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Ship Routing Utilizing Strong Ocean Currents

Yu-Chia Chang[1], Ruo-Shan Tseng[1], Guan-Yu Chen[1], Peter C Chu[2] and Yung-Ting Shen[1]

[1] (*Asia-Pacific Ocean Research Center, National Sun Yat-sen University, Kaohsiung, Taiwan 804*)

[2] (*Department of Oceanography, Naval Postgraduate School, Monterey, CA 93943, USA*)

(E-mail: rstseng@mail.nsysu.edu.tw)

From the Surface Velocity Program (SVP) drifter current data, a detailed and complete track of strong ocean currents in the north-western Pacific is provided using the bin average method. The focus of this study is on the Kuroshio, the strong western boundary current of the North Pacific flowing northward along the east coast of Taiwan and then turning eastward off southern Japan. With its average flow speed of about 2 knots, the Kuroshio can significantly increase the ship's speed for a "super-slow-steaming" container ship travelling at speeds of 12 knots between the ports of Southeast Asia and Japan. By properly utilizing knowledge of strong ocean currents to follow the Kuroshio on the northbound runs and avoid it on the return trip, considerable fuel can be saved and the transit time can be reduced. In the future, the detailed Kuroshio saving-energy route could be built into electronic chart systems for all navigators and shipping routers.

KEY WORDS

1. SVP drifter. 2. Kuroshio. 3. Energy-saving. 4. Route.

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1. INTRODUCTION.

Recently, global warming, weather extremes, and climate change have become hot topics in regard to the impact of actions on the natural environment and the shortage of energy resources (Barneet et al., 2005; Behrenfeld et al., 2006; Spence et al., 2011; Coumou and Rahmstorf, 2012; Shakun, et al., 2012). Increasing concentrations of greenhouse gases produced by human activities has been suggested to be a major factor (Matthews and Zickfeld, 2012; Rosa and Dietz, 2012). Thus saving energy and reducing fossil fuel consumption have become imperative for the Earth's environment.

It is generally recognized that approximately 90% of world trade is carried by about 70 000 ships that make up the international shipping industry. Most major shipping companies have expended great effort to make their ships more efficient. Fuel is the major operational expenditure for all ships and any savings in fuel can have a big impact on a shipping company.

Several major methods are available and adopted to reduce the fuel consumption in the scheduled liner shipping industry. A first measure is to lower voyage speeds from the maximum of approximately 25 knots to 80% or even 50% of the normal speed, which is known as "slow-steaming" or "super-slow-steaming". Speed reduction not only reduces fuel consumption but also decreases CO_2 emissions, according to the International Maritime Organization (IMO) (2009a). A 10% decrease in speed will result in a 19% reduction in engine power and a 27% reduction in energy consumption and thereby CO_2 emissions (IMO, 2010). Secondly, wind power is also used to save fuel through the installation of kites or sails on ships. However, this method is only valid where the wind direction is favourable, and is better in the North Atlantic and North Pacific than in the South Pacific (IMO, 2009b). Overall fuel savings are slightly greater at higher speeds, but, in terms of percentage, the fuel savings are greater at low speed, due to the low total demand for propulsion power, with about 5% at 15 knots and 20% at 10 knots (IMO, 2009b). Thirdly, according to IMO (2011), other technologies are also expected to be used for reducing future ship's fuel consumption such as optimised hull, optimisation of propellers, engine efficiency improvement, reducing on board power demand, and solar power, etc.

In addition to these methods (IMO, 2011), use of favourable ocean currents can further lower fuel consumption and reduce transit time. The vessels are sometimes accelerated and sometimes retarded by the dynamic ocean currents during their voyages. Therefore, it is beneficial to take advantage of ocean currents when they are along the planned route, and to avoid the currents when they are in opposition. The North Atlantic is probably the region with the most extensive use of ocean current information for ship routing, which was demonstrated at least as early as 1769 when Benjamin Franklin printed a chart of the Gulf Stream to expedite voyages between Europe and USA. By using fine-resolution current estimates in portions of the Gulf Stream, Lo and McCord (1995) estimated that relative average fuel savings of 7·5% could be achieved when riding favourable currents and 4·5% when avoiding unfavourable currents for vessels with an average speed of 16 knots. Another example of reducing fuel consumption of merchant ships is the St. Lawrence River in Eastern Canada. Use of the information of tidal currents from a mathematical model shows a saving of up to 25% of fuel consumption and a significant savings of transit time in the lower St. Lawrence River. (http://www.tc.gc.ca/media/documents/programs/innovationmaritime_1.pdf).

Similarly, strong ocean currents such as the Kuroshio can also be used to save operating costs in the North Pacific. The Kuroshio, the principal western boundary current of the North Pacific, is formed from branching of the North Equatorial Current off the east coast of the Philippines between 11°N and 14·5°N (Nitani, 1972). Schematic diagrams of the fragment of the Kuroshio axis were studied in previous studies (Yamashiro and Kawabe, 1996; Hsueh et al., 1997; Jian et al., 2000; Ambe et al., 2004; Centurioni et al., 2004; Yuan et al., 2006; Rudnick et al., 2011). The statistical structures of the surface ocean current speeds were also explored (Chu, 2008; 2009). However, a detailed and complete map of the Kuroshio axis has not yet been constructed. Can a Kurushio map be constructed from direct velocity measurements taken over an extended period? Can this information be used for ship routing and voyage planning, given a high priority in ship operations? How significant is the fuel

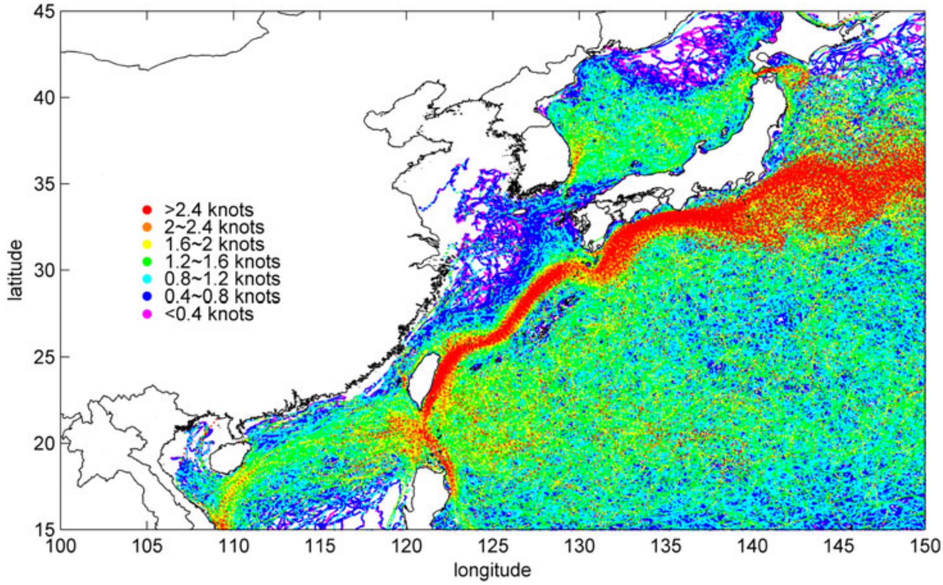

Figure 1. Locations of drifters colour-coded in accordance with their 6-hourly instantaneous speed.

saving after the detailed ocean circulation is constructed? The purpose of this paper is to determine an energy-saving route for all types of ships using near surface ocean circulation data. To do so, the SVP drifter data for the north-western Pacific are used to build a detailed and complete map of the Kuroshio axis in East Asia.

2. DATA.

Direct velocity measurements in the oceanic mixed layer were obtained with Argos satellite-tracked drifters drogued at a nominal depth of 15 m. The positions of each drifter, interpolated to 6-hour intervals, were used to construct the velocity vectors and were obtained online from the NOAA/AOML website, http://www.aoml.noaa.gov/phod/dac/dacdata.html. It was estimated that the velocity measurements have a nominal accuracy of 0·02 knots for wind speeds less than 19·4 knots (Niiler et al., 1995). From 1985 to 2009, a total of 1655 drifters were deployed in, or drifted into the studied region in the north-western Pacific delimited by 15°–45°N, 100°–150°E, resulting in a total of 900 835 6-hourly velocity observations.

3. RESULT.

The ensemble of the individual drifter locations were plotted in Figure 1, colour coded in accordance with the local instantaneous speed. The strongest current system of the north-western Pacific is the Kuroshio, made apparent by speeds greater than 2 knots. Formed from a branching of the North Equatorial Current, the Kuroshio is intensified east of Luzon and Taiwan. This strong ocean current has a wave-like shape as it moves north-eastward along the south coast of Japan. As the Kuroshio propagates further downstream, its flow speed and width also grow. The ensemble mean velocity field, computed from simple averaging (Centurioni and Niiler, 2003; Centurioni et al., 2004) in 0·5° × 0·5° wide bins and is shown only for

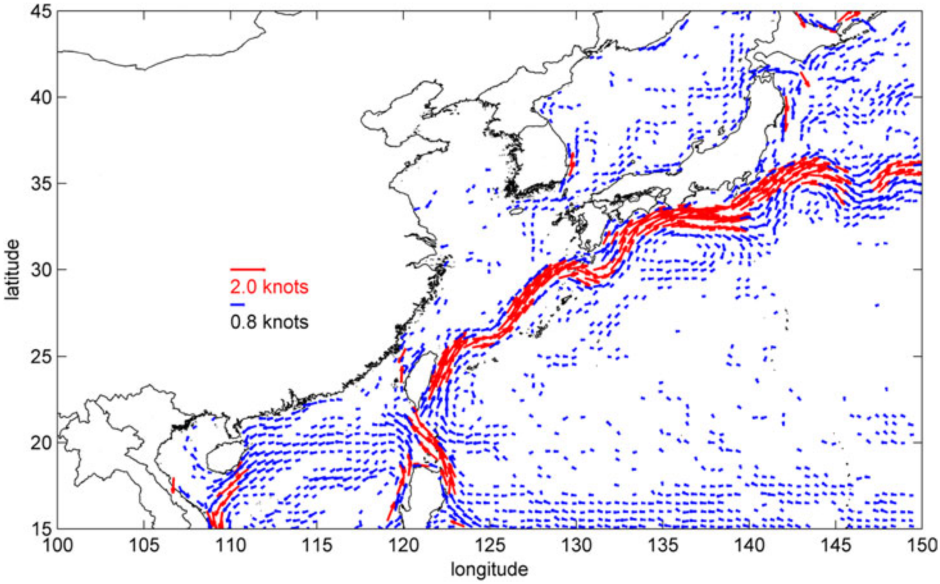

Figure 2. Averaged drifter velocities in 0·5° × 0·5° bins with more than 7 observations. Speeds higher and lower than 0·8 knots are shown in red and blue, respectively.

bins with more than seven observations (Figure 2). Along the east coast of Luzon and Taiwan and off Southern Japan, drifter-measured velocities are often greater than 2·4 knots. A detailed and complete map of the Kuroshio axis is shown for a relatively long time period (25 years, 1985–2009) of direct velocity measurements, useful for optimal ship routing and voyage planning.

To provide ship routers with more details of the primary path of the Kuroshio at different locations, enlargements of bin-averaged drifter vectors in 0·25° × 0·25° bins are plotted in the Luzon Strait, East China Sea, and south of Japan, respectively (black arrows: >0·8 knots; 0·2 knots < grey arrows ⩽0·8 knots). The detailed and complete path of the Kuroshio axis will be described in the following section. Approximately 100 km wide and with speeds of over 1 knot, the Kuroshio flows northward along the east coast of Luzon. Due to the gap of the Luzon Strait (LS), the surface Kuroshio often makes intrusions and the dominant path is from northeast of Luzon to southwest of Taiwan, as was also evidenced from satellite altimeter data (Yuan et al., 2006). The Kuroshio passes by Babuyan island (121° 57′E, 19° 31′N) in the LS (Figure 3), turns toward the north northeast at 21·2°N, and goes around Green Island (121° 29′E, 22° 39′N) off eastern Taiwan. From there the Kuroshio develops into a strong current moving northward along the east coast of Taiwan. As the Kuroshio approaches 25·7°N near Taioyutai island (also named Semkaku Retto island), it starts to change direction to flow eastward (Figure 4). Afterward, the Kuroshio begins to veer round to the northeast at 125·0°E. At 29·8°N, due to Yakushima island (130° 31′E, 30° 21′N) and Tanegashima island (131° 00′E, 30° 36′N), the Kuroshio axis presents a “S”-shape. The Kuroshio flows broadly between 25°N and 30°N along the continental slope of Okinawa trough (Figure 4). After bypassing Yakushima and Tanegashima islands, the north-eastward flowing Kuroshio is close to the south coast of Japan (Figure 5). It changes into eastward

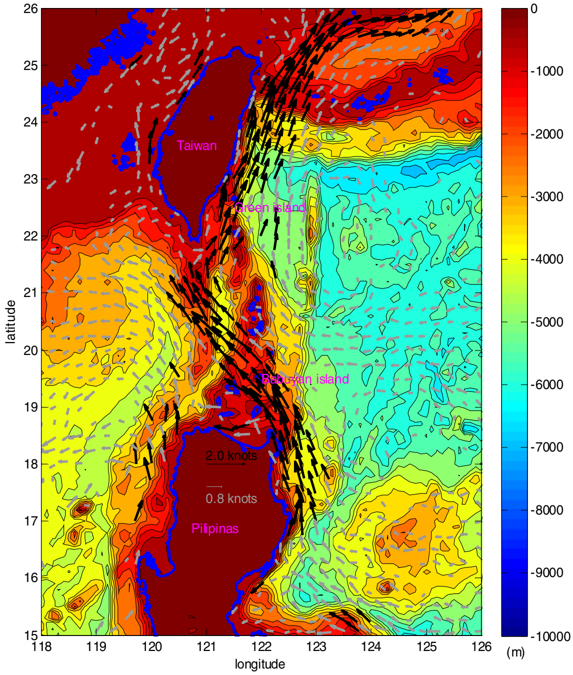

Figure 3. Enlargement of bin-averaged velocity east of Luzon and Taiwan.

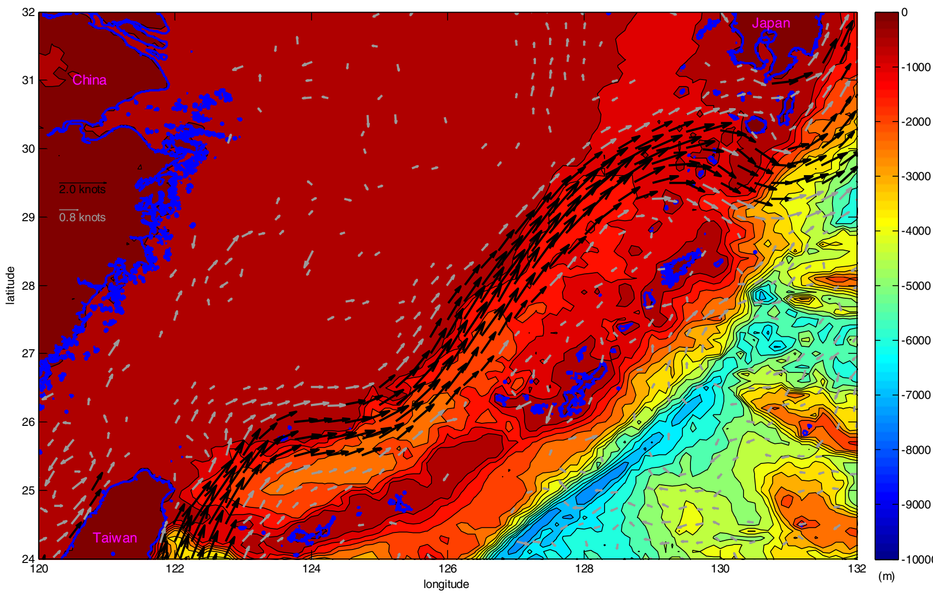

Figure 4. Enlargement of bin-averaged velocity in the East China Sea.

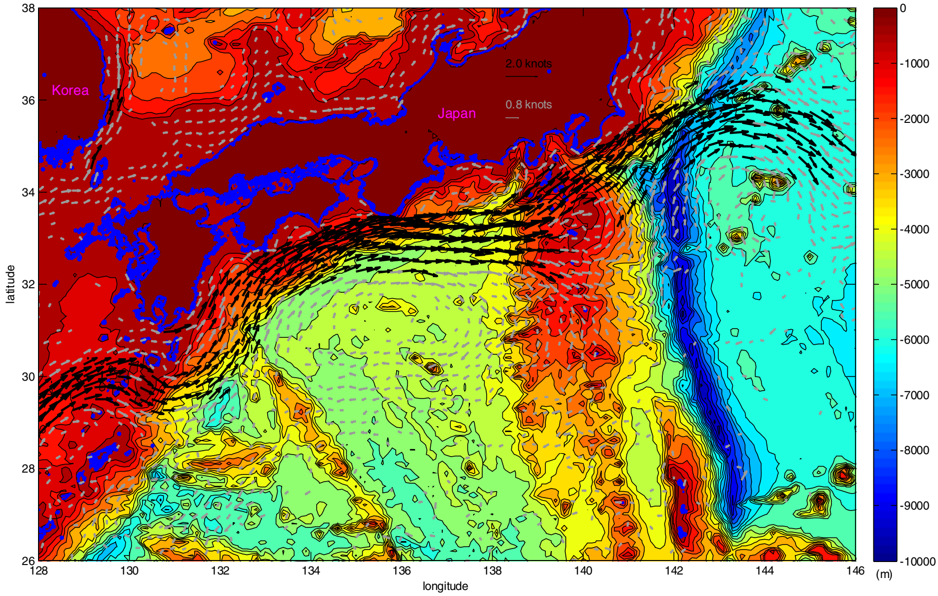

Figure 5. Enlargement of bin-averaged velocity in south of Japan.

flowing until reaching the location of 135·5°E, 33°N, then becomes east north-eastward flowing, and flows around the Miyake island (139° 31′E, 34° 05′N). Finally, it flows forward with a wave shape at 35·5°N. A detailed and complete picture of the ocean current and its geographic position with respect to the surrounding islands have been clearly described, and can be applied to route design and voyage planning.

4. DISCUSSION. Currently there are several shipping routes in East Asia passing through the Kuroshio region (Shipping & Transport Website, 2013). These shipping routes and the connecting ports are (1) Taipei to Tokyo (downstream, JTT), (2) Nagoya to Hong Kong (upstream, NTE), (3) Shekou to Tokyo (downstream, NTE), (4) Taipei to Osaka (downstream, JTH), (5) Hong Kong to Osaka (downstream, NSA), as shown in Figure 6. The relative density of commercial shipping for various shipping routes in East Asia is shown in Figure 7 (Halpern et al., 2008; Wikipedia website, 2013). It is clearly illustrated that these shipping routes were determined based primarily on the shortest distance between destination ports, without considering the effect of strong ocean currents. To distinguish the strong ocean currents and identify their locations in East Asia, we have reanalysed the 6-hourly position and velocity drifter data and obtained the spatial distribution of strong currents. Figure 8 illustrates the average locations and speeds of strong currents in the north-western Pacific, defined as the bin-averaged speeds over 0·8 knots, over a period of 25 years. A detailed and complete map of the Kuroshio main stream is clearly illustrated. The maximum speed of the Kuroshio is approximately 2·4 knots, which appears off the south coast of Japan. Maps of strong ocean currents such as Figure 8 can be used for the optimization of shipping routes. For ships taking northbound routes it would be beneficial to take advantage of the favourable strong

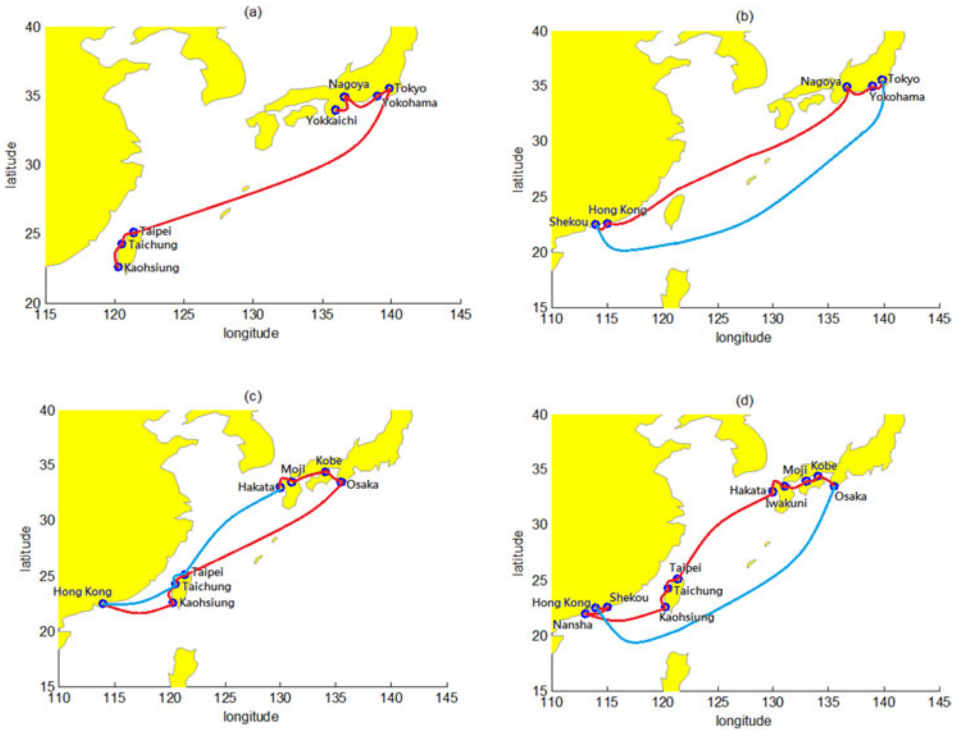

Figure 6. Several current intra-Asia shipping routes: (a) Taiwan-Japan Kanto Service, JTT; (b) Japan-Thailand Service, NTE; (c) Japan-Taiwan-Hong Kong Service, JTH; (d) North East Asia-South East Asia Service-A, NSA (Shipping & Transport Website, 2013).

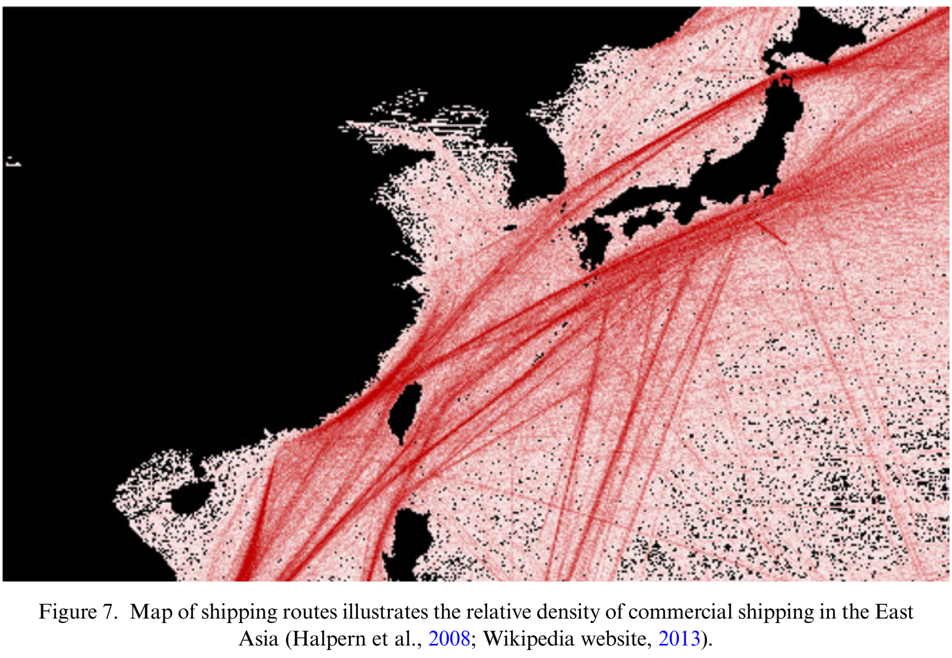

Figure 7. Map of shipping routes illustrates the relative density of commercial shipping in the East Asia (Halpern et al., 2008; Wikipedia website, 2013).

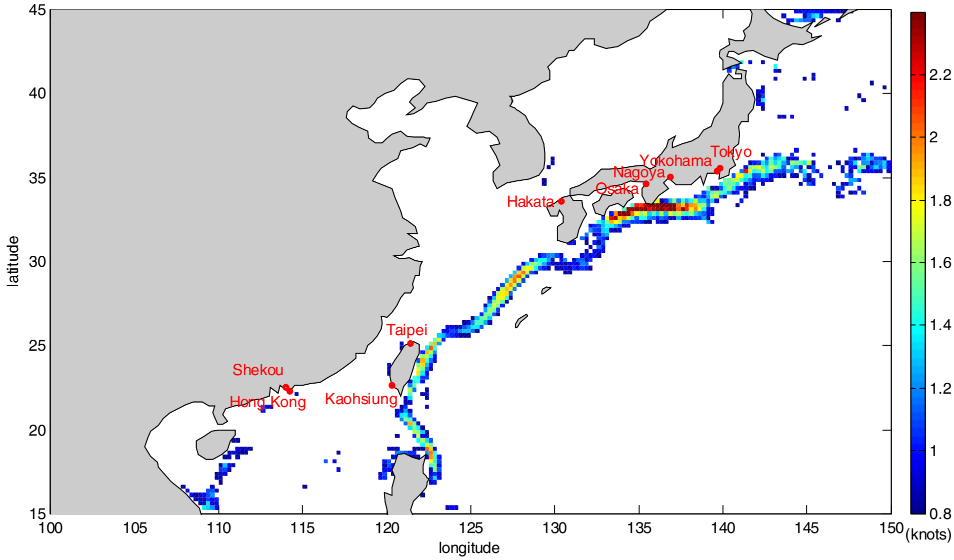

Figure 8. Positions and speeds of the strong ocean currents colour-coded in accordance with their bin-averaged speed in the East Asia.

current of Kuroshio, and avoid it on their return trips. The map of strong ocean currents could be built into electronic chart systems in the future.

To reveal the importance of a strong ocean current map in the optimization of ship routing, a route between Taipei and Tokyo is studied. The straight, most-direct route between these two ports has a distance of 1092·4 nm (red line in Figure 9), and the time it takes to complete this northbound voyage is 87·9 hours at a "super-slow-steaming" speed of approximately 12 knots, with some speed gains from the favourable Kuroshio along the route. Because the return trip of the straight route opposes strong currents, it will take longer (103·2 hours) to complete the southbound voyage at the same ship speed. Now taking into consideration the strong ocean currents, a northbound route (magenta line) that takes advantage of the along-route Kuroshio, and a southbound route (cyan line) that avoids the opposing Kuroshio, is proposed as a better alternative. For the northbound voyage, although an extra mileage of 14 nm will be added to the initial route, the transit time will be reduced by 1·7 hours, or 1·8%, due to the gain of ship speed from the Kuroshio. On the other hand, the return leg will shave 5·9 hours off the initial 103·2-hour trip (or a saving of 5·7%) despite the extra mileage of 3 nm added to the route. This example indicates that the saving of transit time or the equivalent fuel consumption is more pronounced in avoiding the adverse current on the return trip than following the Kuroshio on the northbound route.

5. CONCLUSION.

Theoretically, following the Kuroshio with a speed of 2 knots can increase significantly the ship's speed on a northbound route for the 'slow-steaming' container ships at a sailing speed of 20 knots, or even more pronounced for the 'super-slow-steaming' container ships at a sailing speed of 12 knots. Therefore, following the favourable Kuroshio on a northbound shipping route and avoiding it on the return trip can save considerable fuel and minimize the transit time for many types

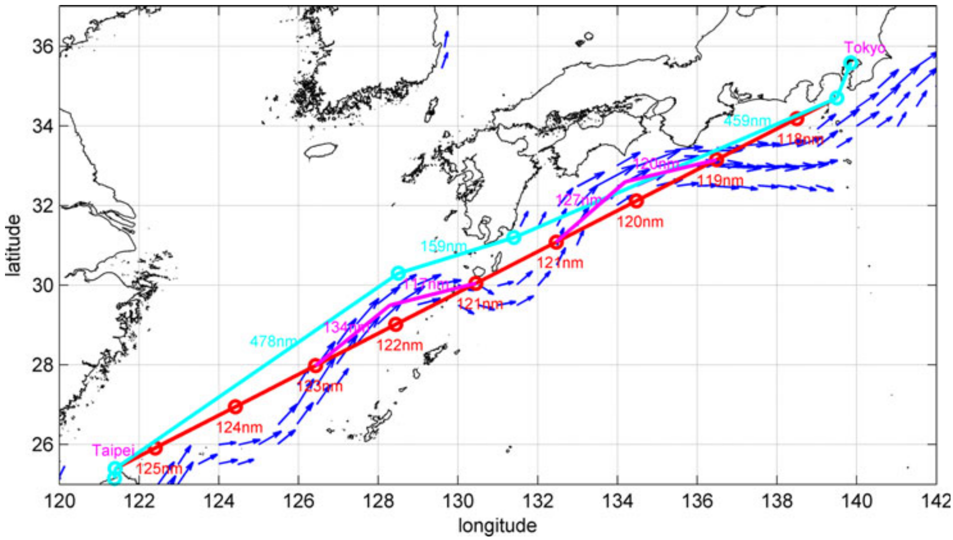

Figure 9. Ship routing laid over bin-averaged strong currents between Taipei and Tokyo. The red line represents the initial proposed straight route. The recommended magenta line takes advantage of strong, along-route currents, and cyan line avoids the Kuroshio on the return leg. See text for details.

of vessels. Knowledge of the Kuroshio dominant path can be beneficial for all ship routers and captains. Take a 1100 nm-long route between Taipei and Tokyo for instance, our proposed route, based on the combination of the shortest distance and the Kuroshio, can save only 1·8% of transit time when riding favourable currents, but a more significant saving of 5·7% in transit time can be achieved when avoiding unfavourable currents on the return leg at "super-slow-steaming" speeds.

The effect of wind and waves has long been considered to be a primary factor in determining optimal ship routes. The effects of dynamic currents have been largely neglected in early strategic routing studies, because there is no practical way to provide reliable and timely estimates of a dynamic current pattern. In this study, a detailed and complete map of strong ocean currents in the East Asia area is provided for ship routing and voyage planning from analysis based on all historical SVP drifter velocity data between 1985 and 2009. Although our analysis only produces a mean flow pattern of Kuroshio without temporal variations, the spatial resolution is sufficiently fine due to the large number of drifter data analysed. Future work incorporating some timely current variations derived from numerical modelling into the mean drifter velocity route will be beneficial to more effective ship routing. In the future, the energy-saving route could be built into electronic chart systems. Application of these routes could help to reduce greenhouse gas emissions, fuel consumption and minimize transit time.

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