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Revisiting the leeway of shipping containers: a case study of the M/V Zim Kingston incident

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Abstract

On 22 October 2021, 109 shipping containers fell overboard from the M/V Zim Kingston in rough seas off the coast of Vancouver Island, British Columbia, Canada. While afloat, these shipping containers pose a significant risk to marine traffic in addition to being a source of marine pollution. Out of the 109 shipping containers, 4 were discovered on the beaches of northwest Vancouver Island 5 days later. Drift simulations were made using the standard leeway tables for shipping containers that vary with the immersion fraction of the shipping container. These leeway values over the expected range of immersion levels underestimated the travelled distance of the shipping containers relative to the observed grounding locations. An increase in the leeway of 1.5% of the wind speed improves the agreement between the simulations and observations, which is consistent with the addition of the Stokes drift to the leeway of the shipping container. It is argued that the leeway measured using the direct method, which was used to calculate the leeway of shipping containers, does not implicitly include the Stokes drift as previously suggested. This result suggests that the Stokes drift should be added to the leeway calculated with the direct method. While the error is small over timescales of 24 to 48 h, it accumulates in time and is appreciable for drift prediction greater than 48 h.

Keywords Leeway · Drift · Shipping container · Stokes drift · Marine pollution · Marine emergency

1 Introduction

Shipping containers pose a significant risk to the marine environment when they fall from the container vessels transporting them. While afloat, these shipping containers pose a risk to marine traffic as they can be difficult to spot and can cause damage when struck. If the containers sink or run aground, the contents are no longer contained in the shipping container and can pollute the local flora and fauna. On 22 October 2021, at approximately 20:00 UTC, 109 shipping containers fell overboard from the M/V Zim Kingston during severe weather off the west coast of British Columbia. Of the 109 shipping containers from the M/V Zim Kingston, only 4 were found ashore while the other 105 containers are believed to have sunk to the sea floor.

Accurate prediction for the drift of shipping containers is a key component of emergency response operations. Shipping containers, like most objects adrift in the sea, do not drift passively with the ambient current, but rather have their own dynamic response to the forcing from the wind, ocean currents and waves. The shape and buoyancy of the drifting object will determine the relative importance of atmosphere and ocean forcing on the drift trajectory. This response of the drifting object relative to the ambient current is commonly referred to as the leeway, and is modelled as a linear function of the wind (Breivik et al. 2011). The linear regression coefficients, more commonly known as the leeway coefficients, are determined from dedicated experiments (Allen and Plourde 1999). It is assumed in these experiments that the leeway is relative to the Eulerian ambient current and that any wave effects, such as the Stokes drift (Kenyon 1969) or direct wave forcing on the object, are included implicitly in the leeway calculation (Breivik et al. 2011). In the ocean, the direct wave forcing can be neglected for objects with linear dimensions

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less than 30 m (Breivik et al. 2011). However, the Stokes drift will still be present and should be accounted for in the leeway.

The leeway coefficient for a shipping container was first formally derived by Daniel et al. (2002). This derivation is based on a steady-state solution with a known drag coefficient above and below the mean waterline. This relative drag between the air and water sides is strongly dependent on the immersion of the shipping container. Wave forcing is not explicitly included in the derivation, but Daniel et al. (2002) argue that any wave effects could be implicitly included in the air side drag coefficient. The leeway of a shipping container is estimated to range from about 5% of the 10 m wind speed at an immersion level of 40% and decreases to 0 at 100% immersion (Daniel et al. 2002).

Breivik et al. (2012) performed field experiments with shipping containers equipped with current meters and wind anemometers to verify the leeway of Daniel et al. (2002). The direct method is used to calculate the leeway coefficient for the shipping container (Breivik et al. 2011). The method derives its name due to it directly measuring the velocity difference between the object and the ambient current. This method contrasts with the other method for leeway determination, the indirect method, which measures the object velocity and ambient current independently to obtain the velocity difference. As the measurements in the direct method are made in the Lagrangian reference frame of the object it is not clear whether the Stokes drift (van den Bremer and Breivik 2018) is included in the relative velocity or not. While the Stokes drift is predominantly aligned with the wind and can be incorporated into a leeway coefficient for an object (Breivik et al. 2011), it remains to be seen if this correction is included in the leeway calculation using the direct method or if it needs to be added as an additional bias. The Stokes drift is typically about 1.5% of the wind speed (Ardhuin et al. 2009), which is comparable to the uncertainties associated with the direct method (Breivik et al. 2011). As the Stokes drift represents a bias in the leeway coefficient, the error in the object trajectory will accumulate over time. For example, a typical wind speed of 7 m/s corresponds to a trajectory bias of 378 m/h. Such a bias is small over the duration of several hours, which are typical of a lot of leeway experiments (Breivik et al. 2012). For the 5-day duration associated with the shipping containers from the M/V Zim Kingston, this bias would reach 45 km for this typical wind speed.

This paper explores the use of the shipping container leeway coefficients derived by Daniel et al. (2002) and verified by Breivik et al. (2012) and applies them to the drift and subsequent grounding of 4 shipping containers from the M/V Zim Kingston incident. This incident provides an opportunity to verify the shipping container leeway coefficient over a 5-day duration. The outline of the paper is as follows. Section 2 reviews the methodology behind the leeway determination using the direct method in order to assess whether the Stokes drift is implicit in the method or not. Section 3 describes the details of the incident and presents the data and methodology used for trajectory predictions of the shipping containers. Results from the simulations and comparisons with observations are presented in Sect. 4. A discussion of the results are presented in Sect. 5 followed by the conclusions in Sect. 6.

2 Leeway and the leeway field method

An additional wind-induced drift, i.e. the leeway, is often a crucial component of accurate drift prediction for objects at the ocean surface (Breivik et al. 2011). The leeway is due to the combined forces of the wind, waves and ocean currents acting on the drifting object (Allen 2005). The relative strength of each of these forces is a complex function of the shape and buoyancy of the object and is predominantly calculated from direct measurements during specifically designed field experiments (Breivik et al. 2011). To ensure that operational centres have a consistent definition for the leeway, (Allen and Plourde 1999) proposed the following standard definition:

> Leeway is the motion of the object induced by wind (10 metre reference height) and waves relative to the ambient current (between 0.3 and 1.0 metres depth).

This operational definition is important as the reference height/depths are consistent with values provided by forecast products and can easily be incorporated into trajectory models. Although not explicit in the definition, the motion of the object is Lagrangian while the wind and ambient current are assumed to be Eulerian. This distinction is important at the sea surface where surface waves exist as the Lagrangian and Eulerian currents are not equivalent here. The difference in the mean current between the Lagrangian and Eulerian reference frames is called the Stokes drift (van den Bremer and Breivik 2018), and can be expressed as

$$\mathbf{u}_S = \mathbf{u}_L - \mathbf{u}_E \qquad (1)$$

where the subscripts S, L and E refer to the Stokes, Lagrangian and Eulerian velocities respectively. As winds and currents provided by environmental prediction systems are on Eulerian grids, it is prudent to provide the leeway relative to Eulerian fields. This distinction between Eulerian and Lagrangian reference frames will be explored further with regard to the two methods used for calculating the leeway (Breivik et al. 2011) in the rest of this section. Specifically, is the leeway measured by the direct method relative to the Lagrangian or Eulerian ambient current?

The time evolution of the horizontal position, i.e. trajectory, of an object with an effective water depth of z_o from an initial location $\mathbf{x}_o$ at time $t = 0$ is given by,

$$\mathbf{x}(z_o, t) = \mathbf{x}(z_o, 0) + \int_0^t \mathbf{u}_L(\mathbf{x}(z_o, t), t)dt, \quad (2)$$

where $\mathbf{u}_L$ is the Lagrangian velocity along the trajectory of the object. For an object at the ocean surface there may be an additional leeway, depending on the shape and buoyancy of the object, which can be expressed as $\alpha_\ell \mathbf{U}_{10}$ where $\mathbf{U}_{10}$ is the wind velocity referenced to 10 m height. As the Stokes drift may be written as a linear function of the wind velocity, i.e. $\mathbf{u}_S = \alpha_S \mathbf{U}_{10}$, we can use (1) to write the classic leeway equation for $\mathbf{u}_L$ as a function of the Eulerian ambient current as

$$\mathbf{u}_L(z_o) = \mathbf{u}_E(z_o) + \alpha \mathbf{U}_{10}, \quad (3)$$

where $\alpha = \alpha_\ell + \alpha_S$ is the combined effective leeway due to the leeway relative to the Lagrangian velocity and the approximation of the Stokes drift as a linear function of the wind. In (3) the time and space dependence of $\mathbf{u}_L$ is implicit. There can exist more complex interactions with the wave field, but for objects much smaller than the dominant wave length they can be neglected. Breivik et al. (2011) state that direct wave forcing can be neglected for objects with a length less than 30 m.

There are two methods that are used to calculate the leeway of an object: the indirect and the direct method (Breivik et al. 2011). Both methods are based on the same leeway model (3) to calculate the leeway coefficient. Where the two methods differ is in how they measure the relative velocity of the object to the ambient current. This relative velocity is the leeway of the object and is also referred to as the slip velocity.

The indirect method measures the object velocity and the ocean current independently. The object velocity is typically measured by tracking the object and calculating the change in location with time. To measure the ocean current, there have been many methods used historically to do this such as current meters, surface drifters with known leeway properties or even other objects and debris floating in the vicinity. The slip velocity is then calculated by taking the difference between the two independent velocity measurements of the drifter and the currents. While the indirect method is relatively simple to implement, it does suffer from some well-known errors that make it difficult to accurately measure the leeway (Breivik et al. 2011). The errors arise from a variety of sources such as velocity differences between the object location and the current meter location, in addition to the combined resolution errors of the object location and the current meter when calculating the slip velocity. For measurement platforms fixed in space, such as a current meter, the reference current is Eulerian and the measured leeway will implicitly include the Stokes drift. It is slightly more complicated when using drifters to measure the ambient current as the leeway is relative to the leeway of another object. In addition, the trajectories will diverge at some point, which limits the duration of the experiment.

The direct method measures the slip velocity directly from the drifting object. This method became possible as current meters became lighter to be added directly to the object, or towed closely behind, while not interfering with the drift properties (Breivik et al. 2011). The direct method significantly reduces the error associated with the linear fits of the leeway parameters (Allen and Plourde 1999). The primary reason for the reduced error is due to the direct measurement of the slip velocity and the co-location of the object and ambient current for the entire duration of the experiment. Since the 1990s, the direct method has become the predominant method to measure the leeway of drifting objects (Breivik et al. 2011). However, as the slip velocity is measured in the Lagrangian reference frame of the drifting object, it stands to reason that the ambient current in the leeway calculation is the Lagrangian velocity and not the Eulerian velocity. If true, this implies that the Stokes drift is not implicit in the leeway measurement using the direct method.

To investigate the leeway calculation using the direct method further, we write out the equation for the measured slip velocity ($\mathbf{u}_{sl}$), i.e. the relative velocity of the drift object relative to the ambient current, as

$$\mathbf{u}_{sl} = \mathbf{u}_L(z_o) - \mathbf{u}_w(z_m) = \alpha_{\mathrm{DM}} \mathbf{U}_{10}, \quad (4)$$

where $\mathbf{u}_{sl}$ is the difference between the Lagrangian velocity of the object at an effective object depth of z_o, $\mathbf{u}_L(z_o)$, and the ambient water velocity, $\mathbf{u}_w(z_m)$, is measured at depth z_m and is assumed from the leeway definition to be between 0.3 and 1.0 m. The leeway estimated with the direct method, $\alpha_{\mathrm{DM}} \mathbf{U}_{10}$, is calculated using a least-squares fit of the slip velocity and $\mathbf{U}_{10}$. Downwind and crosswind components are computed independently with the direct method, but as this study is interested in the downwind bias, only the downwind component is investigated.

An object drifting with a relative velocity to the ambient current is analogous to an AUV (Autonomous Underwater Vehicle) travelling at a defined velocity relative to the ambient current. In a study about ocean current measurements made from an ADCP (Acoustic Doppler Current Profiler) mounted on an AUV, Amador et al. (2017) showed that if the AUV velocity relative to the water is small compared to the phase velocity of the surface waves then the ADCP will measure a positive bias equal to the Stokes drift at the object depth z_o. As the phase velocity for typical ocean waves is the order of 10 m/s, and drifts are less than 1 m/s, then this condition is well satisfied. Using the results of Amador et al. (2017) that the measured velocity includes the Stokes drift of the object, the measured water velocity relative to the earth coordinate system is

$$\mathbf{u}_w(z_M) = \mathbf{u}_E(z_m) + \mathbf{u}_S(z_o), \quad (5)$$

where $\mathbf{u}_E(z_m)$ is the Eulerian velocity at depth z_m and $\mathbf{u}_S$ is the Stokes drift at depth z_o. This result was later shown by Herrera-Vázquez et al. (2023) to be expected for moving platforms in the presence of waves (Herrera-Vázquez et al. 2023).

Substituting (5) into (4) gives the leeway equation, as measured by the direct method, to be

$$\mathbf{u}_L(z_o) = \mathbf{u}_E(z_m) + \mathbf{u}_S(z_o) + \alpha_{\mathrm{DM}}\mathbf{U}_{10}. \quad (6)$$

If the underlying assumption is correct, that the Stokes drift is aliased in ADCP measurements from a moving platform, then the leeway calculated with (6) does not implicitly include the Stokes drift when using the direct method. Therefore, the direct method is underestimating the leeway by a value equivalent to the Stokes drift of the object, which is typically 1.5% of the 10 m wind velocity (Ardhuin et al. 2009; Jones et al. 2016). A constant bias in the velocity corresponds to a bias in the trajectory that increases linearly in time. For example, 1.5% of a typical wind speed of 7 m/s is equal to 0.11 m/s and equates to a bias of 9 km/day. While not large compared to other uncertainties, as it is a bias it will accumulate to a significant distance over several days.

3 Data and methods

3.1 M/V Zim Kingston incident

At 20:00 UTC (10:00 PT) on the evening of 22 October 2021, the M/V Zim Kingston was about 800 km and 3 days out from its predicted arrival when it encountered severe weather with wind gusts up to 44.5 m/s (160 km/h) and a sea state with 5 m significant wave height. The vessel heeled 35 degrees and 109 shipping containers entered the water. During this time, a fire erupted aboard the M/V Zim Kingston which took 5 days to control. It appears many of the shipping containers were damaged during this incident (Fig. 1). Of the 109 shipping containers that went overboard from the M/V Zim Kingston, only 4 of these have been located and it is believed that the remaining 105 have sunk to the sea floor. Each shipping container is a standard 40-foot container with dimensions 40 × 8 × 9.5 ft (12.2 × 2.4 × 2.9 m).

Observations of the floating shipping containers were provided by the National Aerial Surveillance Program (NASP) of Canada and the efforts of the United States Coast Guard (UCSG). Due to the weather conditions and the continuing fire aboard the M/V Zim Kingston, visibility was low and only a few floating objects were observed (Fig. 2). Overflight data is available on 27 October 2021 and 4 shipping containers were observed with three on the shore and one less than 2 nautical miles from the shore (Table 1). Images of two of the grounded shipping containers can be seen in Fig. 2.

3.2 Trajectory modelling

3.2.1 Environmental forcing

Meteorological data are provided by the High-Resolution Deterministic Prediction System (HRDPS; Milbrandt et al. 2016), which is a Numerical Weather Prediction system run operationally at ECCC. HRDPS covers all of Canada and the neighbouring coastal water with a horizontal resolution of 2.5 km. The dynamical core of HRDPS is the Global Environmental Multiscale (GEM) model, which is a non-hydrostatic model that solves the fully compressible Euler

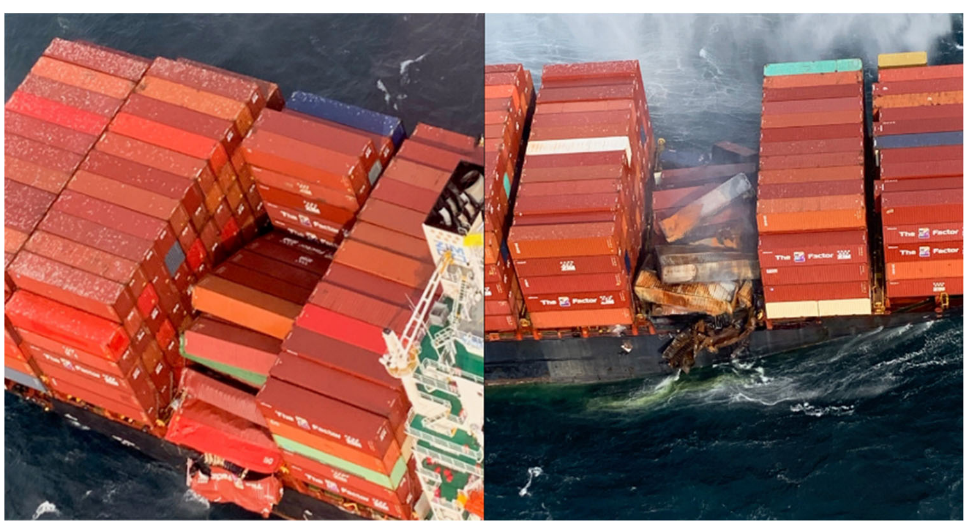


Fig. 1 Images of the M/V Zim Kingston from 24 October 2021 showing damaged and burning shipping containers. Photos courtesy of the government of British Columbia

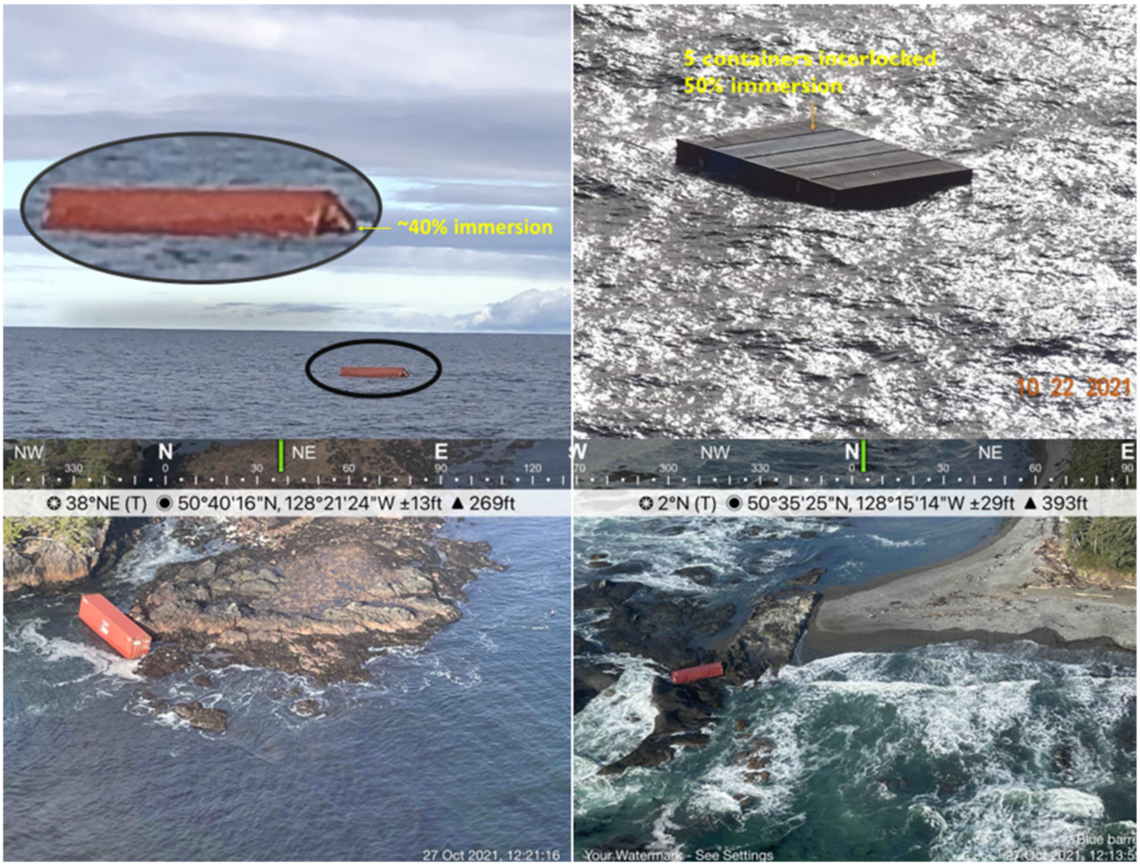


Fig. 2 Observations of shipping containers. The top two images show observations of shipping containers afloat on 22 October 2021 and are courtesy of the United States Coast Guard (UCSG). The bottom two images are of grounded shipping containers observed on 27 October 2021 and are courtesy of the National Aerial Surveillance Program (NASP) of Canada

equations (Côté et al. 1998a, b; Girard et al. 2014). The 10 m wind velocity from HRDPS is available at hourly resolution.

Oceanographic data are provided by the Canadian Ice-Ocean Prediction System West (CIOPS-W; Paquin et al. 2021), which is run operationally at ECCC. CIOPS-W is a regional model that covers the west coast of Canada with a horizontal resolution of 1/36° and 75 vertical levels. The vertical resolution is fixed with 1 m spacing at the surface and gradually increasing to 400 m at 5000 m depth. Only the surface layer from CIOPS-W is used, which is equivalent to the mean over the upper 1 m. CIOPS-W uses a spectrally nudging method to adjust results with the 1/12° Regional Ice-Ocean Prediction System (RIOPS; Dupont et al. 2015), which does use data assimilation and performs a daily analysis. Oceanographic fields from CIOPS-W are available with an hourly resolution.

The forecast ocean surface currents from CIOPS-W (Fig. 3) were predominantly heading northwest along the coast of Vancouver Island. This is consistent with the NASP observations for the direction of the drifting shipping containers from the M/V Zim Kingston. The forecast winds from HRDPS were typically from the west/southwest with a storm passing through 24 October 2021 where the winds were strong and coming from the southeast (Fig. 3d). When the

Table 1 Dates and locations of the grounded shipping containers

Date	Latitude (°N)	Longitude (°W)	Notes
2021-10-27	50.591	128.257	Ashore in Raft Cove
2021-10-27	50.600	128.264	Ashore in Cape Palmerston
2021-10-27	50.672	128.358	Ashore in San Josef Bay
2021-10-27	50.862	128.171	Adrift north of Christensen Point

Data provided by the National Aerial Surveillance Program (NASP) of Canada

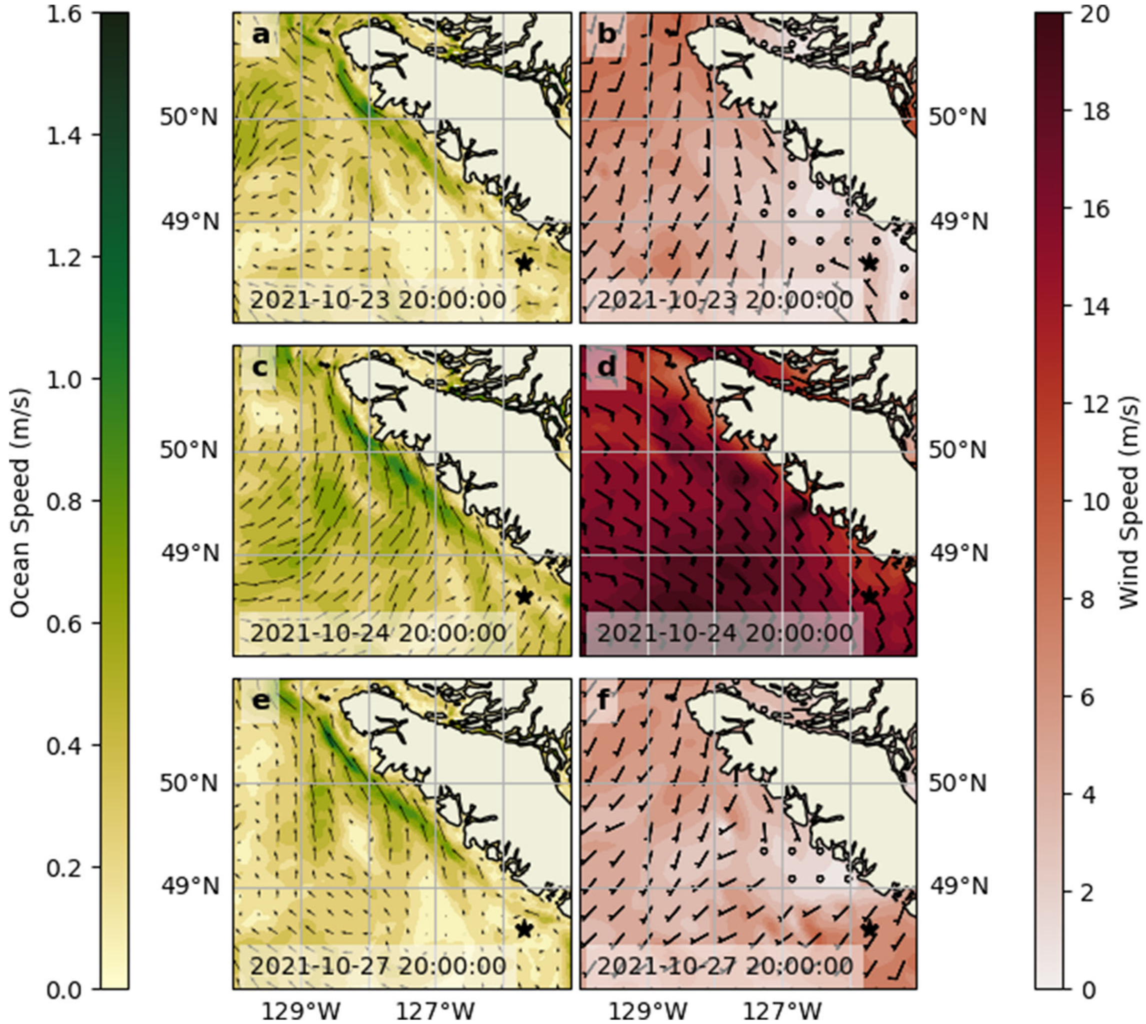


Fig. 3 Snapshots of the ocean surface currents (**a**, **c** and **e**) and 10 m wind speeds (**b**, **d** and **f**) at different times during the incident. The black star shows the location of the initial incident. All times are in UTC

shipping containers were observed on the beach (27 October 2021 at 20:00 UTC) the winds were moving onshore (Fig. 3f). This onshore wind is crucial as the wind forcing, which includes the impact of surface waves, is the primary mechanism, other than the simulated turbulent motion, that can cause the shipping containers to drift aground (Pawlowicz 2021).

3.3 Lagrangian particle tracking

Lagrangian trajectories of shipping containers are simulated with MLDPn (Modèle Lagrangien de Dispersion de Particules d'order n), which is the dispersion model developed and used at ECCC for atmospheric dispersion (D'Amours et al. 2015) and adapted for aquatic use (Paquin et al. 2020; Sutherland et al. 2021; Chang et al. 2020). MLDPn takes the environmental forcing and interpolates these fields to the time and location of the object. The Lagrangian position is obtained by integrating the Lagrangian velocity using a fourth-order Runge-Kutta advection scheme. To account for stochastic turbulent processes which occur at scales below those resolved by numerical forecast products, a random walk is introduced with a horizontal diffusivity of $K_H = 1.0\,\mathrm{m}^2/\mathrm{s}$. Each simulation begins with a uniform distribution of 1000 particles within a radius of 1 km at the location of the M/V Zim Kingston incident. The simulations begin at 22 Oct 2021 20:00 UTC and the trajectories are tracked for 5 days until 27 Oct 2021 20:00 UTC.

3.3.1 Leeway of shipping containers

The leeway coefficient for a shipping container is highly sensitive to the immersion (I) of the container, which is the fraction of the shipping container below the mean waterline (Daniel et al. 2002; Breivik et al. 2011). The immersion can be expressed as a function of the cross-sectional area below (A_w) and above (A_a) the mean waterline as

$$I = \frac{A_w}{A_w + A_a}. \tag{7}$$

The leeway model for a shipping container with immersion I is given by Daniel et al. (2002),

$$\alpha = \frac{1 - I - \sqrt{rI(1-I)}}{1-(1+r)I}, \tag{8}$$

where r is defined by the relative density (ρ) and drag coefficients (C) in water and air as

$$r = \frac{\rho_w C_w}{\rho_a C_a}, \tag{9}$$

where the subscripts w and a denote the water and air sides respectively. Breivik et al. (2011) simplified (8) to

$$\alpha \approx \sqrt{\frac{1}{r}\frac{1-I}{I}}, \tag{10}$$

which is within 5% of (8) for typical immersion levels. As this difference is expected to be much smaller than uncertainties related to I and r, we will follow Breivik et al. (2011) and use the simpler form of (10).

Assuming that the drag coefficients on the air side and the water side are equal, i.e. $C_a = C_w = 1$, and using nominal values for the densities of $\rho_a = 1.3$ kg m^{-3} and $\rho_w = 1025$ kg m^{-3} give a mean value of $r = 788$. Even relatively large variations in r on the order of 30% have a small impact on the leeway coefficient compared to errors in immersion (Fig. 4).

To account for the Stokes drift, a value of 1.5% is added to the downwind leeway coefficient of Breivik et al. (2012) (Fig. 4, dashed line). While the Stokes drift is a function of the surface waves, it is specifically proportional to the wave steepness squared (Kenyon 1969) which is dominated by the local wind-driven sea. Therefore, it is practical to use a wind-based parameterization for the Stokes drift where 1.5% of the 10 m wind speed is typical (Ardhuin et al. 2009; Jones et al. 2016).

Another important aspect of leeway that we are omitting is the leeway divergence (Allen 2005), which is the inclusion of the crosswind leeway (CWL) in addition to the downwind leeway (DWL). Including the CWL improves the estimate of the uncertainty of the object position (Breivik and Allen 2008). However, the impact of the Stokes drift on the leeway will only impact biases in the DWL and will have little influence in the crosswind uncertainty. Given this, and the uncertainty of the CWL term for various immersion values (Breivik et al. 2012), we will only include the DWL term in the leeway estimates.

The leeway coefficients (Fig. 4) are used to model the drift with and without the Stokes drift. The drift modelling compares the effect of including the Stokes drift on the predicted trajectories. One of the leading factors that affect the leeway is the immersion level of the shipping container. Immersion levels for shipping containers typically range between 40 and 70% assuming that they are not damaged and taking on water (Breivik et al. 2012). Simulations are performed over the expected range of immersion levels ± 20%, i.e. 20 to 90%, which allows some uncertainty over the range of possible immersion levels. The immersion value is assumed constant for the duration of the simulation. All simulations begin on 22 October 2021 20:00 UTC and are run for 5 days until 27 October 2021 20:00 UTC.

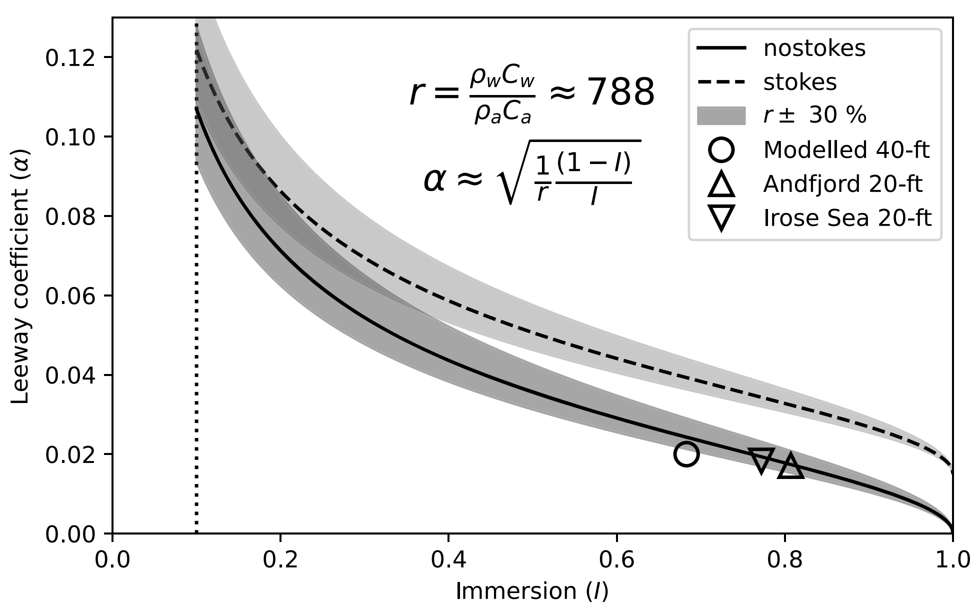


Fig. 4 Shipping container leeway as a function of immersion ratio. Observations are from Breivik et al. (2012). Dashed line shows the shipping container leeway plus a 1.5% offset due to the Stokes drift. Shaded regions the sensitivity to $r \pm 30\%$

4 Results

The shipping container trajectories after 24 h (Fig. 5a, b) and 48 h (Fig. 5c, d) are similar for the no Stokes (Fig. 5a and c) and Stokes (Fig. 5b and d) cases. On 23 October there is an observation of a shipping container that is consistent with the leeway for a low immersion value (between 0.2 and 0.3) for both the Stokes and no Stokes cases. On 24 October, the observations are consistent with the larger immersion values for both the Stokes and no Stokes cases. After 48 h there is a small but noticeable difference in the trajectories with and without the Stokes drift, but the immersion level is clearly

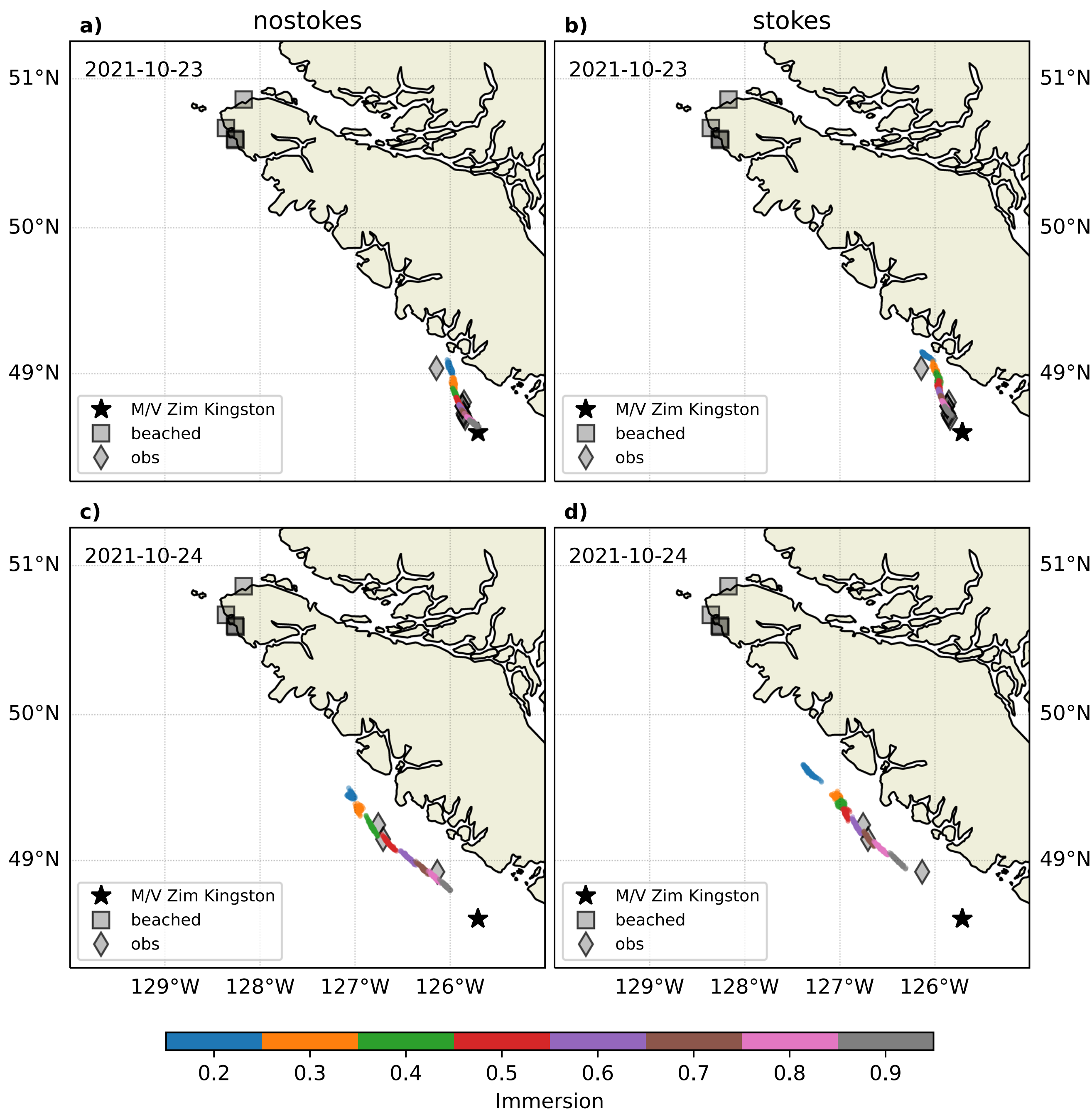


Fig. 5 Snapshots of the simulated locations of the shipping containers at 23 October 2021 and 24 October 2021 for various immersion levels. Observations of grounded containers are shown by squares and floating containers are shown by diamonds. The black star shows the initial incident location. The addition of the Stokes drift to (10) has a minimal impact on the drift after 24 h (**a** and **b**) although the difference is increasing after 48 h (**c** and **d**)

Table 2 Fraction of simulated particles grounded as of 27 October 2021 at 20:00 UTC for the stokes and nostokes cases at different immersion levels

Immersion	nostokes	stokes
0.2	0.999	0.897
0.3	1.000	1.000
0.4	0.991	1.000
0.5	0.970	1.000
0.6	0.953	0.990
0.7	0.978	0.968
0.8	0.934	0.999
0.9	0.915	0.949

the leading factor in how far the shipping container drifts up the coast.

Observations of the grounded shipping containers were made on 27 October 2021 (Table 1), 6 days after the original incident. By this time, the vast majority of simulated particles have grounded (Table 2) along the northwest coast of Vancouver Island (Fig. 6). The exception to this is for the smallest leeway ($I = 0.9$, nostokes) where most of the particles have yet to travel far enough to reach the coast.

The leeway coefficient has a significant impact on the predicted location of the grounded shipping containers along the northwest coast of Vancouver Island (Fig. 6). This leeway dependence causes the grounding location to be sensitive to the immersion level and the inclusion of the Stokes drift. If no Stokes drift is included, the simulated trajectories require large leeway values associated with very small immersion levels of 0.2 to 0.3 to compare qualitatively with the observed grounding locations (Fig. 6a). Including the Stokes drift provides a leeway associated with more realistic immersion levels of 0.3 to 0.5 (Fig. 6b).

To quantify the accuracy of the grounding simulations with the observations, the root mean square (RMS) distance is calculated between the observed grounded locations of the shipping containers and the simulated positions. The RMS distance is calculated individually for each grounded location (Fig. 7).

RMS distance errors are similar for each of the 4 grounding locations (Fig. 7), suggesting a similar immersion level for each of the 4 shipping containers. For the simulation with (10), but with no Stokes drift added, the minimum RMS distance corresponds to an immersion of 0.3 for the two southern grounding locations (Fig. 7a, b) and 0.2 for the other two (Fig. 7c, d). For the simulations with the Stokes drift effect added, the minimum distance now corresponds to an immersion of 0.4 (Fig. 7a, b) and 0.3 (Fig. 7c, d) respectively. Overall, the RMS distance is less with the addition of the Stokes drift to the leeway. This is especially true for the expected immersion range of $0.4 \leq I \leq 0.7$ where the RMS distance also displays less sensitivity to the immersion level (Fig. 7).

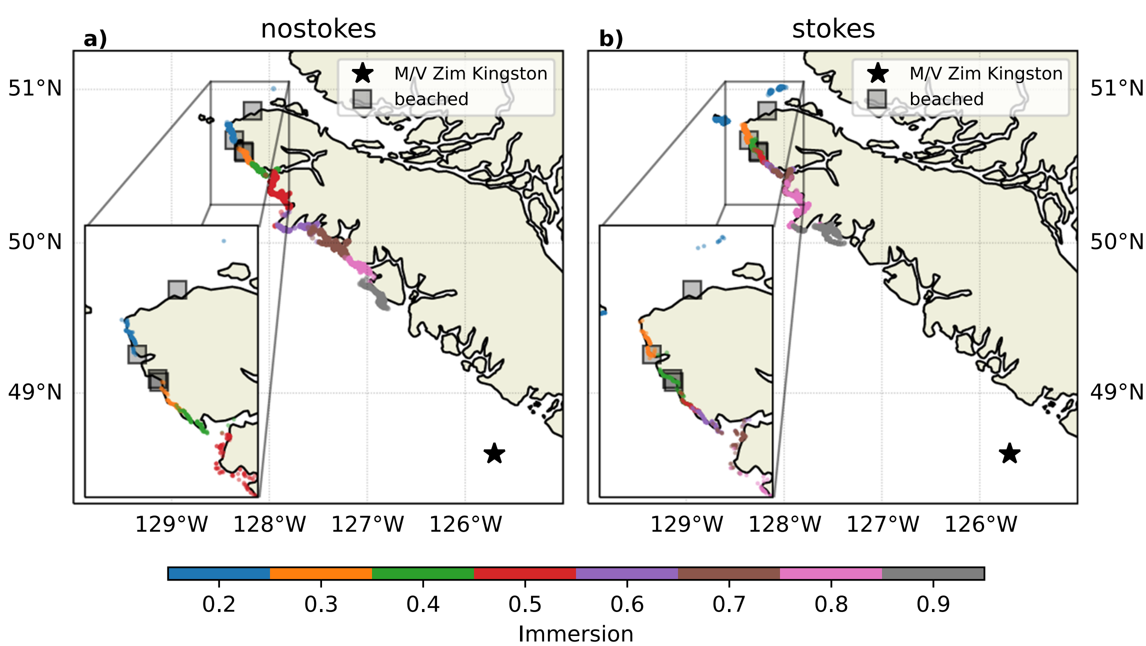


Fig. 6 Particle locations for shipping containers at 27 October 2021 20:00 UTC as a function of immersion. **a** is the leeway of (10) and **b** is the same leeway plus an additional 1.5% to simulate the Stokes drift. Grounding locations are shown by squares. The black star shows the initial incident location. Inset shows detailed view around grounding site

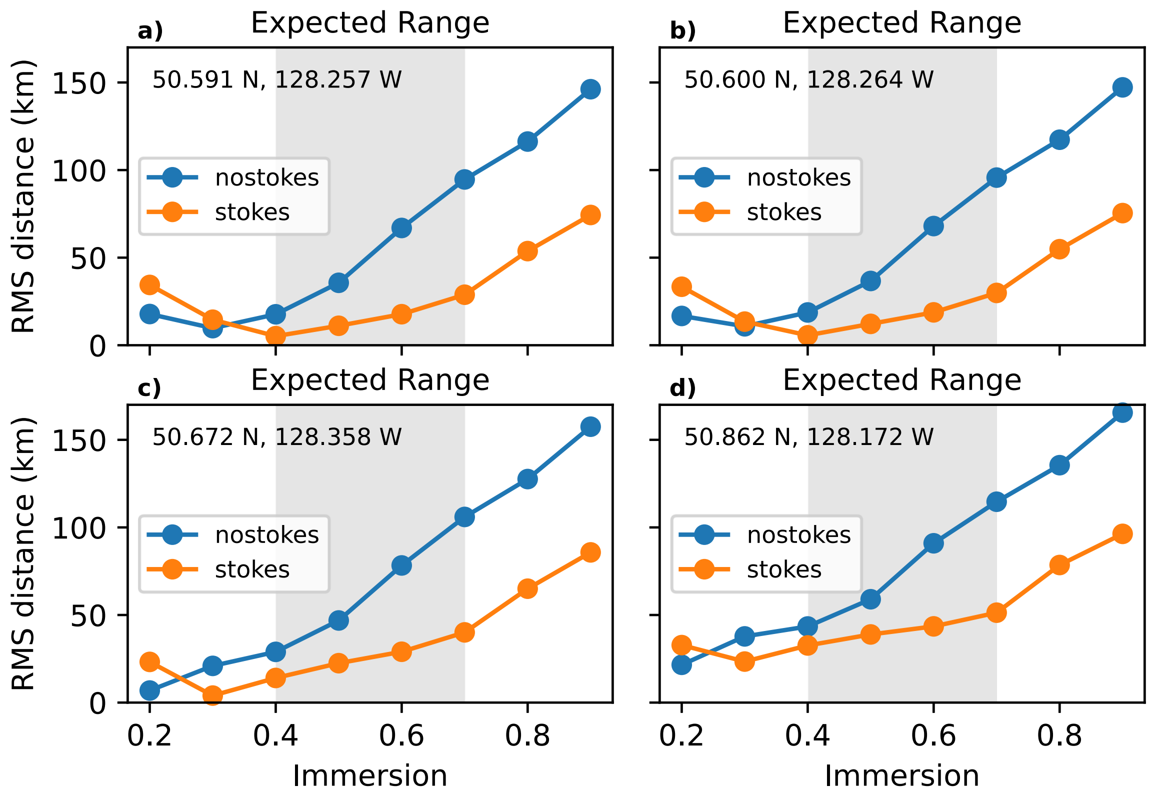
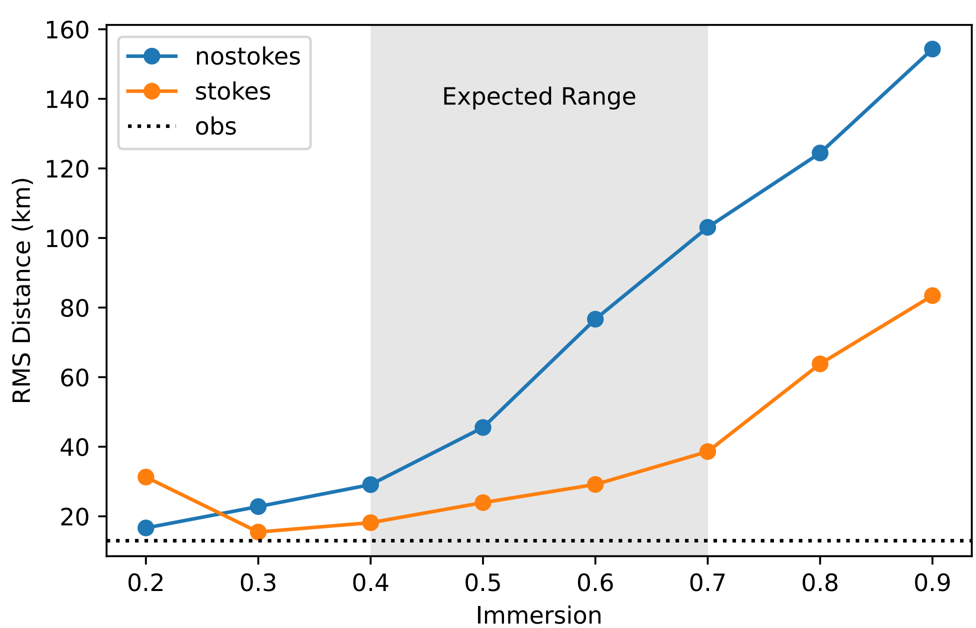


Fig. 7 RMS distance in km for each grounding location as a function of the immersion and the inclusion of the Stokes drift. Locations correspond to those in Table 1

The RMS distance is also calculated over all of the grounding locations (Fig. 8). This is calculated by taking the square root of the mean square distance for each grounding location (Fig. 7). The RMS distance is consistently less with the addition of the Stokes drift over the immersion range $I \geq 0.3$ (Fig. 8). The one exception is where $I = 0.2$, but this value is smaller than what is expected to be encountered and is more likely due to a compensation for the lack of the Stokes drift in the leeway.

Fig. 8 RMS distance in km as a function of the immersion for the cases with and without Stokes drift. Dashed line shows the standard deviation of the grounded observations



5 Discussion

The leeway model for shipping containers of Daniel et al. (2002), and verified by Breivik et al. (2012), consistently underestimates the mean drift of the shipping containers by an amount equivalent to the Stokes drift. Waves are not explicitly included in the derivation by Daniel et al. (2002), but they presented the caveat that any additional wave forcing may be incorporated into the relative drag coefficients on the air and water sides of the container. While this is true if there does exist a direct wave forcing on the shipping container, it does not apply if the only wave effect is the addition of the Stokes drift to the Eulerian ambient current to which the leeway is applied. Specifically, the wave effect is added to the leeway model in (8) when applied to the Eulerian current and cannot be included as a multiplication factor. This is shown in Fig. 4 with a finite leeway as $I \to 1$ when the Stokes drift is included, which is non-zero to the presence of the Stokes drift even if the container is below the mean water line.

In estimating the Stokes drift to be 1.5% of the wind speed, and only in the downwind direction, we are assuming a steady-state wave field. This direction assumption is supported, in general, by previous studies (Ardhuin et al. 2009). In addition, most operational wave models output the Stokes drift vector and this can be used instead of the 1.5% wind speed. Differences between the two methods are expected to be small (van den Bremer and Breivik 2018). Continued research is required to thoroughly investigate any potential differences.

In this study, the impact on the crosswind component of the leeway, i.e. the divergence of the object drift with the wind direction (Allen 2005), has been omitted from the analysis. The crosswind component appears to arise from the direct wind forcing on the object with symmetrical objects experience negligible crosswind leeway (Breivik et al. 2011). The leeway tables calculated from field experiments should still be valid (Allen 2005), but these are relative to the Lagrangian water velocity which can be estimated as the sum of the Eulerian velocity and the Stokes drift.

Additional wave effects, such as wave forcing on the shipping container, are also omitted from the analysis. While they are expected to be small (Breivik et al. 2012) the wave-induced response can introduce uncertainties related to the immersion level (i.e. buoyancy) of the shipping container. That is, as the immersion level increases, and the density approaches that of seawater, the vertical wave-induced motion increases and changes the drift characteristics.

Simulations are performed assuming a constant shipping container immersion for the entire duration, which is impossible to verify. Any damage to the shipping container would lead to an increase in immersion with time as the container took on water. As only 4 of the 109 shipping containers have washed ashore it is clear that there was considerable damage during the incident and it is possible that the immersion of the shipping containers could be increasing over time. It is difficult to assess the impact of this as the leeway of (10) is a non-linear function of the immersion I and we have no way to know the rate at which the immersion could vary by over the 5-day duration. However, as the optimal immersion is already at the low end of the expected range it seems unlikely that the immersion of the 4 shipping containers varied greatly over the 5-day duration.

Errors in the environmental forcing fields will also contribute to the prediction errors and these are notoriously difficult to quantify, especially in the coastal environment. It is indeed possible that the leeway bias of 1.5% of the 10 m wind velocity is required to compensate for a mean bias in the forecast wind speed and ocean currents if these fields have a negative bias (i.e. too slow on average) over the entire Lagrangian trajectory. An order of magnitude calculation suggests that the wind bias would have to be a minimum of 21% too slow, and most likely more, in the model fields in order to compensate for the Stokes drift requirement (Appendix). A 20% bias would be large for operational prediction systems when averaged over 5 days. In addition, environmental prediction systems have been shown to accurately predict the leeway coefficient of ocean drifters with no detectable bias (Sutherland et al. 2020).

6 Conclusions

The leeway coefficient of Daniel et al. (2002), and subsequently verified by Breivik et al. (2012), was found to be too small to reproduce the grounding locations of the drifting shipping containers over a range of realistic immersion levels. A bias correction, on the order of the Stokes drift, was sufficient to account for this bias.

It is argued in this study that the leeway measured using the direct method of Breivik et al. (2011) does not implicitly include the Stokes drift in the calculations. The central tenet of the argument is that the ADCP (or any fixed current meter) measures the water velocity relative to the Lagrangian velocity of the object, which creates an aliasing of the Stokes drift in the relative (i.e. slip) velocity. This has been shown to be true for ADCP measurements from an AUV moving relative to the water (Amador et al. 2017) and from theoretical arguments by Herrera-Vázquez et al. (2023).

This paper suggests that the downwind and crosswind leeway terms measured by the direct field method should remain unchanged, and instead be applied to the Lagrangian ocean velocity rather the Eulerian ocean velocity. As the Lagrangian and Eulerian velocity are related by the Stokes drift as in (1), the only additional requirement is to add the Stokes drift vector to the Eulerian velocity. The Stokes drift vector can easily be obtained either as a fraction of the wind speed (Ardhuin et al. 2009) as in this analysis or directly from the output of an operational wave model. This implementation allows for a simple technique to analyse historical drift predictions of objects whose leeway was determined from the direct method.

A drift velocity bias of 1.5% of the wind speed will not be large compared to the uncertainty in the wind and ocean current fields. For example, 1.5% of 7 m/s (which is a typical wind speed encountered over the ocean) is 0.11 m/s. However, as we are interested in Lagrangian trajectories, this velocity bias accumulates over time to a trajectory bias of 9 km per day. The bias is relatively small compared to many of the uncertainties on short time scales less than the inertial period (Christensen et al. 2018), but does accumulate over time to become significant. Over 5 days, such as the incident involving the M/V Zim Kingston, this difference in trajectory length would be 95 km.

Leeway experiments over longer durations, and including wave measurements, would be required to further verify the results from this study. The errors from not including the Stokes drift are cumulative and only became apparent after 2 days in our study. These errors are also wind speed dependent and their effects will increase in more severe weather conditions.

Appendix. Model bias analysis

It is possible that a larger leeway, as required here, could be due to a negative bias in the forecast surface currents and winds. That is, the true wind and surface currents are larger than the forecast products and, therefore, a larger leeway is required to compensate for this systematic bias.

To begin, a linear model related to the true and modelled fields is used for the wind speed

$$U_{10}^{T} = (1+\epsilon)U_{10}^{M}$$

where the superscripts ^{T} and ^{M} denote the true and modelled wind values respectively and ϵ is the linear perturbation which will be estimated later. Larger true winds will equate to larger true surface currents by the same linear perturbation

$$u_{E}^{T} = (1+\epsilon)u_{E}^{M}$$

assuming a linear transfer coefficient between the wind and the wind-induced surface currents

$$\beta = \frac{u_E}{U_{10}},$$

where $\beta > 0$. This coefficient β is a complicated function of the sea state, near-surface turbulence and the rotation of the earth, but is approximately on the order of $0.01 \leq \beta \leq 0.02$ for the Eulerian component (Weber 1983; Wu 1983).

The Lagrangian velocity for a shipping container with leeway α is calculated using (3) along with the modelled wind and surface currents, i.e.

$$u_{L}^{M} = u_{E}^{M} + \alpha U_{10}^{M}.$$

The true Lagrangian velocity is

$$u_{L}^{T} = (1+\epsilon)\, u_{L}^{M},$$

which would have a bias relative to the modelled Lagrangian velocity of $\epsilon u_{L}^{M} = \epsilon\left(u_{E}^{M} + \alpha U_{10}^{M}\right)$. Equating this with the Stokes drift $\alpha_S U_{10}^{M}$ and substituting $u_{E}^{M} = \beta U_{10}^{M}$ gives the following estimate for ϵ,

$$\epsilon = \frac{\alpha_S}{\beta+\alpha}.$$

Assuming a value of $\alpha_S = 0.015$, a maximum value of $\beta = 0.02$ and a large value for the shipping container leeway of $\alpha = 0.05$ (Breivik et al. 2012) provides a lower bound for the wind bias of 21% that would be required to equate the observed grounding locations using model data. More realistic values for β and α would only increase the required bias. It is unlikely that such a large bias would exist over the temporal and spatial scales covered by the shipping containers.

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Author contribution GS designed the study, performed the simulations, wrote the software for analysis and figure production and wrote the initial manuscript. KHC and PP contributed to data processing, analysis, discussion and manuscript revision.

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Availability of data and materials Observations of shipping containers and trajectory simulations are available at https://doi.org/10.5281/zenodo.10019897. Forecast fields for CIOPS-W and HRDPS are available upon request from the corresponding author or from the Meteorological Service of Canada at ec.dps-client.ec@canada.ca.

Code availability Code to reproduce figures is available at https://doi.org/10.5281/zenodo.10019897.

Declarations

Conflict of interest The authors declare no competing interests.

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