Beneficial Voyage Characteristics for Routing Through Dynamic Currents

MARK R. MCCORD AND YOUNG-KYUN LEE

Anticipating that near real-time estimates of ocean currents could feasibly be used to determine ship routes that would result in reduced fuel consumption, 360 voyages were simulated in the North Atlantic Gulf Stream region to investigate voyage characteristics leading to particularly high or low fuel savings. In the simulations, currents are the primary factor in determining the ship's course. Minimum fuel routes were determined for the currents, and the relative fuel savings of these routes were computed and compared to great circle routes. Ships that modified course slightly to take advantage of the positive effects of the currents had much larger savings than those that avoided the negative effects of contrary currents or went substantially out of the way to catch favorable flows. Determining where and how to cross the core flow was found to be more beneficial than trying to take advantage of the favorable or avoiding the unfavorable effects of rings that are shed from the core. The magnitude of the fuel savings, which often exceeded 10 percent in the study area, depended on the specific realizations of the dynamic current patterns when the voyages were conducted. Therefore, general rules balancing current-induced fuel consumption effects with weather- and wave-induced effects are probably not feasible, and explicit mathematical-based route analyses might be required to reap the benefits of ocean current routing.

Advances in remote sensing technology (*1*), developments in ocean current modeling and forecasting (*2–6*), and the present and planned satellite missions devoted to investigating oceanographic features (*7–9*) make near real-time estimates and forecasts of ocean currents possible (*7,8,10,11*). Using such information to alter strategic ship routes could help decrease voyage time and fuel consumption. In one simulation study, even the very aggregate (in time and space) ocean current data provided in the U.S. Defense Mapping Agency's pilot charts produced an estimated fuel savings of more than 1 percent on transoceanic U.S.-based routes (*12,13*). In other simulation studies, the finer spatial resolution available with advanced technologies produced fuel savings of 5 to more than 10 percent through parts of the Gulf Stream region (*14–16*).

The benefits of routing with ocean currents to minimize fuel consumption or travel time, which shall be referred to simply as "current routing," could complement the benefits of routing through the more traditional means of considering the effects of weather and waves (*17*). The combined environmental effects could conceivably be handled in a computer-based optimization algorithm (*18,19*). The authors' interaction with the commercial routing industry (*7,8*), however, indicates that the individual route analyst's experience is also influential in suggesting a route to the ship master. Analysts may need to update the routes of hundreds of ships dispersed throughout the world at the same time. Therefore, determining when a vessel would benefit by changing course to take advantage of favorable currents or avoid contrary ones would be of value. The current patterns used to determine suggested routes, whether the suggestion is based on a mathematical formulation or an expert router's opinion, are only estimates and subject to a variety of errors (*1,10,20,21*). Observing which vessels benefit most from changing course to take advantage of the currents could help determine whether the potential benefits outweigh the risks of chasing a current that might not be as strong or oriented in as favorable a direction as believed. Finally, knowing route characteristics that would result in large or small benefits could aid the design of simulation studies. These simulations could be used to determine routing benefits and the impacts of errors or sensing limitations of present estimation techniques (*10,20*). For example, the studies could be designed to sample routes more efficiently in various categories of interest instead of needlessly duplicating samples from the same category.

A simulation study was conducted to investigate voyage characteristics that would benefit from strategic current routing through strong dynamic current patterns. The effect on routing performance of the position of the origin and destination of the vessel relative to a portion of the North Atlantic Gulf Stream was examined. The Gulf Stream is typical of rapid Western boundary currents (*22,23*), such as the Kuroshio, the Agulhas, the Brazil, and the East Australian, where velocities can reach 4 knots. In addition to the currents core flow, these dynamic current systems can shed rings with elevated velocities moving in circular patterns. In the area of the Gulf Stream studied (Figure 1), the core flow of the current exhibits a serpentine pattern and sheds cold rings spinning counterclockwise to the warmer water to the south and warm rings spinning clockwise to the colder water to the north. The current routing problem (*14*), then, is deciding which path to follow so that the vessel rides with favorable currents and avoids contrary currents in the core flow or in the rings, thereby conserving fuel and decreasing travel time.

The results indicate that the advantages are greater when ships try to ride favorable currents than avoid contrary ones. They also show that the greatest benefits come from fine-tuning routes along the core flow. Ships that had to cut across the core flow show fewer benefits from current routing, but greater benefits than ships that primarily try to catch rings in the right location. The dynamics of the current pattern were also found to be significant in that some dates are better than others. The results pertaining to the locations appear general; that is, there appears to be enough causal relationship in them that they should give a good indication of the degree to which voyages would benefit from current routing relative to each other.

The results show that the magnitude of current savings cannot be predicted as a function of route characteristics. The results also show that the greatest benefits appear to come from fine-tuning routes or precisely determining when and where to cut across the current structure. Together, these results suggest that a mathematical analy-

---

M. R. McCord, Civil Engineering Department, The Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, Ohio 43210. Y.-K. Lee, Civil and Environmental Engineering Department, Florida International University, University Park Campus, Vh 160, Miami, Fla. 33199.

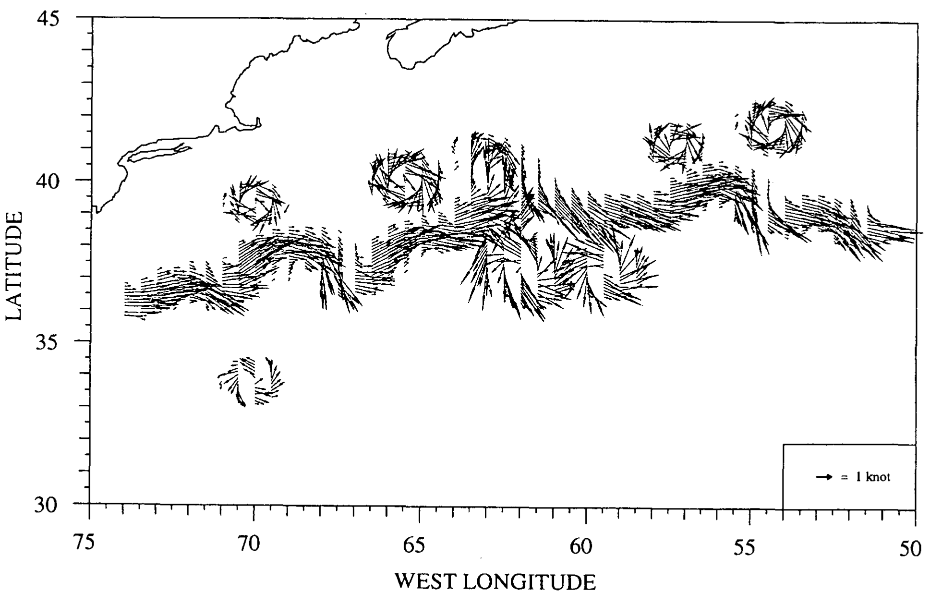

FIGURE 1 Pattern of currents in study region on 5/21/88 based on output of Harvard Gulf Stream model.

sis is needed to estimate the magnitude of fuel savings which would result from routing a vessel through a specific current pattern.

METHODOLOGY

The simulation study consisted of (*a*) choosing the location of the origin and destination of a ship's voyage near a current pattern; (*b*) categorizing this voyage according to the location of its origin and destination with respect to the current pattern; (*c*) determining the path from the origin to the destination that would minimize fuel consumption; (*d*) evaluating the performance of the voyage along this minimum fuel consumption route and using this performance measure as a realization of the performance of voyages in the category; and (*e*) repeating for different origin-destination locations, and different current patterns. (The following section covers these steps in more detail.)

The data consisted of a set of daily estimates of speeds and directions of surface currents in the North Atlantic Gulf Stream region in an area bounded by (north) latitude and (west) longitude coordinates (39°, 74°), (32°, 72°), (38°, 50°), and (46°, 55°) (Figure 1). The current patterns were produced from a forecasting model developed by Harvard University and the U.S. Navy (*2–4,10*) and gridded into 15-km by 15-km cells (one current vector per grid cell). The data was later aggregated into a 0.1°-latitude by 0.5°-longitude grid. Daily estimates from this model were obtained for each day in two 5-week periods, one in 1987 and one in 1988. Voyages beginning on 4 days (2 days in 1987 and two days in 1988) were considered. Voyages selected for the study began on 11/13/87, 11/28/87, 5/06/88, and 5/21/88. Approximately 2-week intervals were chosen between voyage "starting dates" in the same year to increase the independence of the current patterns used (*24*). The fine resolution of the data, the continuity produced by the daily estimates, and the advanced modeling and data acquisition techniques used to produce the estimates make this among the best ocean current data in existence for the types of simulations conducted in this study.

The locations of the origins and destinations were selected by considering five locations near the western boundary and nine locations near the eastern boundary. The five-integer degree latitudes between 34°N and 38°N along 73°W longitude were used as the western locations and the nine-integer degree latitudes between 36°N and 44°N along 53°W longitude were used as the eastern locations (Figure 2). The authors then considered as origin-destination (O-D) pairs the 90 combinations formed by using each of the nine eastern locations as destinations for origins consisting of the five western locations and each of the five western locations as destinations for origins consisting of the nine eastern locations. To study the 90 potential combinations on each of the four voyage starting dates, 360 voyages were simulated.

A western origin and eastern destination pair implies a route traveling primarily eastbound; this is called an eastbound (EB) route. Similarly, a route with an eastern origin and western destination is called a westbound (WB) route. Although these routes are denoted by a geographical direction, the important factor is that the EB routes can be thought of as progressing in the same direction as the primary current flow, and the WB routes can be thought of as progressing in the direction opposite the current flow. Therefore, EB routes primarily try to ride favorable currents and WB routes primarily try to avoid contrary currents. The circular flows of the rings make their effects less straightforward.

For a given starting date of a voyage, each of the 90 O-D pairs was categorized according to whether its origin was "Above," "In," or "Below" the Gulf Stream core flow on the starting date, and whether its destination was "Above," "In," or "Below" the core flow on the starting date. In this way, each of the 90 O-D pairs was placed into one of 18 categories, AA_{EB}, AI_{EB}, AB_{EB}, IA_{EB}, . . . , BA_{WB}, BI_{WB}, BB_{WB}. The first letter denotes the origin location on the starting date, the second letter denotes the destination location on the starting date, and the subscript denotes whether the route was EB or WB. For example, IB_{WB} denotes that the route was a westbound route with origin In and destination Below the core flow of the Gulf Stream on the date the voyage started. The number of voy-

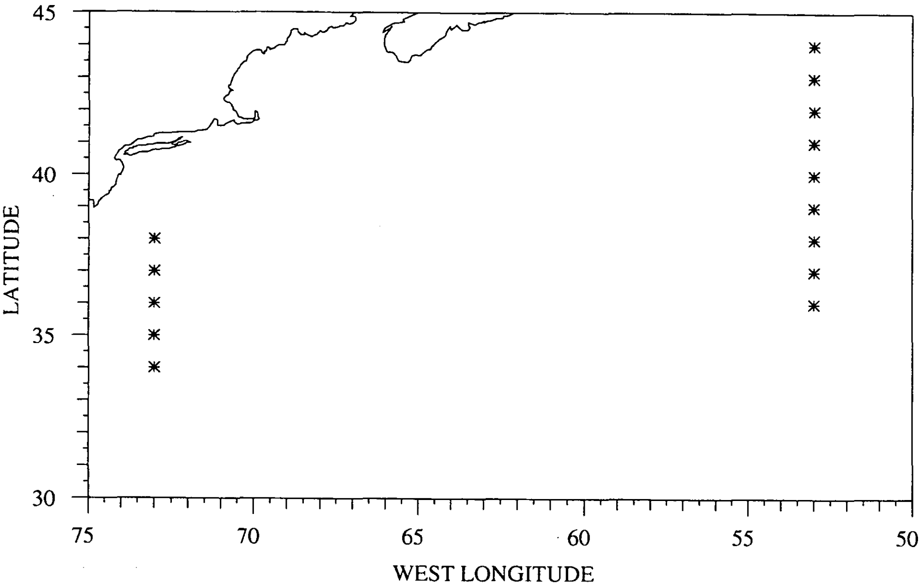

FIGURE 2 Locations of points serving as origins and destinations for simulation study.

ages in each of the 18 categories on each of the starting dates is shown in Table 1. In the In-Below cell, the numbers mean that there were 8, 8, 6, and 6 (4, 4, 4, and 4) EB (WB) voyages with origin In and destination Below the Gulf Stream on 11/13/87, 11/28/87, 5/06/88, and 5/21/88, respectively. The number of voyages can change with the starting date because the core flow is dynamic and changes location in time.

To determine the minimum fuel consumption path between the O-D pair on a particular starting date, a dynamic programming algorithm was used (*10,14,15*). The algorithm determines the minimum time route between the origin and destination through the currents that would be present when a ship traveling at constant velocity (pool velocity V_p) arrived at that location. For example, on the second day of the voyage, the current patterns considered in the optimization algorithm would be different from those on the first day of the voyage. Although the minimum time path is not guaranteed to be the minimum fuel consumption path, the two are practically identical for the types of routes considered in this study (*14,15*).

The variable relative fuel savings (*RFS*) (*12–16*) was used to represent performance of the minimum fuel route. Specifically, (*a*) a voyage time T between the origin and the destination in the study area was determined by routing a vessel at a constant speed V_p along a base route between the study area origin and destination; (*b*) the reduced constant speed through the water V^*, $V^* < V_p$, that would result in a voyage time T along the minimum fuel route between the study area origin and destination was determined; and (*c*) the *RFS* of routing the vessel at V^* along the minimum fuel route through the study area (compared with routing the vessel at V_p along the base route in the study area) was determined. *RFS* is based on the assumption that the fuel consumed by a ship traveling at velocity v for a time t is approximately equal to $c*t*v^3$, where c is a ship constant (*25*). *RFS* is the fuel consumed along the base route minus the fuel consumed along the minimum fuel route, divided by the fuel consumed along the base route, multiplied by 100 percent (*12–16*). This can be shown as

$$RFS = [1-(V^*/V_p)^3]*100\% \qquad (1)$$

V_p = 16 knots was used to represent the class of ships most susceptible to benefits from current routing (*12,13*). Routing at constant speed through the water is consistent with industry practice. It also has proven to be approximately optimal in simulations of current routing (*12,14,15*). The great circle route was used as the base route for comparisons. Basing the comparisons on the great circle route makes sense because the great circle is the shortest distance and therefore is the route that would be followed if currents (and other environmental factors) were ignored (*10,12–16*). Fixing the base and minimum fuel routes to have constant voyage time T

TABLE 1 Number of Voyages in O-D Categories by Starting Date (Starting Date Order: 11/13/87, 11/28/87, 5/06/88, 5/21/88)

Origin	Direction of Voyage	Destination			Category Total
		Above	In	Below	
Above	EB	3,3,4,4	2,2,2,2	4,4,3,3	9,9,9,9
	WB	3,3,4,4	6,6,8,8	6,6,8,8	15,15,20,20
In	EB	6,6,8,8	4,4,4,4	8,8,6,6	18,18,18,18
	WB	2,2,2,2	4,4,4,4	4,4,4,4	10,10,10,10
Below	EB	6,6,8,8	4,4,4,4	8,8,6,6	18,18,18,18
	WB	4,4,3,3	8,8,6,6	8,8,6.6	20,20,15,15
Category Total:	EB	15,15,20,20	10,10,10,10	20,20,15,15	
	WB	9,9,9,9	18,18,18,18	18,18,18,18	

ensures that at the end of the analysis both routes would be at the same point at the same time and simplifies the analysis because the voyage time is eliminated in the math leading to Equation 1.

RESULTS

Table 2 shows the mean *RFS* values for each of the 18 categories and each of the four starting dates. The means are arranged in the order of starting dates. The numbers in the Above-Above category indicate that the average *RFSs* of the voyages whose origins were above and whose destinations were above the core Gulf Stream flow were 7.8, 6.4, 9.7, and 11.0 (3.0, 3.7, 3.6, and 2.6) percent on 11/13/87, 11/28/87, 5/06/88, and 5/21/88, respectively, for EB (WB) routes. The means are determined by averaging the *RFSs* of all the O-D pairs in a category on the specific date. In the Above-Above category in Table 1, the means average 3, 3, 4, and 4 (3, 3, 4, and 4) *RFS* values on 11/13/87, 11/28/87, 5/06/88, and 5/21/88, respectively, for EB (WB) routes.

The way in which the locations of the origins and destinations were determined may lead to some of the Above or Below locations being particularly better or worse than some of the other Above or Below locations on a given starting date because a location may be much closer to or farther from the core flow, or because a location may be particularly well or poorly located with respect to the warm or cold rings. Such a phenomenon could increase the variability of the *RFSs* within the categories. Investigating the effect of specific locations was beyond the scope of this study, however. Moreover, because the number of observations is small in any category and the *RFSs* depend on the common current pattern of the starting date, the authors were hesitant to perform any statistical analysis based on the variances of the categories.

To lessen the possible effect of particularly well or poorly situated locations on the category mean, then, the median *RFS* for each category for each starting date also was computed. Instead of presenting these in a table, the authors chose to present them more graphically in Figure 3. There are some differences in magnitudes between the means of Table 2 and the medians of Figure 3, and even some changes in the position of a category in a ranking from highest to lowest *RFS* value, depending on whether the ranking was according to the mean or median. The differences are slight, however. Both the mean and median were considered in drawing the conclusions in the next section.

In Table 3 the relative ranking of each category on each particular starting date is indicated by dividing the rankings into thirds (i.e., groups of six out of the 18 categories) for each date. Specifically, the number of times the particular category has an *RFS* in one of the top six or bottom six categories on the date is presented. For example, the numbers 3/0 (2/0) in the Above-Below EB category indicate that AB_{EB} ranked in the top and bottom six categories, respectively [3 and 0 out of four times (one for each starting date) when considering the ranking according to the mean, and 2 and 0 out of four times when considering the ranking according to the median].

DISCUSSION

Tables 2 and 3 and Figure 3 show that the effects of current routing depend on the O-D category and the starting date. Given that the latitudes and longitudes of the O-D pairs were the same on different dates, the differences in the fuel savings statistics of the different starting dates must be due to different current patterns (directions, widths, and velocities of the core flow and rings). The implication is that some mathematical analysis, such as the dynamic programming-based algorithms that were used, is required to predict the magnitude of the fuel savings for a given voyage and a given current pattern.

Comparing fuel savings of the O-D categories on a particular date indicates some general characteristics, however. The mean *RFSs* in an O-D category (Table 2), the median *RFSs* in an O-D category (Figure 3), and the number of times that an O-D category ranks high or low (Table 3) all show that EB routes tend to have higher *RFSs* than WB routes. Given that EB routes travel primarily in the direction of the core current flow and that WB routes travel primarily opposite the core flow, the results indicate that the current routing is more useful when trying to catch favorable currents than when avoiding contrary currents. This result is consistent with other, more aggregate studies (14–16).

The results also indicate that the best routes were IA_{EB}, II_{EB}, and especially AI_{EB}. Except for II_{EB}, these routes were in the top third of the rankings on each of the four starting dates. II_{EB} was in the top third three times and in the middle third the fourth time. Figure 3

TABLE 2 Mean RFS of O-D Categories by Starting Date (Starting Date Order: 11/13/87, 11/28/87, 5/06/88, 5/21/88)

Origin	Direction of Voyage	Destination			Category Mean
		Above	In	Below	
Above	EB	7.8; 6.4; 9.7; 11.0	11.8; 8.9; 13.2; 18.2	8.6; 7.1; 11.3; 8.2	9.3; 7.5; 11.4; 12.5
	WB	3.0; 3.7; 3.6; 2.6	6.9; 7.0; 9.3; 6.6	5.1; 5.1; 8.3; 6.4	5.1; 5.3; 7.1; 5.2
In	EB	8.5; 8.6; 12.5; 10.8	6.8; 7.4; 12.8; 14.9	6.7; 5.7; 11.2; 8.6	7.3; 7.2; 12.2; 11.4
	WB	4.6; 6.9; 4.9; 5.8	11.5; 5.5; 9.8; 12.6	8.7; 3.1; 1.9; 4.6	8.2; 5.2; 5.5; 7.6
Below	EB	8.1; 6.1; 7.8; 7.3	6.5; 4.8; 9.8; 15.4	3.8; 4.3; 2.8; 3.9	6.2; 5.1; 6.8; 8.9
	WB	3.5; 1.4; 7.8; 8.1	5.1; 4.4; 6.9; 7.7	1.4; 2.3; 3.1; 4.3	3.3; 2.7; 5.9; 6.7
Category Mean:	EB	8.2; 7.0; 10.0; 9.7	8.4; 7.0; 12.0; 16.2	6.3; 5.7; 8.4; 6.9	7.6; 6.6; 10.2; 10.9
	WB	3.7; 4.0; 5.4; 5.5	7.8; 5.6; 8.7; 8.9	5.0; 3.5; 4.4; 5.1	5.5; 4.4; 6.2; 6.5

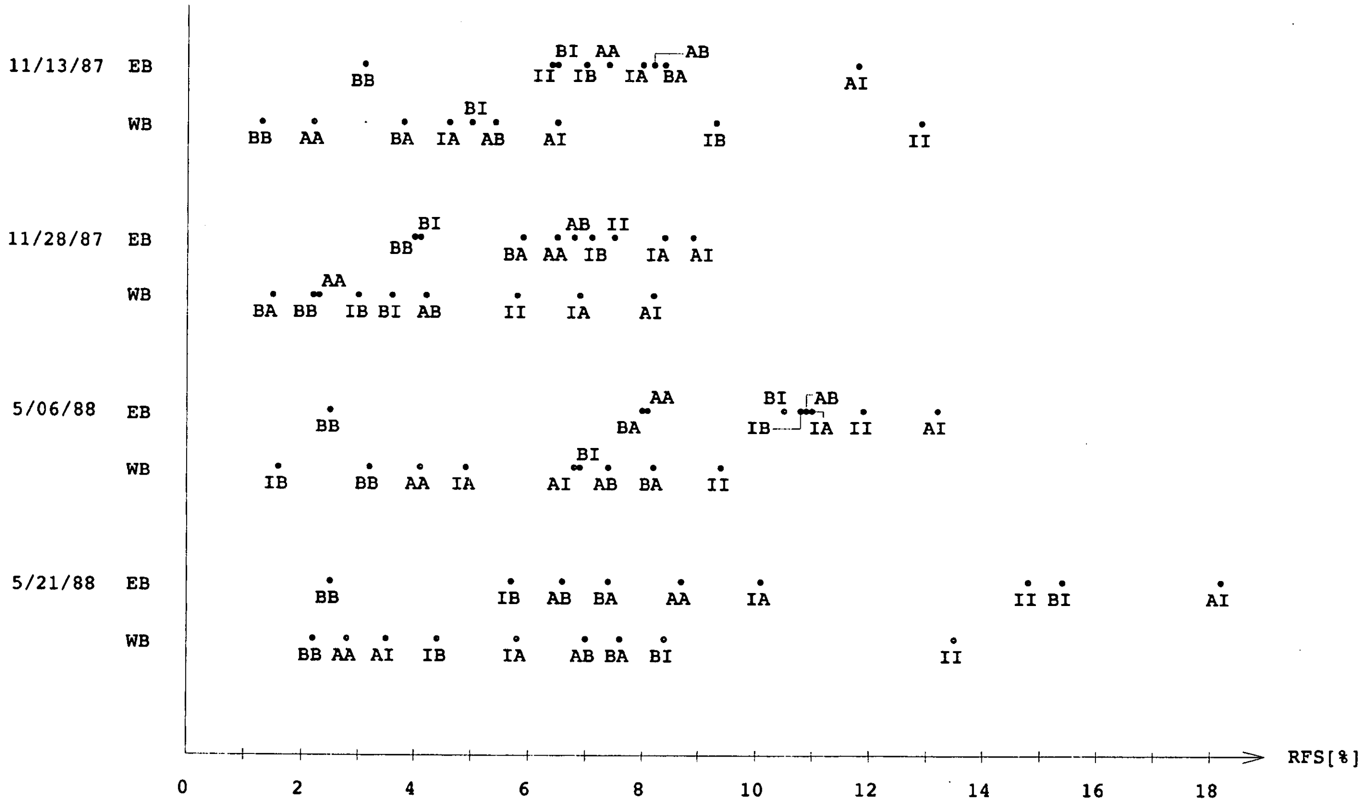

FIGURE 3 Median *RFS* of O-D categories by starting date.

TABLE 3 Number of Times (Based on Four Starting Dates per Category) O-D Category was in Top Third or Bottom Third of Ranking According to *RFS* [Based on Means (Medians)]

Origin	Direction of Voyage	Destination: Above	Destination: In	Destination: Below	Category Total
Above	EB	1/0 (1/0)	4/0 (4/0)	3/0 (2/0)	8/0 (7/0)
	WB	0/4 (0/4)	1/0 (1/2)	0/1 (0/0)	1/5 (1/6)
In	EB	4/0 (4/0)	3/0 (3/0)	1/0 (2/1)	8/0 (9/1)
	WB	1/3 (1/2)	2/0 (2/0)	1/3 (1/3)	4/6 (4/5)
Below	EB	1/0 (1/0)	2/0 (2/0)	0/4 (0/4)	3/4 (3/4)
	WB	0/2 (0/2)	0/3 (0/2)	0/4 (0/4)	0/9 (0/8)
Category Total:	EB	6/0 (6/0)	9/0 (9/0)	4/4 (4/5)	
	WB	1/9 (1/8)	3/3 (3/4)	1/8 (1/7)	

shows that AI_{EB} had the highest median *RFS* on three of the four days, and Table 2 shows that it had the highest mean *RFS* on all four starting dates. To determine exactly what is making these routes so favorable, it would be necessary to superimpose the minimum fuel routes and the great circle routes on the current pattern. Doing so for all of the 360 voyages was beyond the scope of this study, but it appears that the voyages with the best potential for current routing are those that would normally (i.e., in the absence of the current routing) ride through or near the core flow and in its general direction. Having an origin or destination in the core flow would increase the likelihood of the base route going along the core flow for some portion of its time. Based on this reasoning, IB_{EB} and BI_{EB} might be expected to exhibit large fuel savings. Although these categories are not as good as the other EB routes with an origin or destination in the core flow, they are still fairly good categories. Table 3 shows that only IB_{EB} ever fell in the bottom third of the ranking, but that was for only one starting date and only when the ranking was according to the median. Except for this instance, the routes were either in the middle third or, almost as likely, in the top third of the ranking.

The categories with the worst performances were AA_{WB}, BB_{WB}, and BB_{EB}, ranking in the bottom third of the categories on all four starting dates, whether the ranking was according to the mean or median (see Table 3). Note that in these three categories the origin and destination are on the same side of the core flow. BB_{EB} could only benefit from current routing by going out of the way to catch the core flow or by trying to catch a ring at the right location. The core flow would not have much of an effect on the WB voyages, because the base (great circle) route would generally not pass through it and a vessel would never go out of the way to get in the contrary flow of the core. Therefore, it would appear that the benefit to these routes would be primarily from catching the rings at the right location. The tentative conclusion, then, is that taking advantage of the positive impacts or minimizing the negative impacts of the cold or warm rings that shed off of the core flow can lead to fuel savings, but that the magnitude of these savings would generally be less important than the savings associated with routing in or through the core flow. The only other category with both origin and destination on the same side of the core flow is AA_{EB}, which never ranked in the bottom third but generally ranked in the middle third of the categories. The authors speculate that it had greater fuel savings than AA_{WB}, BB_{WB}, and BB_{EB} because there is generally more ring activity above the core than below and because the meandering nature of the Gulf Stream could allow the base path to go nearer the core flow traveling in the same direction than the other three categories (see Figure 1).

Those categories with origins and destinations on opposite sides of the core flow (the categories that must cross the core flow) rank primarily in the middle. Table 3 shows that AB_{EB} did rank in the top third three (two) times according to the mean (median), but Table 2 and Figure 3 show that they were close to the middle third on these occasions. Also, BA_{WB} ranked in the bottom third two times and was ranked particularly low on 11/28/87 (Figure 3). In general, however, the categories that cross the core flow are better than those dealing primarily with rings and worse than those whose base routes would travel a fairly long distance in the core flow.

The routes benefiting most from explicitly considering dynamic current patterns were those whose base routes (routes that would be best if the currents were not considered) were in or close to the core flow and going in the direction of the flow. This result seems logical: if a ship only has to modify its shortest distance route slightly to take advantage of the positive currents, the net benefit will be greater than if it has to travel farther from the shortest distance route. The results also indicate that greater benefits are associated with routing correctly through the core flow than with changing course to avoid contrary currents, and that determining where and how to cross the core flow is more beneficial than trying to take advantage of the favorable or avoiding the unfavorable effects of rings that are shed from the core. Trying to take advantage of or avoid the rings resulted in the least fuel savings of all the characteristics analyzed. Because the orbiting satellites gathering the raw data to estimate the current patterns would have limited spatial coverage (*1,7,8,16*), the ring patterns might not be as well resolved as the core flow. The combined effects of relatively low potential benefits and poorer quality of input data significantly decrease the desirability of changing course to ride the favorable or avoid the contrary velocities in rings.

The results also indicated that the magnitudes of fuel savings depended substantially on the specific current patterns associated with the days of the voyage. It would therefore appear that dynamic programming, or some other form of explicit mathematical analysis, might be necessary to help routing analysts studying the combined fuel consumption effects of currents, winds, waves, and weather.

ACKNOWLEDGMENTS

The authors thank Scott Glenn, Allan Robinson, and the Harvard Physical Oceanography Department for access to their data and Riyaz Fazal for insight on routing practices. This project was partially funded by NASA and Oceanroutes, Inc., NAGW-973, through the Ohio State Center for Mapping, NOAA NA89AA-D-SG132 through the Ohio State Sea Grant Program, and by NSF MSS-8657342. The authors gratefully acknowledge the helpful comments of three anonymous referees and of Arlene Dietz.

REFERENCES

1. Cheney, R., B. Douglas, R. Agreen, L. Miller, and D. Porter. The GEOSAT Altimeter Mission: A Milestone in Satellite Oceanography, EOS. Dec. 1986.
2. Robinson, A., S. Glenn, M. Spall, L. Walstad, G. Gardner, and W. Leslie. Forecasting Gulf Stream Meanders and Rings, EOS. Vol. 7, 1989, pp. 1464–1465.
3. Robinson, A., and L. Walstad. The Harvard Open Ocean Model: Calibration and Application to Dynamical Process, Forecasting and Data Assimilation Studies. *Applied Numerical Mathematics,* Vol. 3, 1987, pp. 89–131.
4. Glenn, S., A. Robinson, and M. Spall. Recent Results from the Harvard Gulf Stream Forecasting Program, Oceanographic Monthly Summary. April 1987.
5. Hurlburt, H., D. Fox, and E. Metzger. Statistical Inference of Weekly Correlated Subthermocline Fields from Satellite Altimetry Data. *Journal of Geophysical Research,* Vol. 95, No. C7, 1990, pp. 11375–11409.
6. Carnes, M., J. Mitchell, and P. de Witt. Synthetic Temperature Profile Derived from GEOSAT Altimetry: Comparison with Air Dropped Expanded Bathythermography Profile. *Journal of Geophysical Research.* Vol. 95, No. C10, 1990, pp. 17979–17992.
7. McCord, M., and M. Berliner. *Improved Ocean Routing Using Remote Sensing, NASA Center for the Commercial Development of Space: Real Time Satellite Mapping.* Annual Report. The Ohio State University Center for Mapping, Columbus, Ohio, 1991, pp. 1–4.
8. McCord, M., and M. Berliner. *Improved Ocean Routing Using Remote Sensing, NASA Center for the Commercial Development of Space: Real Time Satellite Mapping.* Annual Report. The Ohio State University Center for Mapping, Columbus, Ohio, 1990, pp. 6–9.
9. Robinson, I. *Satellite Oceanography: An Introduction for Oceanographers and Remote Sensing Scientists.* Ellis Horwood Limited, Chichester, U.K. 1985.
10. Lo, H. *Dynamic Ship Routing Through Stochastic, Spatially Dependent Ocean Currents.* Ph.D. dissertation. The Ohio State University Civil Engineering Department, Columbus, Ohio, 1991.
11. McCord, M., and S. Smith. Remote Sensing of Ocean Currents for Improved Routing. *Proc., 14th Ship Technology and Research (STAR) Symposium,* Society of Naval Architects and Marine Engineers, Jersey City, N.J. 1989, S5-4-1–S5-4-8.
12. Lo, H., M. McCord, and C. Wall. Value of Ocean Current Information for Strategic Routing. *European Journal of Operational Research.* Vol. 55, 1991, pp. 124–135.
13. Lo, H., M. McCord, and C. Wall. Estimated Fuel Savings from Current Routing on U.S. Transoceanic Trades. Presented at the 70th Annual Meeting of the Transportation Research Board. Washington, D.C., Jan. 1991.
14. Lo, H., and M. McCord. *Routing Through Dynamic Ocean Currents: General Heuristics and Empirical Results in the Gulf Stream Region.* (accepted for publication in *Transportation Research*), 1994.
15. Lo, H., and M. McCord. Heuristics for Dynamic Ocean Current Routing. Presented at the 72nd Annual Meeting of the Transportation Research Board. Washington, D.C., Jan. 1993.
16. Lo, H., and M. McCord. Altimetric Sensing of Currents: Spatial Averaging and Sampling Impacts on Ocean Routing. *Transportation Research Record 1312,* 1991, pp. 177–183.
17. Mays, J. Shipboard Computers for Navigation and Weather Routing. Presented at Marine Computer '86. Society of Naval Architects and Marine Engineers, New England Section, 1986.
18. Chen, H. Ship Routing Made Practical. *Sea Technology,* April 1988, pp. 47–57.
19. Hagiwara, H. *Weather Routing of (Sail Assisted) Motor Vessels.* Ph.D. thesis. University of Delft, Netherlands, 1989.
20. Lee, Y.-K. *Strategic Ship Routing with Satellite Altimeter-Based Dynamic Ocean Current Information: Impacts of Temporal Coverage.* Ph.D. dissertation. The Ohio State University Civil Engineering Department, 1994.
21. Chase, L. *Uncertainty of Current Velocity Measurements Due to Altimeter and Orbit Determination Errors.* Master's thesis. The Ohio State University Civil Engineering Department, Columbus, Ohio, 1988.
22. Tai, C. Estimating the Surface Transport of Meandering Oceanic Jet Streams from Satellite Altimetry: Surface Transport Estimates for the Gulf Stream and Kuroshio Extension. *Journal of Physical Oceanography.* Vol. 20, 1990, pp. 860–879.
23. Van Dorn, W. *Oceanography and Seamanship.* Dodd, Mead, and Company, New York, N.Y. 1974.
24. McCord, M., and H. Lo. *Temporal Variability in Ocean Currents, ASPRS-ACSM Fall Convention: ASPRS Technical Papers,* American Society of Photogrammetry and Remote Sensing. 1989, pp. 83–90.
25. Jansson, J., and D. Shneerson. *Liners Shipping Economics.* Chapman and Hall, New York, N.Y. 1987.

Publication of this paper sponsored by Committee on Ports and Channels.