INTRODUCTION

The recent decade has seen an increasing development in ship routeing services whereby more reliable weather conditions, sea states and surface currents are taken into account (e.g. [3, 13, 11]). Optimum ship routing means the “best route” for a ship based on the marine weather forecasts including wave and surface current conditions as well as sea surface temperature fields the best shipping route are examined. The proposed approach aims to identify the optimum balance between minimisation of transit time and fuel consumption as well as reduction of emissions without placing the vessel at risk to damage or crew injury. As such it is compliant with the International Maritime Organization guidelines [6] for ship routeing to keep the traffic smooth and avoid accidents, notably in the presence of unfavorable marine meteorological conditions. The tool performances will be demonstrated both in post-voyage analyses and real time operations for the North Atlantic Ocean crossings, voyages from Europe through the Mediterranean Sea and the Suez Channel to the Far East (e.g. China, South Korea) and voyages around Southern Africa.

2 DATA AND APPROACH

The types of data and information products considered necessary for provision of reliable and optimized ship routing can be grouped into marine weather data, model forecast fields, near real time satellite data and in-situ measurements. Regarding the satellite data there is a wide range of oceanic variables that will be used to retrieve and validate the surface currents and frontal structures as indicated in Table 1, including sea surface temperature (SST), chlorophyll (Chl) observations, surface geostrophic current, significant wave height and wave length and propagation direction.
Table 1. Key satellite sensor data (level, resolution, provider). Note that radar altimeter data (wave height) are available in the CMEMS multi-observation data set.

| Sensor                          | Product                              | Level | Resolution | Data Provider |
|---------------------------------|--------------------------------------|-------|------------|---------------|
| Sentinel-3 SLSTR SST and SEVIRI | Sea surface temperature/fronts       | L2    | ~ 1 km     | EUMETSAT      |
| Sentinel-3 OLCI Chl             | Chlorophyll/fronts                   | L2    | ~ 300 m    | EUMETSAT      |
| Sentinel-3 and Jason altimeters | Surface geostrophic current/fronts   | L3    | ~ 10 km    | CLS/Salto Duacs |
| Sentinel-3 and Jason altimeters | Significant wave height              | L3    | ~ 10 km    | CLS/Salto Duacs |
| Sentinel-2 spectral imager      | Wave length - direction/glitter      | L2    | ~ 1 km     | ODL           |
| Sentinel-1 A/B SAR              | Wave length - direction              | L2    | ~ 1 km     | Schub/ESA     |
| Sentinel-1 SAR Doppler shift    | Radial surface current               | L3    | ~ 2 km     | Schub/ESA     |
| CMEMS-Multi-Obs (Global)        | All above from Sentinel-3            | L3/L4 | ~ 10 km    | CMEMS         |

Table 2. In-situ sensor data and providers

| Sensor           | Key products/resolution | Coverage     | Data providers       |
|------------------|-------------------------|--------------|---------------------|
| HF radars        | Surface current/order km| surface      | EMODNET PHYSICS     |
| Loch (ship-based)| Surface current/tens of meters | surface | CMA CGM (Watch Report) |
| Argo             | Surface current/~100 m  | surface      | CMEMS, Coriolis     |
| Surface drifting buoys | Current/~100m         | 15 m depth   | CMEMS, Coriolis     |

Table 3. Complementary model-based surface current fields. *The GlobCurrent fields is an interpolated regular global surface current product derived from satellite data. Geostrophic balance and Ekman current estimation applied.

| Product            | Coverage            | Resolution | Model    | Provider       |
|--------------------|---------------------|------------|----------|----------------|
| CMEMS-GLOBAL       | global              | ~ 8 km     | NEMO     | CMEMS          |
| RTOFS              | global              | ~ 8 km     | HYCOM    | NOAA           |
| GOFs               | global              | ~ 8 km     | HYCOM    | NRL            |
| MED-CMems          | Mediterranean Sea    | ~ 4 km     | NEMO     | CMEMS          |
| IBI                 | Iberian Peninsula & Bay of Biscay | ~ 2 km | NEMO | CMEMS          |
| GlobCurrent*       | global              | ~ 25 km    | Geo/Ekman | CMEMS         |
| Wave Model         | global              | ~ 10 km    | MFWAM    | MeteoFrance    |

Importantly, these satellite data can often be complemented and collocated with in-situ data allowing comparison of the surface current and frontal structures derived from the satellite data to the Argo floats, surface drifter data, HF-radars and on-board estimates of surface currents as shown in Table 2.

Finally, the satellite and in-situ based observation data are combined and extended with surface current and wave field forecast products offering global and regional coverages at spatial resolutions ranging from 25 km to 2 km as shown in Table 3.

A major innovation in this project is the systematic use of satellite observations of the marine environment in near real time to generate information products tailored to ship locations and their planned course for the next 24 hours. Presently, the joint EU-ESA Copernicus program (https://marine.copernicus.eu) ensures routine access to the sea surface current, significant wave height, wave spectra and sea surface temperature derived from the Sentinel satellite missions (see Table 1). These variables, in turn, allows the identification and location of meandering surface current frontal boundaries and eddies, evidence of wave-current interactions and presence of crossing seas.

Satellite data regularly collected over time is also highly useful to establish climatology that function as reference conditions for assessing the magnitude of the departure of the near real time product from the climatology mean. This is illustrated in Figure 1 displaying the 4-year mean of significant wave height, significant wave height gradient and surface geostrophic current vorticity (estimated from the gradient in meridional minus zonal current). Not surprisingly the roughest sea state conditions are found in the Southern Ocean with a mean significant wave height between 4 and 5 m. In comparison, the mean significant wave height in the North Atlantic and North Pacific respectively ranges between 3-4 m and 2-3 m.

On the other hand, when looking at the mean of the significant wave height gradient and the surface geostrophic current vorticity the pictures largely change towards the manifestation of the boundaries of the basin-scale surface current system such as the Gulf Stream, the Kuroshio Current and the greater Agulhas Current, known to reach surface current speeds of 1-2 m/s. These intense current regimes are recognized with strong mesoscale and sub-mesoscale variabilities that have large influence on the sea state, in particular due to the change in wave heights invoked by wave refraction from the spatially varying surface current [9]. As noticed in Figure 1, the two fields show a significant degree of collocated expressions of distinct anomalies in both the significant wave height gradient and surface geostrophic current vorticity. This is a key indicator of strong wave-current interaction, notably caused by:

- refraction of the longer waves (> 200 m) as they propagate across the surface current boundaries and feel the significant change in surface geostrophic current and associated vorticity field;
- steepening of the waves and in particular the shorter wind waves (< 50 m) as they propagate against the strong surface currents.

Wave refractions by the surface current are observed in both Sentinel-1 Synthetic Aperture Radar (SAR) images and Sentinel-2 multispectral images (under cloud free conditions) revealing both the incident wavelength and direction and their changes when propagating across the surface current boundaries. Moreover, complementary collocated
observations from Sentinel-3 deliver measurements of the surface current and sea surface temperature (under cloud free conditions).

Figure 1. 4-year mean (2013–2016) for significant wave height (top), significant wave height gradient (middle) and surface geostrophic current vorticity (lower) computed using the constellation of 4 satellite altimeters and projected on a 0.5° * 0.5° grid. The color bars mark the value in the given units.

An example of multi-sensor satellite-based observations of the spatial variability in the significant wave height, the wave propagation direction and the surface geostrophic current blended with swell propagation simulations is shown in Figure 2 with focus on the core of the Agulhas Current.

Evidence of altimeter-based observations of strong wave-current interactions are clearly depicted in which increased significant wave height are collocated with areas of intense surface geostrophic currents, in particular for the opposing currents such as seen near the retroreflection region of the Agulhas Current centered around 39°S and 18°E. The complementary simulated wave-current refraction are highly in consistence with these observations and reveals how the refractions lead to changes in wave propagation and the set-up of crossing seas. The importance of the wave-current interaction can also be explored from the model simulations as highlighted by the comparison of the significant wave height field with and without the presence of the surface current (see Figure 3). As noticed the significant wave height is enhanced by around 50% in the core of the Agulhas Current. Hence, the convergence (growth) of wave energy (higher sea states) and directional spreading (dangerous crossing seas) can be located both from the observations and the model simulations leading to a more reliable assessment of potential navigational risk areas. The assessment may also yield more confidence in model predicted sea state and location of unwanted extreme waves.

Figure 3. Significant wave height from WW3 sea state model for Sept 9, 2015 at 0h UTC. (left) without surface current; (right) relative variations of significant wave height (ΔHs) when considering surface current from the CMEMS operational Mercator model (from [9] pers. com).

3 DEVELOPMENT OF THE ROUTING OPTIMIZATION TOOL

An innovative tool aiming at providing value-added surface current products currently tailored to the Mediterranean Sea, North Indian Ocean, East Asia seas, North Atlantic, South Atlantic and seas around Southern Africa is under development and testing. The products are provided both from available forecasts and from observations. A series of post-processing routines have been developed in order to help the ocean forecaster build the optimized surface current forecast. Different proxies have been defined to qualify the surface current forecast performances at each in-situ measurement location. Moreover, the comparison of models with satellite derived sea surface temperature and surface geostrophic current is used to assess the ability of the ocean models to locate the mesoscale structures (e.g. eddies, meanders fronts). This analysis provides comparison scores ranging from 1 (poor) to 5 (excellent) and is tailored to both current direction and current magnitude as indicated below.

These scores are established automatically through comparison with direct current estimation made on the bridge (e.g. Watch Reports), with surface drifters and visually by comparison with SST field. The closer
the score is to 5, the better is the agreement between
the forecast product and the observations. Hence,
according to the scores within a subregion, the routing
software (ACTIROUTE) proposes an optimized and
qualified surface current field used by external
software to select the most preferred route. Otherwise,
the most direct route is followed. In order to facilitate
the decision support for the operator which makes the
analysis of the performance of the various forecast
products, the current maps from the different
products can be overlaid and displayed in the same
SEAScope visualization portal. The operator can then
quickly verify if the products and observations are
coherent. In the same way, the scores obtained by
comparing the forecast products to the observations
are saved in a format readable by SEAScope.

4 VALIDATION

In the TOPVOYS study, new diagnostics have been
implemented to validate surface currents using tracer
observations such as the sea surface temperature and
the Chlorophyll. The position of the dynamical
current structures can then be assessed when a
satellite-based SST or Chlorophyll map is available.
The frontal structures are extracted from the tracer
image and compared with the Lagrangian Coherent
Structures derived from the surface currents. To
extract the frontal structures, an algorithm consistent
with [1] and [2] is implemented to locate the position
of the fronts as schematically illustrated in Figure 4.
For each moving window, a histogram is used to
detect different population. The points that are
separating the two population are considered as the
representation of the surface front. For each point, a
probability of having a front is then estimated by
counting the number of times it has been detected on
the moving window. A contour-following processing
on the probability for the presence of the front is then
performed to reconstruct the frontal structures.

Next, in order to compare the frontal structure
with the different available velocity products it is
necessary to compute a proxy for each velocity
product using the Finite-Size Lyapunov Exponent
(FSLE) to reveal the possible position of the tracer
gradient in the velocity field (e.g. [5, 10]). From the
FSLE image a contour following algorithm is then
applied to retrieve the corresponding frontal
structures followed by a comparison to the
corresponding fronts derived in the tracer image as
shown in Figure 5. This yields estimates of the distance
between the fronts as well as the differences in
curvature and direction and enables the selection of
the best velocity for each points along the front.

An example of the practical use of this validation
tool is shown in Figure 6. This is based on
reconstruction of a surface current field from the
satellite-based SST frontal maps (derived from
SEVIRI) followed by an interpolation onto the grid of
the surface current products derived from GlobCurrent.
The two surface current maps are then
compared and assessed for consistency and accuracy.
Only points containing frontal information are used
for this validation. The comparison demonstrates that
the mesoscale anticyclonic eddy is satisfactorily
positioned in both fields although there are slight
differences in both surface current magnitudes and
directions.

In the following a more comprehensive test case is
presented for the region extending from the Gulf of
Aden to the East of the Socotra Island. This area (see
Figure 7) encompasses various hydrodynamic features (frontal areas, mesoscale eddies, meandering
currents) that in some cases may require a potential
change in routing. The challenge is thus to precisely
locate the position of these features. Hence, the
comparison shall preferably enable the assessment of
the different products in terms of quality and
reliability in order to select the best route.
Figure 6. Comparison of independent surface current fields. The white arrows represent the surface current field derived from the SST frontal map and re-interpolated on the grid to validate against the black arrows independently derived from the GlobCurrent products.

Figure 7. Schematic hydrodynamic features in the mouth of the Gulf of Aden (extracted from [4] revealing presence of anticyclonic (A) and cyclonic (C) eddies and meandering surface currents.

The results of the comparison between the FSLE retrieved from different observation-based and model-based surface current velocity fields and the SST fronts derived from the SEVIRI product in the North-West of the Arabian Sea in February 2021 are shown in Figure 8. Inside the Gulf of Aden (yellow square), the fronts detected from the SEVIRI SST display the edges of two rings (consistent with structures in Figure 7). The distances between these SST-based fronts and the FSLE-based fronts are smaller for the HYCOM product (~20 km: blue/green color) than for Mercator or the Total Current derived from observations (~80-100 km: brown color). This implies that HYCOM model should be considered for the routing in this area. In contrast, at the mouth of the Gulf of Aden (red rectangle), the distance between the FSLE computed from the Mercator model field and the fronts detected from SEVIRI is on average smaller than the other two products.

The routing (following the ACTIROUTE software) will update its optimization procedure with these new observations (SST) by considering the metrics retrieved from the comparison between FSLE-based and SST-based frontal locations, orientation, structures and curvatures. In particular, it will penalize the local products with larger separation distance between the observed-based and model-based fronts. This work is still under progress.

Figure 8. Comparison between the FSLE-based fronts (white lines) and the observed SST-based fronts (colour). The colour represents the distance from SST to FSLE based fronts from dark blue (0 km) to dark red (80 km). Each line represents the result of one velocity field: FSLE based fronts from the observed total surface current (top), from the HYCOM model (middle) and from the MERCATOR model (bottom). The background grey-scale image is from the SEVIRI L3 SST product (missing data due to cloud cover).

5 SUMMARY

In this paper we have used near real time satellite data and in-situ data of the surface current and sea surface temperature fields for assessment and optimization of the surface current field for ship routing. It has been demonstrated that synoptic maps of surface frontal structures provide highly important products and information on meandering patterns and motions which are proxy for the surface currents dynamics, and as such allowing assessment and validation on the quality of the delivered surface current products with emphasis on the upper 10 to 20 m. Moreover, regular use of wave ray-tracing model with different surface currents will be run for simulations of rapidly changing and possibly occurrences of extreme waves invoked by wave-current interaction.
The ultimate goal is to advance the development of a decision support system for optimization of ship routing that provides a reliable traffic-light system by which indices for the pre-selected ship routes builds on regular near real time updates of:

- meandering fronts and eddies;
- rapidly changing currents;
- evolving wind sea and swell fields;
- likelihood of wave energy focusing caused by wave-current interaction;
- likelihood of crossing seas;
- likelihood of dangerous waves.

The provision of these indices will be based on the combination satellite-based and and-situ based data sources and model fields including:

- surface current from the GlobCurrent database;
- model-based surface current (CMEMS, etc)
- sea state from wave models with and without wave-current interaction;
- altimeter derived significant wave height data;
- Sentinel-1 SAR-based wave mode and interferometric wide acquisitions;
- Satellite-based sea surface temperature fields;
- ECMWF wind field and wind stress

REFERENCES

1. Cayula, J.-F., Cornillon, P.: Edge Detection Algorithm for SST Images. Journal of Atmospheric and Oceanic Technology. 9, 1, 67–80 (1992). https://doi.org/10.1175/1520-0426(1992)009-0067:EDAFSI>2.0.CO;2.

2. Cayula, J.-F., Cornillon, P.: Multi-Image Edge Detection for SST Images. Journal of Atmospheric and Oceanic Technology. 12, 4, 821–829 (1995). https://doi.org/10.1175/1520-0426(1995)012-0821:MIEDFS>2.0.CO;2.

3. Chang, Yu-Chia, Ruo-Shan Tseng, Guan-Yu Chen, Peter C Chu and Yung-Ting Shen (2013), Ship Routing Utilizing Strong Ocean Currents, The Journal of Navigation (2013), 66, 825–835. © The Royal Institute of Navigation 2013, doi:10.1017/S037346313000441.

4. Fratantoni, D.M., Bower, A.S., Johns, W.E., Peters, H.: Somali Current rings in the eastern Gulf of Aden. Journal of Geophysical Research: Oceans. 111, C9, (2006). https://doi.org/10.1029/2005JC003338.

5. Gaultier, L., Verron, J., Brankart, J.-M., Titaud, O., Brasseur, P.: On the inversion of submesoscale tracer fields to estimate the surface ocean circulation. Journal of Marine Systems. 126, 33–42 (2013). https://doi.org/10.1016/j.jmarsys.2012.02.014.

6. International Maritime Organization (IMO) IG927E Ships’ Routing, 14th Edition 2019, IM9272, ISBN: 978-92-801-0049-5 (9789280100495).

7. International Maritime Organization (IMO). Reduction of GHG emissions from ships, IMO-MEPC 61/INF.22, 2 August 2010.

8. Kim, J.-G., Kim, H.-J., and Lee, P. T. W (2013), “Optimising container ship speed and fleet size under a carbon tax and an emission trading scheme.” International Journal of Shipping and Transport Logistics, vol. 5, no. 6, pp. 571–590. DOI: 10.1504/IJSTL.2013.056835.

9. Marechal, G., Arduinu, F.: Surface currents and significant wave height variability: a numerical investigation of the Agulhas current region. Earth and Space Science Open Archive. 18 (2020). https://doi.org/10.1002/essoar.10503641.1.

10. d’Ovidio, F., Fernández, V., Hernández-García, E., López, C.: Mixing structures in the Mediterranean Sea from finite-size Lyapunov exponents. Geophysical Research Letters. 31, 17, (2004). https://doi.org/10.1029/2004GL020328.

11. Pennino, Silvia, Salvatore Gaglione, Anna Innac, Vincenzo Piscopo and Antonio Scaramarrella (2020), Development of a New Ship Adaptive Weather Routing Model Based on Seakeeping Analysis and Optimization, J. Mar. Sci. Eng. 2020, 8, 270; doi:10.3390/jmse8040270.

12. Quilfen, Y., Chapron, B.: Ocean Surface Wave-CURRENT Signatures From Satellite Altimeter Measurements. Geophysical Research Letters. 46, 1, 253–261 (2019). https://doi.org/10.1029/2018GL081029.

13. Yang, Liqian, Gang Chen, Jinlou Zhao and Niels Gorm Maløy Rytter (2020), Ship Speed Optimization Considering Ocean Currents to Enhance Environmental Sustainability in Maritime Shipping, J. Mar. Sci. Eng. 2020, 8, 270; doi:10.3390/jmse8040270.