
CHAPTER 2

Energy-efficient ship route planning considering meteorological navigation conditions

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Abstract

The aim of this study was to examine and address all aspects related to various ship optimization systems, as well as to analyze the impact of currents in the Strait of Gibraltar on the fuel efficiency of maritime vessels and to substantiate navigational decisions that allow for the optimization of energy consumption.

The necessity for the modernization of meteorological support has been considered, and the convenience, speed, and reliability of using software for navigational route adjustments have been demonstrated. Their impact on the management of maritime operations and the enhancement of safety has been analyzed. The influence of hydrodynamic currents in the Mediterranean Sea on the energy efficiency of maritime transport has been studied. Taking into account the spatial and temporal variability of current characteristics, an analysis was conducted on their effect on vessel maneuverability and fuel efficiency. Satellite observations, ERA5 atmospheric reanalysis data, and in-situ NOAA studies were used to construct a current velocity map of the Strait of Gibraltar.

Approaches for optimizing maritime routes considering currents were proposed with the aim of reducing fuel consumption and CO₂ emissions. It was shown that adjusting a vessel's course in accordance with the direction of currents can reduce fuel consumption by up to 15%.

Keywords

Energy efficiency, navigational route optimization, fuel consumption, ocean currents, meteorological conditions, energy model, Mediterranean Sea, Strait of Gibraltar, current velocities, water masses.

2.1 Introduction

Climate change is causing more frequent and severe weather events, such as tropical cyclones, storms, and abnormal waves. This increases the risks to maritime

navigation, especially in sea areas with high traffic density. The use of meteorological software helps ships to quickly adapt their routes to changing conditions and avoid hazardous zones.

Economic fluctuations and rising fuel prices are prompting shipowners to seek ways to minimize operational costs. Route optimization using programs such as SPOS, WNI, and BON VOYAGE allows for a reduction in fuel consumption by selecting the most economical routes, taking into account current weather conditions.

Environmental standards are being tightened globally, requiring a reduction in harmful emissions such as CO₂ from maritime transport. Route optimization can reduce voyage time and fuel consumption, which in turn lowers the environmental impact of shipping activities.

Modern meteorological computer programs help to mitigate the risk of accidents or damage to vessels caused by adverse weather conditions. This is particularly relevant for large cargo ships, tankers, or passenger liners, where accidents can have catastrophic consequences for human lives and the environment.

2.2 Optimization of maritime routes through meteorological decision support systems: SPOS, WNI, and BON VOYAGE

In modern maritime navigation, reducing fuel consumption and minimizing harmful atmospheric emissions are pressing issues. One of the most effective approaches in this regard is the implementation of energy-efficient routing, which relies on real-time adjustment of ship routes based on current meteorological conditions. This method not only optimizes fuel usage but also ensures safer and more reliable voyages.

With the advancement of computer technologies and artificial intelligence, meteorological software tools have become increasingly accurate and reliable, thereby enhancing their operational efficiency. Improved algorithms enable precise weather forecasting and automatic suggestions for optimal routing, reducing the influence of human error in decision-making processes.

The growth of global trade continues to drive the expansion of maritime transportation, thereby increasing the demand for safe and cost-efficient routes. Computer-based navigation systems have become critical tools for shipowners and operators, assisting them in achieving optimal performance.

Effective vessel management depends on accurate meteorological forecasting and route optimization. Rapid changes in weather conditions can significantly impact both the safety and efficiency of maritime operations. Meteorological computer systems provide real-time solutions for route adjustment by accounting for atmospheric factors.

Thus, the use of meteorological software in navigation has become increasingly relevant for the maritime industry, as it addresses current challenges related to weather variability, resource efficiency, and operational safety.

To implement this concept in practice, specialized software packages such as SPOS, WNI, and BON VOYAGE are actively employed. These systems were developed to support decision-making processes for route planning based on meteorological data [1].

These systems allow for the consideration of wind conditions, wave states, currents, and other meteorological factors to formulate the most energy-efficient ship route (Fig. 2.1).

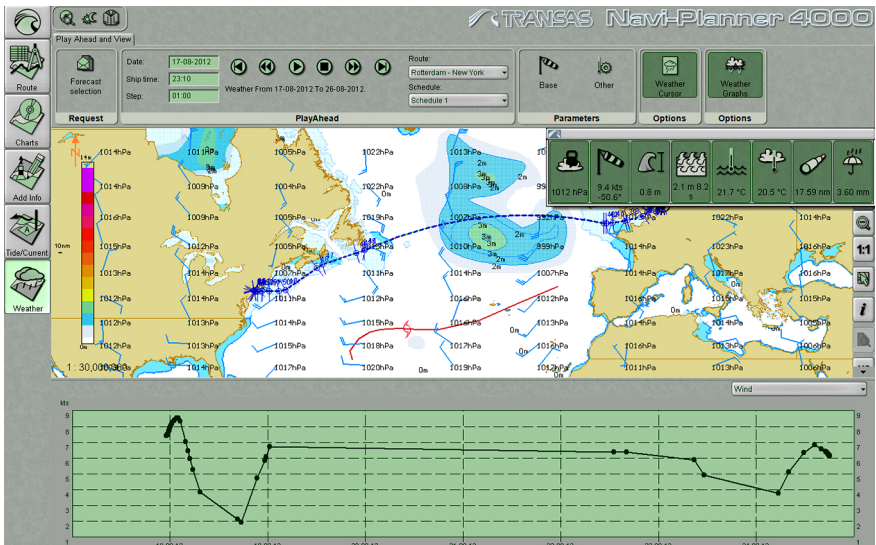


Fig. 2.1 Ship voyage optimized based on weather forecasting using DTN SPOS

Meteorological computer systems share common functional features that enable them to:

- receive forecast weather maps updated in real-time (in GRIB, NetCDF formats);
- analyze the impact of weather factors (wind, current, wave height) on possible ship trajectories;
- construct alternative routes and select the best one based on criteria such as minimizing fuel consumption, reducing transit time, decreasing mechanical stress on the vessel, and ensuring safe navigation.

Integrate weather-optimized routes into ECDIS or other electronic navigation systems for automated course plotting.

Each system has its own distinctive features.

SPOS (Ship Performance Optimization System) focuses on adaptive routing and calculating energy consumption considering the specific characteristics of the vessel. It provides weather forecasts and assists the ship captain in selecting the optimal route by accounting for the effects of wind, waves, and currents on the ship.

SPOS capabilities include:

- providing up to 9-day forecasts with global coverage;
- importing routes from Transas ECS into SPOS;
- subscription, receipt, and display of weather forecasts twice daily;
- calculating multiple routes considering weather conditions;
- comparing route results;
- creating optimal routes and exporting them back to Transas ECS;
- saving the best route as a voyage plan with daily updates.

A notable feature of this program is its ability to analyze historical data and predict the influence of weather conditions on fuel consumption and transit time. Additionally, SPOS allows integration of these data with other onboard systems, making the decision-making process more comprehensive [3].

WNI (Weathernews Inc.) enables shipowners to monitor their fleets online while accounting for weather risks across all transit zones. The program also provides real-time meteorological data and route recommendations, considering possible changes in weather conditions. WNI uses machine learning algorithms to improve forecast accuracy and can be integrated with automatic ship control systems, ensuring maximum adaptability to changes in the navigational environment [4].

The **BON VOYAGE System (BVS)** offers tools for meteorological data analysis and route optimization, helping to avoid hazardous weather conditions and improve voyage efficiency. BVS allows modeling of various weather development scenarios and analyzing their impact on the route, which is particularly useful when navigating challenging regions such as the North Atlantic Ocean or southern latitudes [5]. The software suite is deeply integrated with AIS, enabling ETA forecasting and calculation of expected CO₂ emissions.

In practice, these programs have already demonstrated their effectiveness in real maritime operations. For example, in 2018, a Maersk container vessel using SPOS managed to avoid severe storm conditions in the Pacific Ocean, resulting in a savings of several days in transit time and a significant amount of fuel. Similarly, WNI is used by many cruise lines for route planning, providing maximum passenger comfort and minimizing the impact of stormy weather.

Following the implementation of weather-dependent route adjustments by shipping companies, the following outcomes have been recorded:

- reduction of fuel consumption by 5–10%, corresponding to savings of tens of tons on transatlantic voyages;
- decrease in CO₂ emissions by 3–8%, directly contributing to IMO decarbonization targets;
- improved ETA accuracy, helping to avoid penalties and disruptions in logistics chains;
- enhanced navigation safety, especially in storm-prone areas such as the North Atlantic, Indian Ocean, and South China Sea.

It is also important to note that even a minor route alteration – for instance, a deviation of 50–80 nautical miles – can significantly change the effects of wind and waves on the vessel, resulting in substantial energy savings.

One of the primary advantages of using meteorological software is the reduction of fuel costs. According to various studies, route optimization with the help of these programs can save up to 10% of fuel over long distances, which significantly impacts the overall expenses of shipping companies. Moreover, fuel savings also lead to a reduction in greenhouse gas emissions, an important factor in the context of international environmental protection commitments. At a fuel price of 600–700 USD per ton, saving even 10 tons per voyage translates into 6,000–7,000 USD, which is economically justified even for small-tonnage vessels. For large bulk carriers or container ships, the potential savings increase substantially.

Additionally, considering the implementation of carbon taxes and CII/EEXI regulations, the use of weather-driven routing directly affects the company's environmental indicators and its competitiveness in the freight market.

The development of meteorological software for maritime navigation continues. One promising direction is the integration of these programs with artificial intelligence systems, which will automate decision-making and make navigation even safer and more efficient. Another prospect is the use of real-time satellite data, which will provide even more accurate weather forecasts [6, 7].

2.3 Ensuring meteorological safety of shipping using the SPOS program

The existing information support systems on maritime shipping routes exert a controlling influence on vessel navigation safety, as well as on maneuvering and vessel traffic flow under constrained navigation conditions. Depending on the state of the navigational information environment, the causes of hazards and emergency

situations arise. Until recently, when a vessel was not regarded as an object of waterway information security, the consideration of marine exposure risk factors – which are constantly expanding due to the unpredictability of the volume of data received about natural, technological, economic, and socio-political changes in globalized shipping – was neglected.

At the same time, the relativity of the actual navigational situation on waterways is often explained by deficiencies in the existing scientific and instrumental tools responsible for adequately reflecting the navigational environment. These shortcomings cause distortions of the information space and erroneous situational assessments, thereby creating conditions conducive to accidents. Accordingly, instrumental tools in the form of methods and models of shipping information security have become a top priority in the development of vessel traffic management systems. Their operation is regarded as a key guarantee for ensuring the reliability, sufficiency, and timeliness of managed maritime content.

Amid the global push towards shipping decarbonization, fuel consumption optimization has acquired strategic importance. One of the most effective tools in this context is vessel routing that takes meteorological conditions into account, allowing the reduction of main engine load by utilizing favorable wind and current conditions.

Modern marine vessels are capable of navigating in challenging weather conditions; however, wind, waves, strong opposing currents, and a range of other hydrometeorological factors affect the speed and course of ships and, consequently, the efficiency of shipping operations. These influences lead to increased voyage duration, greater risk of deck damage and cargo shifting, deteriorated working and resting conditions for the crew, and reduced comfort for passengers. Therefore, contemporary consideration of hydrometeorological conditions enhances not only the safety of navigation but also the economic performance by optimizing fleet operations. Utilizing favorable weather conditions represents a significant reserve for reducing maritime transportation costs.

Currently, the description of atmospheric and oceanic phenomena and processes is based on the concept of their complex interactions. Numerical models and advanced physical-statistical forecasting methods are employed to theoretically justify atmospheric phenomena such as frontal tropical cyclones and winds. To explain wave excitation processes, techniques like level oscillation tracking, spectral, and harmonic analysis are used. Additionally, many new theoretical frameworks and practical recommendations are being developed for the analysis and characterization of sea ice as a hazardous phenomenon in navigation.

The application of fundamental principles of marine meteorology and oceanography for shipping needs has led to the emergence of a specialized science –

hydrometeorological support for the navigation of the maritime fleet. This includes a set of measures implemented by the State Hydrometeorological Committee, the Ministry of the Maritime Fleet, other agencies, and ship crews.

An integral part of hydrometeorological support in shipping is the organization of hydrometeorological observations onboard vessels. These observations are used for the operational assessment of hydrometeorological impacts on navigation and for transmitting data to primary organizations where they are processed and analyzed to produce weather forecasts at sea.

The largest provider of meteorological forecasts in Europe, Singapore, and the USA is MeteoGroup. The group employs approximately 100 meteorologists who offer services in nine European languages. Meteorological experts provide forecasts, support, monitoring, and consulting services 24 hours a day, 365 days a year. Moreover, MeteoGroup's specialized research team continuously develops proprietary forecasting systems and methods.

One of their key products, and among the most functional solutions already applied in practice, is the Ship Performance Optimization System (SPOS) – specialized software designed to enable captains and navigation officers to adjust route calculations based on the provided weather information and specific vessel characteristics. This allows the captain to plot the optimal route – both in terms of safety and efficiency – under prevailing weather conditions.

MeteoGroup, together with major ECDIS providers, has combined two key products to deliver an ideal integrated solution for ship route optimization – SPOS integrated with navigational routing in ECDIS.

With the introduction of SPOS, a new method of ship routing that accounts for weather conditions was created. This software is a tool that helps the captain and watch officers onboard make informed decisions regarding voyage planning based on weather conditions.

Using the Ship Performance Optimization System enables safe and efficient global navigation by reducing fuel consumption and promoting a cleaner environment. Installed onboard, SPOS is a leading weather-aware ship routing system. With SPOS, a vessel's route can be optimized considering weather factors such as currents, wave height, wind speed and direction, and other meteorological elements.

The meteorological bureau MeteoGroup prepares a comprehensive set of accurate weather information for oceanic regions and coastal waters. This information includes forecasts of wind speed and direction, wave height and period, as well as data on tropical storm forecasts and ice edge boundaries. Weather information is sent by email to many vessels, and the crew can display the forecasts in a presentation format of their choice.

To evaluate the results of different routes within SPOS, the following analysis tools are available:

- comparative tables;
- charts;
- diagrams.

Once a user selects the preferred route to follow, it can be saved as a voyage plan. With new weather forecasts automatically received daily, the voyage plan can be updated, and the impact on ETA is easily monitored as weather conditions change (Fig. 2.2). At the end of the voyage, SPOS provides a full route log.

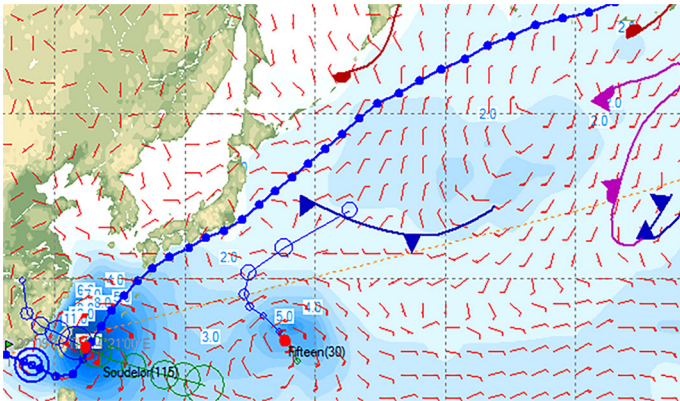


Fig. 2.2 Weather-aware map in the SPOS software

The SPOS system is implemented in several modules designed for use both on-board vessels and onshore.

SPOS On-board is a local module installed on the vessel that allows route planning taking into account current weather data. The captain or navigator can quickly review the impact of meteorological factors on fuel consumption for each segment of the route.

SPOS Fleet Management is a tool for operators and dispatchers ashore that provides centralized analysis of the fleet, routes, and forecasted weather changes.

RouteGuard is a routing and ship performance analysis service. Based on weather information combined with the expertise of qualified meteorologists and navigators, RouteGuard offers vessels optimal routes for any voyage.

Choosing the optimal route and achieving maximum ship performance requires accurate and detailed weather information. RouteGuard helps save time and fuel,

reduce CO₂ emissions, and optimize planning based on precise ETAs, while keeping the crew, vessel, and cargo safe.

Ship performance analysis reports contain information necessary to identify underperformance and corresponding corrective actions.

All modules integrate with the Electronic Chart Display and Information System (ECDIS), ensuring full automation of route construction and data exchange with navigation systems.

SPOS does not have its own communication system; instead, it uses the ship's existing email system or internet connection. This simplifies operation for the crew, as they are already familiar with this system, and regular email is supported by the office.

Secondly, this approach saves money and time because the forecast is automatically sent to the mailbox along with other messages. In most cases, SPOS can automatically place messages into the mailbox using a so-called MAPI connection. However, this can also be done manually by saving files on the local hard drive. If an internet connection is available, HTTP can be used.

Several types of communication exist with SPOS:

- subscription to weather forecasts;
 - receiving daily weather forecasts and optionally sending reports to the office.
- Subscription to forecasts and receiving weather updates are critical for SPOS.

The SPOS system has two sources of weather information needed for route planning:

- a forecast database updated by email from MeteoGroup;
- climatological databases.

For route calculations, forecast data are used as long as the simulated voyage falls within the forecast range. Otherwise, climatological data are used at the end of the forecast period. The dedicated climatological database contains monthly average values for surface pressure, wind, wind waves, and ocean currents. The area covered by the climatological database spans from 75°N to 60°S latitude and 180°W to 180°E longitude, with a resolution of 2.5°.

Forecast data are available four times a day and cover the entire globe from 90°N to 90°S. Preliminary tidal data are divided into ocean regions such as the North Atlantic and the southern part of the Pacific Ocean (at a resolution of 2.5°), as well as smaller areas like the South China Sea and the Mediterranean for coastal waters (at a higher resolution of 1.0°).

Ocean forecasts are available for 5 and 9 days ahead, while coastal areas are forecasted up to 5 days in advance. Users can choose between a standard forecast, which includes wind, waves, and ocean currents, or an extended forecast that also

covers precipitation, air temperature, visibility, and icing risk. Additionally, high-resolution parameters can be selected.

Routes planned with SPOS take into account wind direction and strength, wave height and direction, the hydrodynamic resistance of the vessel caused by wave motion, temperature changes affecting water viscosity, and ocean currents, including the Gulf Stream and trade winds in the oceans.

Forecast information is sourced from global meteorological systems (NOAA, ECMWF) and is updated daily or hourly. For each route option, SPOS provides alternatives ranked by parameters such as fuel savings, transit time, and safety conditions. The navigation team can select the optimal balance of these parameters according to transportation priorities.

The SPOS system demonstrates high efficiency in achieving fuel cost reduction and optimizing vessel routing by incorporating up-to-date meteorological data. Practical use of the system on commercial and passenger vessels confirms its significant impact on improving fuel efficiency, enhancing navigation safety, and ensuring environmental compliance with modern international shipping standards.

One of the key performance indicators of SPOS is fuel savings ranging from 5% to 15%, depending on the vessel type, route length, weather conditions, and correct interpretation of forecast data by the crew. For example, on transatlantic routes (Rotterdam – New York), fuel savings reach 20–25 tons per voyage, equivalent to a cost reduction of 10,000–15,000 USD. In the cruise sector, SPOS application helps avoid storm activity zones while maintaining passenger comfort and reducing the load on the propulsion system.

SPOS not only optimizes fuel consumption but also improves the accuracy of vessel Estimated Time of Arrival (ETA) forecasting. Thanks to daily updates of weather forecasts and the ability to promptly adjust the course, the vessel can:

- avoid delays related to weather conditions;
- reduce the need for "schedule chasing", which typically leads to excessive fuel consumption;
- coordinate port arrival more accurately, optimizing logistical operations at the berth.

Successful implementation of this functionality was demonstrated in the Maersk fleet, where ETA accuracy improved on average by 8–12%, alongside a reduction in energy consumption.

Since fuel savings directly contribute to reducing CO₂ emissions, implementing SPOS aligns with the IMO 2020 regulations and the CII/EEXI goals aimed at decarbonizing shipping. For every ton of fuel saved, CO₂ emissions are reduced by

an average of 3.1 tons. Therefore, saving 20 tons of fuel per voyage corresponds to a reduction of over 60 tons of CO₂ emissions.

Route optimization also allows avoiding areas of heavy seas, which reduces hull vibration loads, the risk of damage to propeller and steering systems, and main engine wear by minimizing unnecessary speed fluctuations.

In the long term, this leads to lower maintenance costs and extends the service life of major components.

Table 2.1 presents a comparison of voyages conducted with and without SPOS, based on aggregated operator reports.

Table 2.1 Comparison of voyages conducted with and without SPOS

Indicator	Without SPOS	With SPOS
Fuel consumption (tons/voyage)	240	210
Transit time (hours)	180	174
CO ₂ emissions (tons/voyage)	744	651
Average engine load	85%	78%
ETA deviation	± 6 hours	± 2 hours

The SPOS system demonstrates high efficiency in real-world shipping conditions by ensuring energy-saving, stable, and safe navigation. Further integration of SPOS with automated course control systems, digital twins of vessels, and satellite weather forecasting enables this tool to be considered a standard for energy efficiency management in the global fleet of the 21st century.

In practice, the use of SPOS allows achieving:

- a reduction in fuel consumption by 5–15%, depending on the type of vessel, route, and weather conditions;
- a corresponding reduction in CO₂ emissions due to lower fuel consumption;
- improved estimated time of arrival by avoiding adverse weather zones and reducing waiting times;
- decreased mechanical stress on the vessel's systems, reducing wear and tear.

The further development of energy-efficient routing is associated with the use of artificial intelligence to forecast weather scenarios and make real-time automatic decisions, as well as the creation of digital twins of vessels, which will allow even more accurate modeling of the environmental impact on energy consumption. Integration with autopilot and autonomous navigation systems will enable dynamic routing without human intervention.

2.4 Energy efficiency of shipping under the influence of hydrodynamic currents in the Mediterranean Sea

The global maritime industry is currently under pressure from requirements for decarbonization and improved fuel efficiency. Considering that maritime transport accounts for about 90% of global trade and over 3% of worldwide greenhouse gas emissions [8], the issue of energy-efficient shipping becomes extremely relevant.

One of the less studied but significant factors influencing fuel consumption and vessel navigation is hydrodynamic currents. In particular, the Mediterranean Sea and the Strait of Gibraltar have a complex water circulation structure, featuring a pronounced two-layer current system that creates both challenges and opportunities for energy-saving route optimization.

The Mediterranean Sea is characterized by its enclosed nature, significant evaporation, and limited freshwater inflow, which form a unique hydrodynamic system. These conditions establish a two-layer circulation: surface waters flow in from the Atlantic Ocean, while deeper waters return, transporting warm, highly saline Mediterranean water. This circulation pattern determines both micro- and macro-scale current dynamics.

The main node of water mass exchange is the Strait of Gibraltar, approximately 58 km long and up to 13 km wide. It facilitates the water exchange between the Atlantic Ocean and the Mediterranean Sea. According to calculations, the average inflow of surface waters from the Atlantic is about 70,000 m³/s, while the deep outflow ranges between 40,000 and 50,000 m³/s depending on seasonal conditions [9].

The water balance of the Mediterranean Sea is a key factor determining not only the overall hydrodynamic conditions in the region but also the spatiotemporal distribution of currents that significantly affect maritime transport conditions. The water balance is primarily shaped by four main components: inflow through the Strait of Gibraltar, river runoff, precipitation, and evaporation.

Current estimates indicate that annual evaporation from the surface of the Mediterranean Sea is approximately 1300 mm/year, corresponding to over 1800 km³ of water. In comparison, total precipitation over the sea is only about 700 mm/year (around 1000 km³), while river runoff is about 300 km³/year. Thus, the overall water deficit exceeds 500 km³ annually, which forces the Strait of Gibraltar to compensate with its two-layer circulation.

The surface inflow of less dense, cooler, and less saline Atlantic waters occurs at an average speed of 1–2 knots at depths up to 100–150 m. The deep outflow of warmer, highly saline Mediterranean waters forms at depths of 300–800 m, where current speeds reach 0.5–1 knot.

This circulation pattern significantly influences maritime routes – especially along the coasts of the Iberian Peninsula, North Africa, and in the Alboran Sea area. Vessels moving against the surface Atlantic inflow face additional resistance, while those traveling in the opposite direction can use the currents to improve fuel efficiency.

The hydrodynamic influence of currents on a vessel is a decisive factor in route planning, fuel consumption calculation, and ensuring energy-efficient navigation. In both open sea and coastal areas, currents can have either a favorable or adverse effect on vessel movement, altering its speed relative to the seabed, course direction, and energy expenditure required to overcome hydrodynamic resistance.

The hydrodynamic load can be described by the following formula:

$$C = f \cdot L \cdot d \cdot V_T,$$

where C – transverse load due to the current; f – empirical coefficient (dependent on hull shape and conditions); L – length at waterline; d – draft (ft); V_T – current velocity.

This model allows estimating the additional load that the ship's main power plant must compensate for during maneuvering or straight-line movement, taking into account the drift caused by currents.

In the study of energy-efficient ship routing, a comprehensive approach is used to analyze data combining multi-component processing of marine, meteorological, and hydrodynamic information. To ensure result accuracy and high resolution of calculations, both satellite and in-situ data sources are applied, alongside numerical modeling that enables assessment of the impact of weather and hydrological factors on the energy efficiency of maritime transport, as well as machine learning methods.

As input materials for calculating current speeds in the Strait of Gibraltar and specific areas of the Mediterranean Sea, data from the National Oceanic and Atmospheric Administration (NOAA) [10] were used. NOAA WaveWatch III is employed to evaluate the state of the sea surface, particularly wave fields. The input data also include results of in-situ expedition studies of temperature and salinity distributions of seawater at different sections in selected Mediterranean areas (Fig. 2.3).

As an alternative information source for assessing water mass exchange between the Mediterranean Sea and the Atlantic Ocean, high-precision climate re-analysis data providing hourly data with a spatial resolution up to 0.25° (~25 km) from ERA5 [11] were utilized, covering precipitation and evaporation for the period 2002–2020.

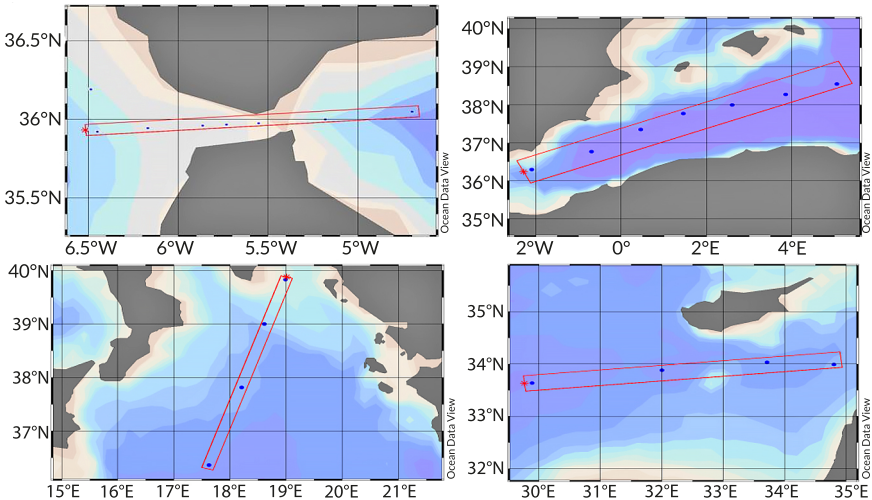


Fig. 2.3 Location of cross-sections in the Mediterranean Sea area

Research methodology is based on an interdisciplinary approach combining maritime navigation, hydrodynamics, meteorology, computational fluid dynamics, ship energy models, and numerical optimization. The primary goal is to develop and test algorithms for determining the most energy-efficient ship routes, minimizing energy consumption under complex marine conditions.

At the first stage, the research objective is formulated as minimizing energy (fuel) consumption along a route of a given length between the start and end points, subject to the following constraints:

- safety (avoiding hazardous areas such as storms, ice, shallow waters);
- time delivery constraints;
- navigational requirements (routes, depths, TSS lanes);
- spatiotemporal variability of hydrometeorological conditions.

Based on spatiotemporal fields (wind, waves, currents), data arrays are created for each maritime region in NetCDF/GRIB2 format. AIS data is used for reconstructing actual routes and conducting comparative analysis. Additionally, a digital map of marine obstacles is generated in vector format.

Building an energy model is a key step for quantitative assessment of a ship's energy consumption along a route under real hydrometeorological conditions. For the Mediterranean Sea area, characterized by complex circulation, the presence of permanent and seasonal currents, as well as spatial heterogeneity of wave regimes,

this model must consider the interactive effects of the following factors, included in general formula for calculating instantaneous energy consumption

$$E(t) = \frac{[R_0 + R_{wave}(t) \pm R_{current}(t)] \cdot V(t)}{\eta(t)},$$

where R_0 – ship resistance in calm water (determined by hull type, draft, speed, and vessel mass); R_{wave} – wave resistance (additional resistance caused by head or side waves); $R_{current}$ – hydrodynamic effect of currents (a decrease or increase in total resistance depending on the direction and speed of the current relative to the vessel's movement); η – efficiency of the propulsion system, which depends on engine load, RPM, propeller type, and varies under conditions of fluctuating speed.

The circulation system of the Mediterranean Sea is shaped by several key factors:

- the main countercurrent along the southern coast (Libya, Egypt);
- the Ligurian, Ionian, and Aegean cyclonic currents;
- the strong reverse flow of the Alghero-Provencal current (from west to east) and its branches;
- seasonal reversibility in the Aegean Sea due to wind action (Etesian winds).

In modeling energy consumption, the following are considered:

- the vector component of the current relative to the vessel's direction;
- vertical variation in current velocity, especially relevant for vessels with deep draught;
- turbulence and drift, which affect energy consumption during maneuvering or course changes;
- integration of current fields (from CMEMS or HYCOM data) at every waypoint with temporal resolution.

Corrected resistance accounting for currents is calculated using the formula

$$R_{current} = f(\rho, V_{rel}, A_{wet}, C_D),$$

where $V_{rel} = V_{ship} - V_{current}$ – speed of the vessel relative to the current; A_{wet} – wetted surface area of the hull; C_D – resistance coefficient dependent on the Reynolds number; ρ – density of seawater.

Total energy consumption along the route is calculated as the numerical integration over the trajectory

$$E_{total} = \int_{t_0}^{t_1} \frac{[R_0 + R_{wave}(t) \pm R_{current}(t)] \cdot V(t)}{\eta(t)} dt.$$

This integration is performed discretely for each route segment (for example, every 10–15 nautical miles or every 30 minutes of simulation), taking into account the corresponding hydrometeorological conditions at the location.

The presented model is applied to construct energy maps of maritime areas where fuel consumption increases due to opposing currents or wave systems; to optimize routes by avoiding zones with high wave resistance or strong head currents; and to analyze the sensitivity of energy consumption to changes in current direction (e.g., in the Ionian Sea during summer/winter seasons).

The developed ship energy model, which considers the influence of currents, wave conditions, and wind loading in the Mediterranean Sea, enables a thorough analysis of the mechanisms of energy consumption at various stages of the maritime route. Based on the results obtained, a number of critical factors determining the ship's energy efficiency level have been identified.

The presence and direction of currents have a direct impact on energy consumption: modeling data show that favorable currents can reduce fuel consumption by 8–12%, while opposing currents, especially in narrow regions (the Strait of Gibraltar, the Strait of Sicily), can lead to overconsumption of 15% or more.

Wave conditions play a complex role in energy usage – when wave heights exceed 2.5 m, resistance to movement increases by 20–25%, which particularly affects vessels with large tonnage. Moreover, the dependence of energy consumption on wave direction is asymmetric – side waves cause course instability, while head waves directly increase hydrodynamic resistance.

The interaction between different environmental factors (currents + waves + wind) is nonlinear.

For example, a combination of headwind with waves and a lateral current shift can lead to a "hydrodynamic reversal" effect, requiring constant course corrections and increasing energy consumption by up to 18%.

Seasonal analysis of energy consumption shows that during the winter period, when wind activity and wave energy are at their peak, fuel consumption on average rises by 10–15% compared to the summer period. This necessitates seasonal adjustments to routing and navigation strategies.

High efficiency of using numerical current forecasts (in particular, from the Copernicus Marine Environment Monitoring Service) in real-time adaptive routing has been demonstrated. Optimized scenarios achieved fuel savings of up to 9.5% by changing the route according to current direction shifts.

Future research should focus on integrating machine learning into energy models, allowing automatic adaptation of route parameters to rapidly changing marine conditions. This approach opens the prospect for developing next-generation

intelligent navigation systems aimed at sustainable development and maximum energy efficiency in maritime transport.

2.5 Conclusion

The use of meteorological software systems such as SPOS, WNI, and BON VOYAGE significantly enhances the safety and economic efficiency of maritime transportation. Their integration with other navigational systems enables more informed decision-making in route selection, thereby reducing weather-related risks, cutting fuel consumption, and lowering harmful emissions. This is especially critical amid current global environmental challenges. Further development of these technologies, particularly their integration with artificial intelligence systems, opens new opportunities for improving maritime operations management.

Route adjustments considering meteorological conditions via SPOS, WNI, and BON VOYAGE have proven to be effective tools for energy-efficient ship navigation. This approach achieves fuel savings, improves safety, and promotes environmentally responsible shipping.

In the future, the integration of such systems with AI modules, autonomous control, and satellite platforms will make weather-dependent routing an integral part of digital navigation.

The continuous implementation and updating of cutting-edge technologies and software onboard maritime fleets have made route planning more convenient, faster, and reliable by accounting for weather factors, economic aspects, and navigation safety.

An analysis and review of the SPOS system demonstrate that this software allows the easy construction of optimal routes based on weather forecasts for sailing areas, estimation of probable fuel consumption, safe port anchoring, and automatic notification of shipowners regarding weather conditions during voyages.

Energy-efficient ship route planning considering meteorological conditions is one of the key directions for sustainable development in shipping. Tools like SPOS provide practical realization of this concept and show significant potential in reducing costs, emissions, and risks. Further digitalization and the advancement of analytical platforms will make these solutions standard practice in the maritime industry.

A detailed analysis of the energy model confirms that integrating hydrodynamic environmental factors into navigational planning is a critical condition for achieving energy-efficient shipping in the Mediterranean Sea. Implementing such models in practice helps reduce fuel and operational costs, minimize greenhouse gas emissions – which aligns with the International Maritime Organization's decarbonization

goals for maritime transport – and enhance the reliability and safety of voyages through more accurate navigation condition forecasting.

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