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ORIGINAL PAPER

Weather routing in long-distance Mediterranean routes

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Abstract The selection of ship routes based on modern weather forecasting is a mean of computing optimum shipping routes thereby increasing safety and comfort at sea, cutting down on transit time, and reducing fuel consumption. Further empirical research in the effectiveness of modern weather routing applications is required especially in applications concerning shorter routes in enclosed seas of limited geographical extent such as the Mediterranean Sea. The present study used two climatological simulations to test this state-of-the-art approach to ship routing. Simulations represented two theoretical routes: (1) a route between Italy and Greece and (2) a route between Cyprus and Italy. Both routes were analyzed across varying simulated climatic conditions and the results were compared with those of control routes. Furthermore, results were analyzed in terms of passenger and crew comfort, bunker consumption by ships, and time of crossing. The first simulation showed that weather routing would improve ship performance on 37% of days while the second simulation revealed that weather routing would support ship captains virtually all the time.

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1 Introduction

The rapid growth in knowledge on atmospheric and hydrospheric processes since the second half of the twentieth century—supported largely by the dramatic improvements in of computer technology—has provided meteorologists with sophisticated operational tools that facilitate increasingly accurate climate analyses and weather forecasting. A vivid example of such advances is the incorporation of weather forecasting techniques in marine operations. Marine navigation before the 1990s relied heavily on good weather and sea forecasts, the precision of which had been growing year by year; however, the task of estimating the benefits of forecasts to end users was left to human ability. A ship master, for example, would know the wave and wind forecasts for a specific sea, but he ought to have estimated by himself the delay to be caused to his trip or the risks he could encounter. As a consequence, the choice of the best route, either the fastest or the safest, would simply be based upon his own experience and a good weather forecast. A historical perspective of how weather routing worked in the second half of the twentieth century is described in Motte (1972) or Bowditch (1995).

In the past decade, however, resolution and precision of geophysical models (see e.g. Accadia et al. 2003; Janssen et al. 2000), accompanied by a dramatic increase in computational power, enabled scientists to install numerical models dedicated to specific applications with high resolution in space and time. In the case of navigation, for example, it was finally possible to install quantitative models of ship hydrodynamics in parallel to weather and sea state models. This important improvement enabled marine meteorologists to directly forecast ship performances along routes and to propose optimal routes among a set of alternative options. Hoffschildt et al. (1999), Saetra (2004), and Böttner (2007) provide three excellent theoretical examples of how numerical weather and sea forecasts can be the input to numerical ship routing.

Nowadays, operational ship-routing services mainly exist for oceanic navigation. An assessment of the possibility of extending weather routing to Mediterranean navigation was conducted in 2005–2007 (Delitala and Speranza 2008), by developing a tool for simulating ship performances along routes and by testing it in real situations for several months. Results of such tests were encouraging and suggested the authors of some of the contributions therein to perform the present climatological study.

In this work the authors assessed two long-distance routes in the central–eastern Mediterranean, connecting Italy to Greece or Cyprus and passing near Malta. Routes are not operated by real ships, but have been devised in order to present significant alternatives in terms of meteo-marine conditions especially during predictions of high impact weather at sea (high winds and waves).

Two years of continual simulations, from October 2006 to September 2008, were performed by applying a route optimization software to the output of a limited area weather model and to a wave model; the two models were BoLAM (Buzzi et al. 1994) and WAM (the WAMDI group 1988) in their most recent versions.

The results were analyzed, taking particular care of crossing time, passengers' comfort, bunker consumption, and safety.

2 Current weather-routing practices

2.1 Ship routing for oceanic navigation

Weather routing, intended as a tool for optimizing ship routes according to meteo-marine conditions, is generally implemented in two ways:

A. Issuing targeted weather and sea forecasts with detailed information about adverse phenomena that could be harmful for navigation in a set of seas or along desired routes
B. Preparing specific bulletins that include ship performances along a set of routes

The type A information is the more traditional one and it assumes that the ship captain would make his own decision, simply using his knowledge of how marine phenomena can affect the ship. On the other hand, Type B information adds quantitative information about the ship to the marine forecasts.

Both forecasts make use of numerical models of weather and sea state, but type B information are estimated by implementing ship models on the lee of the former.

Type A services (i.e., traditional bulletins) are offered by most of meteorological services. They may include the following information:

- Surface forecasts (usually up to 72 h) of main weather quantities
- Synoptic surface analysis
- Upper air charts
- Distribution of ice and icebergs
- Wave height
- Swell height and direction
- Ad hoc alerts for gales or storms

Some of them, such as in the case of Météo-France or the UK Met Office, can provide tailored forecasts along desired routes or in a set of seas specified by the user.

Type B services (i.e., those including numerical estimations of ship performances) are mainly dedicated to oceanic navigation. Two European meteorological offices, the Danish Meteorological Institute (DMI, Denmark) and the Swedish HydroMeteorological Institute (SMHI, Sweden) as well as some private companies, regularly offer this type of service.

2.2 Weather routing in the Mediterranean

A recent experiment of weather routing in the Mediterranean was fostered by the European Union Project WERMED (*Weather-routing dans la Méditerranée*) partly funded by the Program Interreg IIIB-MEDOCC (Delitala and Speranza 2008).

In the frame of this project a route simulator was developed for seven Mediterranean routes and 15 different ships: passenger, cargo, and RO-PAX (i.e., dedicated to carry both passengers and tracks). For the last quarter of the project, i.e., for about 6 months, external users could request free operational support, as outlined in Fig. 1. The weather-routing bulletin could be automatically generated through a dedicated web page or could be prepared daily by dedicated personnel and sent via e-mail.

The route simulator would optimize ship performances according to three criteria which the user could adjust

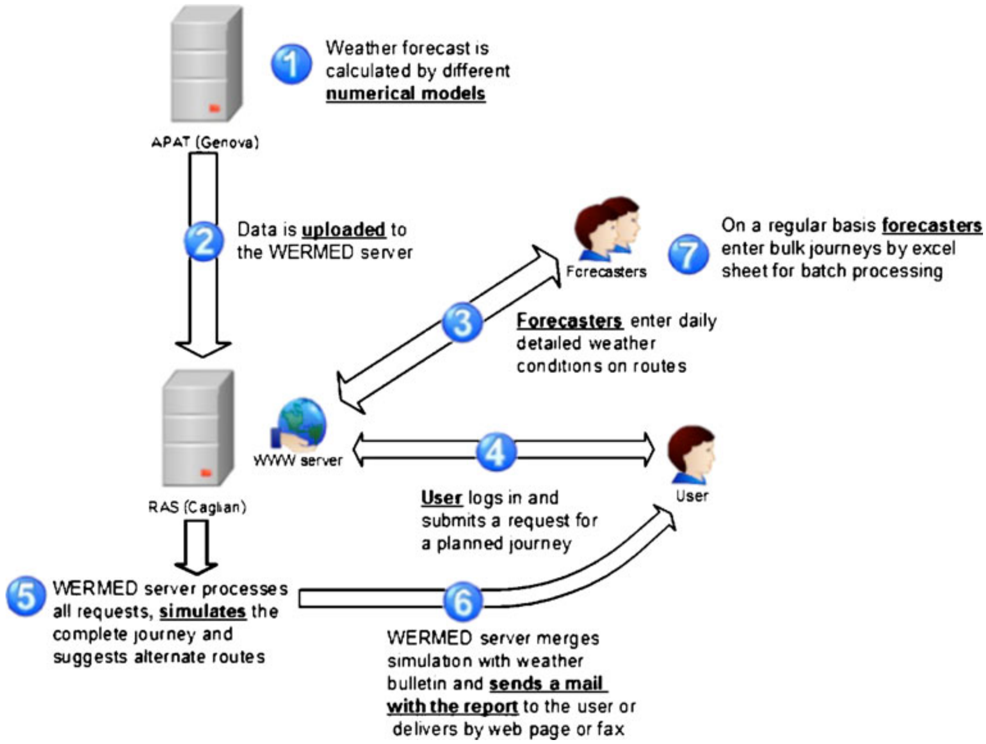

Fig. 1 Flow-chart of the experimental weather-routing service of WERMED

according to his/her needs: crossing time, ship power, and passengers' or crew's comfort.

In order to launch a simulation, the user had to set the following parameters:

- The desired route, among seven possible ones in both directions
- The ship, among 15 possible ones
- Date and time of departure
- Ship velocity (target, minimum, and maximum)
- Ship power (target, minimum, and maximum)
- Optimization criteria (i.e., weights from 0 to 1, for time, power, and comfort)

For each request the simulator would forecast a set of information along all pre-defined route options:

- Length of navigation
- Ship power
- Comfort
- Wind (direction and speed)
- Waves (direction, period, and significant height)

Both synthetic information for each route option and detailed information for all legs of each route option were provided. In the scheduled bulletins, an outline of such information written by a meteorologist was added.

For several months, the service was tested with two ship companies, Italian *Grandi Navi Veloci* and Greek *Minoan Lines*, in three real routes:

- Porto Torres–Genova
- Genova–Tunis
- Patras–Ancona

While navigating in Porto Torres–Genova and Genova–Tunis routes, the captain could chose between two options; on the other hand, Patras–Ancona had three options.

Each day the ship captain would receive a dedicated bulletin with information for any route option he could chose. For example, for Porto Torres–Genova, the ship captain would receive a description of the possible weather and sea conditions expected by choosing option A (traveling west of Corsica) or alternatively option B (east of Corsica). Every week, ship captains would send their response in the form of written reports describing the actual navigational conditions encountered and the ship power actually set.

The experimental phase was really satisfactory and ship captains often used the bulletins as a support to facilitate the choice of the best route option.

3 Physics of modern weather routing

3.1 Physical interactions between the geophysical medium and the ships

Numerical modeling is a fundamental tool for modern weather routing. The key interaction between a ship and the two geophysical media (air and sea) is the resistance to ship advancement. The latter is composed of two elements: the *resistance* due to still water and the so-called *added resistance* due to wind and waves.

Still water resistance is a square function of speed v and can be described by a simple function:

$$F_w = av^2 + bv + c$$

where a, b, and c are constants that can be estimated as a function of characteristics of the underbody (shape and roughness) and of water density.

The added resistance is still governed by ship hydrodynamics, but it is the result of much more complex interactions between the ship and both waves and the wind: added resistance due to waves is usually stronger than the former and it depends on wave train characteristics (significant height, direction, and period), on the velocity of the ship and on its actual load drought; resistance due to wind depends on its velocity (considering both speed and direction), on the velocity of the ship and on the portion of ship directly exposed to the wind.

As shown in Fig. 2, added resistance is higher whenever a ship moves opposite to the wave group velocity and is lower (but still higher than zero) when it goes in the same direction; therefore, even waves hitting the stern retard ship advancement, especially in adverse conditions.

However, the dependence on the angle between the ship velocity and wind or waves is neither linear nor monotonic. There are two resistance maxima corresponding to a ship sailing very near the wind with a secondary minimum in between (corresponding to a ship moving exactly against the wind). On the other side, two absolute minima correspond to the sea reaching the beam, while a secondary maximum corresponds to the sea exactly hitting the stern.

An example on the action of the wind is reported in Fig. 3. Although this is commonly called *added resistance*, it does act as a resistance only when the wind blows on the bow. On the other hand, when the wind hits the stern it actually pushes the ship and thus increases its velocity.

With regards to the dependence of added resistance on wind intensity and wave height, a rapid monotonic growth can be observed in Figs. 2 and 3. In order to keep the desired velocity with growing waves or opposing wind, the ship's engine power must be increased. It is however clear that in adverse meteo-marine conditions, resistance can become so high that the ship's power is not enough to overcome it and as such the speed decreases.

Beside ship resistance, in recent years some objective techniques were developed to estimate comfort in an objective way (Sebastiani et al. 2008; Turan et al. 2005). Such a technique applies ISO regulation 2631-3: 1997 which was derived from O'Hanlon and McCauley integral of motion sickness incidence (MSI), described in details in McCauley et al. (1976).

The physical quantity used to this scope is the acceleration undergone by a person inside the ship for a 2-h time: whenever a ship oscillates vertically, a vertical acceleration is felt by the person; if waves or wind cause significant rolling and pitching, accelerations perpendicular to the person's body arise as well.

The MSI experiment, however, proved that the main cause of seasickness is the vertical acceleration with a maximum effect at the oscillation period of about 6 s. Secondary effects due to perpendicular accelerations are still to be explored.

Quantitative estimates of comfort, on a scale of 1 to 5 (as in Table 1), are a function of the net vertical acceleration upon the person; the table reports how comfort can translate into a reduction of the person's capacity to concentrate or to perform different kinds of work.

Although it is clearly difficult to estimate these effects in an objective way and despite the fact that some numerical

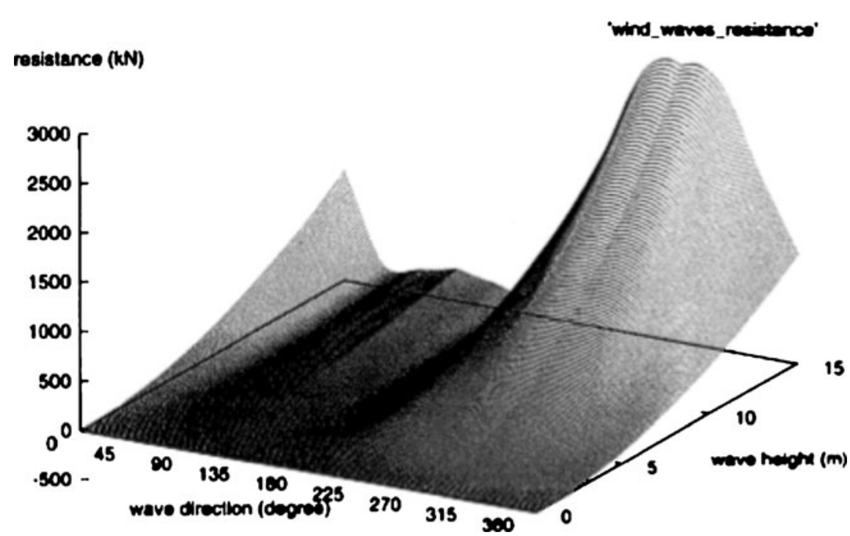

Fig. 2 Example of added resistance to ship movement due to wind-waves (Hoffschildt et al. 1999)

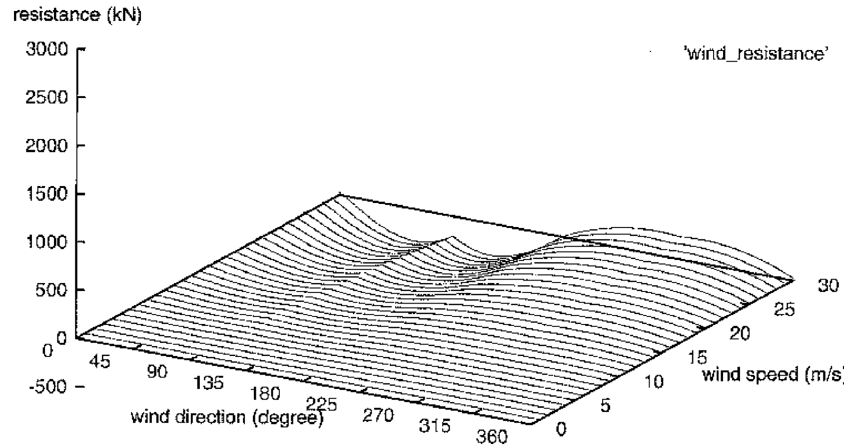

Fig. 3 Example of added resistance to ship movement due to winds (Hoffschildt et al. 1999)

problems still need to be solved, this tool can be very useful to forecast comfort on a daily basis or to make climatological estimates of comfort of specific routes.

3.2 Numerical simulation of atmosphere, hydrosphere, and ship dynamics

In order to calculate the power needed to navigate at a desired speed and to estimate passenger and crew comfort, a precise forecast of wind and waves along routes is needed. Atmospheric models (either Global Circulation Models or Limited Area Models) and wave models are the optimal solution, depending upon the desired forecast length and the desired spatial resolution.

Once an adequate numerical forecast is available, still water and added resistance can be estimated for every leg of a desired route, simply by using the wind and the waves forecast for the instant at which the ship is expected to cross it.

Forecast resistance is then the quantity to be used to forecast navigation characteristics, such as power or velocity. In order to do that, however, the appropriate ship hydrodynamics must be available; therefore, a good weather-routing service needs a rich database of ship hydrodynamics.

By making usage of such information, weather-routing techniques can then suggest either the optimal route between two ports, or the optimal power to be set along a defined route, in order to meet some specific criteria. The suggestion of the optimal route is typical of oceanic weather routing, that is when an infinite set of route options is possible. On the other hand, in the Mediterranean, only a finite number of significantly different options for the same route are actually possible and optimal navigation parameters for all possible options are provided to ship captains.

In the current study, atmospheric models and wave models run by the CINFAI research unit of the University of Genova were used. The atmospheric model was BoLAM (Buzzi et al. 1994); the wave model was WAM (The WAMDI group 1988). Spatial and temporal resolutions of the model versions used are given in Table 2.

The route optimization routine implemented on the basis of the two geophysical models is described in Sebastiani et

Table 1 Comfort index, corresponding vertical acceleration, and typical effects

Comfort index	Vertical acceleration A[g]	Effects or problems for
0	A<0.02	Passengers on a cruise. Older people close to the threshold below which vomiting is unlikely to take place.
1	0.02<A<0.05	Passengers on a ferry. Causes symptoms of motion sickness (vomiting) in approximately 10% of un-acclimatized adults.
2	0.05<A<0.08	Problems for intellectual work by people not so well adapted to ship motions.
3	0.08<A<0.11	Problems for heavy manual work.
4	0.11<A<0.15	Problem even for light manual work to be carried out by people adapted to ship motions. Causes quickly fatigue.
5	A>0.15	Problems even for simply light work. Most of attention must be devoted to keeping balance. Tolerable only for short periods on high speed craft.

Vertical acceleration is expressed in unit of g (9.8 ms^{-2}) and effects arise for a continuous (2 h) exposure to a sinusoidal acceleration of amplitude A[g] and frequency belonging to a complex set of spectral bands

Table 2 Characteristics of numerical models

	Atmospheric (surface wind)	Wave
Name	BoLAM	WAM
Spatial resolution	0.20°	1.25°
Forecasts available every	3 h	3 h
Initialization time	0000UTC	0300UTC

al. (2008). The routine is based upon three target values that must be met:

- Optimal power, corresponding to an expected fuel consumption
- Optimal crossing time, corresponding to a desired arrival time
- Minimum comfort index, corresponding to the best possible comfort conditions for passengers

Weights from 0 to 1 are to be set for each one of the three parameters to express their respective importance in the optimization routine.

Each route is divided into tracks. The optimal sequence of ship power to be applied is the one which minimize the following equation

$$C = c_p \sum_{i=1}^{N\text{track}} \left(P_i + P_{\text{target}}\right)^2 + c_t \sum_{i=1}^{N\text{track}} \left(T_i - T_{\text{target}}\right)^2 + c_c \sum_{i=1}^{N\text{track}} \left(I_C - I_{\text{target}}\right)^2$$

where c_p, c_t, and c_c are optimization parameter (from 0 to 1) for power, time, and comfort; P_{target}, T_{target}, and I_{target} are target values; P_i, T_i, and I_i are actual values of track i.

Considering that simulated ships are designed to navigate in the Mediterranean in most of weather conditions, if reasonable navigation targets are set, the optimization criteria are usually met for all possible options. In such cases the choice can be done without the help of weather routing.

However, whenever adverse conditions are forecasted, a specific sequence of engine power must be planned for the different route legs by a ship captain wishing to meet such targets or to get as close as possible to them. In all such cases, the routine will suggest the optimal sequence of powers for each possible route option.

4 Weather routing in long-distance Central and Eastern Mediterranean Routes

4.1 Setting up the experiment

The numerical simulation of operations of two ships along two long-distance routes were examined. The chosen test routes are not really operated by shipping companies, but they have been devised in order to have three characteristics:

1. Presenting possible options providing quite different meteorological and sea conditions during adverse weather
2. Being long enough to make weather routing actually useful
3. Covering some of the EU *motorways of the sea*

Figure 4a shows route 3/4,[1] joining Genova to Peireos and back. The main option presented by this route is the choice of passing by Messina Straits (option A) or along the southern coast of Sicily (option B); peculiar conditions may even suggest ship captains to pass south of Malta (option C). As it can be seen from Table 3, option A is shorter, but the ship has to cross the Messina Straits, thus being forced to slow down and to hire a pilot.

Figure 4b shows route 5/6, joining Cagliari to Larnaca and back, and presenting two groups of alternative routes. One group is the same as for route 3/4 (North of Sicily via Messina Straits; South of Sicily via Malta Channel; South of Malta), the second group has two alternatives: passing North or South of Crete. Overall (see Table 3), route 5/6 presents six options, each one of them suitable for different weather conditions.

The test simulates an idealized company operating a RO-PAX service between Genova and Peireos, by means of a 180-m/20,000-ton ship, and a second idealized company operating a cargo service between Cagliari and Larnaca, by means of a 160-m/20,000-ton ship. In order to make simulations realistic as much as possible, hydrodynamical models of two real ships were actually used, and power and speed were set to real values.

The test used 2 years of numerical weather and sea forecasts from October 2006 to September 2008. In such a long period of time, quite different weather conditions occur, thus making possible a climatological study.

In non-adverse weather conditions, the ship captain would usually choose option B for Genova–Peireos (South of Sicily via Malta Channel) and would need about 50 h to complete the whole crossing. As for Cagliari–Larnaca, the captain would preferably use option E (South of Sicily via Malta Channel and South of Crete) and would take about 90 h.

A control run was then performed for each route, assuming a ship captain without weather-routing information would always use that option route, possibly modulating ship power in order to arrive in time. On

[1] The original route numbers of Delitala and Speranza (2008) are preserved.

Fig. 4 Experimental routes with alternative options: **a** Genova-Peireos; **b** Cagliari-Larnaca

the same 2-year dataset, a weather-routing experiment was then performed, by simulating all route options with optimization constraints described in Table 4, and then comparing ship performance in all possible options. Constraints were set assuming a ship captain would try to optimize comfort and time in route Genova–Peireos and optimize both time and power in Cagliari–Larnaca.

5 Results of Genova–Peireos simulation

5.1 Description of the route

The route connecting Genova to Peireos (Fig. 4a) can be roughly divided into three parts: Ligurian and Tyrrhenian Sea, from Sicily to Greece and Aegean Sea. While the latter

Table 3 Characteristics of route options

Route	Option	Description	Length (nm)
3/4 (Genova-Peireos or vice versa)	A	Via Messina Straits	995
	B	North of Malta	1,081
	C	South of Malta	1,198
5/6 (Cagliari-Larnaca or vice versa)	A	via Messina Straits–N Crete	1,259
	B	N of Malta–N of Crete	1,257
	C	S of Malta–N of Crete	1,307
	D	via Messina Straits–N. of Crete	1,277
	E	N of Malta–S of Crete	1,256
	F	S of Malta–S of Crete	1,310

leg (after rounding Cape Tainaron in southern continental Greece) is bound to a fixed path, the former two parts allow the ship captain to make a number of choices.

Option A is 87 nautical miles shorter than option B, but captains would prefer the latter, in order to avoid costs and delays of crossing the Messina Straits. Therefore, we consider option B as the control case (i.e., without weather routing); constraints for the control case (Table 4) are set on the basis that the captain would just do his best for being in time.

From the climatological point of view, the crossing of the Tyrrhenian Sea is a long straight leg, well exposed to all types of adverse weather. Moreover, the cyclogenesis on the lee of the Alps (Speranza et al. 1985) frequently produces disturbances affecting this sea, often causing wind and sea storms.

Table 4 Optimization constraints of two simulations

Constraint	Control simulation	Operational simulation
Genova-Peireos		
Minimum power	14,000 kW	14,000 kW
Target power	20,283 kW	20,283 kW
Maximum power	24,630 kW	24,630 kW
Minimum speed	17.0 Kn	17.0 Kn
Target speed	21.5 Kn	21.5 Kn
Maximum speed	22.5 Kn	22.5 Kn
CT (time weight)	1.0	1.0
CP (power weight)	0.0	1.0
CC (comfort weight)	0.0	0.5
Cagliari-Larnaca		
Target power	6,600 kW	6,600 kW
Maximum power	7,700 kW	7,700 kW
Minimum speed	12.0 Kn	12.0 Kn
Target speed	14.0 Kn	14.0 Kn
Maximum speed	18.0 Kn	18.0 Kn
CT (time weight)	1.0	1.0
CP (power weight)	0.0	0.0

As it can be seen from climatology (Orasi et al. 2007), waves coming from all directions comprised between S and NW are frequent, often in excess of 2 m of significant height. North Westerly waves, the most frequent, cause delays, and discomfort especially in Peireos–Genova direction. Waves from W and SW negatively affect navigation in both directions, while Southern waves only affect the route from Genova. Since options A, B, or C imply a different angle between predominant waves and ship direction, choosing any of them properly can provide a better comfort, reduce fuel consumption, and help save time during adverse weather.

On the other hand, the Sicily Straits and Sicily Channel are less exposed to cyclogenesis and therefore less exposed to wind storms. For what concerns waves, the North Westerly waves dominate, often growing over 2 m; whenever passing south of Sicily (options B and C), this situation would delay navigation mainly in the route from Peireos.

5.2 Analysis of comfort

In the 2 years (731 days) of the control simulation of Genova–Peireos route with constraints of Table 4, the simulator forces the power to ensure that the ship arrive always in time.

The passengers' comfort, well correlated with maximum significant wave height, suffers the consequences (see Table 5):

- The mean comfort is higher or equal to 1 in 6% of events (45 days) up to an upper value of 1.8
- The maximum comfort value among all those recorded in each route leg is higher or equal to 2 in 27% of events (201 days), it is higher or equal to 3 in 8% the of cases (60 days) and it reaches 5 in 4 days

As a consequence, navigating without weather routing, i.e., choosing the control route and aiming to be in time, can guarantee acceptable comfort conditions for passengers (comfort <2) for the entire crossing only 63% of times.

Table 5 Comfort of control route Genova-Peireos and vice-versa

Mean comfort	Maximum comfort	Route 3B (Genova-Peireos)	Route 4B (Peireos-Genova)
$C_{\mathrm{mean}}=0$	$C_{\mathrm{max}}<3$	657	640
	$C_{\mathrm{max}}\geq 3$	30	38
$C_{\mathrm{mean}}=1$	$C_{\mathrm{max}}<3$	5	5
	$C_{\mathrm{max}}\geq 3$	5	9
$C_{\mathrm{mean}}>1$	$C_{\mathrm{max}}<3$	14	5
	$C_{\mathrm{max}}\geq 3$	20	34

C_{mean} indicates the mean comfort of the route, C_{max} is the maximum comfort

In the remainder of cases, passengers are expected to suffer (i.e., comfort ≥2) during at least one leg of crossing, especially if that occurs during daytime; finally, in 8% of the cases comfort conditions would be very bad or extreme, at least once.

In 6% of days, even mean comfort is adverse, meaning that passengers are expected to feel bad/sick during most of the navigation. Moreover, such comfort conditions are likely to affect the crew, as well, thus reducing the ability of performing their job properly.

Peireos–Genova route (Table 5) shows a few more cases of adverse comfort condition, but the same considerations as for Genova–Peireos direction apply.

These situations are too frequent to be overlooked by a company which chooses to operate such a route, considering that in RO-PAX services passengers' comfort contributes to the company's image. A company could thus suggest ship captains to use weather-routing information before sailing, as a tool to choose alternatives.

As a matter of fact, weather routing can operationally forecast adverse comfort situations for the route option usually preferred by the captain and it can often suggest options with better comfort values. In this respect, the 2 years of operational simulations, provided some interesting results for the three options of Genova–Peireos and back.

Figure 5 shows the mean comfort for the three options of Genova–Peireos route in the 2 years of operational simulations of Table 4.

Option A has a mean comfort higher or equal to 1 in 21 days, option B has such comfort values in 32 days, and option C has it in 44 days. It is immediately clear that simply following option B with ship power optimized by means of weather routing would reduce the frequency of uncomfortable days. Since option A is uncomfortable less often than option B, it is also clear that it would provide a good alternative in several situations.

Considering that by navigating along option A a captain is less likely to encounter adverse weather, he could simply decide to completely abandon option B and option C, taking option A every time. However, this would turn out to be a naive way of using weather routing, because there are days in which option A is actually less comfortable, so it does not make sense to go there in those days. Moreover, crossing Messina Straits is generally not convenient, unless there are specific reasons to do so.

The best way to use weather routing to improve comfort then is by choosing the least uncomfortable route option on a daily basis. Figure 6 shows how often each option has a better comfort than both others, and how often two of them are better than the third one, let alone those days where all three options have comfort 0.

As it was expected, option A is the best one (either alone or with another one) in 75% of considered days for the Genova–Peireos route and 59% for the Peireos-Genova lag; it is thus clear that when adverse comfort is forecast, option B or even option C can turn out to be the best choice. The latter is particularly true for Peireos–Genova, since weather routing suggests either of them in 41% of days with discomfort.

By using weather routing, a ship captain can thus improve comfort of the route Genova–Peireos in two ways:

– By optimizing power when choosing to keep route option B, thus reducing the frequency of uncomfortable days
– By choosing option A or option C when its comfort is expected to be the best one

6 Results of Cagliari–Larnaca simulation

6.1 Description of the route

The route connecting Cagliari to Larnaca (Fig. 4b) can also be roughly divided into three parts, though quite longer: from Cagliari to Sicily, crossing the Ionian Sea, and from Crete to Larnaca.

The western part of the route can be covered along the Northern coast of Sicily (via Messina Straits), along the southern coast of Sicily (via Malta Channel) or along the coast of Tunisia. On the other hand, the eastern part presents two alternatives only: passing south of Crete and North of Crete, respectively. The central part is just a long crossing of an open sea.

Adverse weather in the eastern part of Cagliari–Larnaca is similar to that of Genova–Peireos. Whenever passing north of Sicily, a ship captain could be exposed to rough North

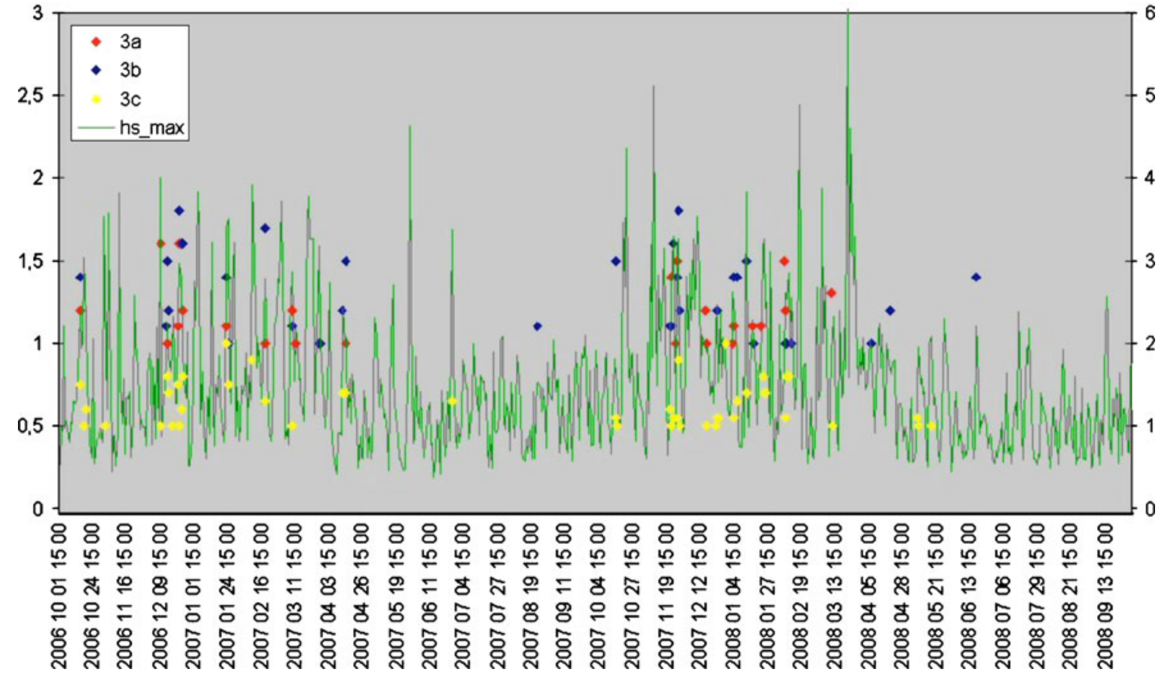

Fig. 5 Mean comfort for operational simulation of options A, B, and C of route 3 Genova-Peireos and maximum significant wave height for the control route

Westerly and North–North Westerly sea which could greatly grow due to a very long fetch (the whole Tyrrhenian Sea); that would cause problems to ships heading in both directions, mainly the westbound one. If the captain chooses to follow the southern coast of Sicily, he could face adverse North Westerly sea, reinforced in the Straits of Sicily; this would mainly delay westbound navigation. The option of following the coast of Tunisia is longer than the other two, but it is less exposed to North Westerly waves. A captain can then choose such navigation if the weather routing suggests so.

According to climatology, east of Sicily (i.e., in the second and third part of the route) northerly sea dominates strongly. Captains would thus tend to pass south of Crete in order to avoid it, especially when sailing westbound. Weather routing, however, may recommend the route passing north of Crete in specific situations, like in the case of the strong Ghibli winds from the Sahara desert; alternatively, weather routing could advise the captain to modulate power in order to cross the Ionian Sea during less adverse sea.

6.2 Time and comfort[2]

In this part of the analysis, the control route option was chosen, considering that the main concern of a cargo ship captain is to arrive in time. Without weather routing, the preferred option would be E, since it is slightly shorter than all other ones, it avoids passing by Messina Straits and it sails north of Crete.

In Table 4, constraints of Larnaca–Cagliari simulations for 2006–2008 are outlined for both control and operational simulations. The operational optimization was set in order to optimize both comfort and time; the reason for optimizing comfort, as well, will be made clear further ahead.

Figure 7 shows that option B is the best both in terms of timing and in operational simulations (66% of route 6 Larnaca–Cagliari). However, 24% of times, one of the other options performs better, especially option E (23% of times) and option A (8% of times).

Although the present simulation concerns a cargo ship, very bad comfort conditions should be avoided, as well. In fact, keeping the crew in good psycho-physical conditions automatically implies they can do their work at best. Moreover, the comfort index is based upon acceleration of a body inside the ship (Table 2); therefore, a bad comfort implies that even ship loading is subject to harmful accelerations.

6.3 Bunker consumption and safety

Optimization constraints force the simulator to suggest quite different power combinations to be set and, as a consequence, different bunker consumptions are expected. Figure 8 shows how often each option has the best estimated bunker consumption in the 2006–2008 period.

[2] For technical reasons, information about the last part of navigation should be taken with care. Still for technical reasons, only results of Larnaca–Cagliari direction will be shown.

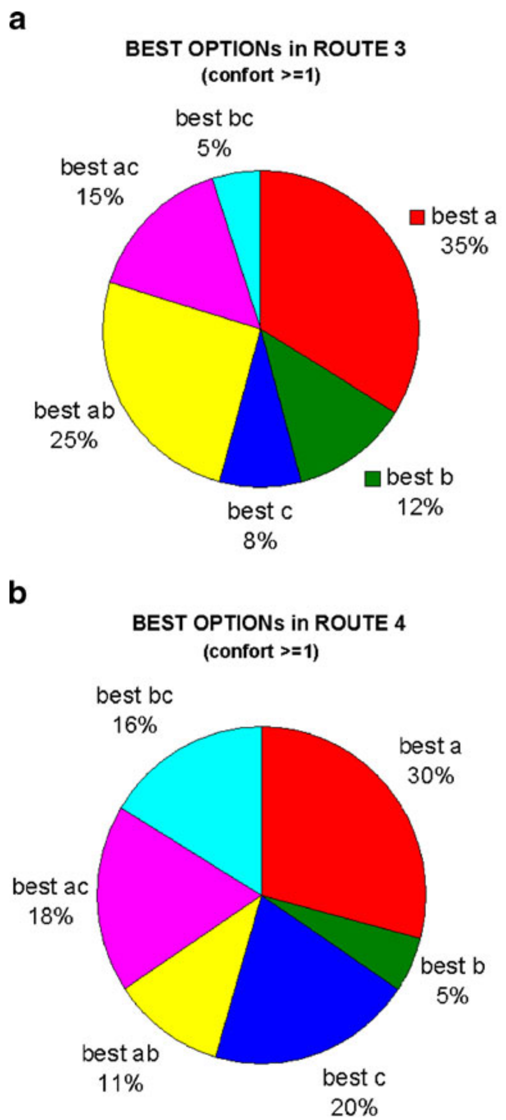

Fig. 6 Comparison of comfort of the three options of **a** route 3 (Genova-Peireos) and **b** route 4 (Peireos-Genova). *Best a*, *best b*, and *best c* indicate how often a single route is the best one; *best ab*, *best ac*, and *best bc* indicate how often two routes are better than the third, but the two better ones have the same comfort index value

The least consuming option is D, almost 1 day out of two (44% of time). Option A consumes the least amount of bunker for 24% of the times. Option B, though having the best timing, is far from being the most economic.

Considering that the simulation deals with a medium-size ship equipped with a single engine, adverse weather or marine conditions can turn out to be very harmful. It is then important to assess how weather routing can help to increase safety of cargo navigation.

Although a fair maintenance status is assumed, the risk of an unexpected dangerous event, such as an engine failure or a rudder problem, is not null. Since these events are random, if they occur during adverse weather conditions

Fig. 7 Frequency of times when the six options of route 6 (Larnaca-Cagliari) are best in time

they can easily turn out to be a serious threat, leading to ship damages or even a shipwreck.

In the present work, then, two situations leading to an increase of risk for the ship safety were considered:

1. Maximum significant wave height higher than 4 m (or even 6 m)
2. Maximum comfort higher or equal to 4

In such conditions, the ship has a reduced ability to cope with unexpected adverse events: situation 1 implies the ship would be difficult to steer in at least one leg of route; situation 2, on the other hand, implies that even manual tasks are hard to perform and, in such conditions, the crew could not be able to efficiently do their job.

Table 6 outlines the number of occasions in the 2 years of simulation with dangerous HS_{max} (maximum significant wave height) or dangerous comfort conditions. The three options passing N of Crete are clearly more exposed to such dangerous situations, but no route option is exempted.

Fortunately, these are rare events; however, this scarcity can lead a company or a ship captain to overlook them. For example, it is important to observe that option B is at the

Table 6 Number of occasions with dangerous maximum significant wave height (HS_{max}) or dangerous maximum comfort (C_{max}); high sea (i.e., $HS_{max} \geq 6$m) events are highlighted in a separate column

Route option	No. of events with $HS_{max} \geq 4$	No. of events with $HS_{max} \geq 6$	No. of events with $C_{max} \geq 4$
A	8	2	0
B	9	2	0
C	6	2	1
D	4	0	0
E	5	0	0
F	3	0	1

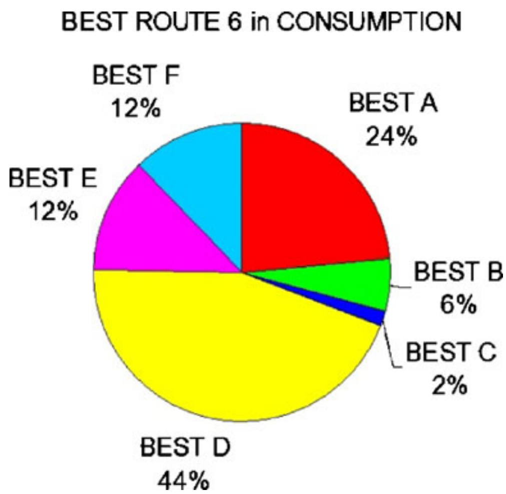

Fig. 8 Frequency of times when the six options of route 6 (Larnaca-Cagliari) are best in bunker consumption

same time the most dangerous and the best in time, so that a captain is usually tempted to take it, overlooking risks.

Only by means of weather routing a captain would be able to know which route option is the briefest for each day and, at the same time, to stay informed whether it is a dangerous choice.

6.4 Planning operations in Cagliari–Larnaca

The present analysis would not only be useful to run operation on a daily basis, but also to plan operations along Cagliari–Larnaca, by comparing the six route options for a long period of time.

Table 7 attempts to make a synoptic judgment of the four aspects of Cagliari–Larnaca examined so far: comfort, delay, safety, and bunker consumption. Keeping this in mind, an ideal company wishing to assess the Cagliari–Larnaca route can draw the following conclusions:

- Option E is fair in every aspect, but in many cases it is not the optimal one since better choices exist from time to time
- Option B is the best for timing and it presents fair comfort, but it is the most dangerous and it causes greater bunker consumption
- Option A is fair for many aspects, but it is less safe than others
- Option D is an appealing choice with respect to comfort, safety, and bunker consumption, but it would cause delays
- Options C and F are the worst ones, so they should be considered only in a few special cases

This synoptic analysis confirms that, if weather routing is available only on a climatological basis, choosing route option E would be the best idea. However, if weather routing is available on a daily operational basis, it can be a very useful tool to improve and optimize route decision.

7 Conclusions

The recent developments in weather and wave modeling, permitting to provide detailed (in space and time) forecasts of wind and waves over the sea, together with the development of route simulators were used in the frame of this study in order to perform a climatology of weather routing along long-distance maritime routes in the Central and Easter part of the Mediterranean Sea.

The climatology was performed for a 2-year period and for two routes: Genova to Peireos and Cagliari to Larnaca. The route simulator, based on the available wind and wave forecasts, takes into account the optimal velocity, corresponding to a desired arrival time; the optimal power, corresponding to the expected fuel consumption as well as the minimum comfort index, corresponding to the best possible comfort conditions for passengers.

The study revealed that weather-routing techniques can clearly give some added value to standard marine forecasts. Ship captains who use them as a help to plan their work can improve passenger and crew comfort, reduce delays, and save bunker. Cargoes and medium-sized ships in general can also use weather routing to obtain precious information to increase safety of navigation.

Navigating with traditional routing, for example, is biased towards choosing the shortest route option, except for a few extreme situations. Weather routing, on the other hand, can indicate that in some situations a longer route can actually be covered with a lesser bunker consumption.

Moreover, for one of the simulated routes (Genova–Peireos) the simulated ship could navigate without weather routing with no trouble only in 63% of cases. In the

Table 7 Synoptic judgment of comfort, safety, danger, and bunker consumption

	Option A	OPT B	OPT C	OPT D	OPT E	OPT F
Comfort	Fair	Fair	Fair	Fair	Fair	Bad
Delay	Fair	Good	Bad	Bad	Fair	Bad
Safety	Bad	Bad	Bad	Fair	Fair	Fair
Bunker Consumption	Fair	Bad	Bad	Good	Fair	Fair

reminder, weather routing would contribute to improve passenger and crew comfort. Moreover, there is a tail of the distribution (the 6% of most adverse weather conditions), in which major discomfort of people inside the ship cannot be avoided, but weather routing would be fundamental in trying to reduce it.

In the case of the simulated cargo ship from Larnaca to Cagliari, options are so many that weather routing would always be useful, as no route option is really better than the others. Moreover, there is 2–3% of occasions in which weather routing would turn out to be useful even for reducing the risk of a hazard to the ship or to its loading.

Finally, weather routing (actually "climate routing") can also be a good tool for a company's planning of an operational commercial line in the Mediterranean Sea, taking into account comfort, safety, delay, and fuel consumption with respect to the policy of the company and environmental constraints.

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