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Potential Benefit of Ensemble Forecasts for Ship Routing

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Abstract

Whether and to what extent ensemble forecasts of wave fields can be useful to the commercial application of ship routing is evaluated here. For this purpose, a ship routing program was developed and used to simulate the daily crossing of a container ship from Brest to New York.

The ship routing optimization scheme is of Bellman type. It optimizes in space and in time simultaneously. Two numerical improvements were included to force the iterations to be strictly convergent. Fields of swell, wind waves and wind are used to calculate an optimal route for the given weather situation. Ship routing is applied on each of the ensemble members, the ensemble control forecast and the deterministic forecast. Since the knowledge about the uncertainty of an optimal ship route is not entirely useful to a ship's captain, several methods are developed to create a single ship route out of the 50 ensemble ship routes. All ship routes derived from forecasts or created from the ensemble are verified against the weather of the analysis. It is shown that using the deterministic forecast already yields a big cost reduction compared to using the shortest navigable route. A further improvement can however be achieved by using ensemble forecasts.

1. Introduction

In June 1998, when the ECMWF atmospheric model was coupled to the wave model, the daily wave ensemble forecasts became an operational product (*Janssen* (1999)). Alongside the deterministic forecast of wave fields on a 0.5 degrees irregular grid, a control forecast and 50 ensemble forecasts are produced daily on a regular 1.5 degrees grid. The fifty members of the ensemble are generated by perturbing the initial atmospheric conditions by means of the most unstable singular vectors (*Molteni et al.* (1996)). The initial wave fields are not perturbed, however.

The skill and economic value of ensemble forecasts of atmospheric fields have already been discussed (*Richardson* (1998)). The main concerns are reliability and the possible benefit the forecast could have for a user. Concerning the reliability issue, there is a wide range of verification methods to monitor the performance of the forecast. In general, large regions like Europe or the north Pacific are considered. Extreme local events are thereby averaged out. This type of verification is applied on a daily basis at operational weather centres. In fact, there are inter comparisons between weather centres to determine who performs best when comparing the relevant scores. On the other hand, the benefit issue is often closely connected to locally confined regions (e.g. a farmer who wants to know about the precipitation in the coming week or an oil rig manager who has to take measures when a storm is approaching). In contrast, the optimization of ship routes is a commercial application in which wave forecasts are considered over a large area while local extrema are taken into account rather than averaged out.

Ship routing became an issue as soon as mankind decided to travel across the oceans. When considering sailing boats which were used until the turn of the 20th century, applied ship routing could have had an even bigger impact on costs (and safety) than it has today. However, only in recent years when numerical forecasting of wind and waves became feasible due to the rapid improvement in computer power and observational means like satellites, has the development of enhanced new methods to exploit weather forecasts for ship routing been reconsidered.

Lehner et al. (1996) successfully tested a ship routing system in which space borne synthetic apertures radar (SAR) wave spectra in combination with the wave model WAM were used as input to the ship routing program installed on a PC on board the Hapag Lloyd container vessel BONN EXPRESS. Though the weather during the test voyages was calm, savings in the order of 1% could be achieved in comparison to the shortest navigable route.

The ship routing program described in this paper was developed in Autumn 1998. It relies on a Bellman-like optimization scheme with various numerical improvements to make the iterative process strictly convergent. It uses wind and wave forecasts or analysis data. The resistance of the ship to wind and waves is processed by a routine which models the ship's propulsion to yield the various costs involved. Tables of specific ship data for this routine were kindly supplied by *Lehner*. Therefore mechanical features of the ship are those of the BONN EXPRESS *Lehner et al.* used. Furthermore, the program permits flexibility in departure and arrival time in order to avoid overloading the engine which occurs frequently when too rigid time limits are imposed.

To get an idea on ship route optimization, we will first discuss the optimization principles as well as the aspect of how weather influences the running costs of a ship. Then, a more detailed description of the ship routing program will follow, describing qualitatively the Bellman optimization scheme. After a brief definition of the relevant area where the ship routing was performed, some sample cases are studied. Methods of how to get relevant information from ensemble ship routes are then discussed. Finally, these routes together with routes obtained with the ensemble control and the deterministic forecasts are evaluated and compared with respect to analysed weather conditions.

2. Optimization of Ship Routes

The objective in numerical ship routing is to find the global minimum of a cost integral within the relevant phase space where a cost function f is integrated from the time of departure to the time of arrival (for a more detailed explanation of the cost integral refer to the appendix). The function f depends on various variables which are themselves implicitly or explicitly dependent on time.

In our case, the essential weather parameters are wind, wind waves and swell. The resistance of the ship depends on the velocity and direction of the ship as well as on the wave height, direction and period of swell and wind waves and on the wind speed and direction. Additionally, there is resistance due to water friction upon the ship's hull. To overcome the total resistance, the engine of the ship is required to output a certain power when rotating at a given revolution. This process is connected to consumption values of fuel and grease (figure 1). Multiplying these figures with the current price for fuel and grease and by the integration time step yields the costs of the ship route segment under consideration. However, sometimes the resistance can reach such high values that it is not possible to run the engine with a power output and a rotational speed compliant with the engine's limits. In this case, a large number is added to the costs to account for the additional wear and tear and potential damage of the machine. Because these costs are too complex to assess, they are used to indicate in the current routing program that engine damage occurred along the routes. Thereby, those routes can be discriminated from routes without engine damage in the following statistical analysis. As the costs for engine damage are fictitious costs, they do not have to be integrated along the ship route. In fact, they are added to the route costs for each single point of the discretized route. This is sufficient to guide the optimization scheme.

Together with the ship's physical limits, there are economic constraints which have to be regarded. Since the investment in a container terminal is so enormous, it cannot be allowed to stand idle, ships have to be as punctual as possible. However, in order to prevent the ship from engine damage during the voyage, late arrival cannot always be avoided. The calculation of the harbour costs are quite complicated in reality, because every single ship company contractor has to be taken into account. In this current study, the costs of 1000 'points' (the 'points' can be converted into any currency) for late arrival by one hour are added to the costs of the route. Since it turns out that on average, running the ship for one hour is about 700 points, the figure of 1000 seems quite plausible as a delay penalty. The added costs are determined using a quadratic interpolation between exact punctuality and the actual arrival. The same procedure applies to cases where the ship is too early on arrival and too late/early on departure. Although it does not seem to be a good idea to depart early because some cargo might not yet been loaded, it should be mentioned that a two-day forecast of the estimated time of departure could help coordinating things in time.

It may seem that the calculation of the cost function is already complicated enough. In fact things are even more complex. The only impact of waves upon the ship included in the program is their resistance. However, waves have the potential to influence the behaviour of the ship and hence the route, via rotational forces with respect to the ship's three major axes of rotation (rolling, pitching and yawing). In addition there is also the vertical movement of the ship called heaving (*Motte* (1972)). Although these movements might not affect fuel consumption, they can be a serious threat to the ship and its cargo. Including these motion effects in the cost function is yet again a very difficult task, depending on the ship's structure as well as on the type of the cargo loaded. Any cargo damage will also have to be included into the cost function.

Also not included in the cost function of the ship routing program are ocean currents. Although they may reach speeds of similar magnitude to the ship's velocity, they can mostly be neglected because of their confined extend. However, in extreme events, they may be decisive and should therefore be included in operational ship routing programs.

3. The Bellman Optimization Scheme

The gradient method to optimize a process is the best known and the easiest to program. However, as it looks for the minimum within a phase space by shifting the solution against a gradient, it might end up with only a relative minimum rather than with the absolute. There is no way for the gradient method to get an idea whether there could be a better solution in the direction of the local gradient. This also implies that the solution may depend on the choice of the first guess.

This clear disadvantage of the gradient method can be avoided by using the Bellman method (*Bellman* (1957)). In this method, not only the direction of the gradient is taken into account but also its magnitude and whether the gradient changes sign after a certain distance. The principle of the Bellman method in two dimensions is displayed in figure 2. It shows a schematic optimization over a 2-dimensional field of a cost function which is for simplicity static in time. The darker squares stand for high costs, the lighter for low costs. The harbour of departure is point 'A', the harbour of arrival is point 'B'. The white points in between depict the first guess route which is in this case the great circle as no land points are considered. The first step of the iteration (a) is to construct a search grid perpendicular to the first guess for the second point of the route. To keep things simple, a search grid of only five points is considered. Three points would be equivalent to the gradient method. Any odd number of search grid points greater than five will be better in terms of finding the absolute minimum of the cost integral within the region. The only limit is computation time. Each of the cost integrals along the paths from 'A' to any of the second search grid points is evaluated. In (b), all integrals between the search grid points of the second route point and the third route point are computed. However, from any of the third search grid points back to harbour 'A' only the cheapest alternative paths are memorized. The rest is discarded. Though there is a chance to inadvertently discard a path which would have been better for later steps of the iteration this limitation has to be introduced in order to comply with a computer's capabilities. As in step (b) optimal paths back to 'A' are computed for any of the following search grid points (step (c) to (e)). On reaching 'B'(step (f)) the decision which one of the remaining paths back to 'A' is the best is made. So far for the first iteration. Successive iteration will take the optimal outcome of the previous one as first guess and proceed as above. When no further improvement can be done i.e. when the result of an iteration is identical to its first guess then the distance between the search grid points is halved in order to account for details of finer resolution within the cost function.

Beside a greater demand for computer power (in comparison with the gradient method), there are some numerical disadvantages of the Bellman method. If there is a strong kink within the iteration's first guess, it may well happen that search grids of adjacent route points overlap. As a consequence, there can be loops within the calculated route. This does not make much sense for a route which is supposed to be optimal in terms of costs. In order to avoid such a detrimental effect, the resulting route must be checked for loops after each iteration. A smoothing procedure is used (similar to the one described in *Hoffschildt* (1997)) to unravel the loops before proceeding.

The advantage of the method which can take into account locations which lie beyond a maximum of the cost function may turn into a disadvantage when points of the search grid of two adjacent route points are too far from each other. Changes in the cost function between these points can not be detected and are therefore overlooked by the integration. To cope with this stretching of the route, points on an iterated route are redistributed with equal spacing when a certain maximal distance between two consecutive points is exceeded.

4. From weather data to operating costs

The ship's engines have to overcome four different kinds of resistance. Firstly, there is the simple viscous friction of water upon the hull of the ship. This friction is assumed to be weather independent, though it may depend on sea surface temperature since water viscosity may vary by a factor of 2 between the tropics and the arctic regions. Secondly, there is the resistance due to wind. This resistance is dependent on the strength and direction of the wind relative to the ship as well as on the vessel's superstructures. However, the contribution of the wind resistance is very small (as explained in the appendix). The largest contribution to the total resistance is due to wind waves for a container ship of a size for which the ship routing program is written. Swell which consists of waves of longer period also contributes to the total resistance. Apart from wave height and direction, wave resistance depends on the period of the waves. The difference between wind waves and swell is of spectral as well as of morphological nature. As swell is no longer under the influence of the forcing wind, it consists mainly of long sinusoidal waves which have propagated from far to the studied region. Wind waves are waves which have been recently created by the wind. Their period is shorter and they are sharp crested due to their interaction with the wind. The direction of their propagation is roughly that of the wind.

The four types of resistance are fed into a propulsion subroutine together with the ship's velocity. This propulsion routine models the ship's engine and outputs two crucial parameters: the propulsive power the ship's engine has to perform to overcome the total resistance and the related engine revolutions. These two parameters are translated into fuel consumption, grease consumption and engine damage by a penalty routine. As mentioned before, the costs of engine damage are fictitious costs which have only poor relation to real costs. They are not integrated along the distance between two route points and have the sole purpose of indicating that the route cannot be followed in its three dimensions (two in space one in time) by a real ship experiencing such weather. For an optimal route, no engine damage should be experienced. However, when a forecast route is verified against the analysed weather, it may well happen that adverse weather is encountered where favourable weather was forecast, and in order to maintain the ship's speed, the engine would have to perform beyond its limits. In reality the captain would slow down the ship and wait until the storm has passed. This would result in the ship's late arrival and additional harbour costs.

5. The Ship

The shape and size of a ship are important parameters for route optimization. It is evident that different optimization criteria apply for a rowing boat or for a container vessel! The current ship routing program takes the features of the container ship 'BONN EXPRESS' of the ship's owner Hapag Lloyd to define its propulsion routine. The ship's maximum speed is 22.8 knots which is about 11.7 m/s. A maximum power of about 24,800 kW can be achieved by the ship's engine. The container vessel is about 235m in length and 32m in breadth and its draught is about 12m. Its gross tonnage is 36Mt and the dead weight 46Mt (*Hapag-Lloyd* (1999)).

6. Geography

In this paper, the potential of ship routing is investigated for the link between Brest (France) and New York (USA). The departure point is actually shifted slightly to the northeast for historical reasons corresponding to a ship departure out of the English Channel. During the winter season of 1998/1999, the ship leaves the port of Brest at noon (GMT) and is supposed to arrive in New York harbour 6 1/2 days later. The ship routing software was run for the period of the of December 1st 1998 until March 31st 1999, for a total of 121 days.

The grid on which the weather parameters are presented to the optimization system is a x1.5° regular grid. This corresponds to the resolution of ensemble wave fields. For the deterministic forecast, the fields were interpolated from the 0.5° irregular lat-lon grid (*Bidlot and Holt* 1999).

Likewise, the land/sea mask is represented on a 1.5°x1.5° regular grid. There is no separate finer land/sea mask included in the ship routing program. For plots, this can look odd when the land/sea resolution of the plotting program is better than the program's land/sea resolution. Some ship routes end up cutting through coastal land features. However, as this feature does not jeopardize any real ship, there is no point in wasting computation time on a finer land/sea mask. The same is true for ice points. These are identified by checking on zero swell (even when there are no waves due to a calm there is always some swell present. For sea ice points, swell was explicitly set to zero by the wave model using the corresponding sea surface temperature field at the start of the forecast). This leads to another important issue which should be included in an operational ship routing program that of icebergs. However, in this program which can only be used for research purposes at this stage, warning for icebergs is not included. This might lead to quite severe discrepancies to real ship routes in winter.

7. Search Grid Features

The choice of the search grid structure on which the optimization is done highly depends on the resolution of the meteorological grid involved. For a 1.5° grid, a 1° search grid seems to be sufficient. However, from experience, a perfect match with weather patterns can only be achieved by using a finer resolution. To account for that, and in order to keep computation costs as low as possible, the iterations of the optimization are first performed on a 1° search grid and when no further improvement can be made at that scale, the distance between search grid points is halved and the optimization routine reiterates. Refining the search grid is done four times until a final resolution of 0.0625° at which stage, no further improvement is expected. This strategy applies for the spatial grid. For the time grid, no static initial resolution can be given because one has to make sure that the ship is not able to go back in time due to an overlap of time search grids of two adjacent route points. Nevertheless, the maximal possible grid width is also halved four times. The number of spatial search grid points is nine for each route point. An initial width of the search corridor of 9° was the best compromise between good optimization results and lowest computational costs. For the time search grid, it is sufficient to only use three points (basically the gradient method). As the time separation of consecutive route points is about three hours while the forecast step is twelve hours, a finer resolution would not make much sense here, neither does an overlapping of time search grid points of two adjacent route points.

8. The First Guess

Although the Bellman method is supposed to be first guess independent, one should choose a first guess which appears to be reasonable as it may influence the speed of convergence of the iterations quite severely. For a start, a good choice is certainly the great circle as it is the shortest distance between two points on a sphere. To comply with the resolution of the search grid, an initial distance of 1° between route points is chosen so that the great circle is discretized by 49 route points. To make sure that there are no land points along the route, a preliminary simplified optimization is performed. Switching off all influences by weather, the only constraints which still act on the ship are the water friction, the presence of land and sea ice. The optimization then yields the shortest possible route circumventing land and ice points.

An example of the constructed shortest navigable route and the encompassing spatial search grid are shown in figure 3. It turned out that for the chosen resolution of the weather grid, an initial search grid of this kind performs best in terms of good optimization and computation time.

9. Some different ship routes

As this paper deals with the subject of how ship routing can benefit from ensemble forecasts, routes obtained by means of ensembles have to be compared with other forecast ship routes, as well as scored against a ship route which would have been optimal for the corresponding analysis sequence.

9.1 The analysis

The analysis is assumed to give the truth. On the one hand, plots of the optimized ship route on analysis fields yield a qualitative comparison by looking at the spatial deviations with the forecast ship routes. On the other hand, the analysis is taken to verify a forecast route by running the forecast route on the analysis weather without any change to the forecast routes. On days of severe weather, a forecast route can deviate substantially from its referring analysis route leading to engine damage within the ship route. In reality, the captain would slow down the ship to keep the ship speed within the engine's limits. In this paper however, a clear indication of how reliable the forecast ship route would have been is preferred and therefore any changes in space nor time during the forecast ship route's verification are precluded.

9.2 The deterministic forecast

When considering the benefits of ensemble forecasts for ship routing, the target is to find routes based on ensemble forecast results which outscore the routes optimized by using the traditional deterministic forecasts. Therefore, the route obtained from the TL319 operational deterministic forecast of ECMWF will serve as a benchmark against which ensemble forecast means will be evaluated.

9.3 The ensemble run

The ensemble system consists of the unperturbed control forecast and the 50 perturbed ensemble members (*Molteni et al.* (1996)). Whereas the ship route based on the control forecast is verified separately over analysed conditions, the ensemble member ship routes are not. They will be processed further in order to yield a single ship route which can be used as an unambiguous recommendation.

9.4 The climatology

From the wind and wave fields of the reanalysis run by *Sterl et al.* (1998), a climatology for ship routes was produced. For each day of the winter period from December 1979 to March 1993, an optimal ship route was calculated. These were combined to yield a plot of probability density of ship routes over the north Atlantic. As can be seen in figure 4, the most likely route corresponds to the shortest navigable one. Therefore, the first guess used can be regarded as a good estimate of the climatological route. This first guess plays an important role within the scoring in this paper because climatology is normally what one would use without any forecast information. It should be mentioned that, based on experience, a ship's captain certainly knows routes which are perfectly safe for the intended journey and season. Therefore, a route using forecast information should be compared with routes obtained from experience. Coordinates of such routes are however not available, climatology will be taken instead.

9.5 Ensemble conversion

The performance of four methods to exploit ship routes optimized on ensemble forecasts was tested. The first is based on the verification of the 50 ensemble routes on any other ensemble member for which it was not optimized. For each route, the costs when running over all 50 ensemble weathers are averaged. These averaged costs of all 50 routes are compared and the route for which the averaged costs are minimal is taken to be the most likely one, however, there was no significant improvement in comparison to the deterministic or the control forecast. The idea is based on the notion that at least one of the ensemble members is at least very close to the analysis. Moreover it is assumed that the optimal route for this specific ensemble member performs best on average over all other members of the ensemble. The first assumption may well be true as ensemble members are supposed to represent the whole variety of possible weather situations. However, there is no point in assuming that the costs of the selected route are lowest for any other weather situation within the ensemble. To illustrate that, it is supposed that there is in fact a member which is identical to the analysis. Within the ensemble also assume that there are two clusters. One consists only of the analysis member, the other comprises all the other members. Any member out of the second cluster will perform quite well on any other member except the analysis member due to the similarity within the second cluster. The analysis member, however, as it is not a member of the second cluster will perform worse within the whole ensemble. Although this is a very crude example because it violates the notion of selecting which member is the most likely one, it may nevertheless underline the fact that all members of the ensemble are themselves equally likely, and the task of linking them is not so easy. Moreover it should be emphasized that the computational costs of this method were the highest. Apart from 50 runs of the ship routing optimization, 2450 verifying ship routing runs had to be performed for each single day.

Another method which assumes that there is a prominent route among all the 50 ensemble routes is based on the probability density distribution of the ship routes. From the distribution of ship routes over the Atlantic a probability density field is constructed by approximating each single route by a gaussian probability curve. These curves are then superimposed to yield a field of probability density that the ship crosses a certain location (see figure 5). The route of the ensemble which has the highest integral of the probability density along its track is determined to be the best estimate for the analysis. As for the previous method, this one didn't perform exceptionally well during the study period.

Also based on the spatial probability density distribution, is the artificial construction of the ship route. In other words, the route is not selected from any of the ensemble routes but is computed by means of the probability density distribution. It is quite straight forward to find the region where the spatial probability density of ship routes is highest (in fact this can also be done by the Bellman method). The location of the constructed route points is selected along this region of highest probability. The time assignments of the discretized route points must also be solved. For each discretized point of the constructed route, the relative ratio between the distance covered from the harbour of departure to the point in question and the total length of route is computed. Then the location with the same relative ratio is determined along each ensemble route while maintaining the actual ship's velocity along the route. The corresponding times for all ensemble route points are averaged and assigned to the relevant point of the constructed route. The performance of this method was no worse than any other method or forecast mentioned before, but not impressive either.

The idea for the method which performed significantly better than the deterministic or the control forecast relies on a simple mean of the three-dimensional positions of the 50 ensemble ship routes. The averaging is done on the basis of the shift of route points to distance ratio covered from the harbour of departure to the route point, as described above. Although this method has the potential to fail for certain weather situations as we will be discussed later, it provides a major improvement over the deterministic and the control forecast.

10. Prominent weather situations

The success of a optimized ship route depends highly on the type of weather situation the ship is likely to experience (as verified against analysis weather). This can be roughly assessed in some cases by looking at the distribution of the different ship routes. Four extreme cases are presented for which one could immediately say whether a given method will succeed without even knowing the analysis. In the following figures 6 to 9, the grey lines mark the optimal routes of the 50 ensemble members ('Ens.'), the climatological route ('First Guess') is red, the analysis ('Analysis') green and the operational forecast ('Det. fc.') blue. The route of the ensemble control forecast ('Control') is drawn in yellow and the route of the ensemble route's mean ('mean') is outlined in turquoise.

The first case is of very calm weather (figure 6). All the optimized ship routes drawn in the plot keep very close to each other. There is virtually no spread in the ensemble and deviations from the climatology route are hardly visible. Although all ship routes succeed, ship routing is not worth the money spent because the climatology route would have been sufficient. (Notice that the routes cut through Newfoundland due to the difference of resolution between the land/sea mask of the ship routing program and the plotting application).

The second case (figure 7) is similar to the first in the way that all routes stay close together. No matter what forecast or method is used for an optimal ship route, all perform equally well. The big difference to the previous case is that the deviation from the climatological route for any of the routes is quite pronounced. In fact, while none of the routes have engine damage and the actual costs are relatively low, the climatology implies quite severe engine damage. In this case, ship routing is a safe business and savings in costs above 10% can be achieved.

If the pattern of ship routes looks like the one in figure 8, the best recommendation is not to leave the harbour. The fact that there is a large spread in the ensemble routes indicates that the forecast weather is very uncertain. Accordingly, none of the forecast routes have the potential to represent a safe journey, and the amount of engine damage is quite large when any of the relevant forecast routes is verified over the analysed weather.

The example depicted in figure 9 is a very clear case of a bifurcation. Adverse weather in the middle of the relevant area causes most of the ensemble routes to deviate to the north including the control forecast, whereas some others opt to go south. It turns out that the analysis prefers the southern option as does the deterministic forecast. Thus the deterministic forecast performs best on that day whereas the control forecast gets a few points of engine damage. The bifurcation around the axis of the climatology with approximately half of the ensemble member routes going to the north and half of them going to the south causes the mean route to be quite close to the climatology. When verified over the analysis weather it is evident that the mean route runs right through the storm, and hence causes this method (together with the climatology) to perform worst. (However there are two ensemble member routes which do the same so that according to the ensemble forecast the probability for that option is not zero.)

11. Performance of the forecast methods

Fuel consumption is the most important parameter when assessing ship routing. It readily displays what a ship's owner can save by using ship routing instead of a climatological route. Table 1 was computed for all ship routing forecast methods when none of them had engine damage. It corresponds to quite favourable weather so that the deviations from the climatological route were not very large. To compare fuel- or grease consumption of the different methods, it is necessary to filter out engine damage cases where unrealistic power and revolutions of the ship's engine are encountered which yield odd figures of consumption. Therefore only 56 days out of 121 could be used. As a result, days where potentially the biggest improvements could be made (like in figure 7) are not considered. Nevertheless, for the cases considered with favourable weather, the plot already shows that there are some savings to be made. Whereas for the climatological routes, over 2.5% more fuel has to be spent than for optimized routes over the referring analysed weather conditions, only half a percent more has to be added when optimized by the method computed from ensemble forecasts. The standard deviation is around 0.11 in each case. Therefore the mean method is well within the range of the control forecast which is also within the range of the deterministic forecast.

The plot for grease consumption (table 1) is very similar to the plot for fuel consumption. This is nothing special because these two parameters are closely related. As for fuel consumption, climatology performs worst whereas the mean method is best. The error range is of the same nature as those for fuel consumption.

Table 2 shows whether a route that is forecast by a certain method is reliable in terms of being manageable over analysed weather conditions without experiencing unrealistic values of the two crucial engine parameters, power and revolutions. When engine damage occurs, the actual costs are no longer computable by static ship routing calculation but are highly dependent on how the captain will react when confronted with the situation. He might just decide to slow down the ship and wait until the adverse weather is over. In that case, the spatial positions of the ship might be maintained so that an evaluation can be done by simply recalculating the harbour costs. Or he might ignore the ship routing forecast as a whole before leaving when failure of ship routing is to be expected and take a route which is based on his experience. Therefore, it is evident that costs of ship routes with engine damage over analysed weather conditions are hard to be assessed and the figure of engine damage makes sense in a statistical evaluation of forecast ship routes. The less a forecast method for ship routes fails (in terms of engine damage) the more reliable it is and the more it should be preferred among others. Ensemble forecasts based on the mean of the ensemble members suffer engine damage in about 16% of all observed days. This is a big achievement when compared to the climatological route where engine damage occurs in more than half of all days. The deterministic forecast with 18% and the ensemble control with 16.5% have in this respect a similar quality than the ensemble forecast method.

The previous figures have shown that there are some advantages to using a route based on a forecast instead of using the climatological route. Among those routes, the mean method inferred from the ensemble forecast seemed to score best. However, the difference to the other forecasts could not be regarded as outstanding. Table 3 is more convincing on the benefit of the ensemble method. It is based on all days where at least one of the forecast routes had no engine damage. This was true 108 days out of the 121 days e.g. 89% of the time. All days a certain forecast method performs best (no matter what the difference to the second best method on that day is) are counted together and expressed in a percentage figure relating them to all 121 days. In this perspective the advantage of the ensemble related method to the other forecasts is clearly visible. The ensemble route mean method performs best in 52% of all cases. This is significantly better than the control with 17% and the deterministic (20%) forecast. The climatology never performs best. In the remaining 11% the weather was so uncertain over the Atlantic that proper ship routing was not possible.

The main issue of ship routing is the total cost. It seems clear that the ensemble method offers some advantages to the other forecast methods. But is it also the safest? To answer this question let us look at days where one of the methods had engine damage whereas the other methods had none. Table 4 shows what happened when the deterministic forecast had engine damage. In nine days during the 121 day period, the deterministic forecast failed against the ensemble control forecast in this respect. For the ensemble method this is slightly better with only seven days. However, there is also one day where it would have been better not to trust the deterministic forecast but rather to take the climatology. For the ensemble control forecast these figures are slightly better (table 4, 2nd row) with seven days when the deterministic forecast has no engine damage in contrast to the control forecast, 6 days when the ensemble method is better and again one day where climatology is better. Table 4 (3rd row) indicates that also for best security, it is advisable to use the ensemble forecast method. On only five days did the mean method incur engine damage when the control forecast succeeded and for the deterministic forecast there are only four days. There is no case where climatology was better. Running ship routing for statistical significant number of days would give more evidence on the issue. However, the current results can at least be regarded as an indication of the potential value of ensemble forecast for ship routing.

There is another issue where ship routes based on ensemble weather prediction could be useful. When great effort and money was spent on computing ship routes, one might want to be sure that all this was not in vain or even counterproductive. This, however, would be the case if it turned out that the computed 'optimal' ship route would be worse on analysed weather conditions than the climatological route. Table 5 shows that there were two of such days within the period for the control and the deterministic forecast. None of those cases were detected within the period for the ensemble based method. Although the chosen winter period is far too small to get definitive evidence, it may nevertheless be an indication of the potential of ensemble forecasts. (In this respect a summer period would be of much more interesting because weather conditions are better and therefore the actual route closer to the climatological route).

12. Conclusion and Outlook

It has been shown that it is possible to get relevant information for ship routing from ensemble forecasts. The simulated crossing of a container ship from Brest (France) to New York (USA) was taken as a basis for this study. For a 121 day winter period, the ship routes based on the deterministic forecast and the ensemble control have been compared with the climatological route and a ship route computed from ensemble ship routes. It was shown that although the ship route based on the ensemble has only slight advantages in fuel consumption in favourable weather situations compared with the deterministic and the control forecast, it is still the best choice on a day-to-day basis in more than half of all cases. This comprises fuel consumption as well as safety.

To get information out of the ensemble, four different methods have been investigated. Two of them depend on the probability density distribution of ensemble ship routes over the studied area, the third is a verification of all ensemble ship routes over all ensemble weathers and the fourth combines the space and time average from all ensemble ship routes into a single ship route. Although the fourth method is likely to fail in weather situations which cause strong bifurcations of the ensemble ship routes, it turned out that it is the best way to construct an ensemble based ship route. Moreover, cases with bifurcation can easily be filtered out and another method of ship routing computation can be chosen so that this feature of an ensemble route mean does not poses any major threat.

The ship routing described in this paper is a research project. It was set up to show whether and how ship routing can benefit from ensemble prediction of wind and waves. There are some prominent differences to operational ship routing. Concerning the ship routing program itself, the rotational motions of the ship and their effect on the ship and its cargo are not included. Although this is not of great importance for the statistical considerations in this paper, it can be lethal for a real ship in a specific situations. The forecast was not updated during the whole 156 hours of the crossing. This was useful in the ship routing project to enhance uncertainties of weather prediction. However, in today's operational ship routing business, with proper means of satellite communication, an update of the current optimal ship route is done regularly. The north Atlantic area was regarded to be free from any land a ship had to circumvent (apart from the eastern tip of Newfoundland). It is of further interest how ship routing could benefit from ensemble forecasts when there are obstacles which force a bifurcation of the ensemble ship routes more often than weather could do over the Atlantic (example: Hamburg to New York with the two possibilities of going around Scotland or through the English Channel). The suggested methods of computing a single optimal ship route from ensemble ship routes will need to be re-evaluated and others invented to deal with this new configuration.

Acknowledgements

For kind advice concerning the development of the ship routing program we would like to thank Susanne Lehner from DLR Oberpfaffenhofen, Germany and Thomas Bruns from Deutschen Seewetteramt Hamburg Germany. Thanks also to Anders Persson with whom we had lively discussions on how to obtain informations out of ensemble ship routes.

APPENDIX

The target in ship routing is to minimize the costs of running a ship from the harbour of departure to the harbour of arrival. Therefore an integral of the total costs has to be established:

$$J(\underline{x}, \underline{v}, t_D, t_A) = \int_{t_D}^{t_A} F_C(\underline{v}, par)dt + f_D(T_D, t_D) + f_A(T_A, t_A)$$

the cost integral is dependent on the time of departure t_D, the time of arrival t_A and the positions and velocities of the ship in between ($\underline{x}$, $\underline{v}$). Apart from the integral there are the cost terms for unpunctual departure f_D (for departure at t_D instead of T_D) and arrival f_A (for arrival at t_A instead of T_A). They are assumed to be equal and are approximated by a quadratic function:

$$f_D = f_A = \left(\frac{T_{A/D} - t_{A/D}}{\frac{3600}{\sqrt{1000}}}\right)^2$$

The cost function F_C inside the integral is dependent on the velocity of the ship $\underline{v}$ and the weather (*par*) the ship experiences during its voyage. F_C consists of several terms which contribute to the integral with different magnitude. First, there is the resistance due to friction upon the ship's hull. It is only a function of the ship's velocity relative to the water. The dependency is a quadratic function of the form:

$$res_h = a \cdot v^2 + b \cdot v + c$$

where $a = 8.5$, $b = 5.5$ and $c = 0.001$. The assumed draught of the ship is 12m. At maximum speed of 11.7 m/s the water friction resistance is about 1235kN.

The wind resistance is dependent on the wind speed, the wind direction, the ship's velocity and the course of the ship. From a table of discrete values, the appropriate number is obtained by cubic splines interpolation. Figure 10 shows a 3D plot of wind resistance for a motionless ship depending on the direction of the wind and its magnitude. The 90° tick indicates tailwind, and 270° corresponds to headwind. It is evident that tailwind drives the ship rather than slowing it down. Therefore negative values of resistance are experienced from 0° to 180°. The largest tailwind effect is experienced at 60° with -332kN when the wind speed is 30 m/s. The effect of headwind is largest at 248kN when a 30m/s wind is blowing from 252°. It seems clear that due to the structure of the ship the impact of headwind is less than tailwind

Figure 11 shows the resistance of wind waves with a mean period of 8 seconds which is typical for well established wind waves. There is only a slight effect of wind waves driving the ship of about 2.8kN when their direction is 72°. However the potential of wind waves slowing down the ship is far higher than that of pure wind. For a wave height of 15m and a direction of 260° the resistance is 2826kN. This means that the effect of wind waves upon the ship is more than ten times larger that the effect of wind. It has to be mentioned that the chosen maximum values of wind and wind waves are quite extreme and a captain should try to circumvent those situations. If this was not possible, the ship is slowed down to a near standstill to wait the passing of the storm. Therefore resistance is not of any interest in those situations. However, they serve well as a comparative example.

The impact of swell upon the resistance of the ship is quite similar to the resistance of wind waves. In figure 12, the swell resistance is shown depending on direction and height. 12 seconds is taken as a typical period for swell. The ability of swell hitting the stern to drive on the ship is virtually negligible (for a direction of 54° only 1.2kN drive the ship). The maximal resistance is 1471kN when swell comes from 270° (pure headswell). A maximal swell height of 15m is again assumed.

Recapitulating the above figures and numbers. Resistance is largest for wind waves. The impact of swell is only half as big. Resistance of pure friction of the water is of slightly smaller magnitude than that of swell, whereas resistance due to wind is lowest being less than a tenth of the potential wind wave resistance.

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Tables:

Table 1: Average additional fuel and grease consumption compared to analysis

	cf	fg	mean	opfc
fuel	0.74%	2.51%	0.54%	0.91%
grease	0.65%	2.42%	0.48%	0.85%

Table 1: In calm weather situations when all ship routes are free from engine damage, the additional percentage compared to the analysis route of fuel consumption (first row) averages out to 2.50% for the climatological route (fg). For the ensemble mean method only 0.54% more fuel has to be provided, 0.91% for the operational deterministic forecast (opfc), and 0.74% for the control forecast (cf). The standard deviation was each time of the order of 0.11%. Second row is the same as above but for grease consumption. Savings by the different methods are of similar percentage as for fuel.

Table 2: Percentage of routes with engine damage

cf	fg	mean	opfc
16.5%	52.1%	15.7%	18.2%

Table 2: When engine damage occurs, the two engine parameters power and revolutions fall out of the permitted range indicating a bad reliability and unsafe ship route. During the chosen period, the climatological ship route (fg) was unsafe in more than half of all days whereas the ensemble mean method performed best with only 16% of failure.

Table 3: Method of best performance

cf	fg	mean	opfc
17.4%	0%	52.1%	19.1%

Table 3: Taking all days where at least one method did not have any engine damage, the ensemble mean method performs best in more than half of the days with respect to the total costs. There is not a single day where the climatological route is best.

Table 4: Number of days when one method had engine damage whereas the others had none

engine damage in	cf	fg	mean	opfc
opfc	9	1	7	-
cf	-	1	6	7
mean	5	0	-	4

Table 4: The first row shows the number of days where it would have been advantageous in terms of occurrence of engine damage to take one of the other forecast routes rather than the route optimized for the deterministic forecast (opfc). Second row is for the control forecast (cf) and the third row for ensemble route mean.

Table 5: Number of days when a method performed worse than climatology

cf	mean	opfc
2	0	2

Table 5: During the chosen period one could be certain that applying the ensemble mean method leads to a better result in total costs than the climatological route. This was not the case for two days of the period for the deterministic forecast (opfc) and the control forecast (cf).

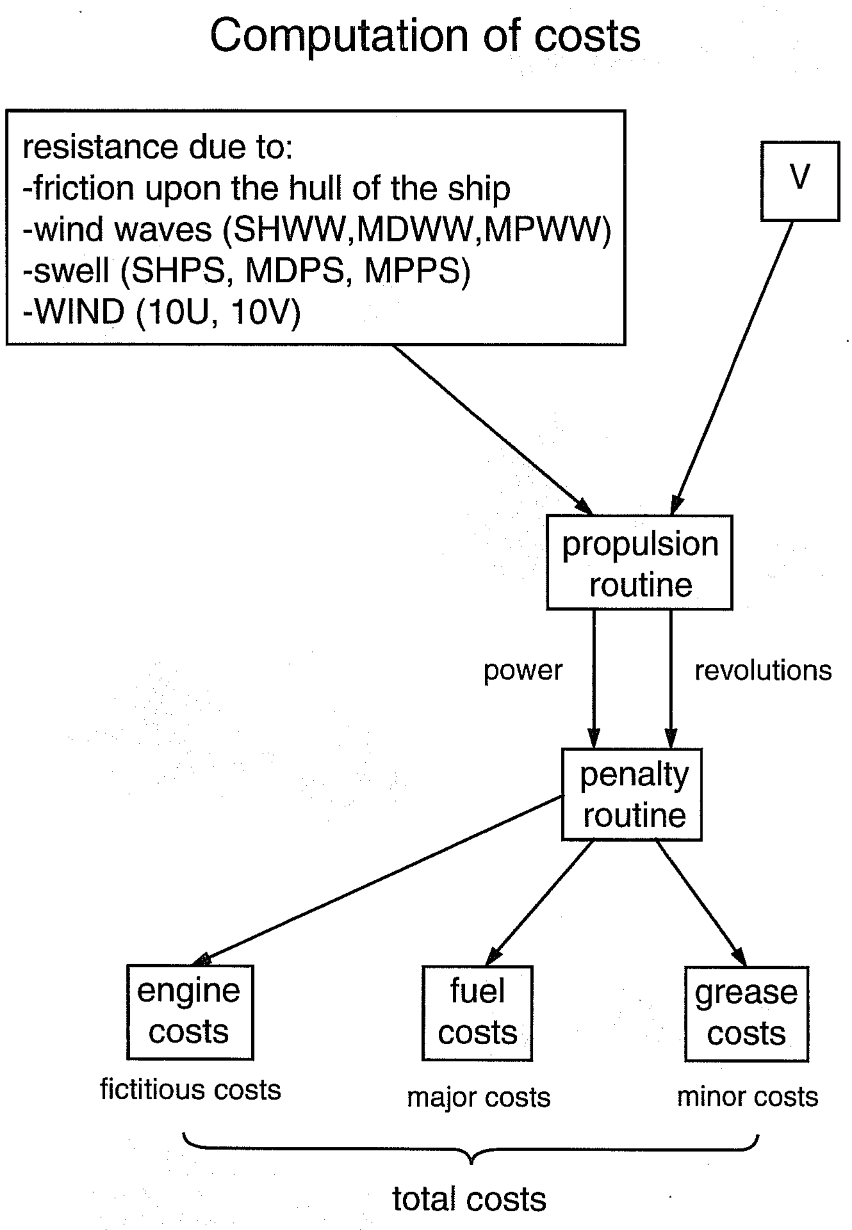

Fig. 1 From the input of the resistance due to water viscosity, wind, swell, wind waves and the ship's velocity (v), the propulsion costs are calculated. The power and revolutions of the ship's engine are used to discriminate cases where the total resistance leads to an overload of the engine.

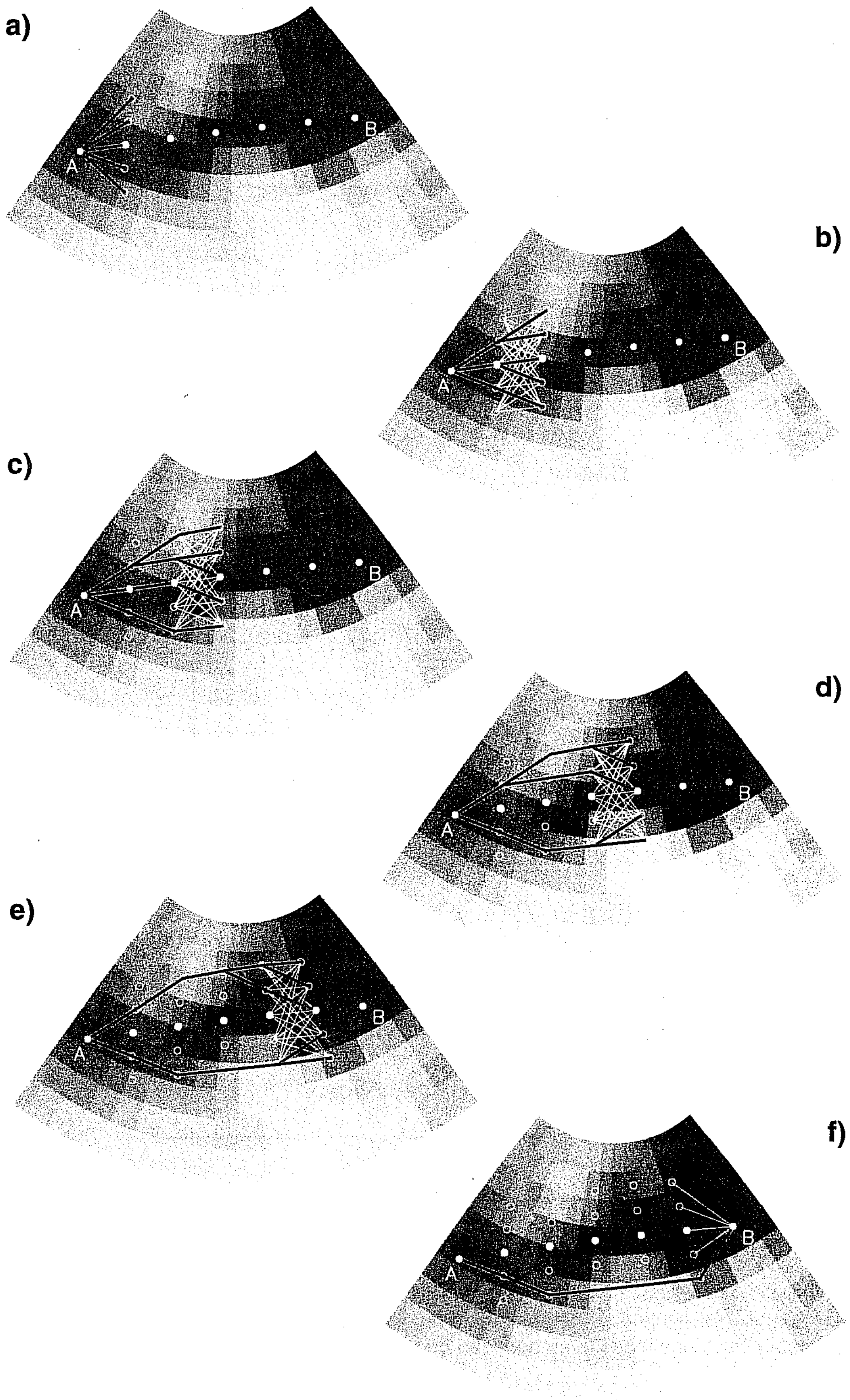

Fig. 2 Schematic principle of the Bellman method applied on the static field of a cost function (the darker the shading, the larger the cost function). Starting with a first guess (white dots), the algorithm finds the best alternative routes within a region confined by the extend of the search grid (all round dots) while progressing to the point of arrival. Upon arrival, the route with the lowest cost is kept. Unlike the gradient method, areas which are along the local gradient are also taken into account.

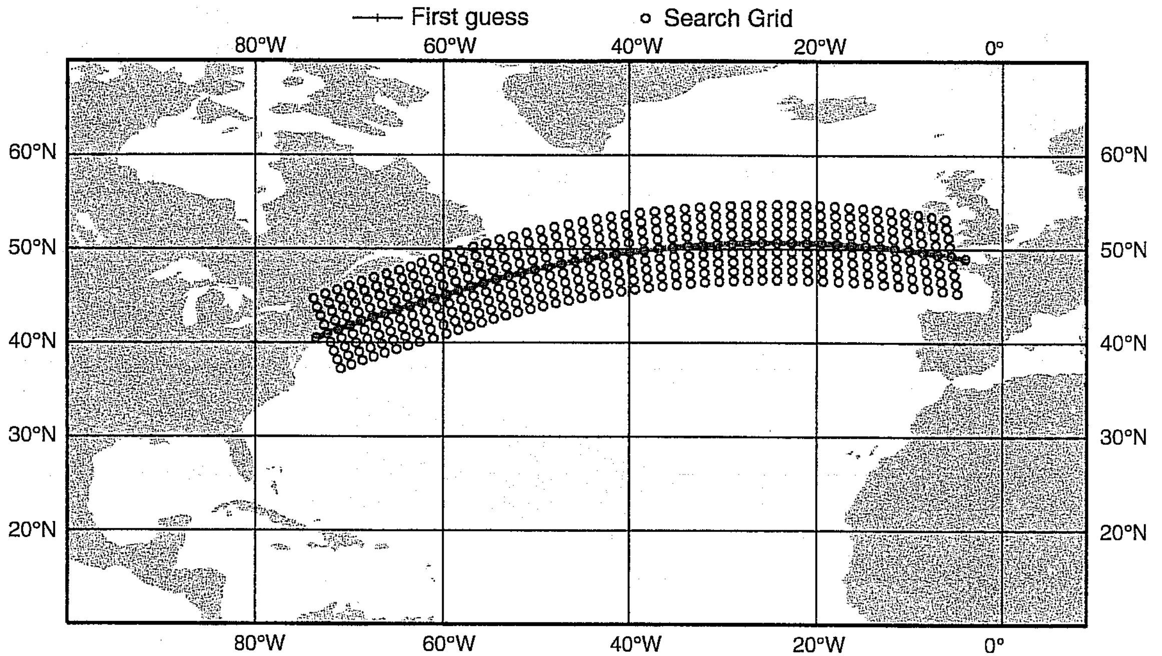

Fig. 3 The first guess for the Bellman method as used for the connection Brest to New York and its adjunctive spatial search grid (circles). Starting with a grid mesh length of 1°, a refinement is performed during the optimization.

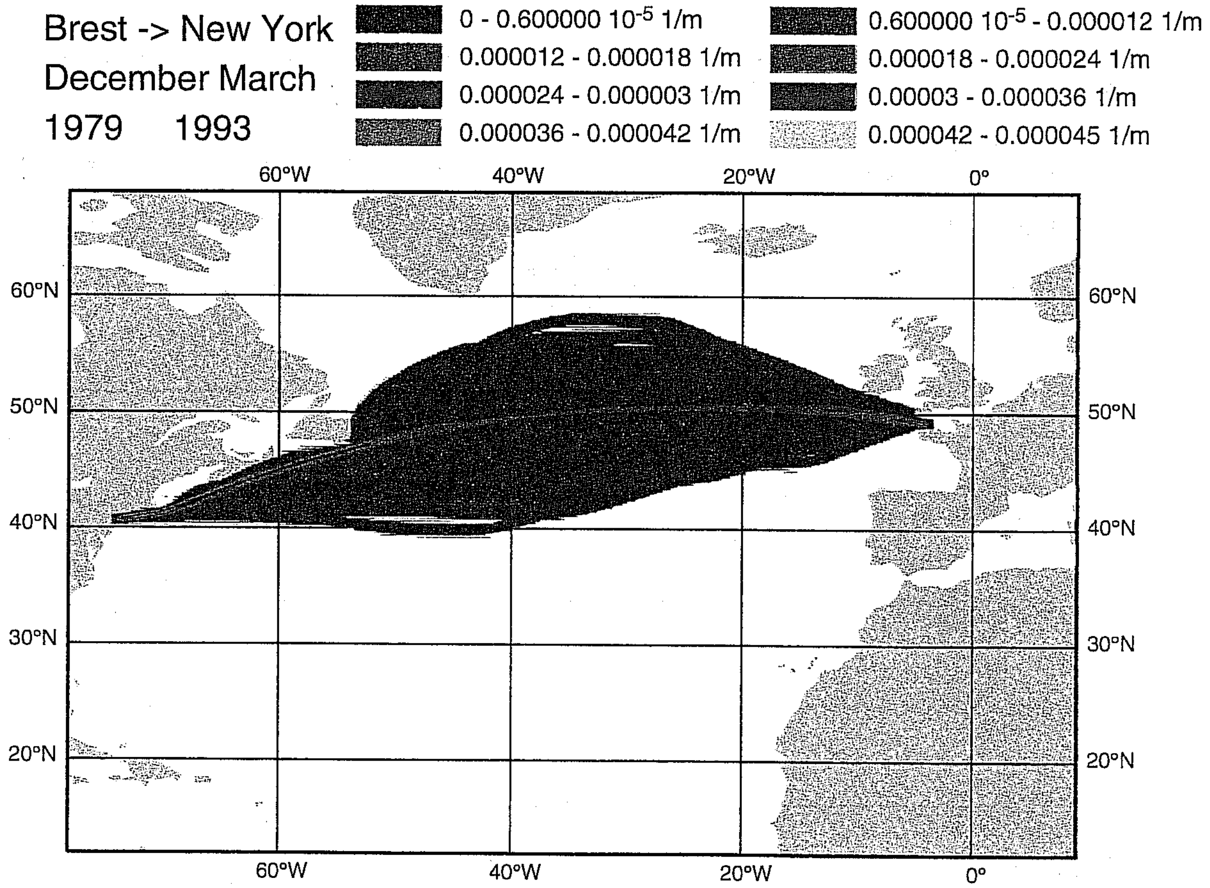

Fig. 4 Probability density of ship route climatology for the winters from 1979 to 1993 based on daily departure at 12Z from the English Channel and a 6 1/2 day journey to New York. The probability density was obtained by smoothing out the route density with a gaussian function on a 0.2°x0.2° grid. Weather and wave conditions were given by the ERA-15 reanalysis. It indicates that the climatological route, which is found by drawing a line through all local maxima, is very similar to the shortest navigable route.

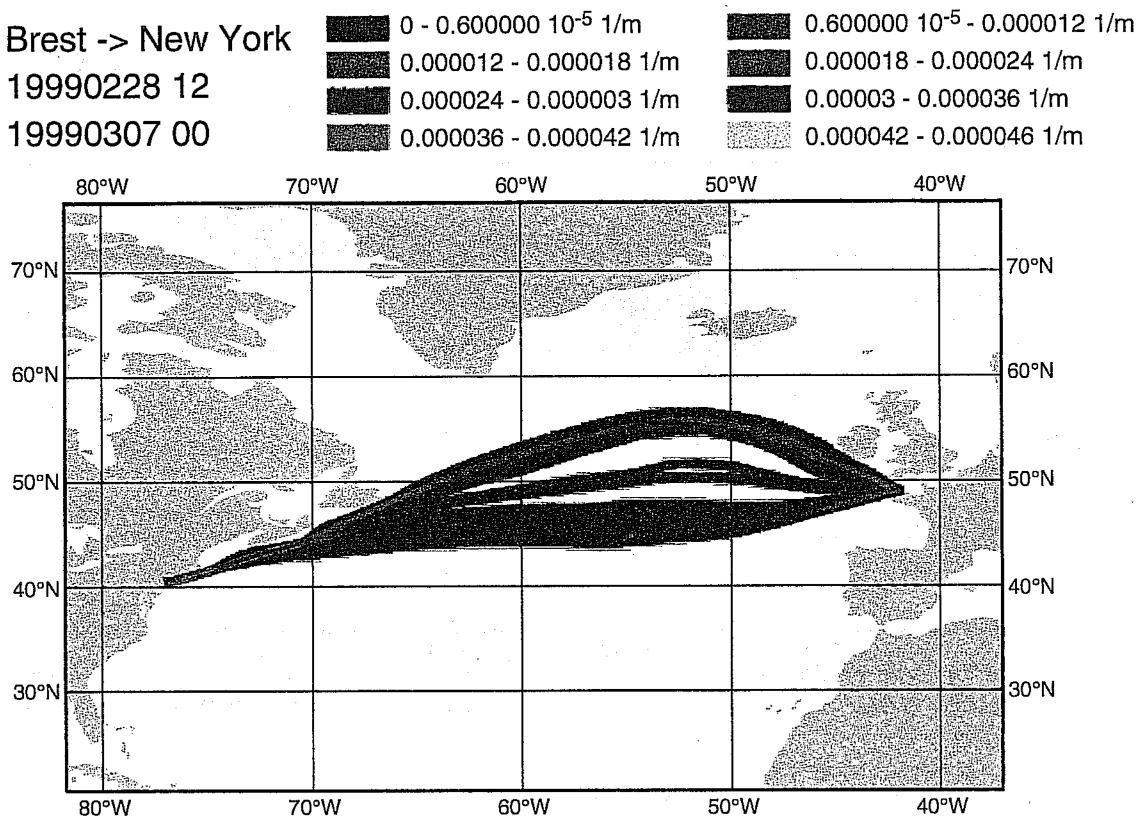

Fig. 5 A plot of the probability density of ensemble ship routes is used to determine a single ship route out of the 50 ensemble ship routes by using two different methods described in the text.

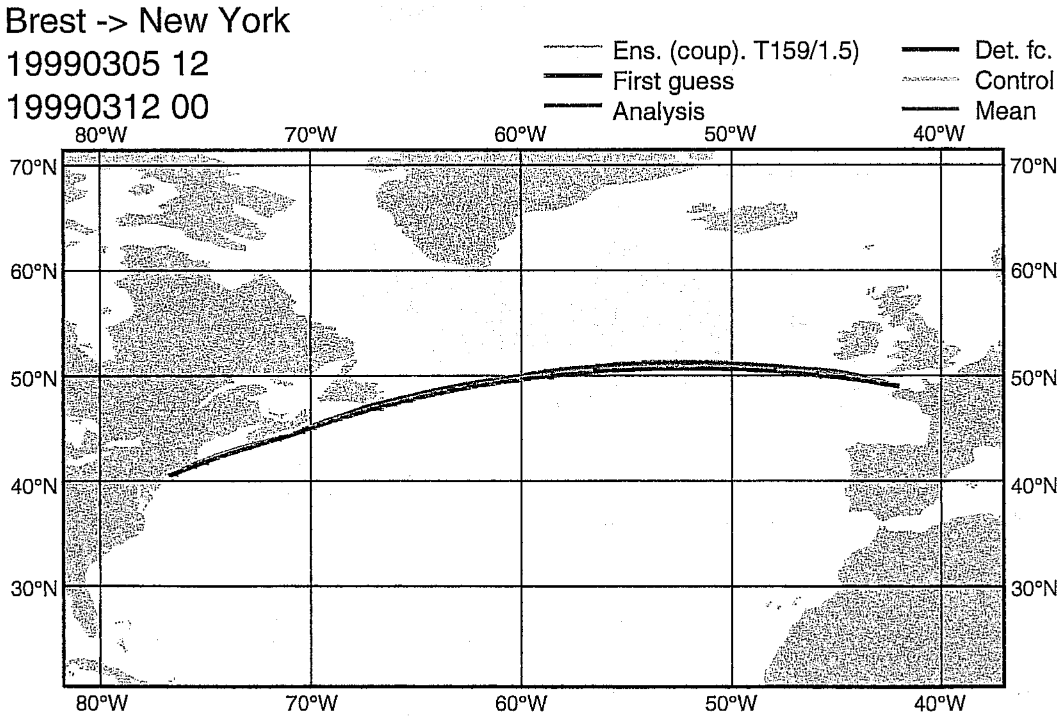

Fig. 6 Ship routes for the crossing leaving Brest on March 5th, 1999 12Z and arriving in New York on March 12th, 1999 0Z. The grey lines mark the optimal routes of the 50 ensemble members ('Ens.'), the climatological route ('First Guess') is red, the analysis ('Analysis') green and the operational forecast ('Det. fc.') blue. The route of the ensemble control forecast ('Control') is drawn in yellow and the route of the ensemble route's mean ('mean') is outlined in turquoise. In calm weather situations, ship routes obtained by different methods are nearly identical. No great savings in costs can be achieved by ship routing.

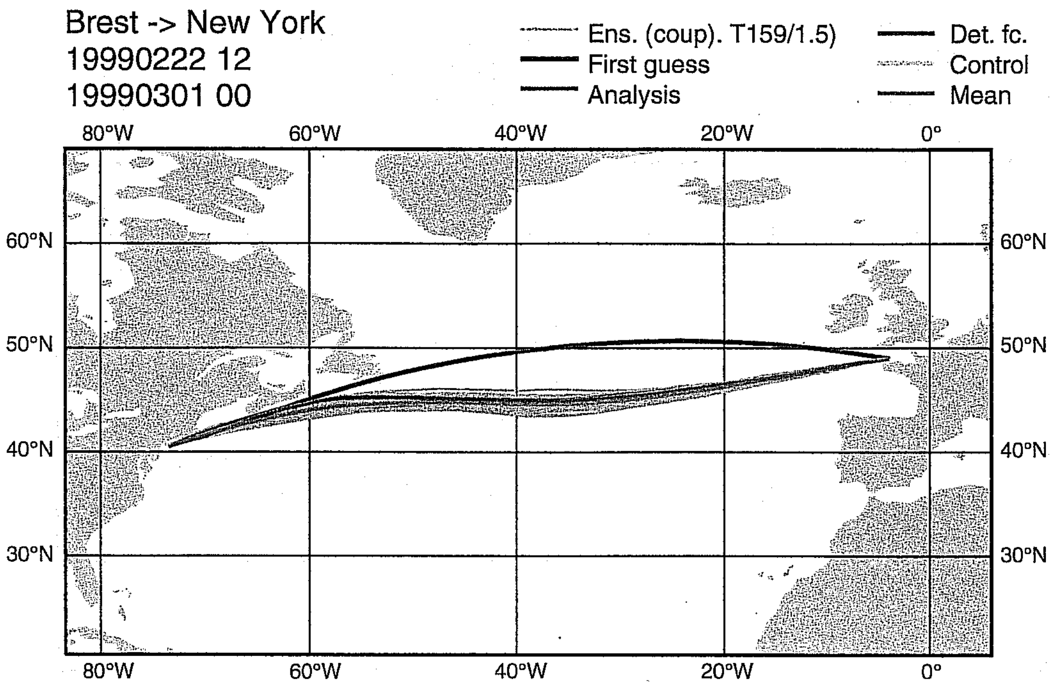

Fig. 7 Ship routes for the crossing leaving Brest on February 22nd, 1999 12Z and arriving in New York on March 1st, 1999 0Z. The grey lines mark the optimal routes of the 50 ensemble members ('Ens.'), the climatological route ('First Guess') is red, the analysis ('Analysis') green and the operational forecast ('Det. fc.') blue. The route of the ensemble control forecast ('Control') is drawn in yellow and the route of the ensemble route's mean ('mean') is outlined in turquoise. Good conditions for ship routing. Although deviations from the climatological route are large, the weather is very certain and efforts in ship routing yield good savings.

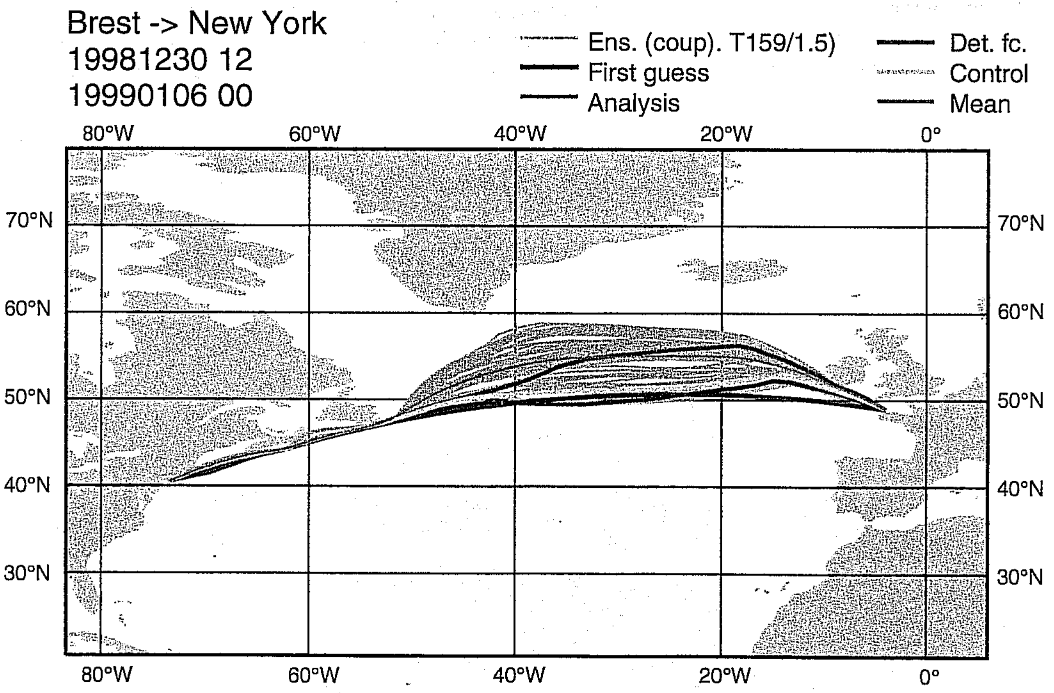

Fig. 8 Ship routes for the crossing leaving Brest on December 30th, 1998 12Z and arriving in New York on January 6tht, 1999 0Z. The grey lines mark the optimal routes of the 50 ensemble members ('Ens.'), the climatological route ('First Guess') is red, the analysis ('Analysis') green and the operational forecast ('Det. fc.') blue. The route of the ensemble control forecast ('Control') is drawn in yellow and the route of the ensemble route's mean ('mean') is outlined in turquoise. Bad conditions for a voyage. Due to a storm the ship is urged to deviate from the shortest navigable route. Furthermore the optimal route is very uncertain which is indicated by the large, homogeneous scatter of ship routes on the plot.

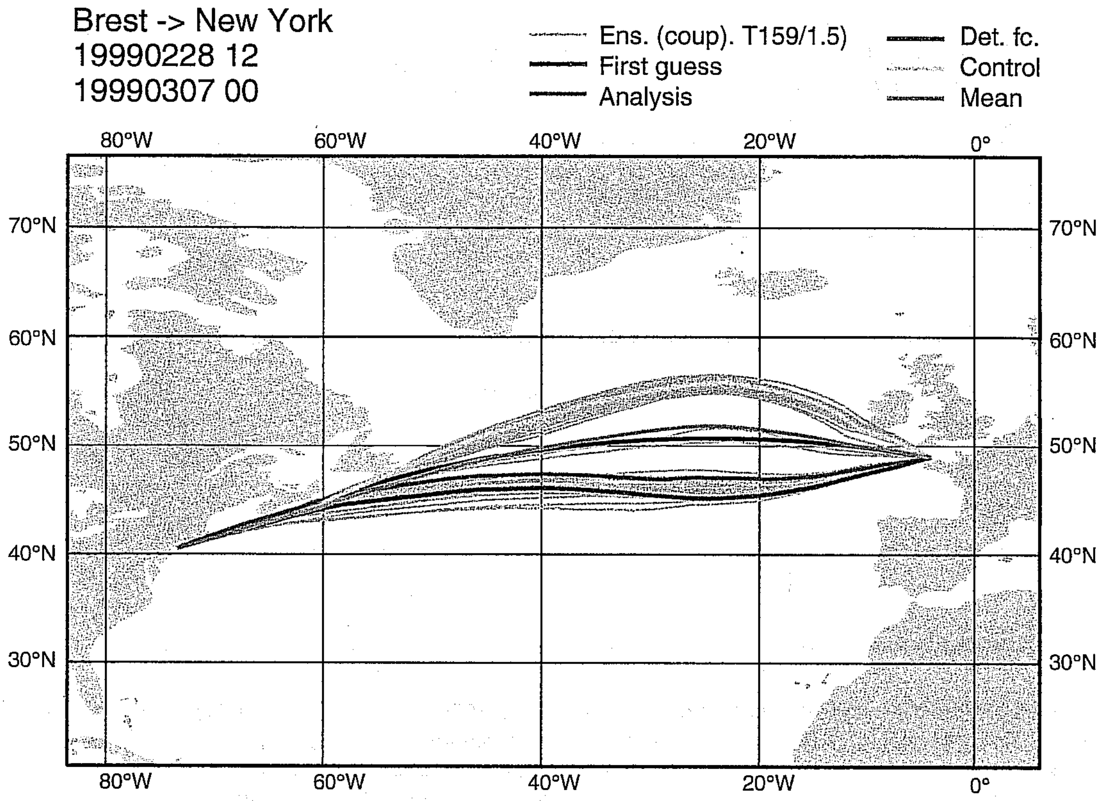

Fig. 9 Ship routes for the crossing leaving Brest on February 28th, 1999 12Z and arriving in New York on March 7th, 1999 0Z. The grey lines mark the optimal routes of the 50 ensemble members ('Ens.'), the climatological route ('First Guess') is red, the analysis ('Analysis') green and the operational forecast ('Det. fc.') blue. The route of the ensemble control forecast ('Control') is drawn in yellow and the route of the ensemble route's mean ('mean') is outlined in turquoise. Bifurcation. A storm centre is circumvented by routing either to the north or the south. The method which takes the spatial mean values of the ensemble ship routes is destined to fail in those situations.

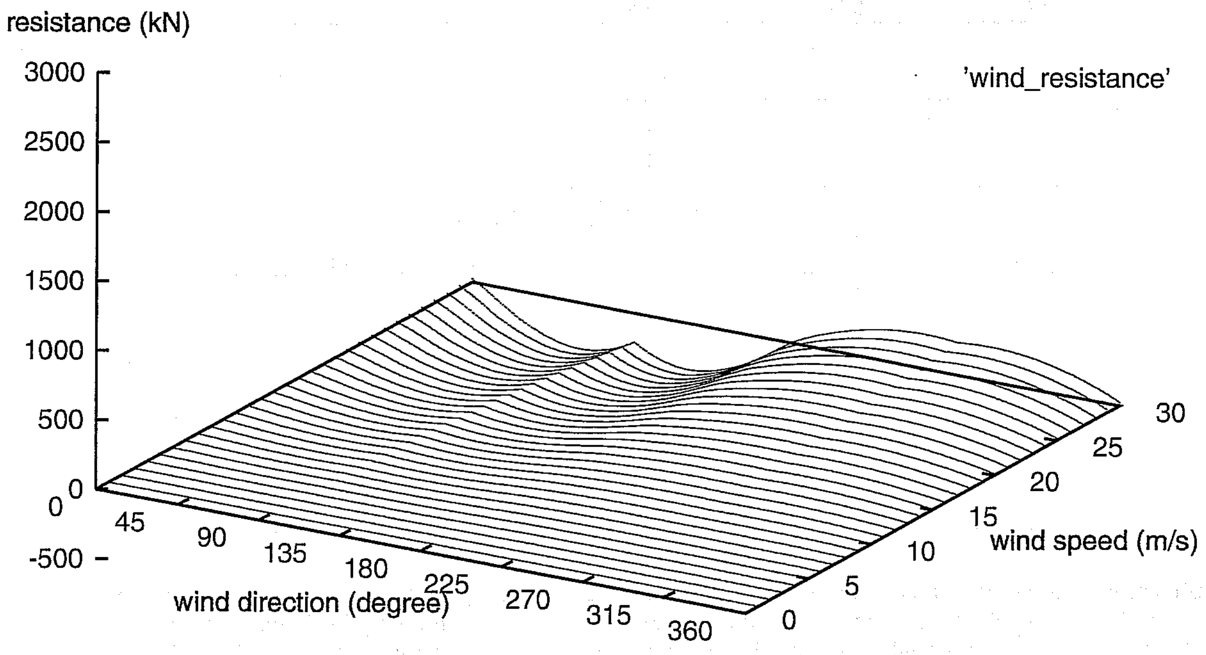

Fig. 10 Ship resistance to wind. The strength of wind resistance depends on direction (270° is headwind) and wind speed. The maximal effect is experienced when wind direction is slightly turned to the ship's orientation. For tailwind, there is a slight drive by the wind.

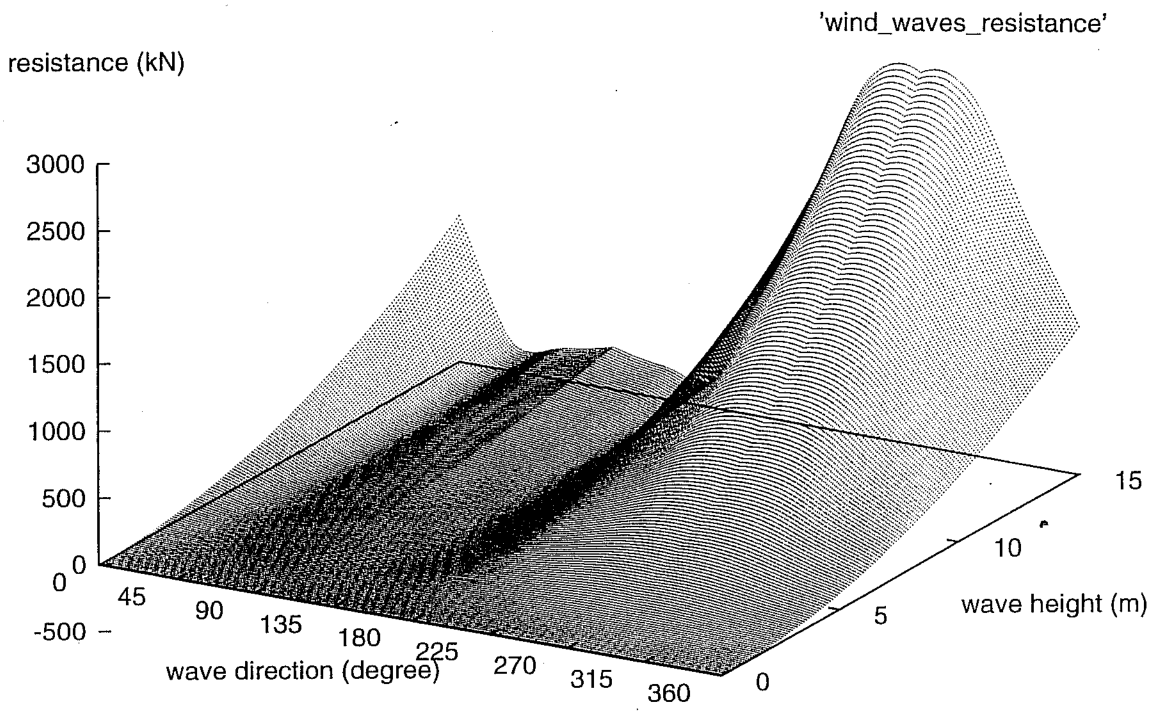

Fig. 11 Ship resistance to wind waves. The magnitude of the resistance due to wind waves with a mean period of eight seconds depends on wave direction and height. The potential of wind waves driving the ship when it is incident with the stern is negligible. The resistance due to wind waves hitting the bow is the predominant amongst the considered sources of resistance.

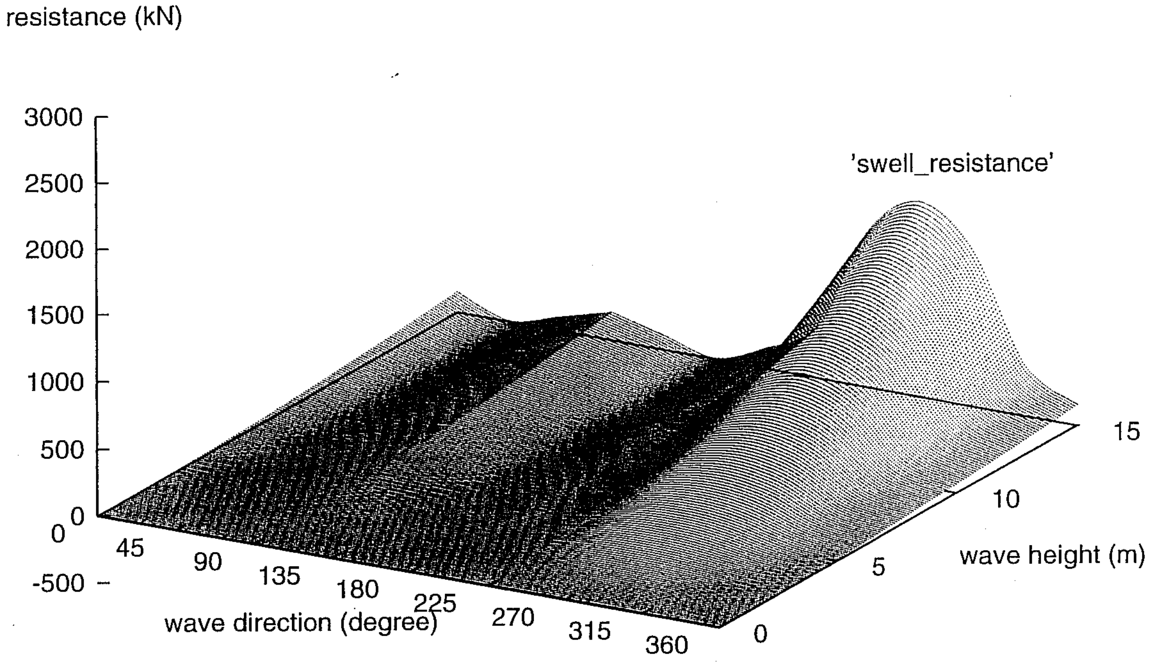

Fig. 12 Ship resistance to swell. The magnitude of resistance due to swell with a mean period of twelve seconds depends on wave direction and height. Unlike wind and wind waves, the resistance is maximal when swell hits directly the bow (270°). Its strength in 15m swell wave height is only half as big as for wind waves.