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Low Carbon Intensity Routes via Ocean Currents and Waves

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Abstract. The VISIR ship routing model is augmented with the capability to employ, on top of waves, also ocean currents for optimising vessel routes. A case study for a cargo vessel sailing between the Chesapeake Bay (USA) and Lisbon (Portugal) is considered. The seasonal variability of the route pattern is visualised, with the major ocean boundary current impacting in a specific way, depending on the prevailing sailing direction. In the approximation of CO_2 emissions proportional to sailing time, the impact on the Energy Efficiency Operational Indicator (EEOI) proposed by the International Maritime Organization is also computed. The seasonal variability of EEOI demonstrates, for a given parametrisation of vessel energy loss in waves, potential savings in the 3–12% range, with respect to navigation along a least-distance route, and in the 1–5% range, with respect to navigation along a least-time route which neglects the role of ocean currents. These figures refer to monthly mean values, while individual routes may exhibit EEOI savings up to 20% and 6%, respectively.

Keywords. optimal route, waves and currents, Atlantic Ocean, EEOI

1. Introduction

In year 2007, CO_2 emissions from maritime shipping amounted to more than 3% of the global grand total [4]. Shipping's year 2015 emission level of about 0.8 $GtCO_2$/year might triple up to year 2050, depending on the representative concentration scenario [14].

In order to deliver a proportionate contribution to climate change mitigation, the sector of shipping is called to engage in actions for reducing its CO_2 footprint [1]. This objective might be hampered by several legal issues, including the fact that neither the Kyoto protocol [12] nor the Paris agreement [15] included mandatory measures for emissions from international shipping. However, both the European Union (EU) and the International Maritime Organization (IMO) have recently started setting both voluntary and mandatory objectives on CO_2 emissions from shipping.

EU Directive 757/2015[2] requires all vessels above 5 000 gross tonnes calling to and from European ports to do Monitoring, Reporting and Verification (MRV) of own CO_2 emissions.

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[2] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex

IMO introduced two indexes for assessing efficiency of ships: the Energy Efficiency Design Index (EEDI, [11]), being the amount of CO_2 emissions from a ship per unit of transport work, and the Energy Efficiency Operational Indicator (EEOI, [10]), the same physical quantity of EEDI, but referred to the actual performance and not to a designed point of operation. While EEOI is a voluntary measure, EEDI is mandatory for all new ships of 400 gross tonnes and above.

Nevertheless, neither voluntary nor mandatory reporting of CO_2 emissions would have any environmental effect in itself. Rather, an effect could be triggered by incentive/disincentive schemes being set up to make use of these indexes [4]. For instance, the EU Directive 757/2015 explicitly states that MRV will be followed by pricing of the emissions. Thus – assuming an economic scenario where such schemes are implemented – the purpose of this manuscript is to assess how EEOI savings could be achieved through the specific operational practice of voyage optimization. In particular, optimization by means of meteo-oceanographic data is here considered.

The potential of operational oceanography for climate change mitigation and other societal benefits has been already highlighted: downstream services in fact benefit from high spatial- and temporal resolution, data assimilation, and open-access policies of the data [13].

Building on the open-source model VISIR [8], an operational service for least-time navigation in the Mediterranean Sea was realized [9]. That system is now being extended to large vessels sailing in the Atlantic Ocean and is being augmented in its functionalities. They include the impact of ocean currents and the effect of optimization on fuel consumption and CO_2 emissions.

In this manuscript, preliminary results on a case study route in the northern Atlantic are reported. A compact description of the path planning algorithm of VISIR is provided in Sect. 2; the method of estimation of EEOI is described in Sect. 3 and actual case study's results are presented in Sect. 4; closing remarks and perspectives can be found in Sect. 5.

2. Path planner setup

VISIR is a ship routing model based on a graph-search method[3]. It aims at computing least-time routes in presence of time-dependent meteo-oceanographic fields such as waves, ocean currents, and wind. Both static and dynamic navigational constraints can be considered. A few more details are provided in the following subsections.

2.1. Graph set-up

A graph with a connectivity up to the 8th level of grid neighbours is employed for this case study, leading to 288 edges for each node. At a mesh spacing $1/8^o$, this implies that there are about $7 \cdot 10^4$ nodes in a typical grid required for a Northern Atlantic crossing. With 10 daily time-steps, this amounts to about $2 \cdot 10^8$ degrees of freedom for the path planning algorithm. Thus, the spatial and angular resolution of the graph is chosen in order to compromise between route smoothness and computational cost of the numerical jobs.

[3]www.visir-model.net

The environmental fields are evaluated on the graph edges before flowing into the shortest-path algorithm. In [8] such edge weights are obtained by evaluating the fields at the time-step nearest to the time of transit at each route waypoint. Here, following new VISIR developments still to be published, the edge weights are obtained from time-interpolation of the environmental fields.

2.2. *Interaction with ocean currents and waves*

Following the approach of [7], the interaction of the vessel with ocean currents and waves is based on a two-step procedure.

First, the speed through water (STW) is computed from a balance of thrust and resistance at the vessel propeller. This is done with the model of [8] and using the container ship parameters of Tab. 1. This model presently accounts for significant wave height and wave period but is independent of wave direction.

Secondly, the speed over ground (SOG) is obtained from the vector sum of STW and ocean current. The current across the vessel is balanced by a part of the vessel speed, with an angle of attack through water depending on the ratio of cross-current to STW.

2.3. *Vessel intact stability*

VISIR employs waves also for performing a few checks on vessel intact stability, namely related to: parametric roll, pure loss of stability, and surfriding/broaching-to. The algorithm then constructs the optimal route by ensuring that vessel intact stability is always fulfilled. For parametric roll, the wave height criterion of [8, Eq.32] is generalised for vessels with $L_{\mathrm{WL}} > 100$ m by implementing the piecewise linear function of L_{WL} given in [3, Eq.2.37].

3. EEOI ratio estimation

Reporting EEOI has been proposed by IMO as a voluntary practice for monitoring and limiting greenhouse gas emissions from ships in operation [10]. EEOI is defined as the ratio of CO_2 emissions per unit of transport work. Thus, EEOI is a measure of carbon intensity of a route. Depending on vessel type, there are several possible definitions of transport work. We here restrict ourselves to a cargo vessel carrying solely containers, for which transport work is defined as deadweight times sailed distance L.

Table 1. Vessel propulsion parameters and principal particulars used in this work. γ_q was defined in [8]. Maximum cargo is 2 500 TEUs. Data source: Florian Aendekerk (Compagnie Maritime Belge).

Symbol	Name	Units	Value
SMCR	optimal maximum continuous rating power	kW	19 166
$V_{\max}$	top design speed	kts	21.1
L_{WL}	length at waterline	m	210
B_{WL}	beam (width at waterline)	m	30
T	draught	m	11.5
T_{R}	ship natural roll period	s	21.2
C_T	drag coefficient	-	$\gamma_q\,\mathrm{STW}^q$
q	exponent in C_T	-	2

Furthermore, in order to estimate the CO_2 emissions, a linear approximation is here employed: CO_2 emissions proportional to fuel consumption, and fuel consumption proportional to sailing time. The latter in turn is assumed to be given by the optimal sailing time T^* from the path planning algorithm, cf. Sect. 2.

In such linear hypothesis, the EEOI ratio $\rho_{\beta,\alpha}$ of two routes sailed with same deadweight is found to be independent of deadweight and given by

$$\rho_{\beta,\alpha} = \frac{\mathrm{EEOI}_\beta}{\mathrm{EEOI}_\alpha} = \frac{T^*_\beta}{L_\beta} \Big/ \frac{T^*_\alpha}{L_\alpha} \tag{1}$$

where the subscripts label the β route being compared to the α route. Eq. 1 shows that $\rho_{\beta,\alpha}$ only depends on route optimal durations T^* and corresponding lengths L. Furthermore, $\rho_{\beta,\alpha}$ is recognised to be the inverse ratio of the average speeds along the β and α routes: if the average speed in the β route is higher than in the α route, then $\rho_{\beta,\alpha} < 1$.

The EEOI relative change of β to α route is then given by

$$\Delta(\mathrm{EEOI})_{\beta,\alpha} = \frac{\mathrm{EEOI}_\beta - \mathrm{EEOI}_\alpha}{\mathrm{EEOI}_\alpha} = \rho_{\beta,\alpha} - 1 \tag{2}$$

If the average speed in the β route is higher than in the α route, then $-\Delta(\mathrm{EEOI})_{\beta,\alpha} > 0$.

4. Case study in the Atlantic Ocean

In order to demonstrate how and to what extent ocean currents and waves can be exploited for EEOI savings, we now consider a case study route in the Atlantic Ocean.

4.1. Environmental fields

Time-dependent datasets have been downloaded from the Copernicus Marine Environment Monitoring Service (CMEMS[4]), which provides them with an open and free policy.

Wave forecast datasets are available in near real-time from CMEMS. However, they are not long enough (5 days) for planning transatlantic passages. CMEMS also provides wave analyses, which are reconstructions of past sea state employing data assimilation. The time series starts on April 1st, 2015, allowing long aggregation of data. Thus, wave analysis datasets are used in this work. They are produced by the operational global ocean analysis and forecast system of Météo-France, based on third generation wave model MFWAM, [2]. It assimilates significant wave height from Jason 2 & 3, Saral and Cryosat-2 altimeters observations. The spatial resolution is $1/5^o$ (i.e. 12 nmi[5] in the meridional direction). 3-hourly analysis fields of integrated wave parameters from the total spectrum (spectral significant wave height, mean wave direction, wave period at spectral peak) are averaged within VISIR into daily fields.

As in the wave case, ocean current analyses are employed in this work. They are obtained via CMEMS from the operational Mercator Océan global ocean analysis and forecasting system, based on NEMO v3.1 ocean model, [6]. It assimilates observations of sea level anomaly, sea surface temperature, temperature and salinity, profiles, sea ice.

[4] http://marine.copernicus.eu/
[5] 1 nmi= 1852 m

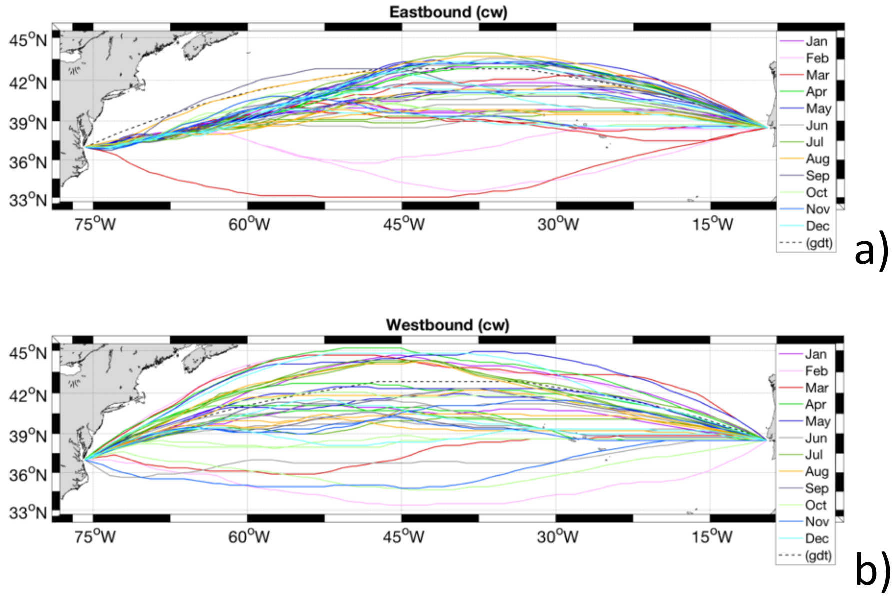

Figure 1. Spatial variability of the transatlantic crossings optimised considering both ocean currents and wave heights. Panels a,b) for East- and Westbound crossings respectively. The geodetic (or: least-distance) route is displayed as a black dashed line.

The time series starts on December 27th, 2006. The spatial resolution is $1/12^o$ (i.e. 5 nmi in meridional direction). Daily analysis of surface velocity fields are employed.

4.2. Route settings

We consider (both East- and Westbound) crossings of the northern Atlantic Ocean, between the mouth of the Chesapeake Bay, USA (37^o00' N, 76^o00' W) and Lisbon, Portugal (38^o30' N, 9^o30' W). The departure time is kept fixed at 12:00 UTC, for all routes.

From Fig. 1 it is seen that resulting geodetic (i.e.: least-distance) route is northwards bent, as it is to be expected from an arc of Great Circle (GC) of the Northern hemisphere on an equi-rectangular projection. The northern edge of the route is flattened due to the finite angular resolution of the graph, which is about 7.1^o. At this graph resolution, the error made by VISIR in the length of the least-distance route is still below 1 permil.

Different from what already accomplished for the Mediterranean Sea [8], the graph pruning for the Atlantic shoreline has not yet been realised. This implies that the routes may still cross the landmass. This mandatory development for navigational use will be completed soon. For the moment being, 26 routes crossing the shoreline are manually removed from the plots in Fig. 1 and are not employed in oder to compute the results of Fig.2–3.

4.3. Seasonal variability

VISIR computations are carried out for several departure dates during the whole calendar year 2017. In particular, departures at a 5-day distance are considered (days 1st, 6th,

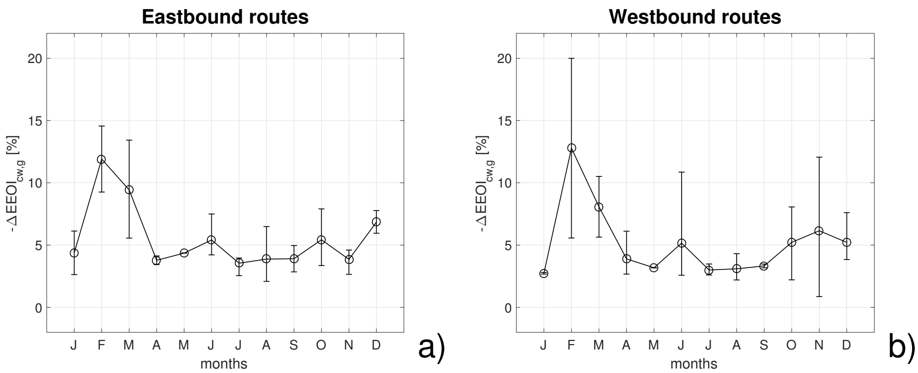

Figure 2. Seasonal variability of EEOI relative change of the optimal route accounting for both ocean currents and waves with respect to the geodetic route. Eastbound and Westbound routes are considered in panel a) and b) respectively. For each calendar month, the empty circle position is the mean and the error bars span between minimum and maximum value of the (four) routes pertaining to that month.

11th, 16th of each month) for accounting for decorrelation of the ocean current fields after a Lagrangian eddy timescale of about 5 days [5]. The results are analyzed in terms of both spatial variability of the routes (Sect. 4.3.1) and seasonal variability of the EEOI relative changes (Sect. 4.3.2).

4.3.1. Spatial patterns

A direct visualisation of the annual variability of the route topology is shown in Fig. 1.a–b. The two panels refer to optimal routes considering both ocean currents and waves, with East- and Westbound orientation respectively. The least-time routes extend far beyond the GC route: they are comprised within the 33–45^{o}N latitudinal band.

Most of the Eastbound routes, at least W of 60^{o}W, divert from the GC route for exploiting advection by a branch of the Atlantic boundary current called Gulf Stream (GS) proper. In fact, according to the approach of Sect. 2.2, the algorithm attempts to add STW up with ocean current for obtaining a larger vessel SOG.

For Westbound routes instead the GS is encountered in unfavourable direction. This results in several routes diverting either N, towards the coast of Nova Scotia (Canada), or as S as 33^{o}N, for both avoiding the counter-current and experiencing a milder sea state. Of course, all diversions from the GC route come at the cost of a longer sailed distance.

4.3.2. EEOI relative changes

For estimating the benefits of ocean currents and waves on the optimal route's environmental impact, the EEOI relative changes are computed according to Eq. 2.

With reference to the nomenclature of Sect. 3, the β route is optimized making use of both ocean currents and waves ($\beta = cw$); the α route instead is, in Fig. 2, the least-distance or geodetic route ($\alpha = g$) while, in Fig. 3, it is the least-time route in presence of waves only ($\alpha = w$). For both Fig.2–3, the seasonal variability of such EEOI relative changes is provided for either prevailing sailing direction: East- or Westbound.

$-\Delta\mathrm{EEOI}_{cw,g}$ exihibits monthly mean peak values of 12% in February and minimum of about 3% (Fig. 2.a–b). This should reflect the seasonal variability of the wave climate in the North-Atlantic. The intra-month variability is found however to be even larger than

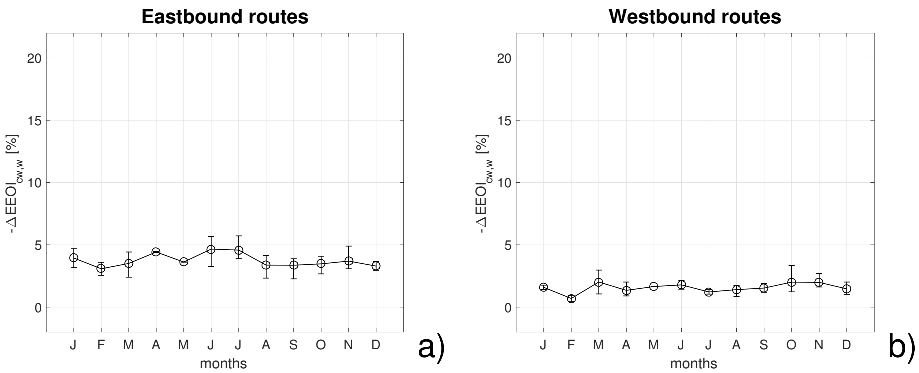

Figure 3. As in Fig. 2 but the EEOI relative changes refer to the optimal route in presence of waves only.

the seasonal one. In order to disentangle the role of ocean currents, also $-\Delta\text{EEOI}_{cw,w}$ is computed (Fig. 3). For the Eastbound route, monthly-mean EEOI savings between about 3 and 5% can be ascribed to ocean currents, while for the Westbound route savings are about 1.5%.

5. Conclusions

The extension of VISIR ship routing model to ocean currents allowed studying their seasonal impact on a specific transatlantic crossing.

The optimal routes computed along a whole calendar year form a bundle, with significant diversions from the least-distance route. The bundle carries the specific signature of the orientation of the main boundary current (the Gulf Stream), which attracts the East- and repels the Westbound routes.

A simplified EEOI computation for these routes is carried out, allowing to appreciate the seasonal trend of the EEOI savings. The results indicate a dominant role of waves in total EEOI savings, which on a monthly basis can be as high as 3–12%. Nevertheless, the role of currents is not negligible and ranges 1–5%: exploiting or avoiding ocean currents enhances vessel average speed, leading to a lower EEOI.

These results suggest a great potential in CO_2 emission reduction from optimal use of both ocean currents and waves for transatlantic passages. However, a couple of caveats should be clearly stated at this place:

i) The results heavily depend on how energy-loss in waves is parametrised, as this determines vessel STW and the whole kinematics of the route. At present, the vessel propulsion and seakeeping model employed is the same of [8] and thus suffers from several technical limitations;

ii) A larger spatial and temporal statistics is required for a comprehensive assessment of potential EEOI savings. In particular, while this work highlights the specific benefits of a transatlantic passage with significant spatial overlap with the Gulf Stream, also other common routes should be investigated.

Nevertheless, these preliminary results based on 70 route computations for the year 2017 support the message that open-access state-of-the-art meteo-oceanographic model outputs (such as those provided by the European CMEMS) together with open-source models of human activities (such as VISIR) can deliver outstanding contributions to matters of societal concern, such as the contribution of the sector of maritime transportation to the mitigation of climate change.

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