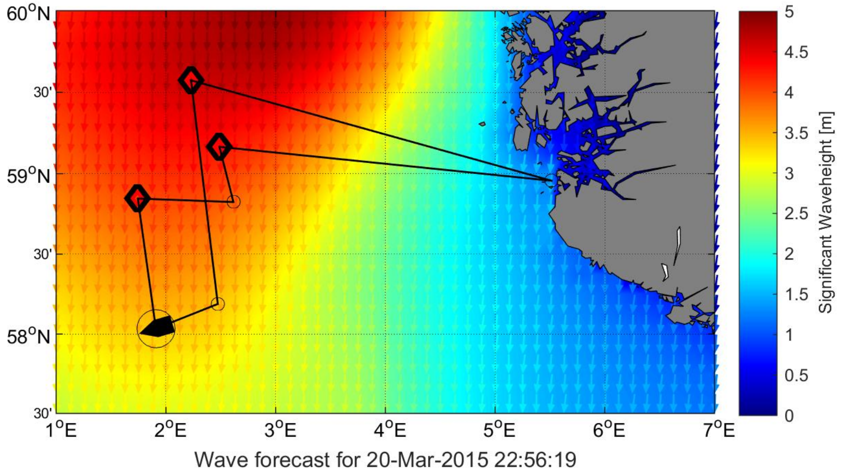
1.5
1
0.5
0
Significant Waveheight [m]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Wave forecast for 20-Mar-2015 22:56:19
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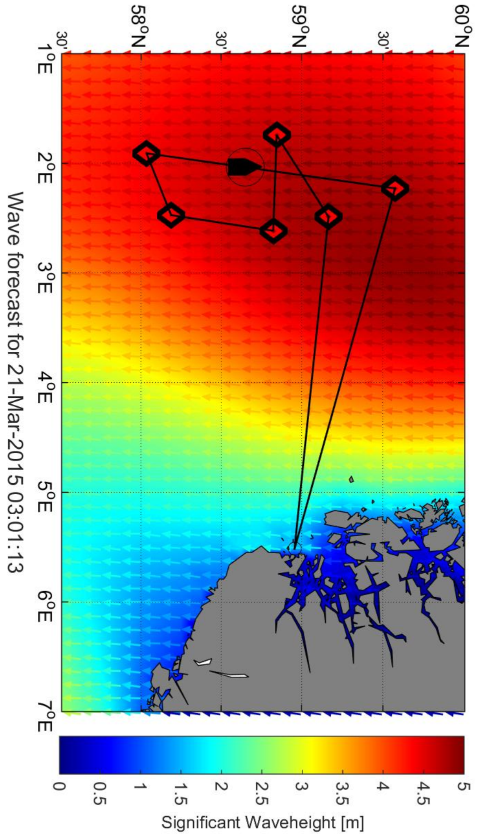
Significant Waveheight [m]


Wave forecast for 21-Mar-2015 03:01:13
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58°N
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1°E
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3°E
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3.5
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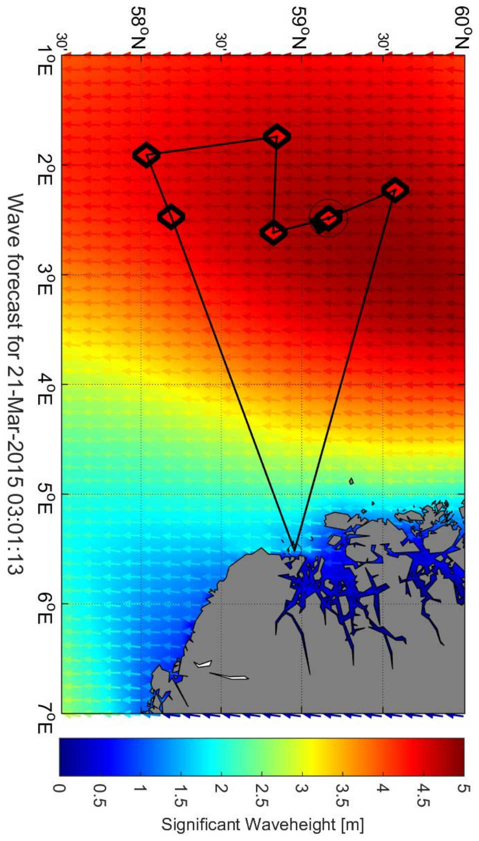
4.5
5
Significant Waveheight [m]


Wave forecast for 21-Mar-2015 03:01:13
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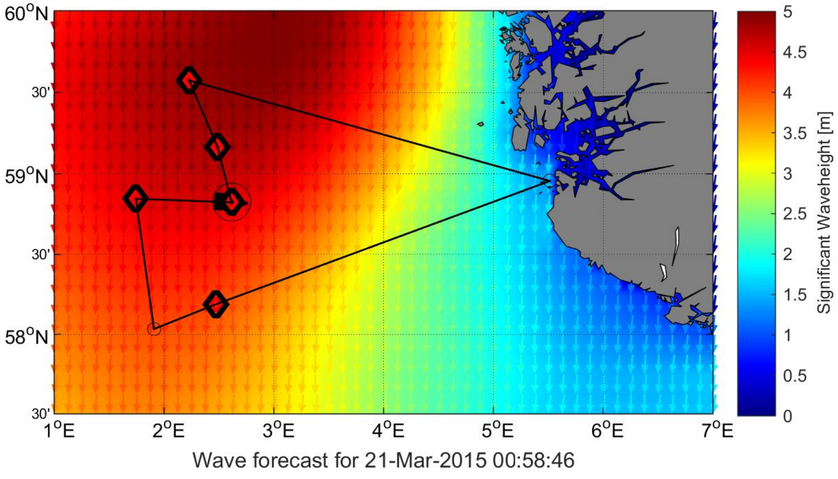
Significant Waveheight [m]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Wave forecast for 21-Mar-2015 00:58:46
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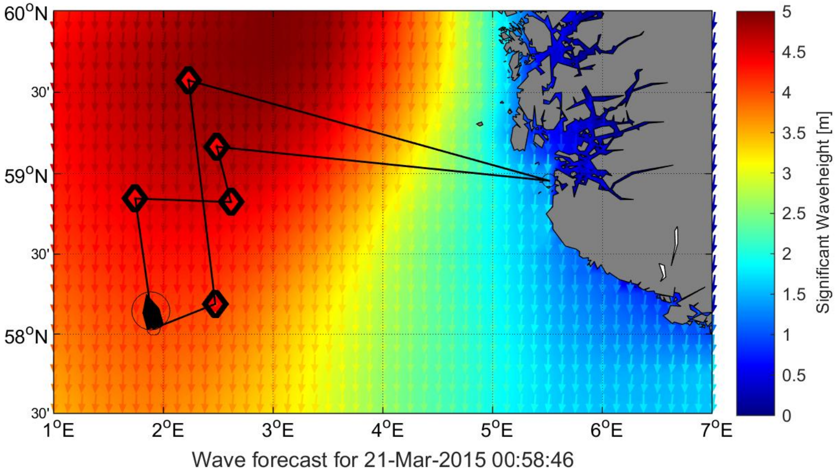
Significant Waveheight [m]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Wave forecast for 21-Mar-2015 00:58:46
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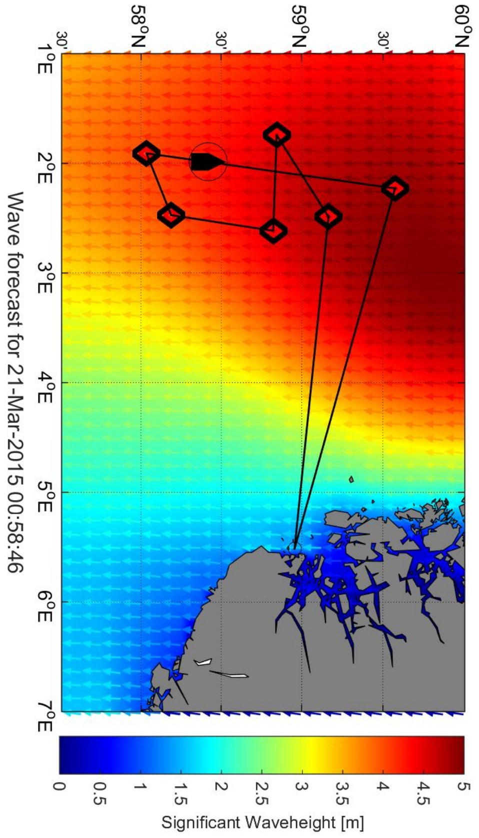
Significant Waveheight [m]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Wave forecast for 21-Mar-2015 00:58:46
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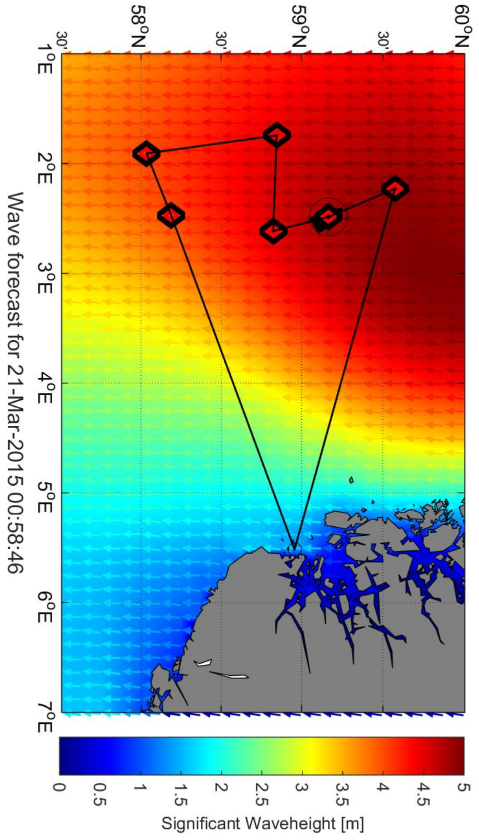
Significant Waveheight [m]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Wave forecast for 21-Mar-2015 00:58:46
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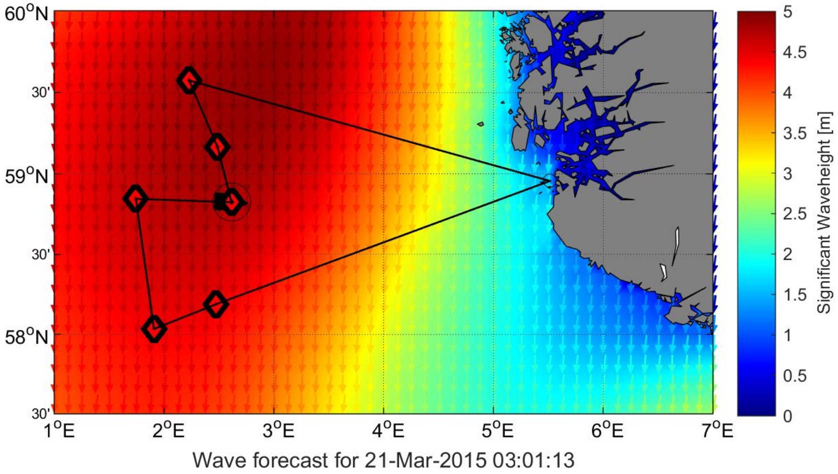
Significant Waveheight [m]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Wave forecast for 21-Mar-2015 03:01:13
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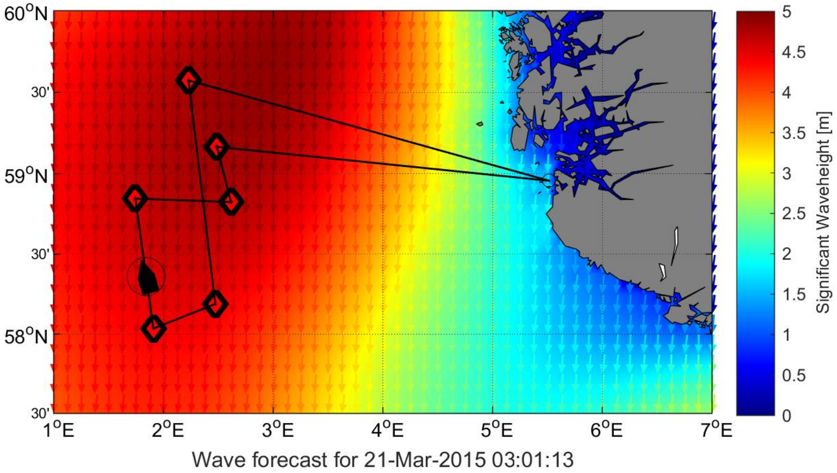
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Wave forecast for 21-Mar-2015 03:01:13
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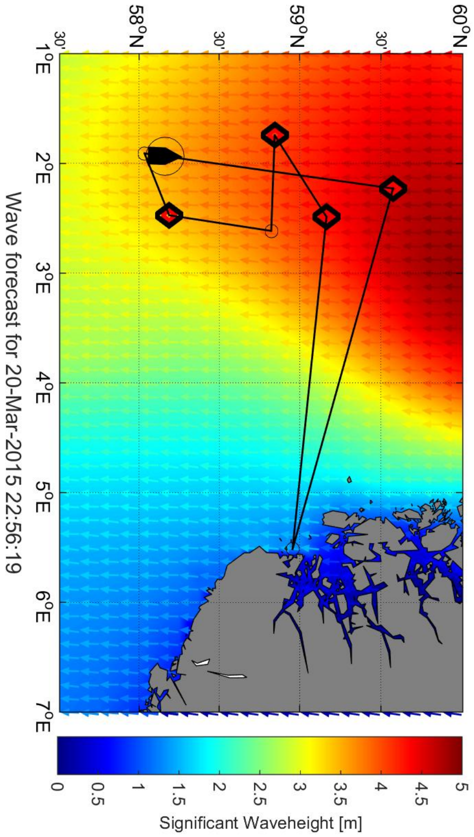
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Wave forecast for 20-Mar-2015 22:56:19
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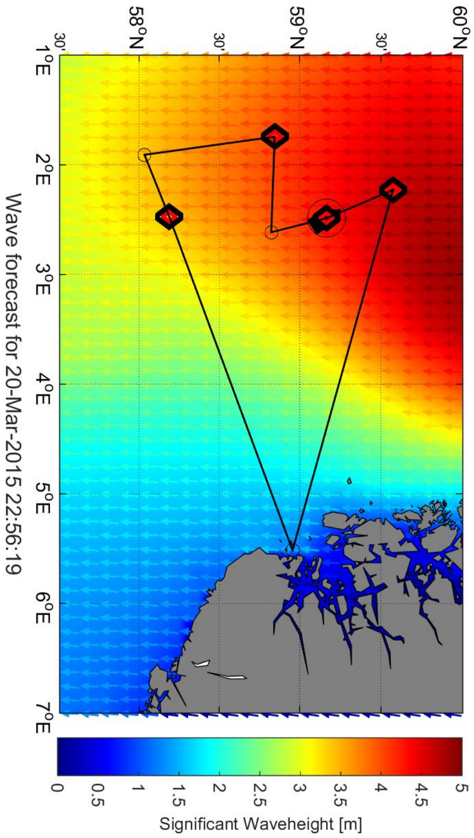
Significant Waveheight [m]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Wave forecast for 20-Mar-2015 22:56:19
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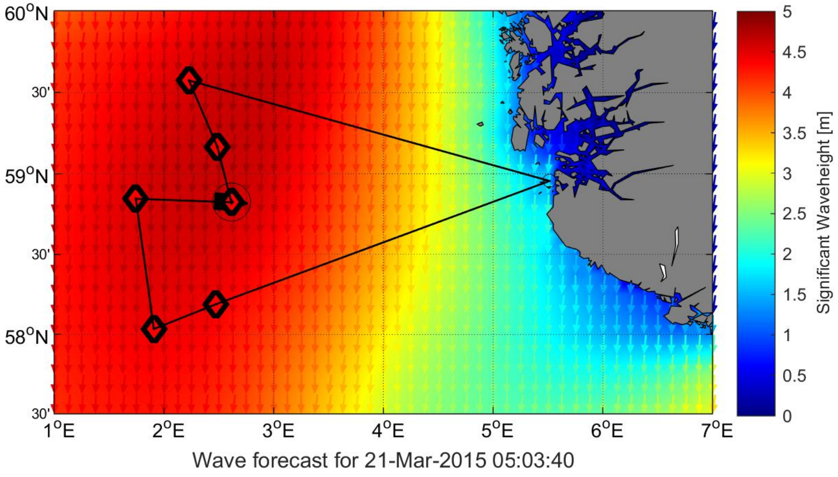
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Wave forecast for 21-Mar-2015 05:03:40
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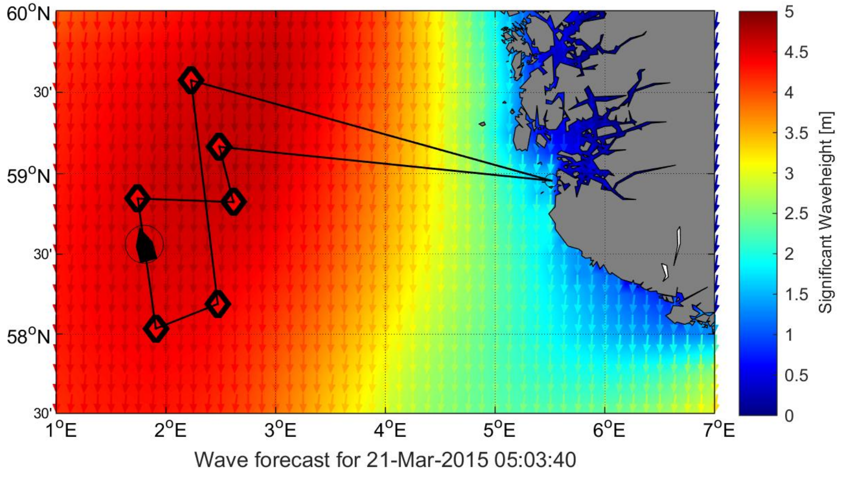
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Wave forecast for 21-Mar-2015 05:03:40
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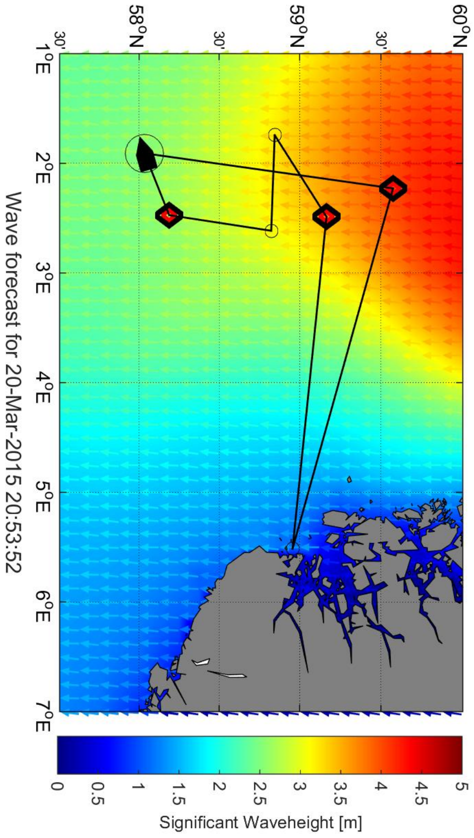
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Wave forecast for 20-Mar-2015 20:53:52
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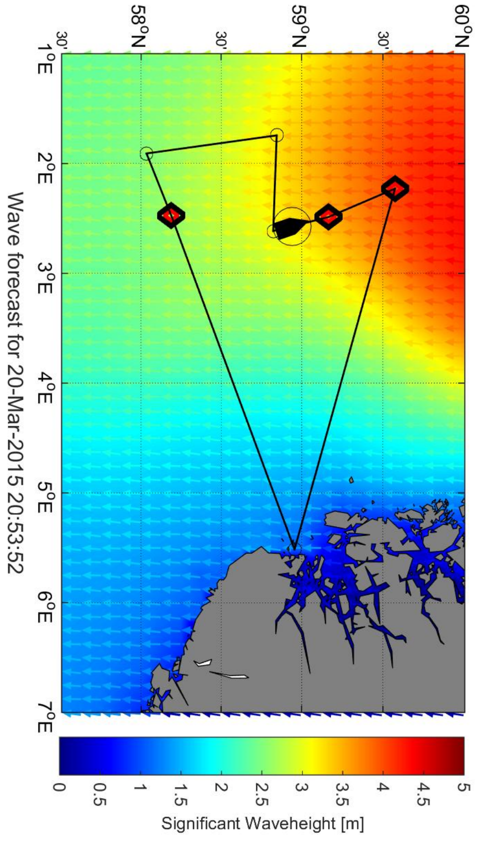
Significant Waveheight [m]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Wave forecast for 20-Mar-2015 20:53:52
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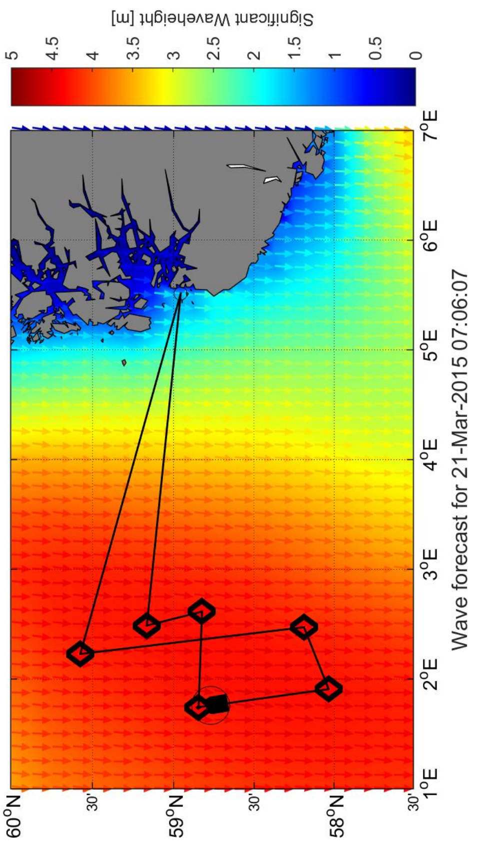
Wave forecast for 21-Mar-2015 07:06:07
Significant Waveheight [m]
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3.5
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1.5
1
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0
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
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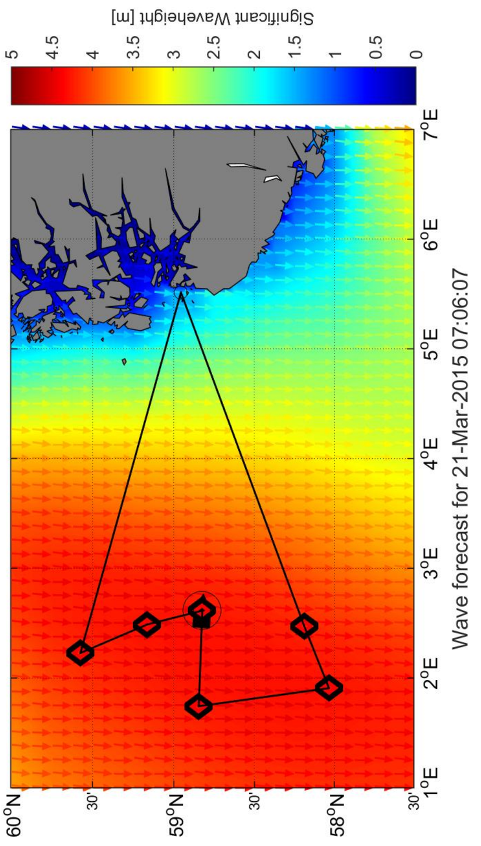
4°E
5°E
6°E
7°E


Wave forecast for 21-Mar-2015 07:06:07
Significant Waveheight [m]
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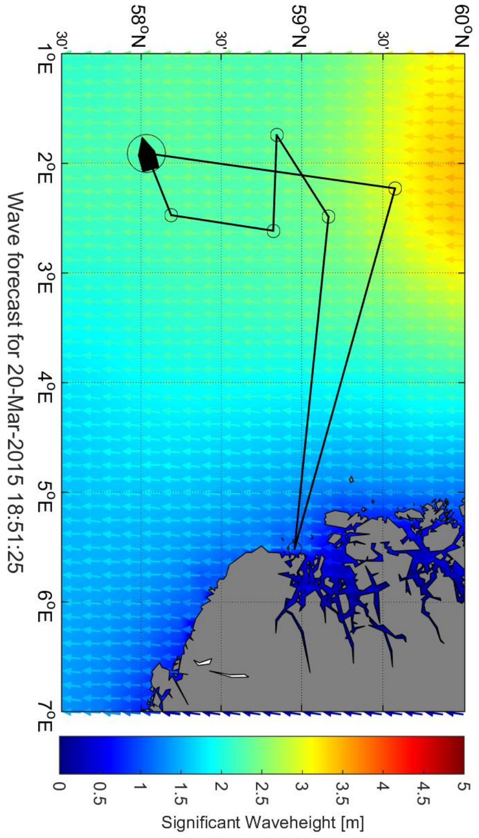
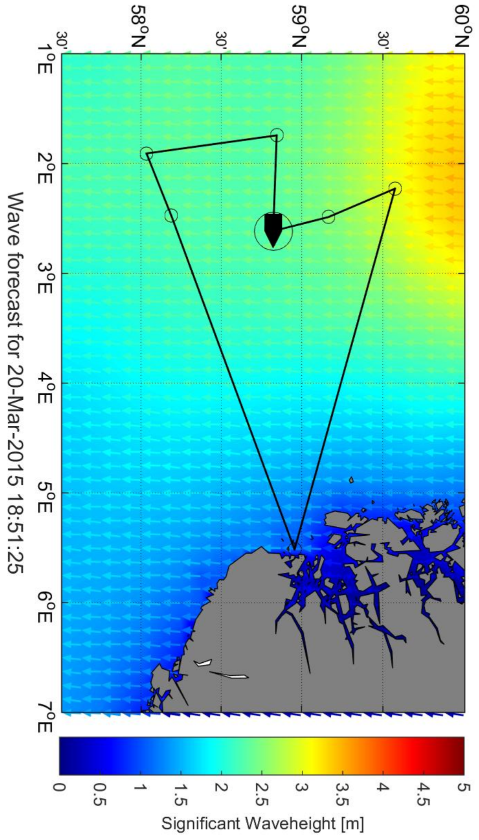
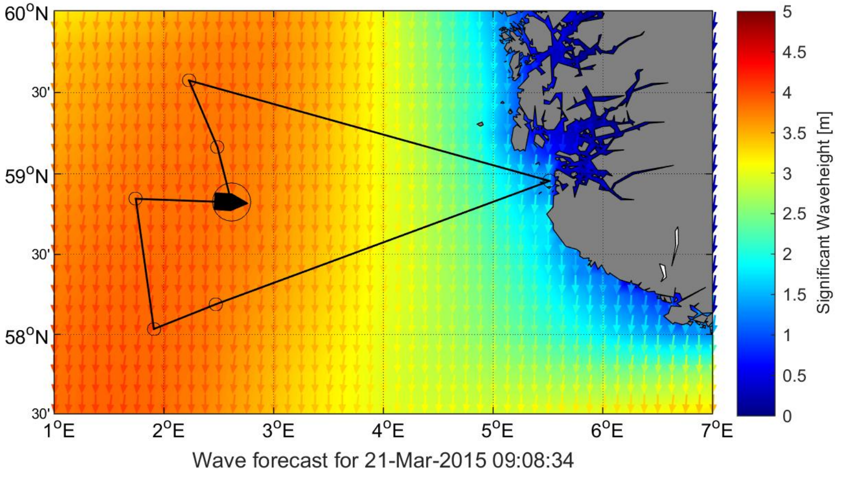

Wave forecast for 20-Mar-2015 18:51:25


Wave forecast for 20-Mar-2015 18:51:25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30'
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1°E
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6°E
7°E
Wave forecast for 21-Mar-2015 09:08:34
Significant Waveheight [m]
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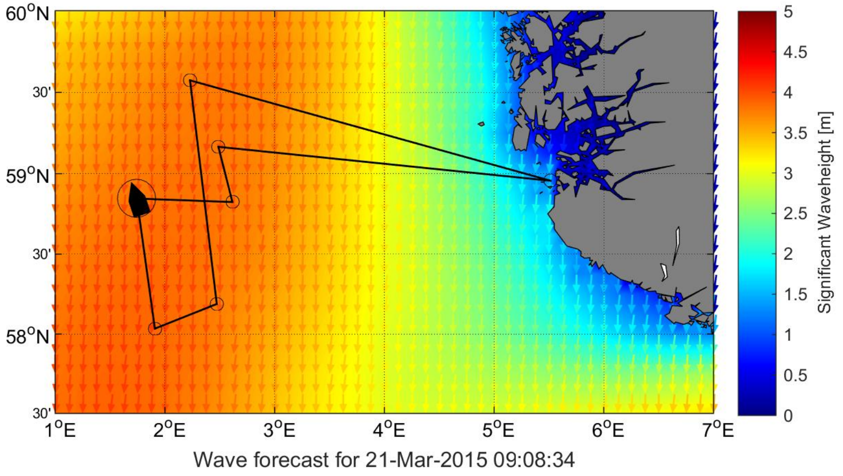
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Wave forecast for 21-Mar-2015 09:08:34
Significant Waveheight [m]
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1
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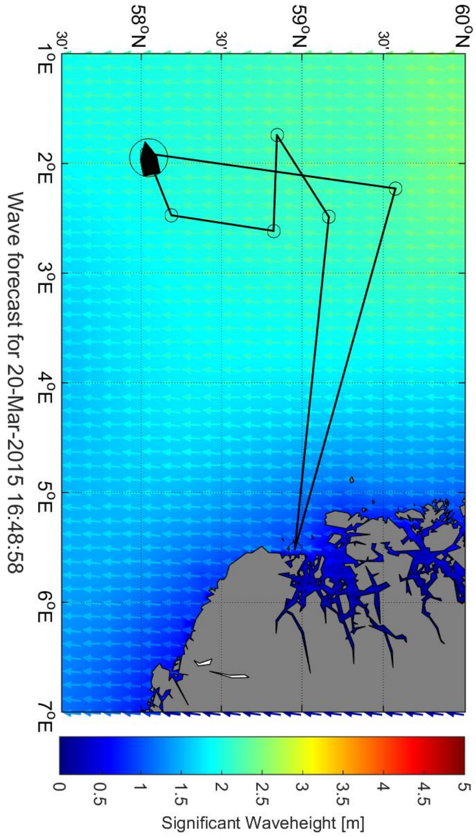
Wave forecast for 20-Mar-2015 16:48:58
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4°E
5°E
6°E
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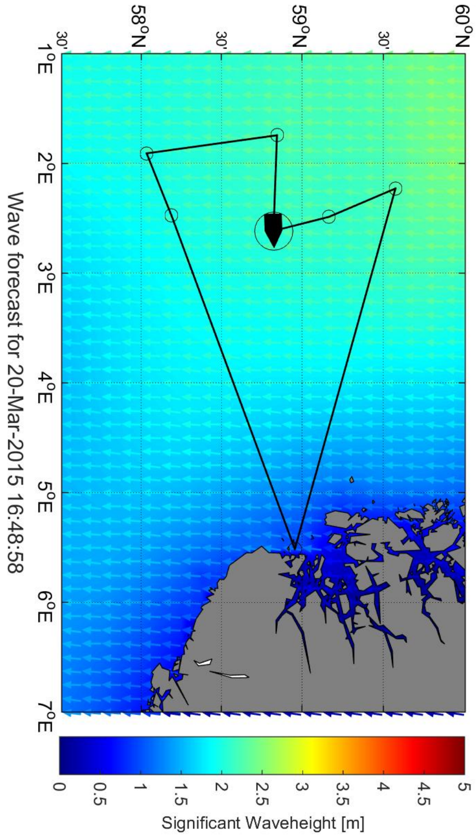
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 20-Mar-2015 16:48:58
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58°N
30'
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2°E
3°E
4°E
5°E
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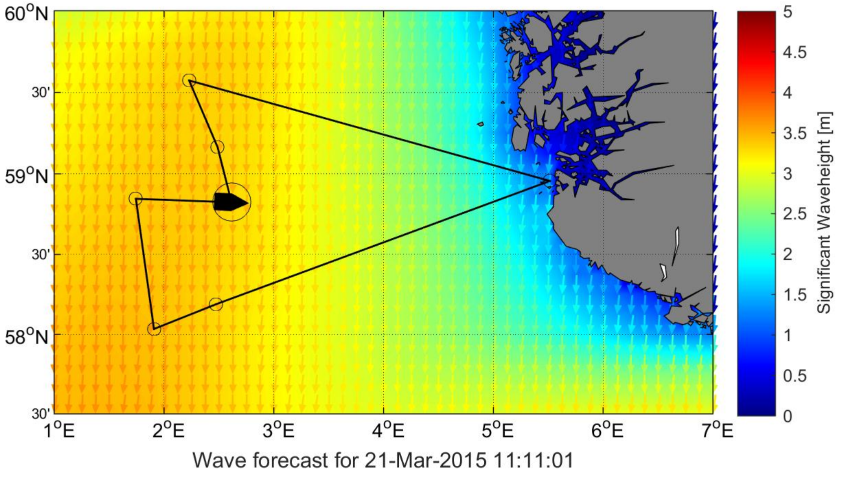
4.5
5
Significant Waveheight [m]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30'
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30'
58°N
30'
1°E
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3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 11:11:01
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1
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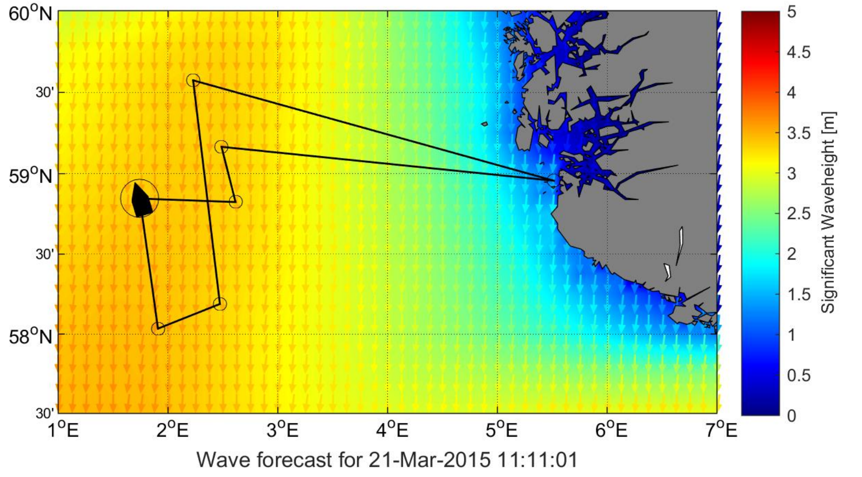
0
Significant Waveheight [m]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30'
58°N
30'
1°E
2°E
3°E
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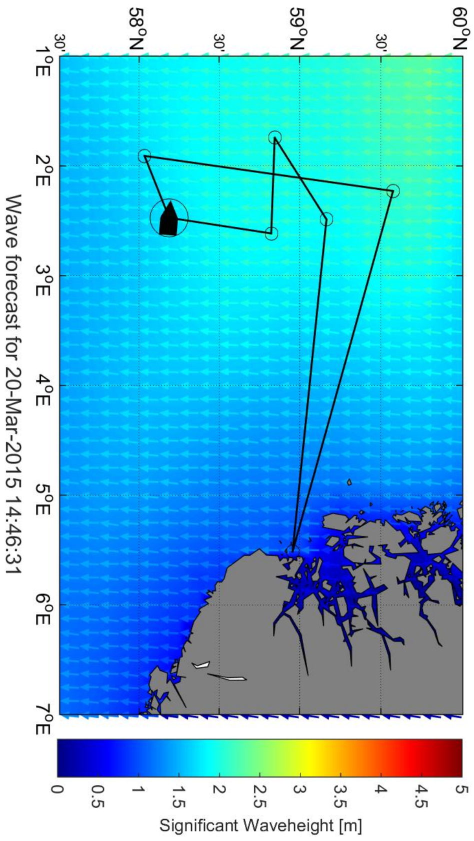
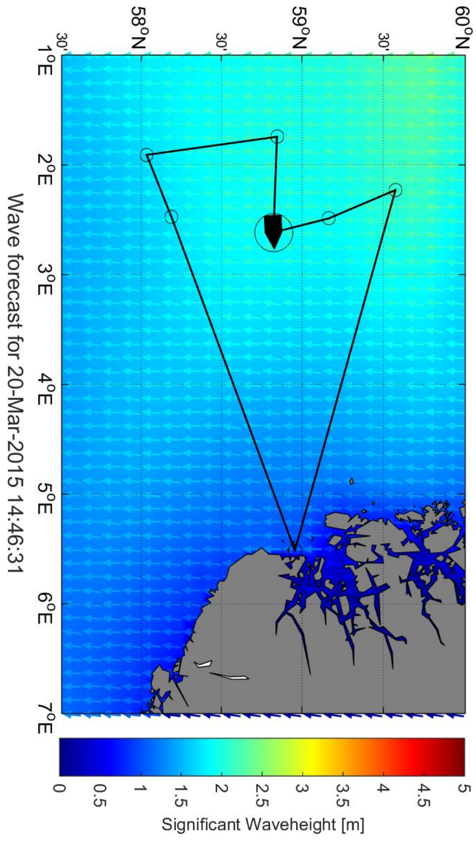
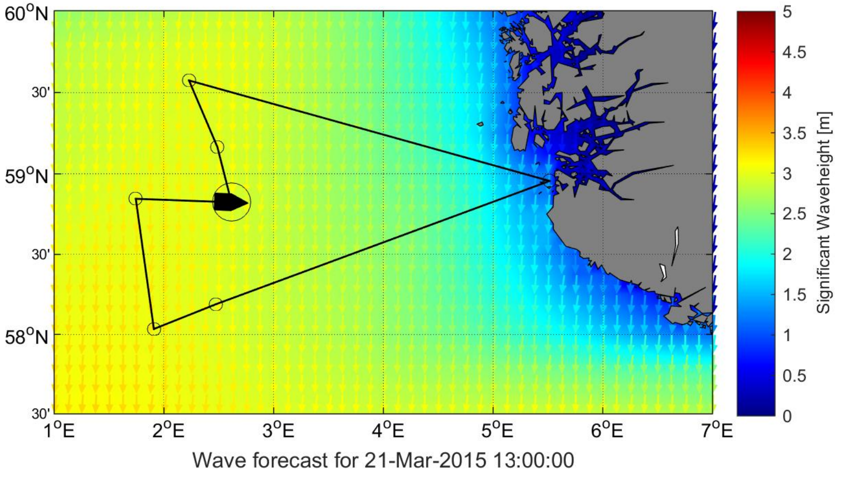
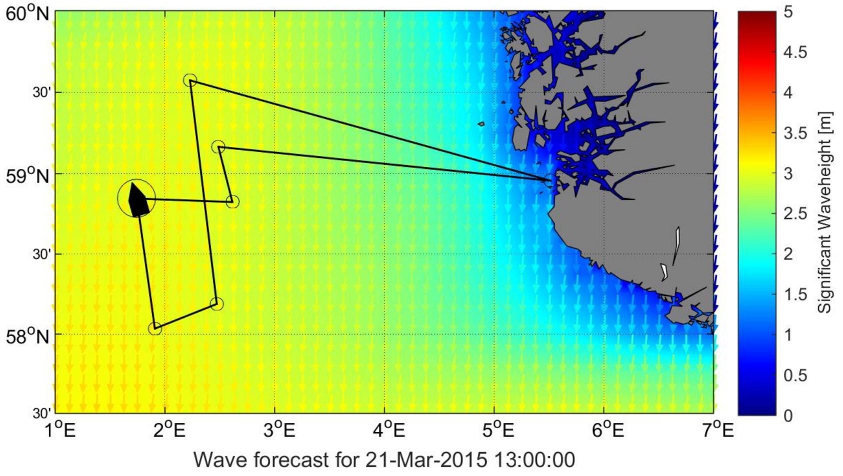
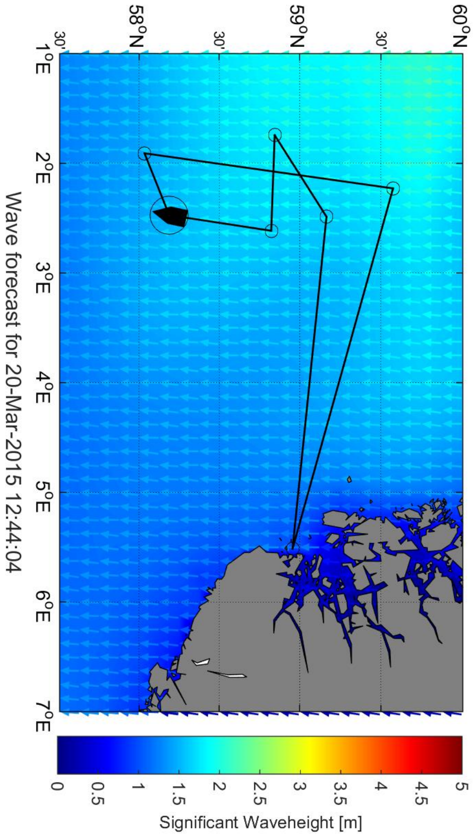
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 11:11:01
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

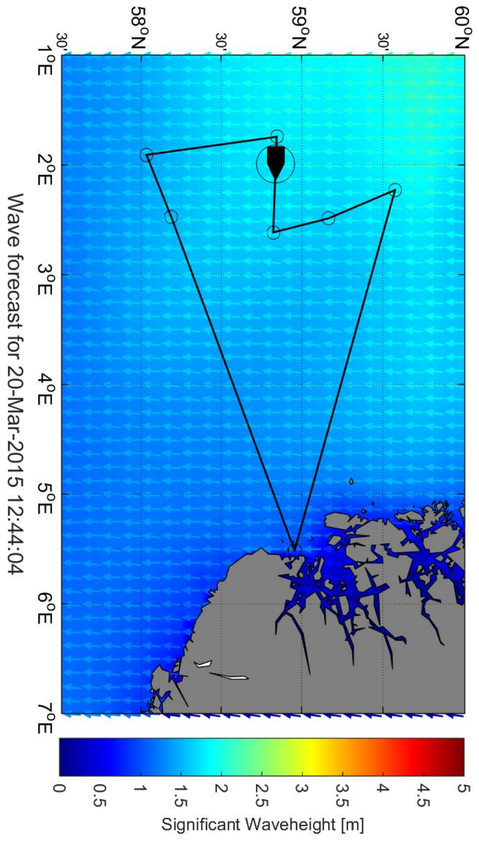

Wave forecast for 20-Mar-2015 14:46:31
1°E
2°E
3°E
4°E
5°E
6°E
7°E
30'
58°N
30'
59°N
30'
60°N
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

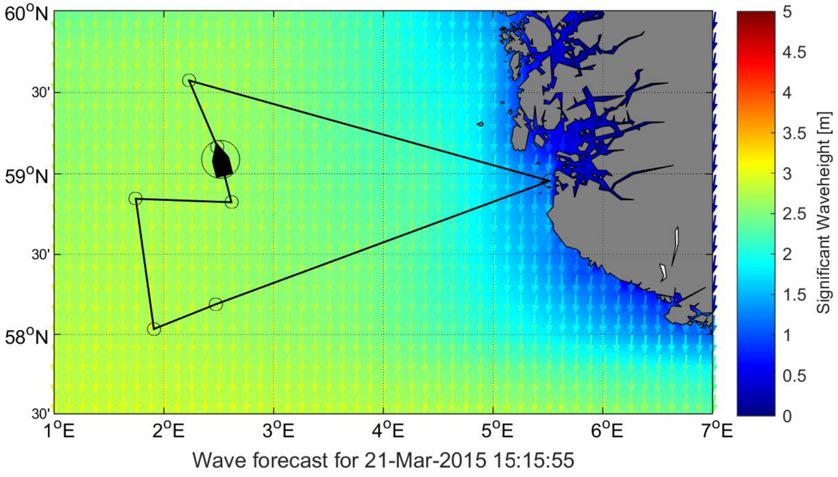

Wave forecast for 20-Mar-2015 14:46:31
1°E
2°E
3°E
4°E
5°E
6°E
7°E
30'
58°N
30'
59°N
30'
60°N
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

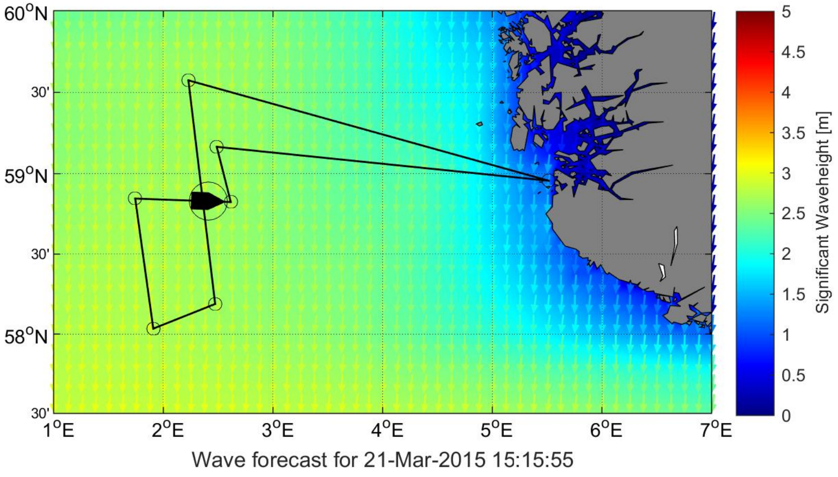

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 13:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

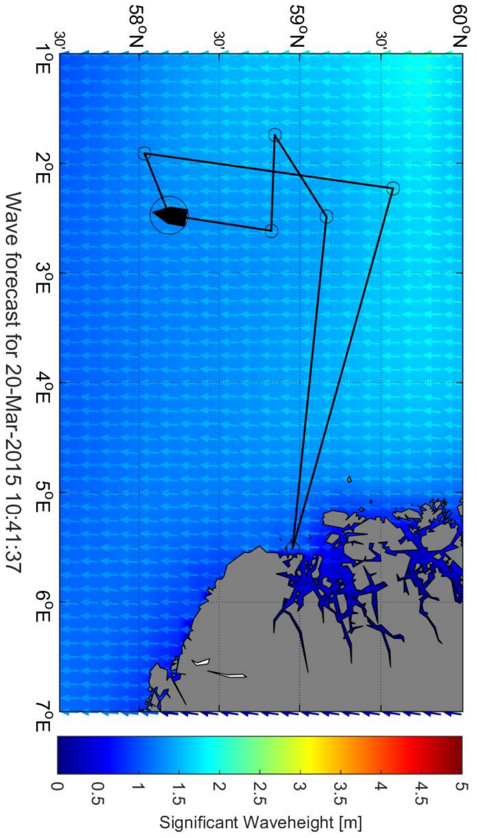

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 13:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

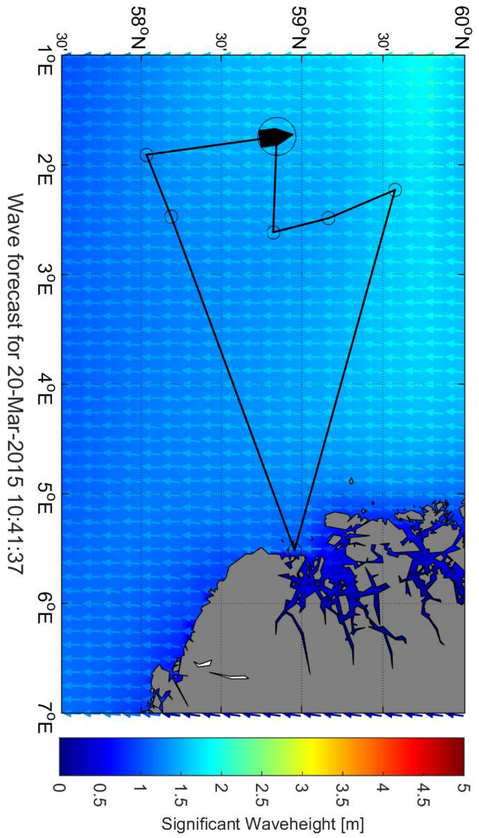

Wave forecast for 20-Mar-2015 12:44:04
58°N
59°N
60°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

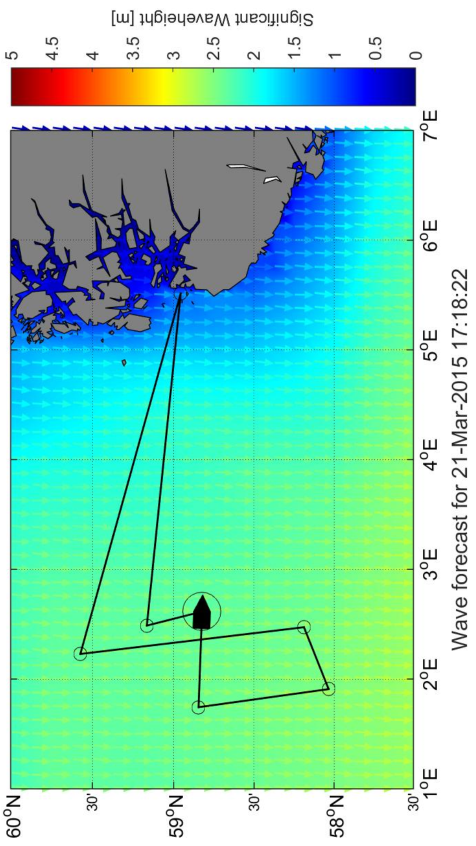

Wave forecast for 20-Mar-2015 12:44:04
58°N
59°N
60°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

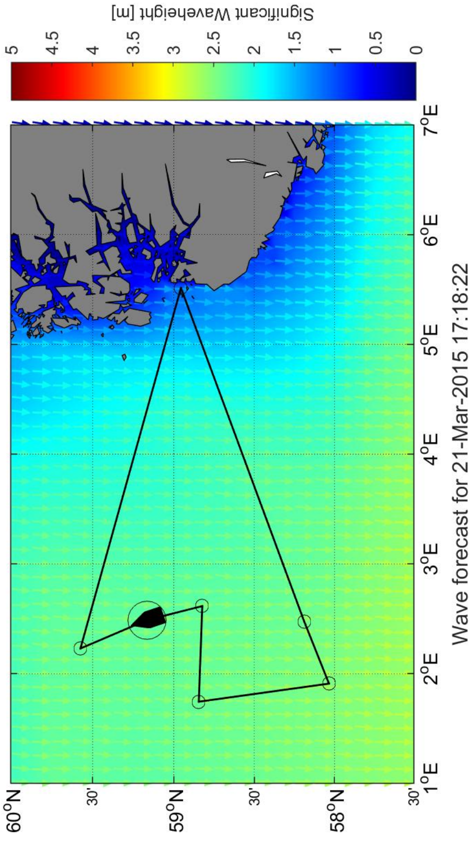

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]
Wave forecast for 21-Mar-2015 15:15:55

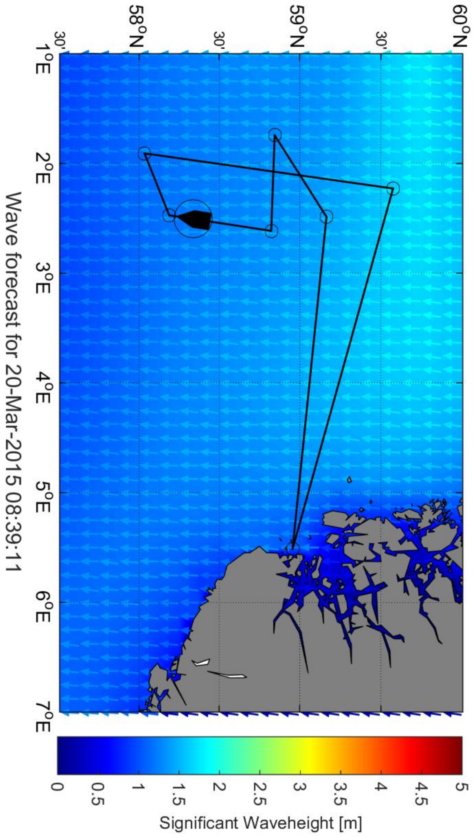

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]
Wave forecast for 21-Mar-2015 15:15:55

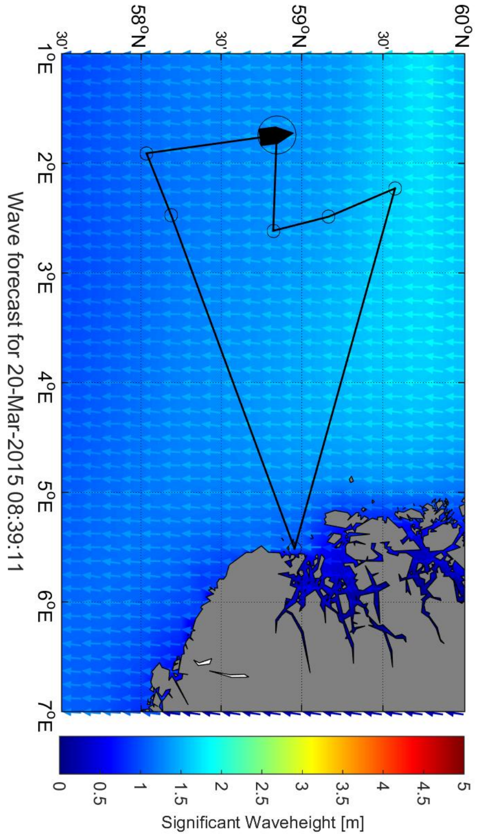

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 10:41:37
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

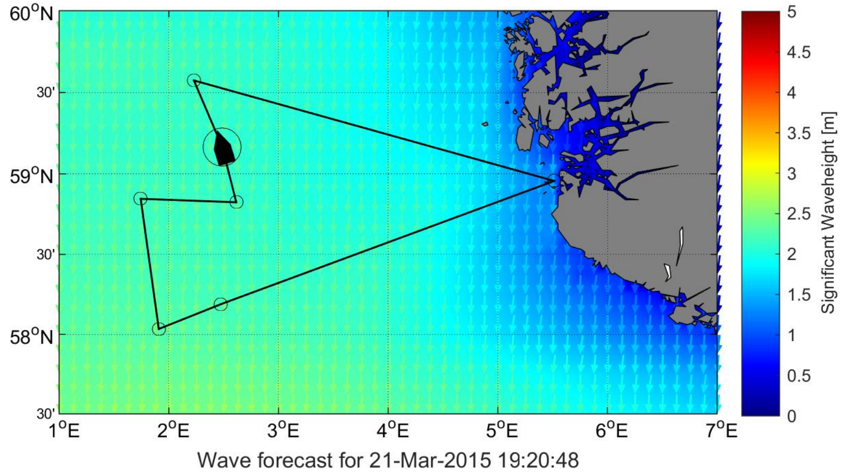

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 10:41:37
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

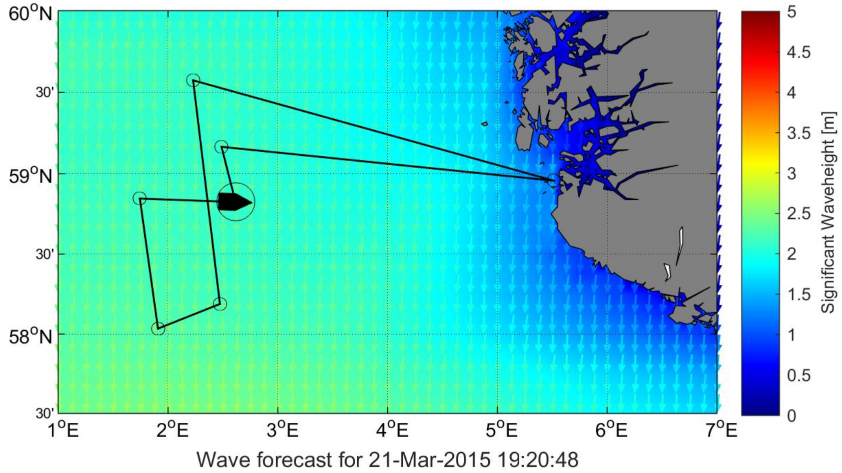

Wave forecast for 21-Mar-2015 17:18:22
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

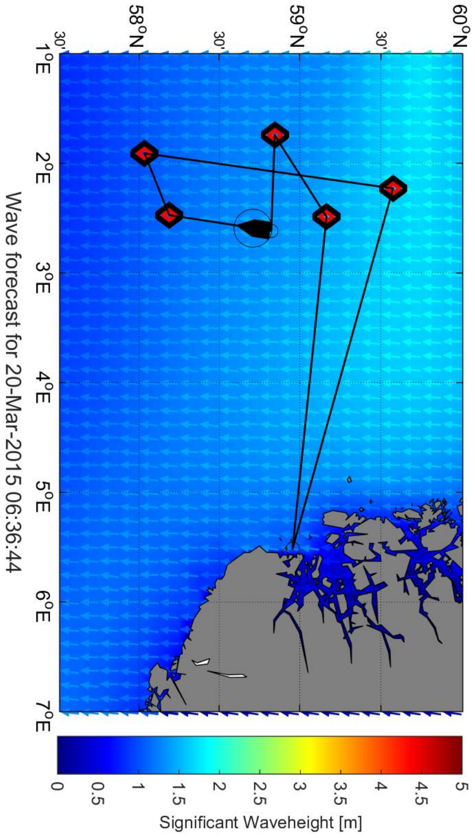

Wave forecast for 21-Mar-2015 17:18:22
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

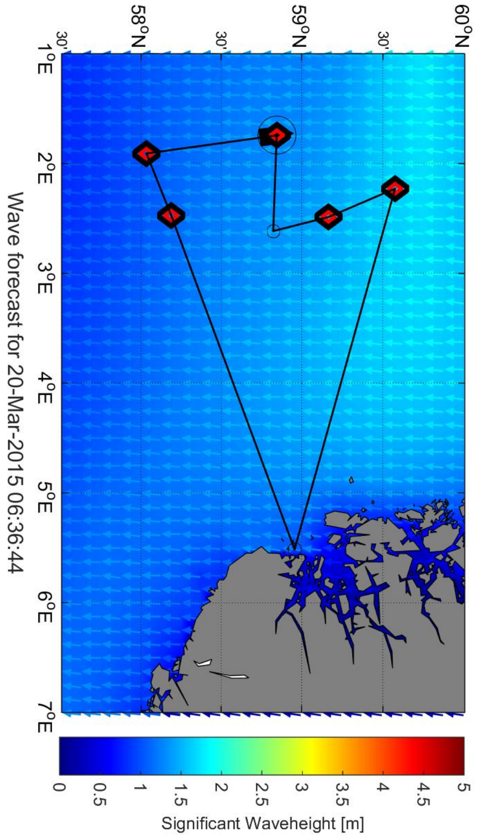

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 08:39:11
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

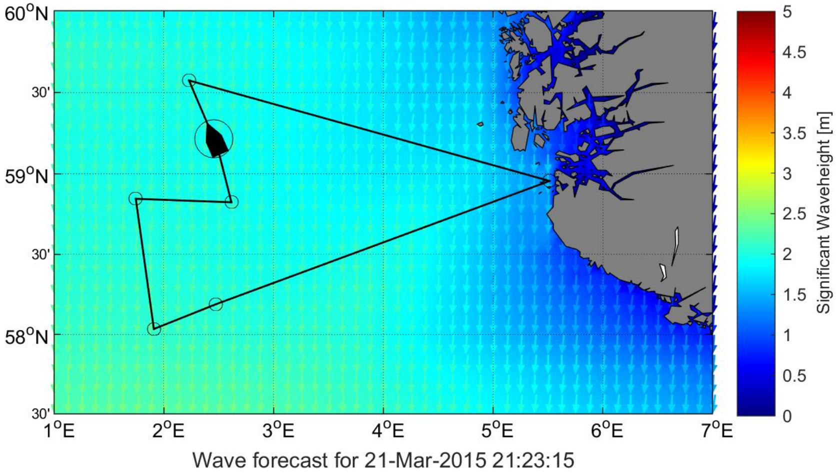

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 08:39:11
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

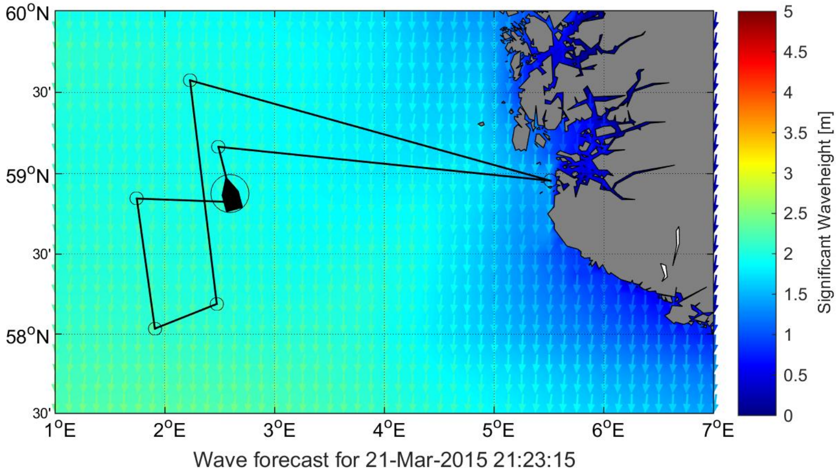

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 19:20:48
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

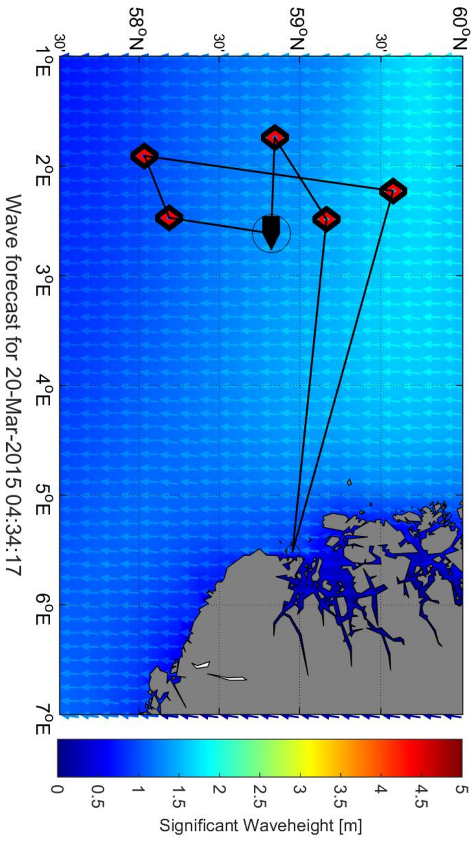

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 19:20:48
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

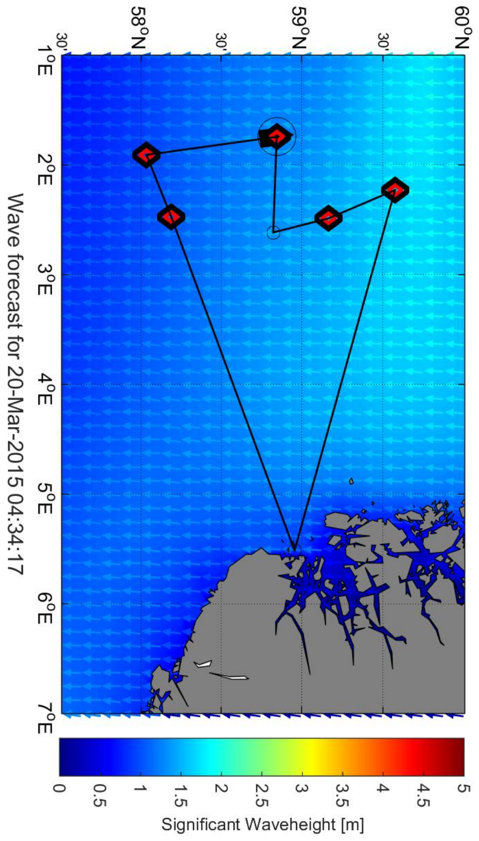

Wave forecast for 20-Mar-2015 06:36:44
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

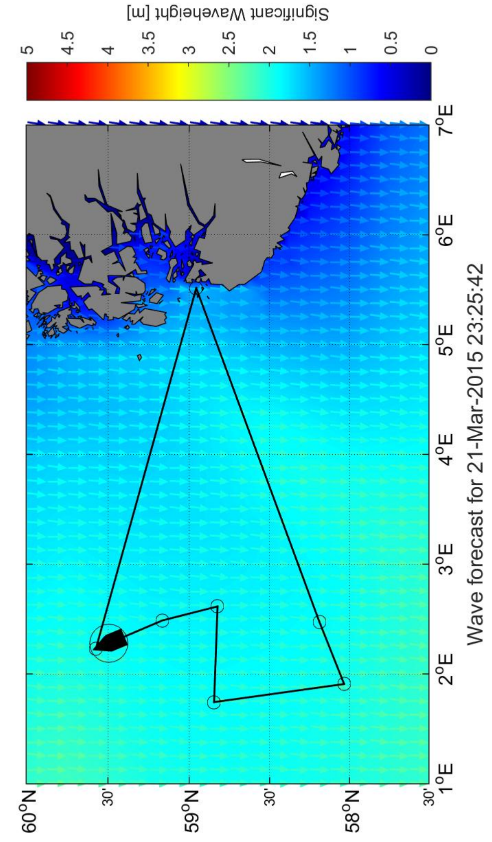

Wave forecast for 20-Mar-2015 06:36:44
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

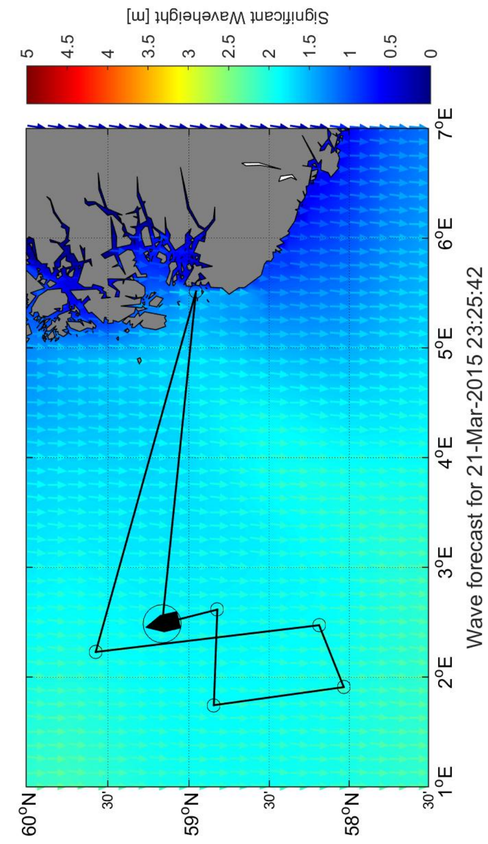

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 21:23:15
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

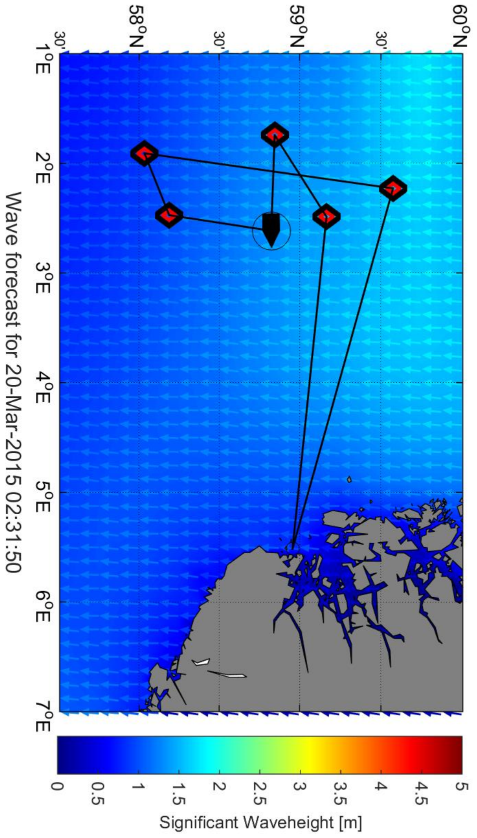

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 21-Mar-2015 21:23:15
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

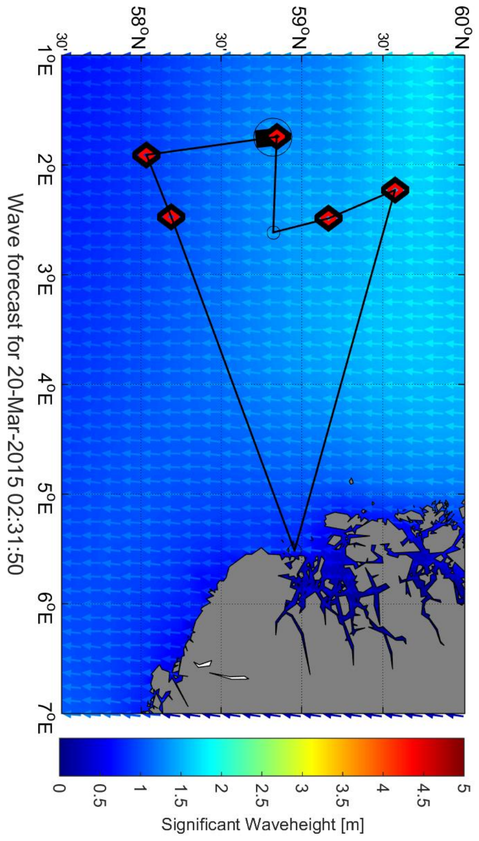

Wave forecast for 20-Mar-2015 04:34:17
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

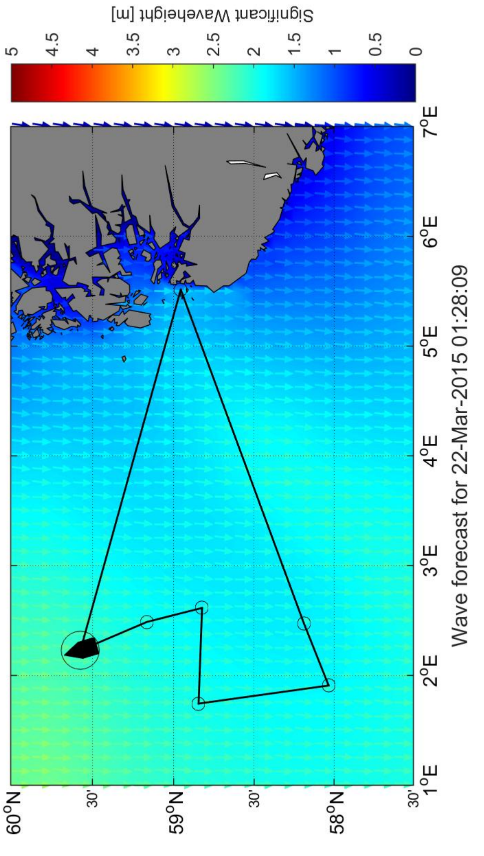

Wave forecast for 20-Mar-2015 04:34:17
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

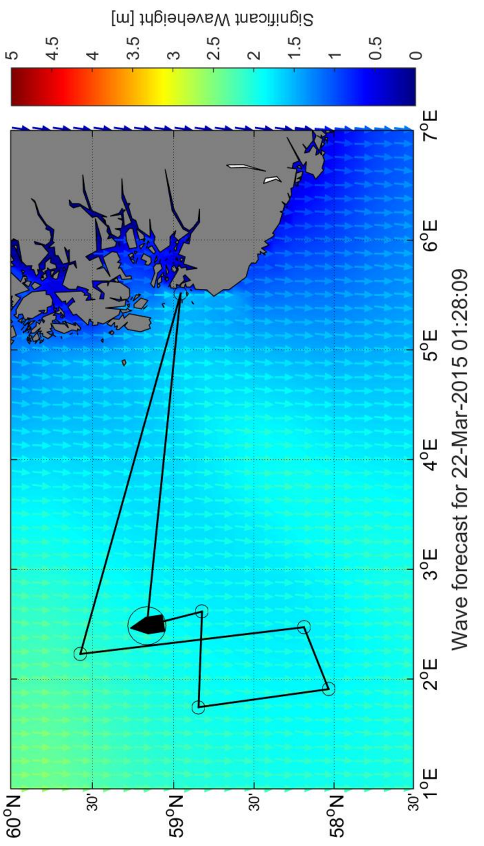

Wave forecast for 21-Mar-2015 23:25:42
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

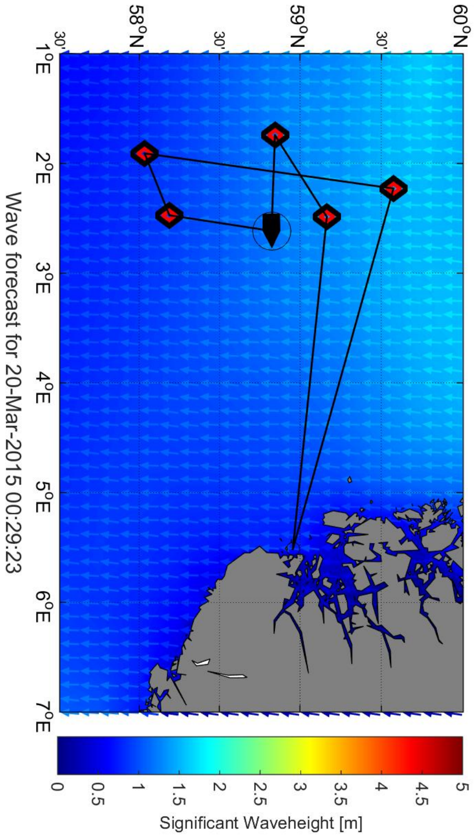

Wave forecast for 21-Mar-2015 23:25:42
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

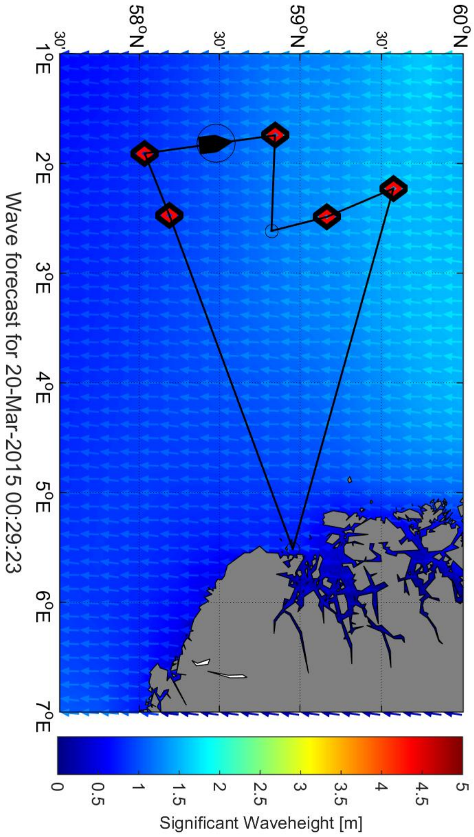

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 02:31:50
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

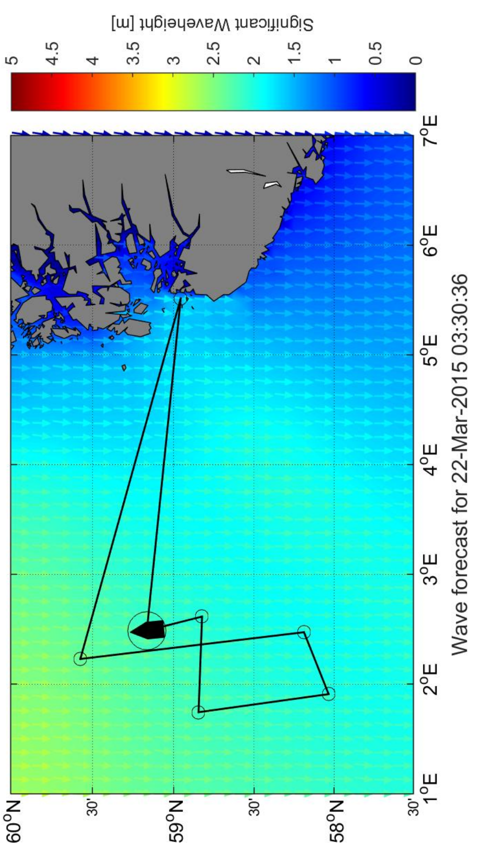

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 20-Mar-2015 02:31:50
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

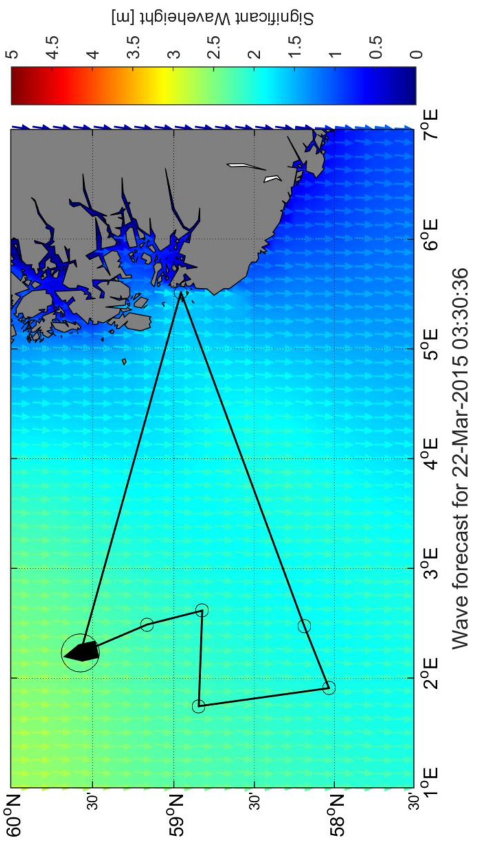

Wave forecast for 22-Mar-2015 01:28:09
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E

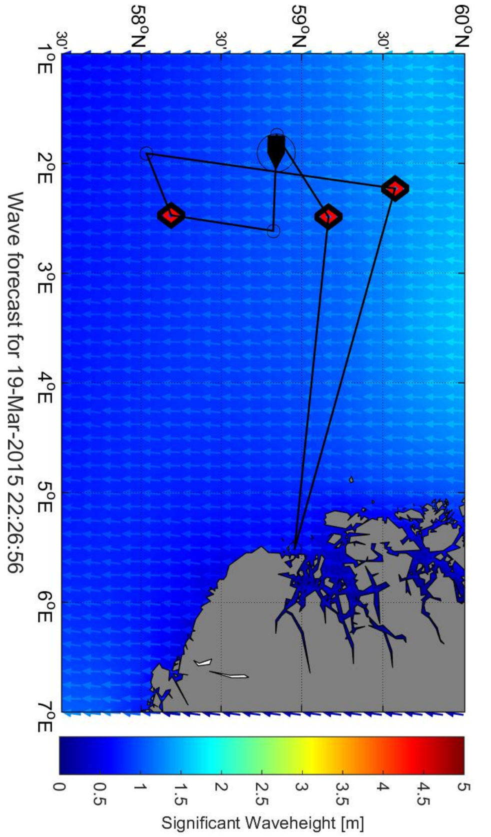

Wave forecast for 22-Mar-2015 01:28:09
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E

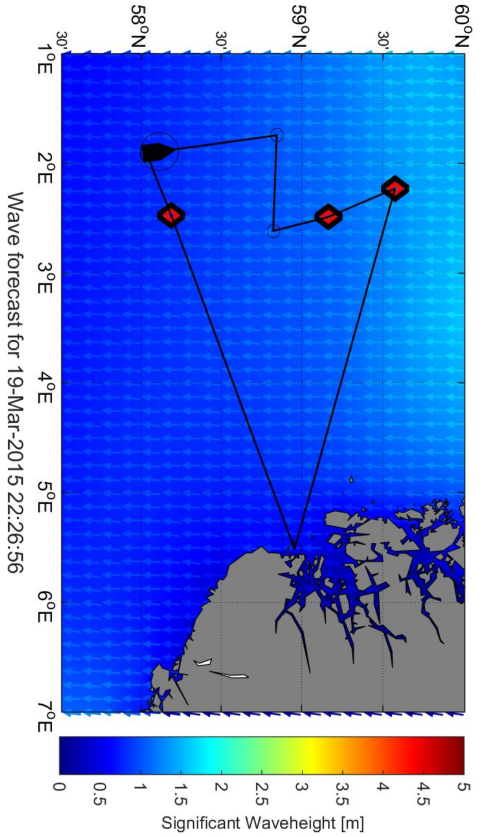

Wave forecast for 20-Mar-2015 00:29:23
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

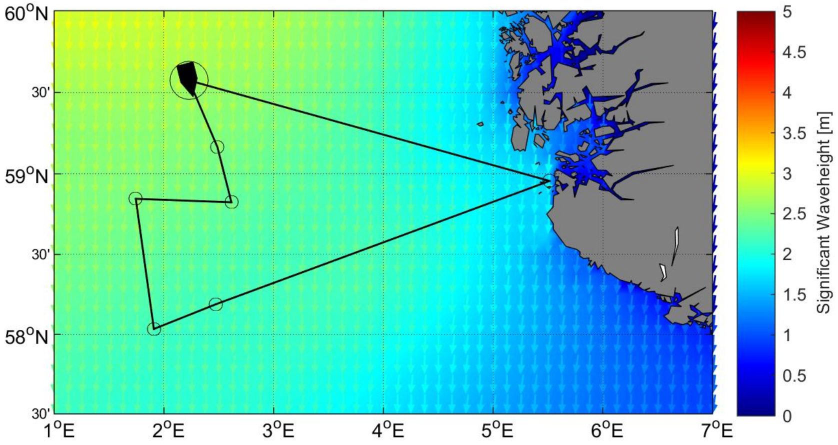

Wave forecast for 20-Mar-2015 00:29:23
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 22-Mar-2015 03:30:36
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

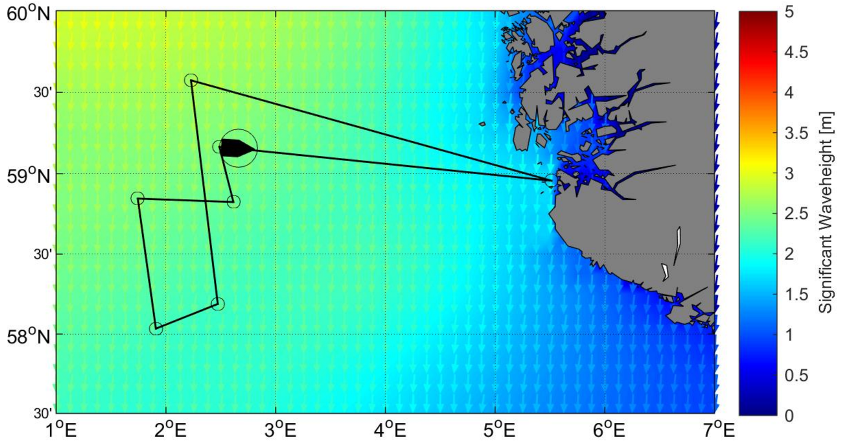

Wave forecast for 22-Mar-2015 03:30:36
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Wave forecast for 19-Mar-2015 22:26:56
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

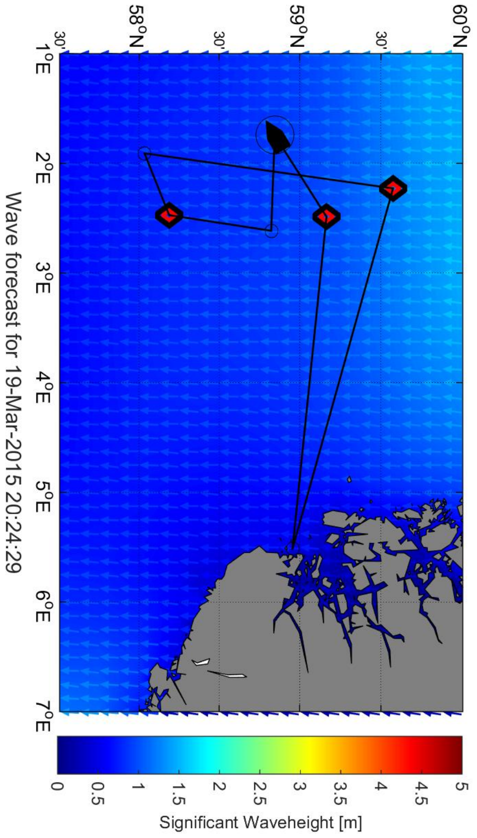

Wave forecast for 19-Mar-2015 22:26:56
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

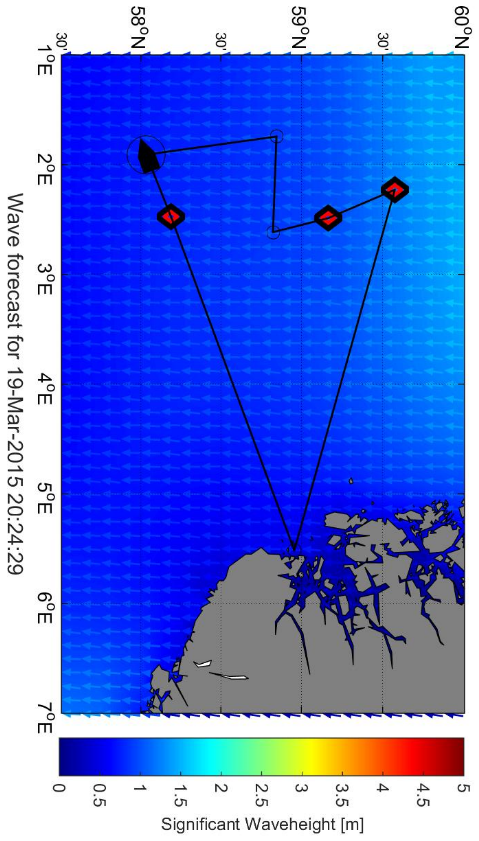


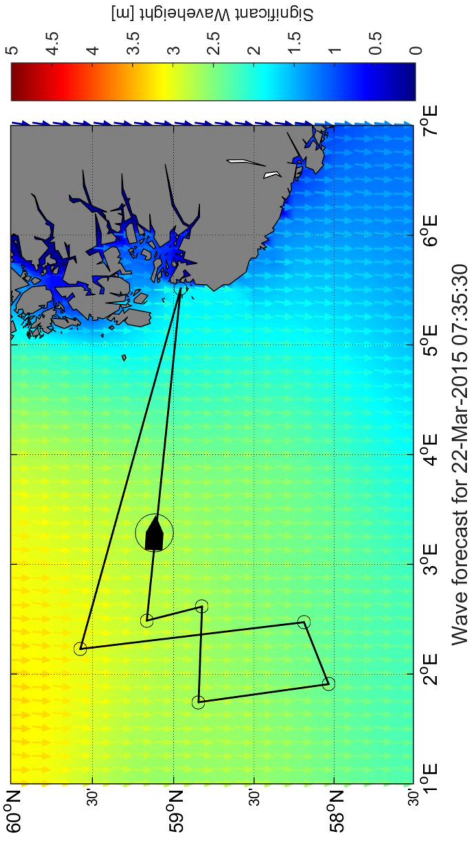
Wave forecast for 22-Mar-2015 05:33:03

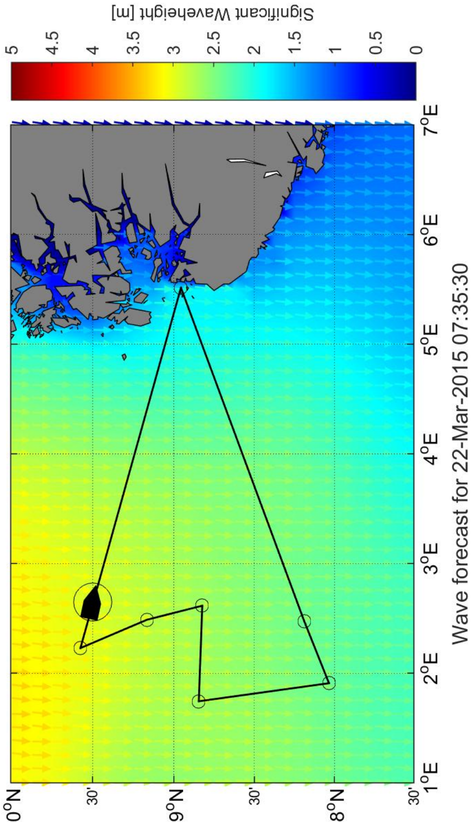


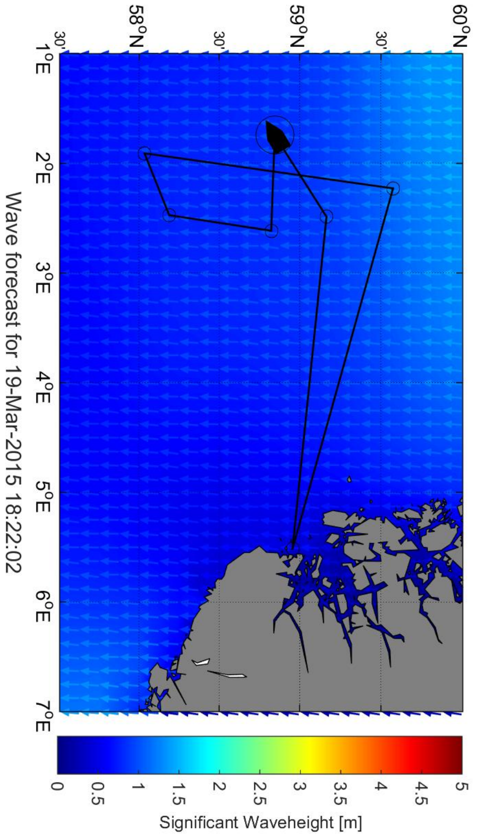
Wave forecast for 22-Mar-2015 05:33:03

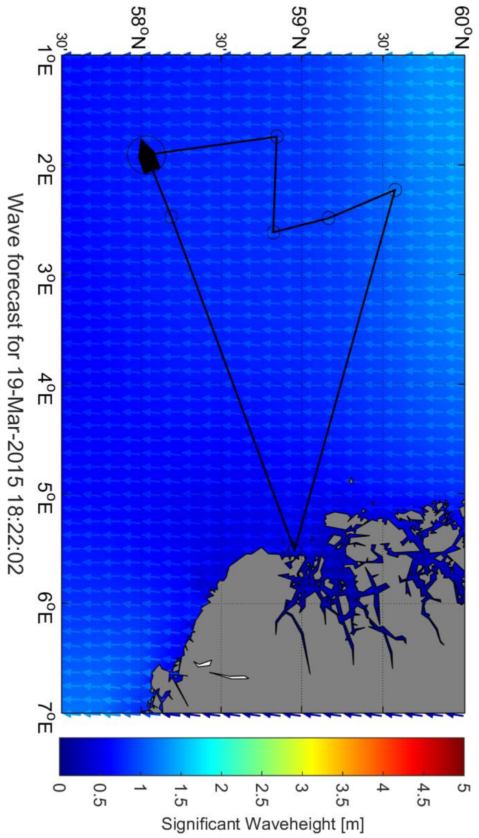

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 20:24:29
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

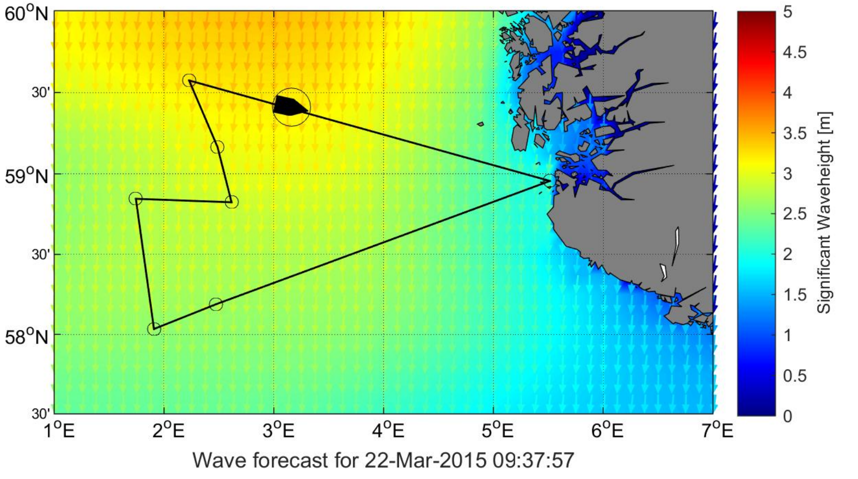

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 20:24:29
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

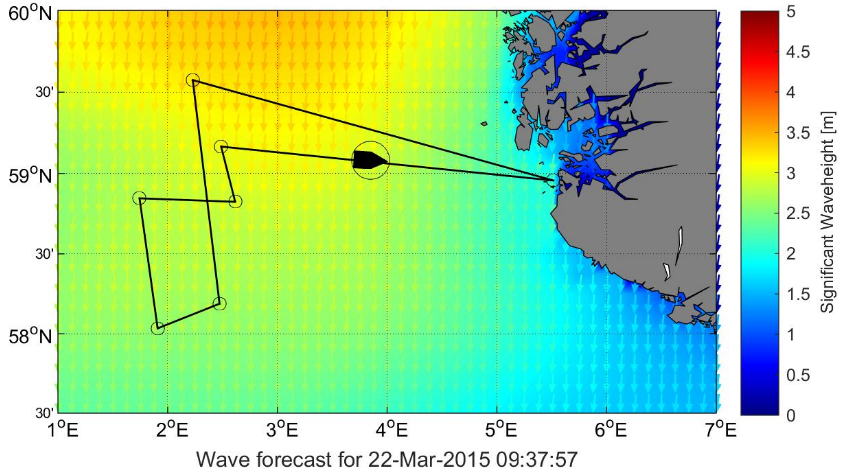

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 07:35:30
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

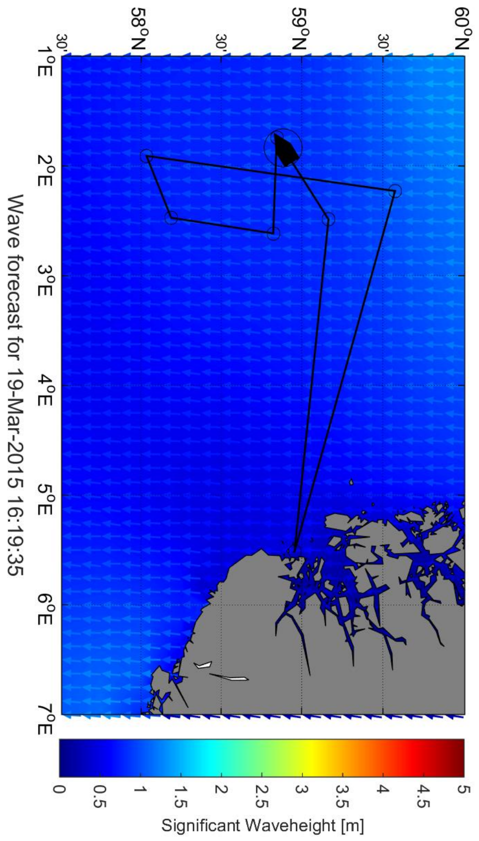

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 07:35:30
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

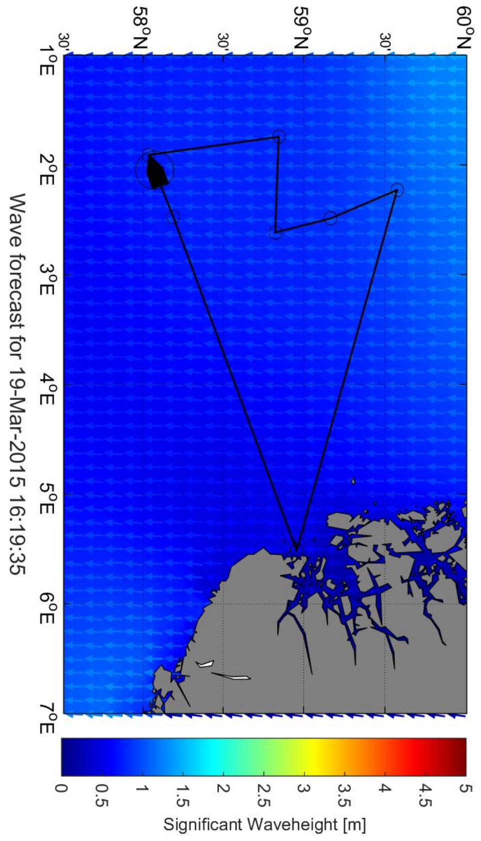

Wave forecast for 19-Mar-2015 18:22:02

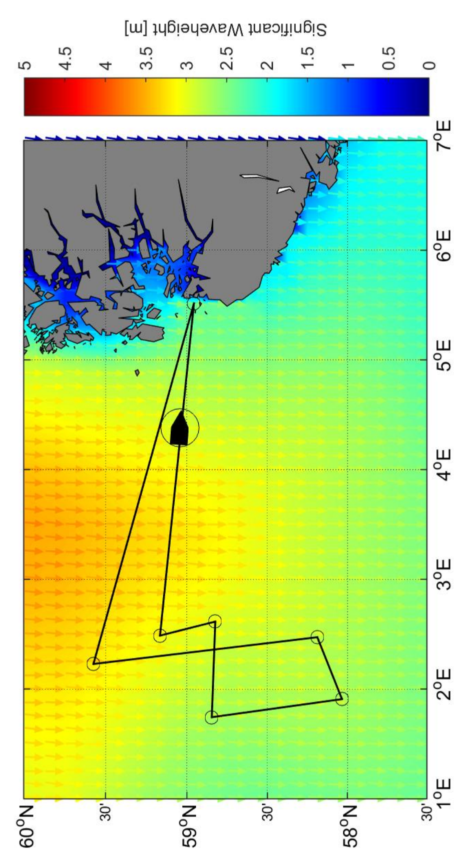

Wave forecast for 19-Mar-2015 18:22:02

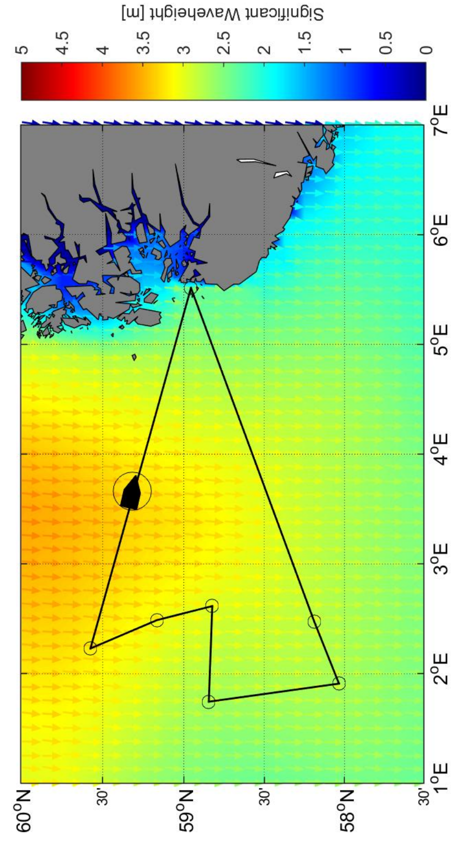

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 09:37:57
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

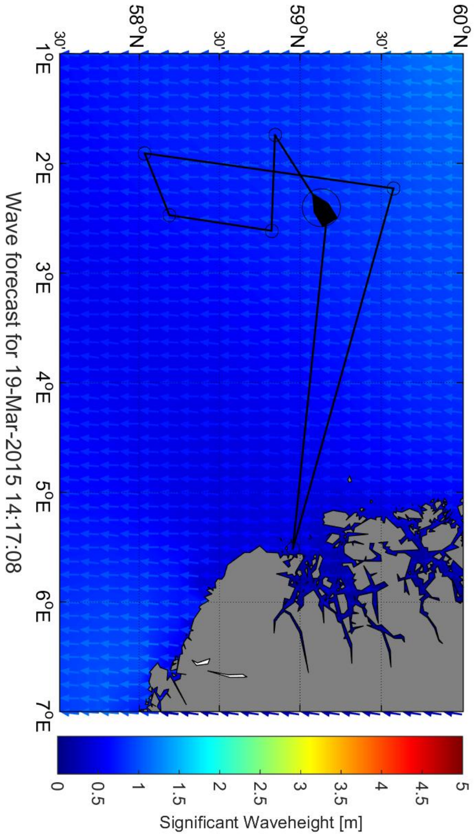

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 09:37:57
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

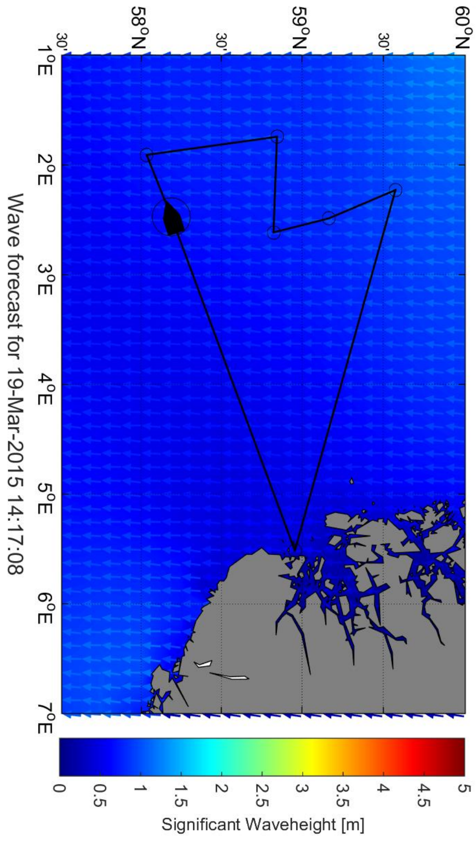

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 16:19:35
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

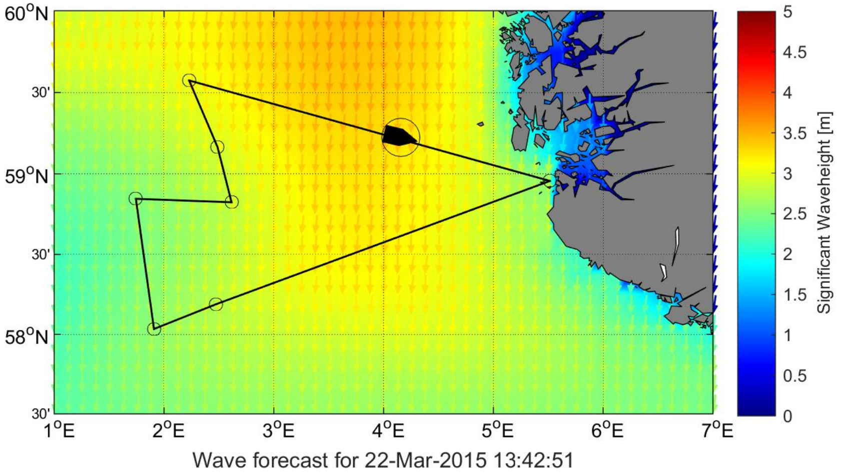

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 16:19:35
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

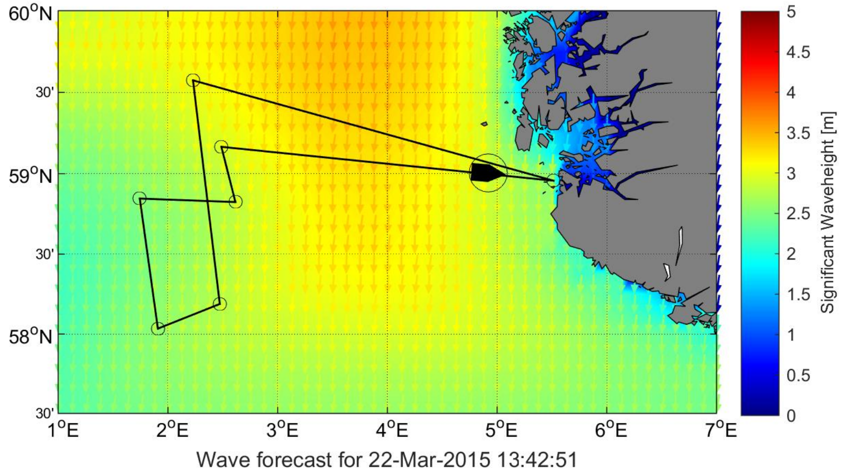

Wave forecast for 22-Mar-2015 11:40:24
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

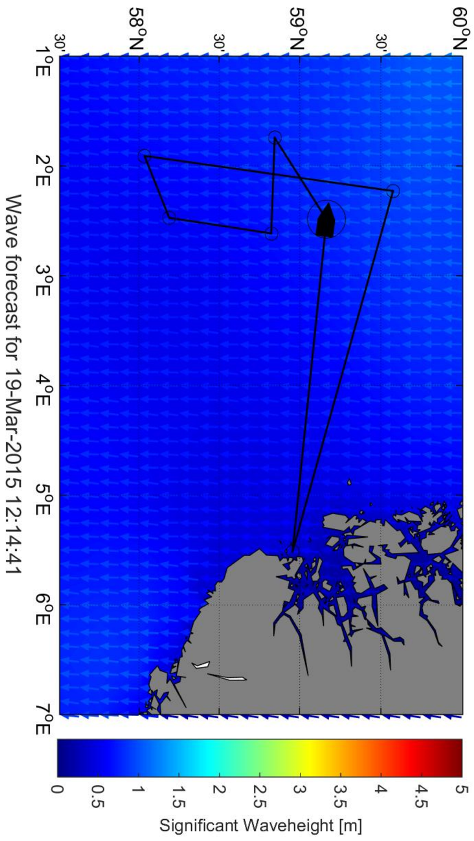

Wave forecast for 22-Mar-2015 11:40:24
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

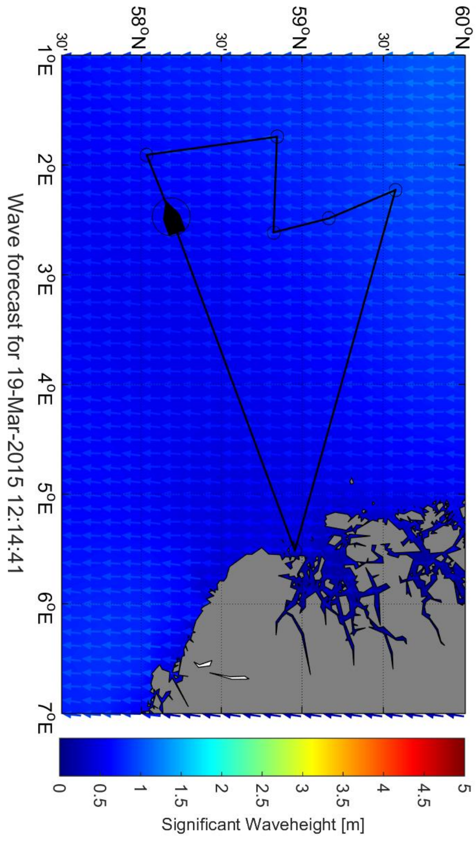

Wave forecast for 19-Mar-2015 14:17:08
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

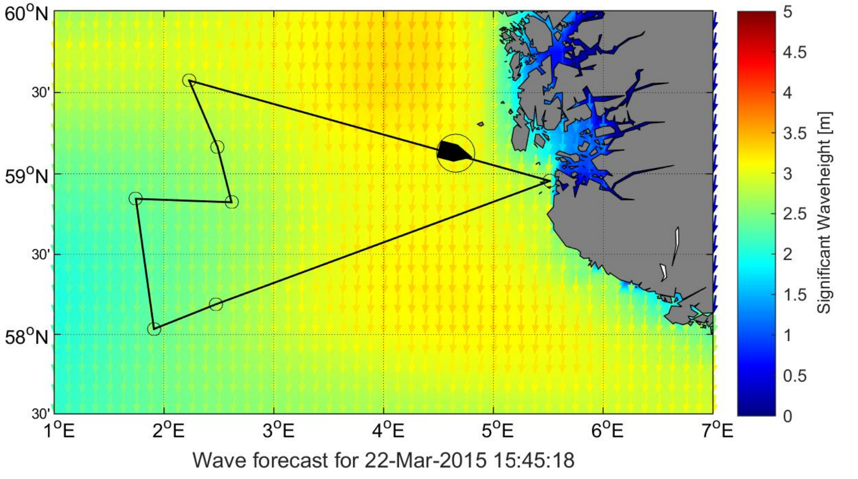

Wave forecast for 19-Mar-2015 14:17:08
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

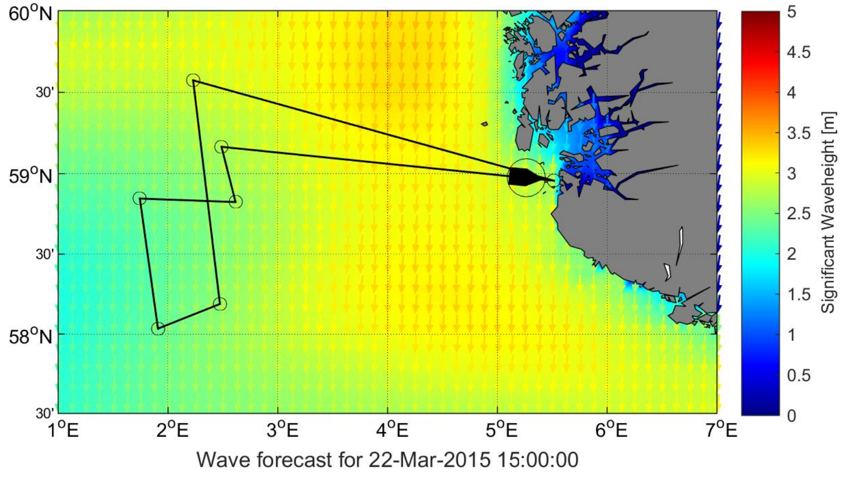

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 13:42:51
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

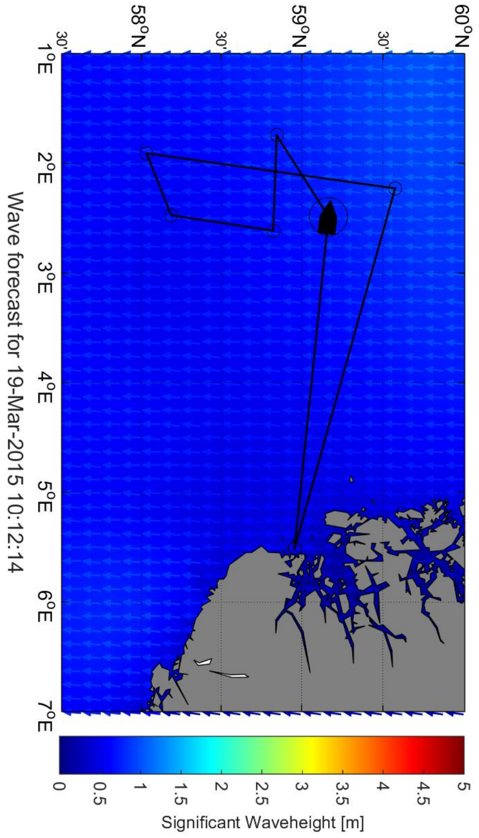

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 13:42:51
Significant Waveheight [m]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

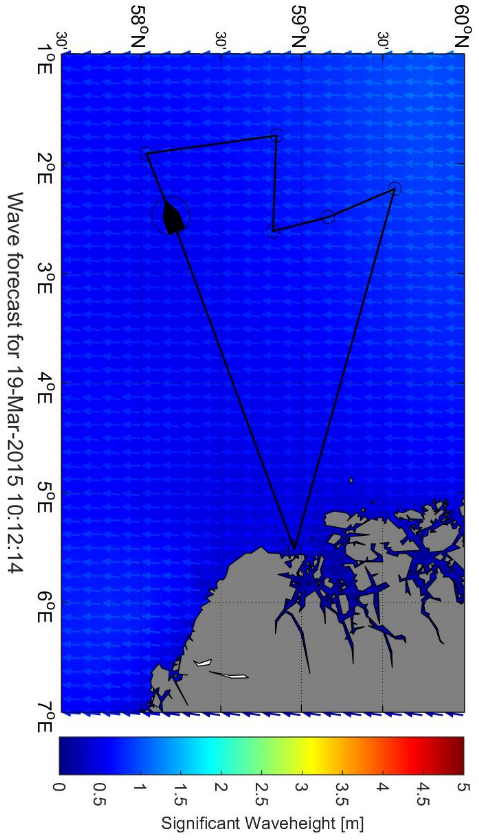

Wave forecast for 19-Mar-2015 12:14:41
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

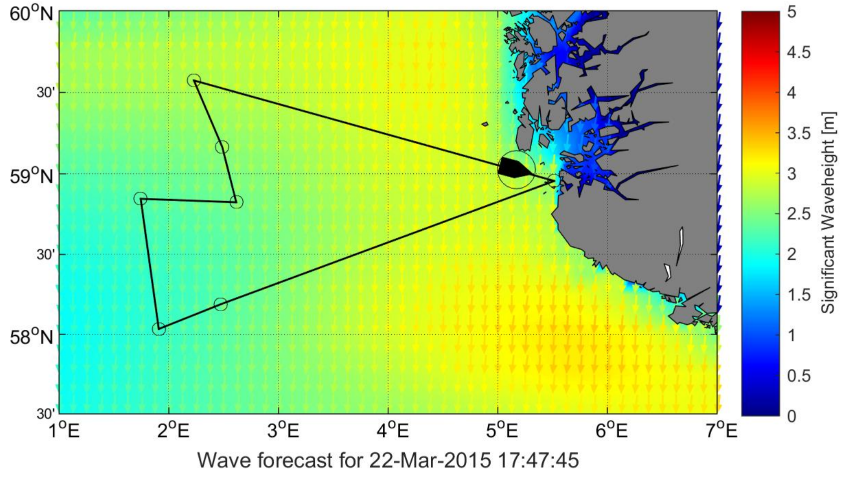

Wave forecast for 19-Mar-2015 12:14:41
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

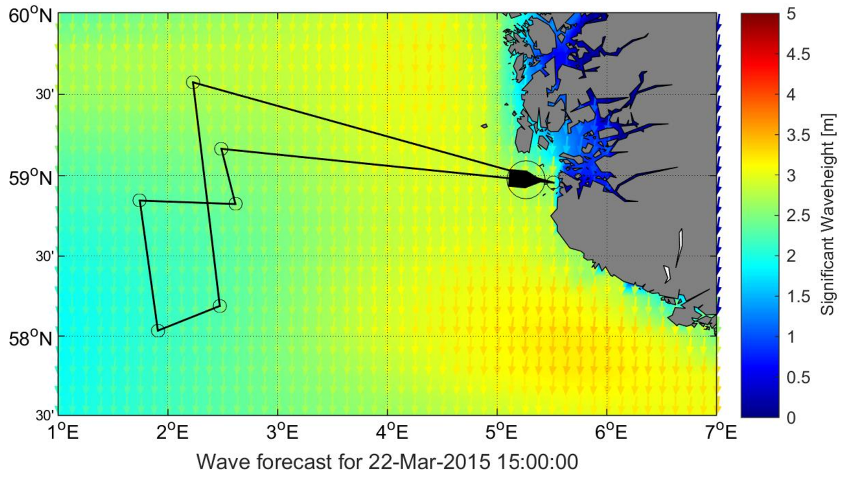

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 15:45:18
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

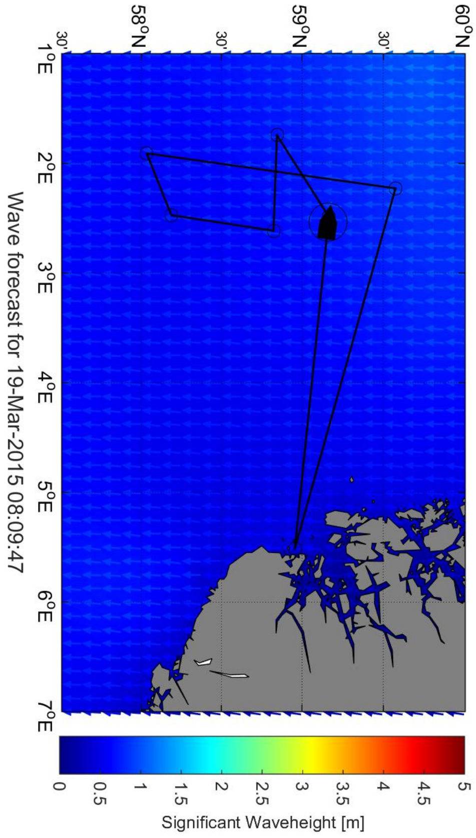

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 15:00:00
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

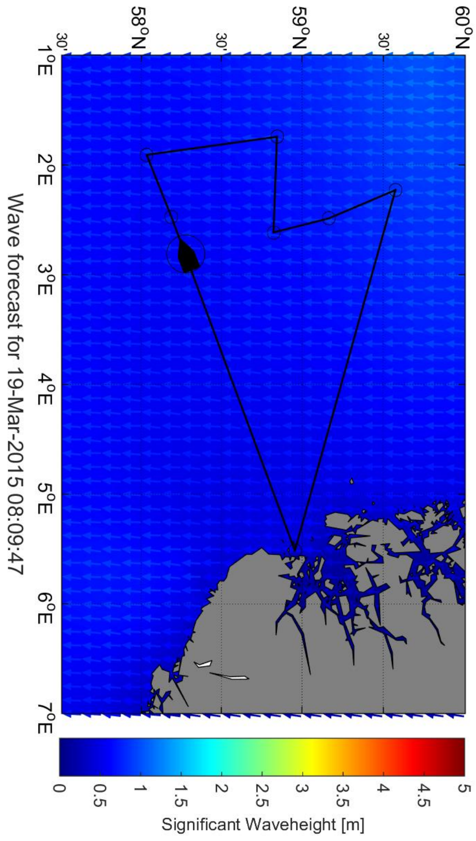

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 10:12:14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

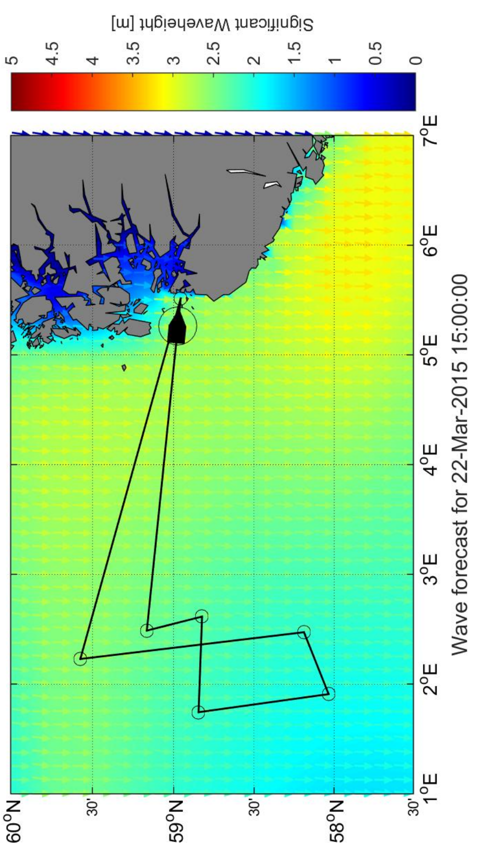

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 10:12:14
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

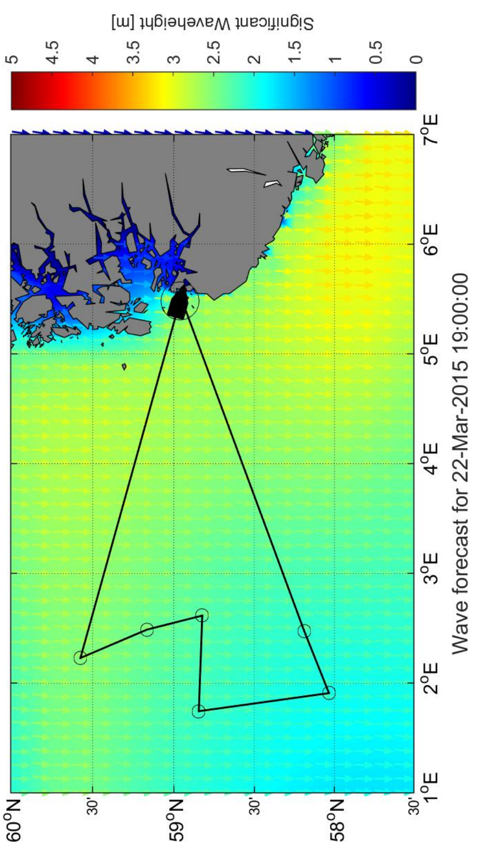

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 17:47:45
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

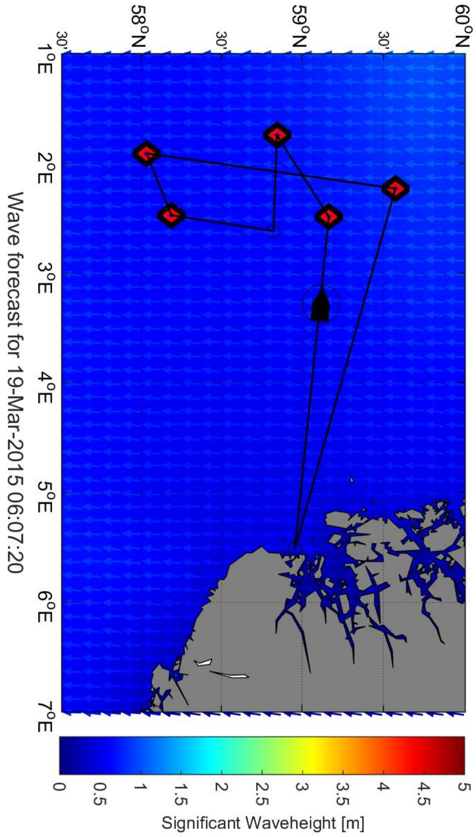

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 22-Mar-2015 15:00:00
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Significant Waveheight [m]

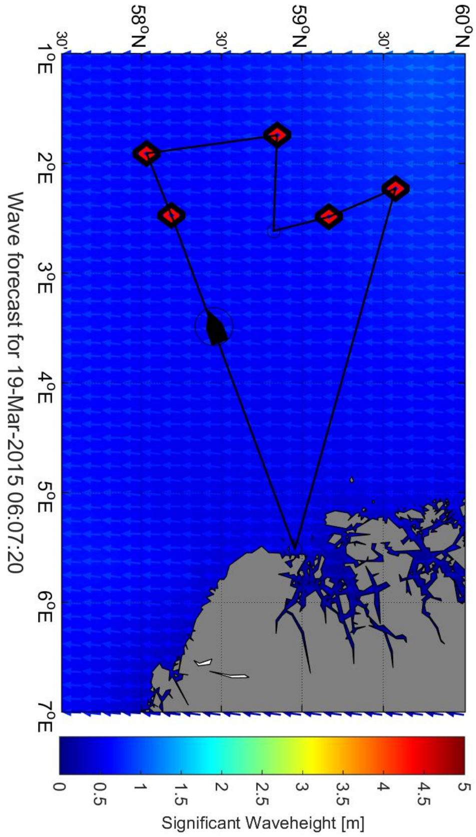

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 08:09:47
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

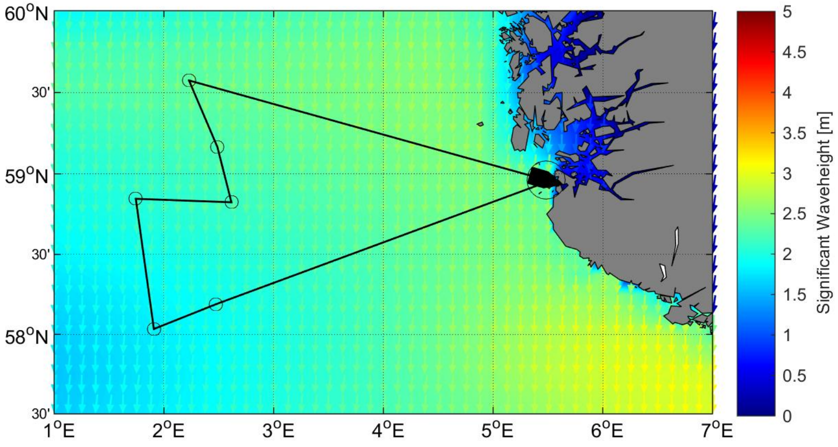

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 08:09:47
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 22-Mar-2015 15:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

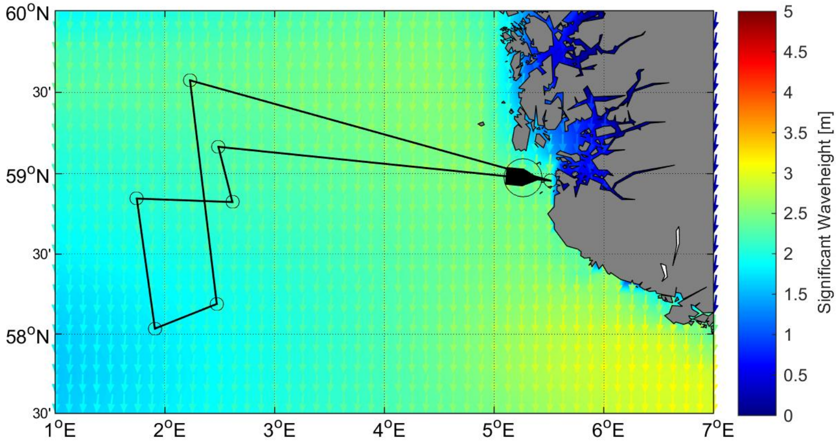

Wave forecast for 22-Mar-2015 19:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 06:07:20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

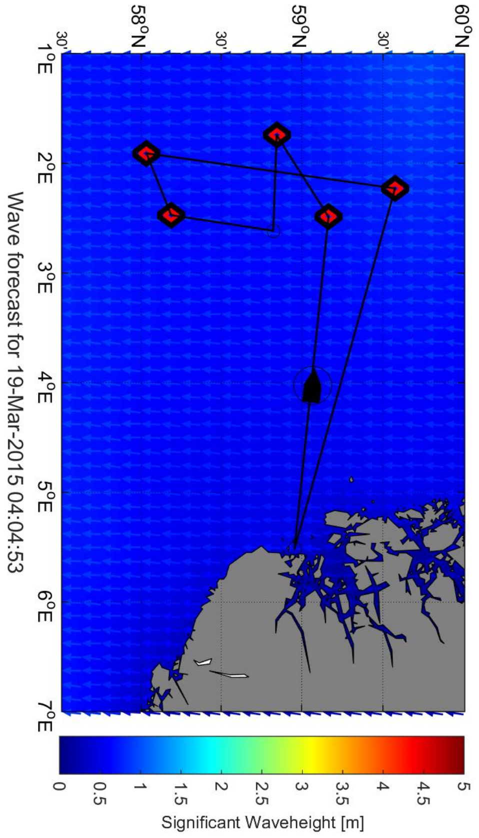

60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015 06:07:20
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

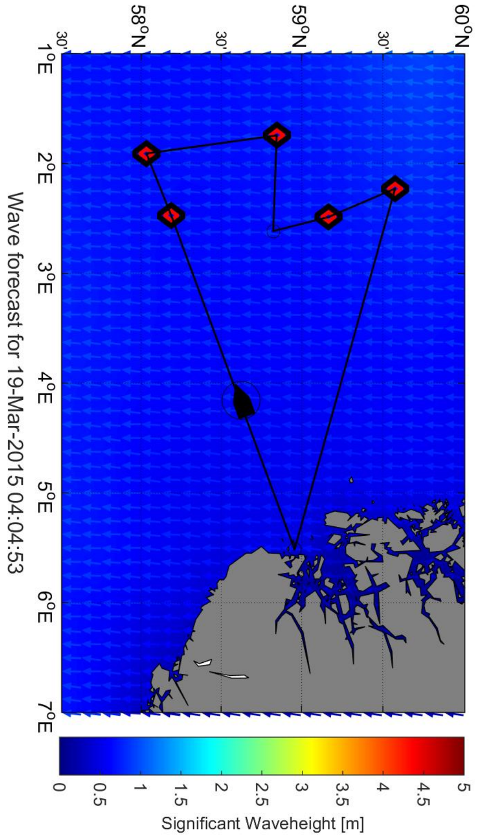


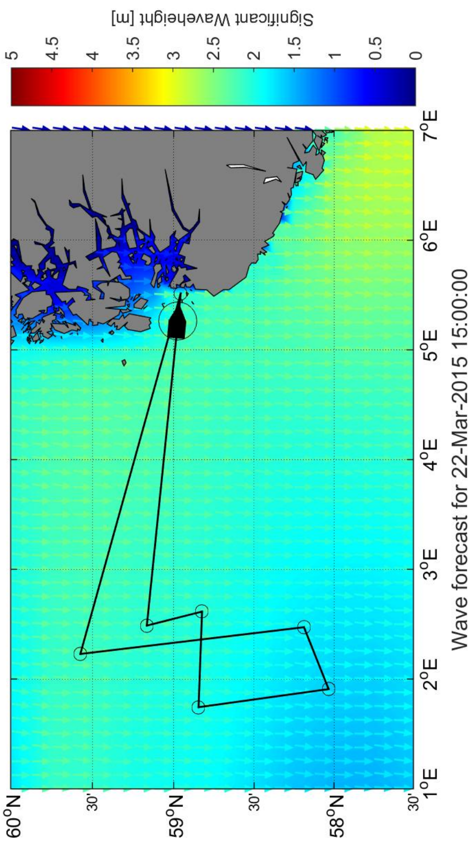
Wave forecast for 22-Mar-2015 19:00:00

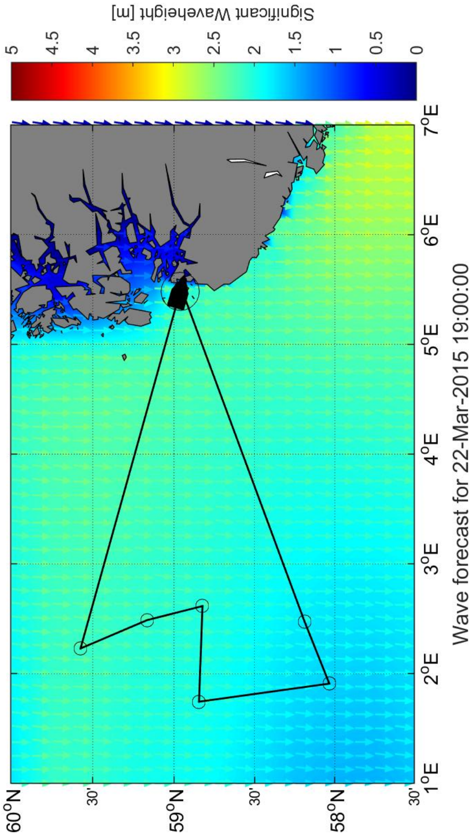


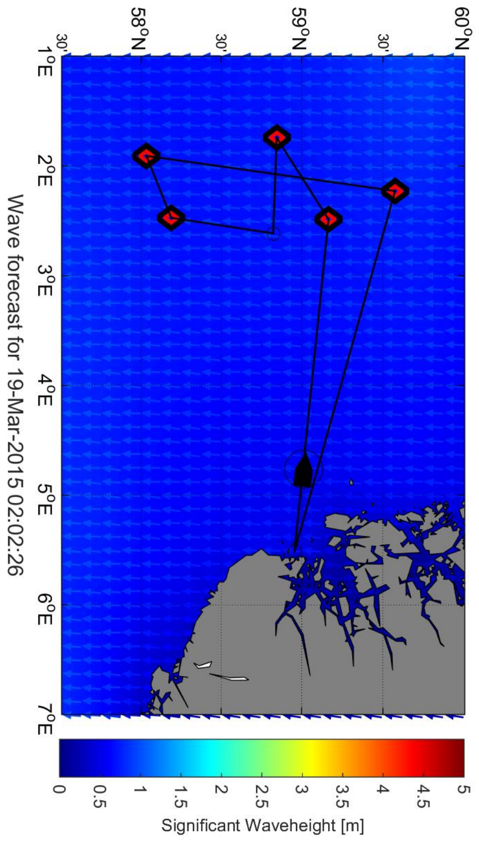
Wave forecast for 22-Mar-2015 15:00:00

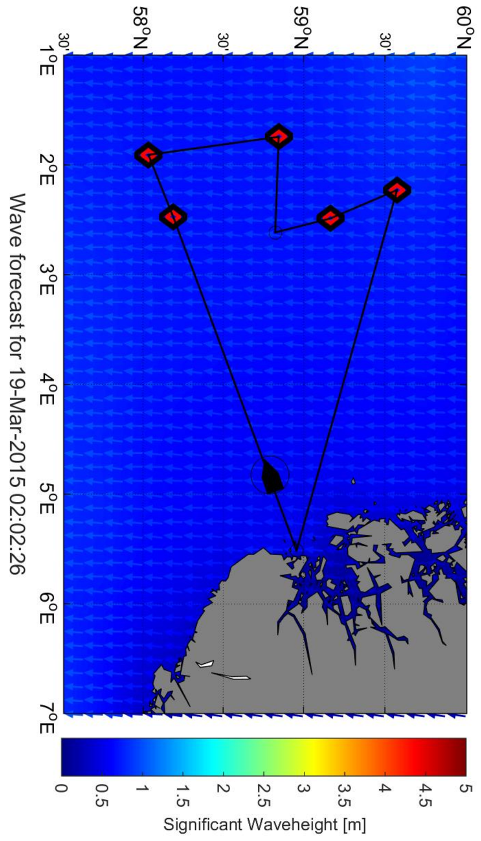

Wave forecast for 19-Mar-2015 04:04:53
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

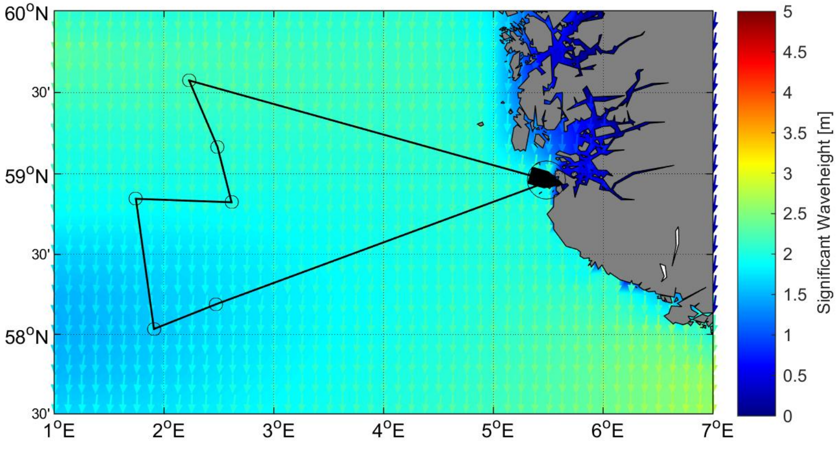

Wave forecast for 19-Mar-2015 04:04:53
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 22-Mar-2015 15:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

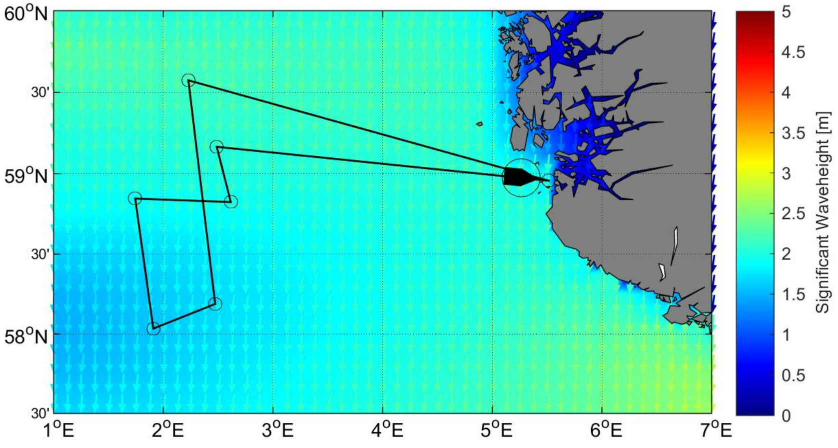

Wave forecast for 22-Mar-2015 19:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Wave forecast for 19-Mar-2015 02:02:26
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

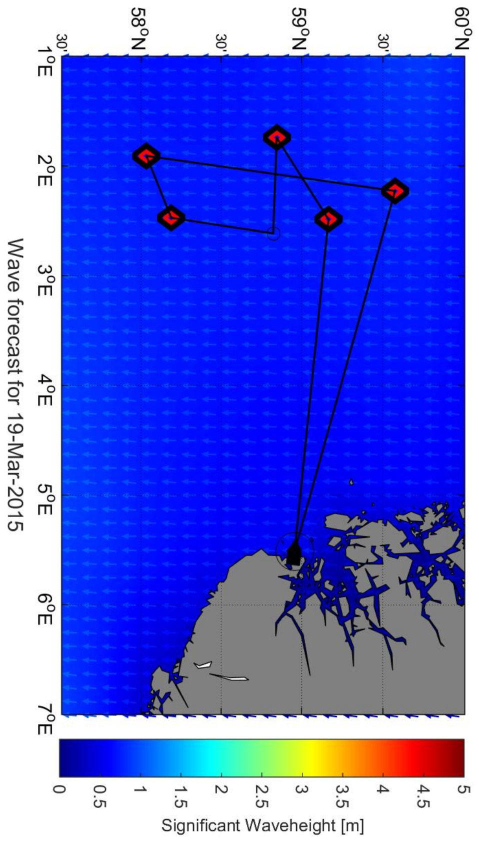

Wave forecast for 19-Mar-2015 02:02:26
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]

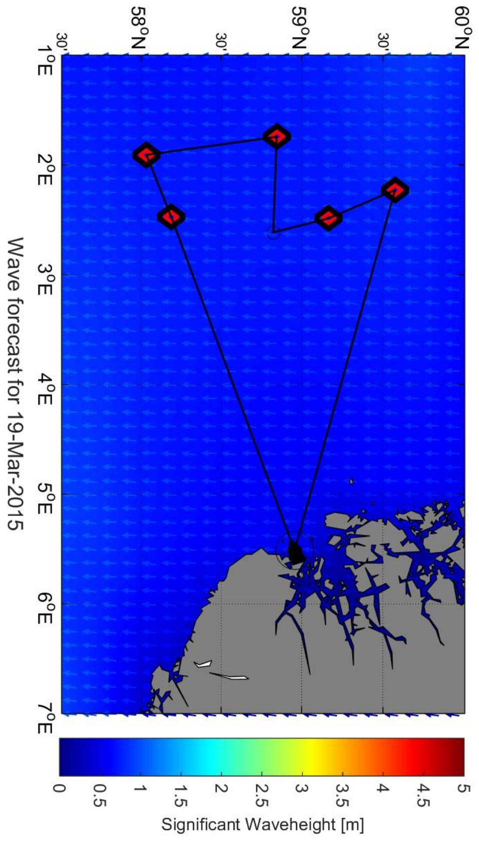


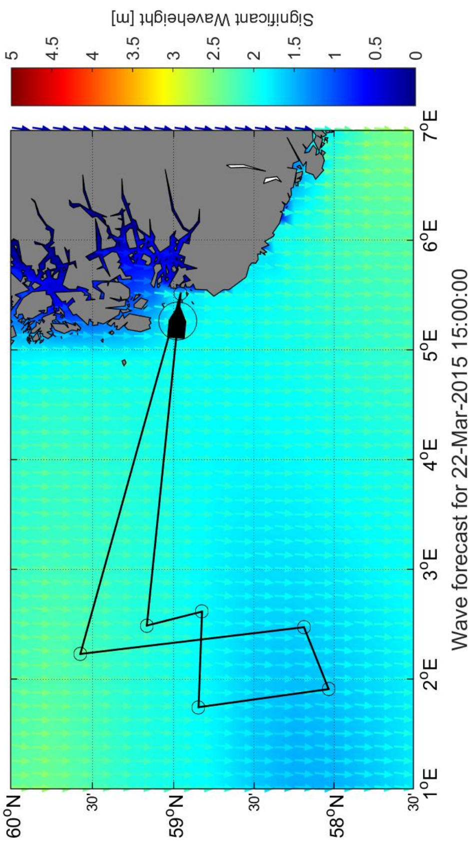
Wave forecast for 22-Mar-2015 19:00:00

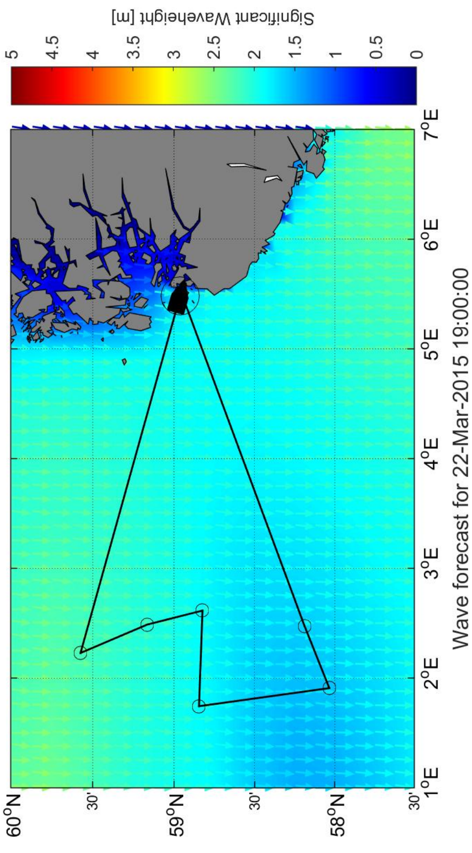


Wave forecast for 22-Mar-2015 15:00:00


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Wave forecast for 19-Mar-2015
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Significant Waveheight [m]


Wave forecast for 22-Mar-2015 15:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Wave forecast for 22-Mar-2015 19:00:00
60°N
30'
59°N
30'
58°N
30'
1°E
2°E
3°E
4°E
5°E
6°E
7°E
Significant Waveheight [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5