

# Drifting in the wind: leeway error in shipdrift data

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Abstract—Much of our knowledge of the large scale pattern of surface velocity in the oceans comes from historical shipdrift velocity data. One concern about these data is the possibility of a substantial systematic error due to leeway, the downwind sideslip of ships through the water normal to their steered courses. The leeway error is investigated here both theoretically and observationally and its magnitude is estimated for the tradewind region of the North Atlantic. The goal is to correct and improve the shipdrift velocity data set.

Leeway was calculated from the difference between surface currents measured on two intersecting tracklines, one nearly aligned with the mean wind direction, the other nearly normal to the wind. The residual current is ascribed to leeway. The estimated magnitude of leeway was found to be  $3.5\pm0.4$  cm/sec in a region of 5.9 m/s winds. Expressed as a percentage of the mean wind velocity this leeway is  $0.60\pm0.09\%$ . For the general case of ship lines oriented randomly with respect to the wind, leeway would be around half of the above values. Errors of this size are usually much smaller than the mean surface currents, except in regions of slow currents and fast winds like the North Equatorial Current—Trade Wind region of the North Atlantic. © 1998 Published by Elsevier Science Ltd. All rights reserved

# **INTRODUCTION**

A shipdrift measurement of surface current is obtained by subtracting the velocity vector between two measured ship position fixes from the estimated dead reckoning velocity vector over the same interval of time (Fig. 1). Dead reckoning combines a measurement of the ship's speed through the water by the ship's speed log and the direction of ship's course by compass. In navigation it is customary to use the term "current" to include all factors introducing geographical error in the dead reckoning, whether their immediate effects are on the vessel or the water (Bowditch, 1995). A current is said to have a set and drift, referring respectively to the direction toward which the current is flowing and the speed with which it moves. In addition to random errors in position fixing and dead reckoning, there is a systematic downwind error due to the wind acting on a ship. Leeway will be the term used here to describe the transverse drift through the water or sideslip of an underway ship leeward of her course due to wind and wave forces on the ship. Since under normal circumstances surface currents are much larger than leeway and in practice leeway is difficult to distinguish from local wind-driven currents, shipdrift measurements of current include a leeway error. At least this is my conclusion from talking to several ship captains, reading about shipdrifts and calculating shipdrift velocity on several cruises. Although the best captains probably had a rough idea of their ship's leeway and possibly corrected measurements of their ship's drift velocity for leeway if they thought it was significant, I

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Fig. 1. Schematic diagram of a shipdrift measurement of surface current. In the figure, the size of the surface current and leeway are exaggerated compared to the ship velocity. For the region discussed in this paper the angle between the ship's velocity and course steered is on the order of one degree. Leeway is assumed to be perpendicular to the steered course. Shipdrift data obtained from NODC include the measured surface current and location, not the wind velocity, ship velocity, dead reckoning velocity, or position fixes.

think most captains did not make the leeway correction. We do not know how large the leeway error is nor do we know the extent to which recorded shipdrift velocities have been corrected for leeway.

The suspected contamination of surface current measurements by leeway has prevented many oceanographers from using shipdrifts quantitatively or believing results of quantitative shipdrift analyses. Estimates of leeway are important in order to assess the size of this error, especially since our understanding of surface currents in the ocean is based strongly on the historical shipdrift data. If one could accurately estimate leeway, then the shipdrift velocities could be corrected for leeway, providing a much more accurate and useful data set.

This work is relevant to some earlier analyses of shipdrifts, which discussed the circulation and seasonal variations in the tropical Atlantic (Richardson and McKee, 1984; Richardson and Walsh, 1986; Arnault, 1987; Richardson and Philander, 1987). It is also

relevant to some more recent studies of Pacific Equatorial Currents that attempt to reconcile differences between shipdrifts and drogued drifting buoys (Reverdin *et al.*, 1994; McPhaden *et al.*, 1991). If the differences can be explained and modelled, then data from shipdrifts and drifters might be combined, resulting in a much longer (in time) and more comprehensive data set of near surface velocities.

# THEORETICAL CONSIDERATIONS AND MODELLED LEEWAY

The following is an investigation of how leeway varies with ship speed and the local wind velocity by using the equations of motion and applying the results of studies that measured the forces on model ships in tow tanks and wind tunnels. It is convenient to define a set of axes fixed relative to the ship, such that the x-direction is aligned with the ship's heading, the y-direction is normal to the ship's main axis and directed 90° to the right of the heading and the z-direction is vertically downward (Fig. 2a, see Crane *et al.*, 1989). The instantaneous linear ship velocity is given by V. The orientation of the moving axes with respect to the direction of motion is given by  $\beta$ , the drift angle or angle of attack of the ship's hull through the water. For a ship with a constant speed and heading there must be a balance among the forces and moments acting on the ship (Fig. 2b). The balance of forces in the y-direction and the balance of yawing moments about the z-axis through the center of gravity is given by:

$$Y + Y_a = 0; N + N_a = 0$$

where Y is the hydrodynamic force on the underwater part of the hull and rudder and  $Y_a$  is the aerodynamic force on the above-water part of the hull and superstructure and similarly for moments N and  $N_a$ . The forces in the x-direction and those due to waves are neglected here for simplicity; the effect of waves will be discussed later. The main force balance in the y-direction is between the hydrodynamic lift and the sum of aerodynamic lift and drag (Fig. 2a).

It is convenient to define nondimensional variables

$$\begin{split} Y' &= \frac{Y}{\frac{\rho_w}{2} A_w V^2}, \\ Y'_a &= \frac{Y_a}{\frac{\rho_a}{2} A_a W_R^2}, \\ N' &= \frac{N}{\frac{\rho_w}{2} A_w L V^2}, \\ N'_a &= \frac{N_a}{\frac{\rho_a}{2} A_a L W_R^2}, \end{split}$$

where  $\rho_w$  is the density of water and  $\rho_a$  that of air,  $A_w$  is the transverse projection area of the underwater part of the hull and  $A_a$  that of the above-water part of the hull and superstructure, L is the length of the ship, V is the ship's velocity through the water and  $W_R$  is the relative wind. The relative wind is a vector sum of the local (true) wind and the wind induced by the movement of the ship. Rewriting the force and moment equations in nondimensional form we obtain

$$Y' + SY'_a = 0, N' + SN'_a = 0, where S = \frac{\rho_a A_a W_R^2}{\rho_w A_w V^2}$$



(a)



Fig. 2a. Schematic diagram showing the aerodynamic and hydrodynamic forces on a steaming ship. A set of axes is fixed with respect to the ship such that the x-direction is aligned with the ship's heading, y is normal to the ship's main axis and directed 90° to the right of the heading, and z is downward. A local wind  $W_L$  blows at angle  $\theta$  against the port side of a ship steaming in the xdirection at speed u. The combination of the ship's velocity and local wind causes a relative wind  $W_R$ to blow at angle  $\alpha$  against the ship, generating an aerodynamic force made up of both lift and drag. The component of force in the y-direction pushes the ship sideways through the water with a leeway velocity v. Water impinges on the hull at a small angle of attack  $\beta$ , generating hydrodynamic lift and drag. The main force balance in the y-direction is hydrodynamic lift = aerodynamic lift + aerodynamic drag. The leeway, the angle of attack, and the magnitude of hydrodynamic lift compared to hydrodynamic drag are exaggerated in this figure in order to show them clearly. Figure 2b: Schematic diagram of the transverse (y-direction) forces and moments acting on a steaming ship with the relative wind blowing from the port side forward of the beam.  $Y_a$  and  $N_a$  are the transverse aerodynamic force and the aerodynamic moment generated by a relative wind. The wind generates a positive (to starboard) transverse force and positive (clockwise) moment.  $Y_{\nu}$  and  $N_{\nu}$ are the derivatives of the transverse hydrodynamic force Y and moment N with respect to the leeway velocity v. Positive leeway (to starboard) generates a negative (to port) transverse hydrodynamic force and a negative (counterclockwise) hydrodynamic moment.  $\delta$  is the rudder deflection angle measured from the y axis to the rudder axis. A negative (counterclockwise) deflection angle generates a negative (to port) force and a positive (clockwise) moment.  $Y_{\delta}$  and  $N_{\delta}$  are the derivatives of the transverse hydrodynamic force Y and moment N with respect to the rudder deflection angle  $\delta$ . This figure is based on one shown by Crane et al. (1989, their Figure 5).

For small angles of attack  $\beta$  and small rudder angles  $\delta$  (less than around 5 degrees) both Y' and N' are linearly related to the nondimensional leeway velocity v' = v/V (Crane *et al.*, 1989; Strøm-Tejsen and Chislett, 1966). Therefore the equations can be rewritten:

$$Y'_{\nu}\nu' = Y'_{\delta}\delta + SY'_{a} = 0$$
  

$$N'_{\nu}\nu' + N'_{\delta}\delta + SN'_{a} = 0$$
(1)

where  $Y'_{\nu}$  is the nondimensional partial derivative  $\partial Y'/\partial \nu'$ , etc. (except for  $Y'_a$  and  $N'_a$ , which are the nondimensional aerodynamic force and moment). The nondimensional leeway is easily found to be

$$v' = S\left(\frac{Y'_a N'_\delta - N'_a Y'_\delta}{N'_v Y'_\delta - Y'_v N'_\delta}\right)$$
(2)

The nondimensional hydrodynamic derivatives (coefficients) have been measured by towing model ships in tow tanks. Typical values for Series 60 cargo ship hulls are  $Y'_{\nu} = -0.302$ ,  $Y'_{\delta} = 0.0526$ ,  $N'_{\nu} = -0.0936$ ,  $N'_{\delta} = -0.026$  (Crane *et al.*, 1989). Values from five different Series 60 hulls were combined to produce an average equation for nondimensional leeway

$$v' = SY'_{a}[2.04(\pm 0.09) + 4.16(\pm 0.24)x'_{a}]$$
(3)

where  $x'_a = \frac{x_a}{L}$  is the nondimensional distance toward the bow from the center of mass such that  $N'_a = Y'_a x'_a$ . The quantities in parentheses are the standard errors calculated using the five different sets of coefficients.  $Y'_a$  varies as a function of the relative wind angle  $\alpha$  and hull configuration. Plots of  $Y'_a$  versus  $\alpha$  for numerous ships show that a reasonable model for these ships is given by  $Y'_a = \sin \alpha$  (Crane *et al.*, 1989 their Fig. 82). Plots of  $x'_a$  versus  $\alpha$  for various ships show that the data fit a linear model  $x'_a = 0.300 - 0.00278\alpha$  quite well (Hughes, 1930; Wagner, 1967). This relation states that the transverse aerodynamic force  $Y'_a$  acts with an increasingly large moment arm  $x'_a$  as the direction of the relative wind moves closer toward the bow (smaller  $\alpha$ ). Incorporating these two relationships into equation 3 and redimensionalizing the result gives the dimensional leeway

$$v = (3.29 - 0.0116\alpha)\sin\alpha \frac{\rho_a}{\rho_w} \frac{A_a}{A_w} \frac{W_R^2}{V}.$$
 (4)

As we see in Fig. 2b, an aerodynamic moment caused by a relative wind blowing from a direction forward of the beam  $\alpha < 90^{\circ}$  will tend to counter the hydrodynamic moment acting on the hull. When these two moments are perfectly balanced a steady course can be maintained with zero rudder angle. For this simple situation, in which the transverse aerodynamic and hydrodynamic forces exactly balance with zero rudder deflection, the nondimensional leeway reduces to  $v' = -SY'_a/Y'_v = 3.35(\pm 0.19)SY'_a$ . Five different values of  $Y'_v$  from the Series 60 hulls were used to obtain the mean and standard error. The dimensional leeway is

$$v = 3.35 \sin \alpha \frac{\rho_a}{\rho_w} \frac{A_a}{A_w} \frac{W_R^2}{V}$$
(5)

In order to evaluate equations 4 and 5 we need values for  $\rho_a/\rho_w$ , which is estimated to be  $1.15 \times 10^{-3}$  for the tradewind region, and for  $A_a/A_w$ , which is estimated to equal 1.0 from

drawings of typical cargo ships. Using these values, a typical tradewind velocity of 5.9 m/s from abeam,  $\theta = 90^{\circ}$ , and a 6.2 m/s (12 knot) ship speed, the modelled leeway is 3.2 cm/sec (equation 5). In this example the relative wind  $W_R$  is 8.5 m/s from  $\alpha = 44^{\circ}$ . Evaluating equation 4 as above, we obtain a modelled leeway of 2.6 cm/sec. This is somewhat smaller than the previous value due to the rudder deflection, which is estimated to be 2.2° in a downwind direction. In this case the hydrodynamic moment acting on the ship hull is greater than the aerodynamic moment; this requires a downwind rudder angle and an upwind rudder force, which tends to counter the aerodynamic force and to reduce leeway (Fig. 2b). The general effect of rudder angle needed to balance the yawing moment for a relative wind forward of abeam is to reduce leeway somewhat.

# Leeway versus wind speed and direction

Equations 4 and 5 and Fig. 3 show that the leeway of underway ships is a nonlinear function of the local wind velocity. We can use this information to help interpret the results of the data analysis presented later and to help estimate corrections to shipdrift velocities. There are several results worth noting in the plots shown in Fig. 3. Leeway is asymmetrical with respect to the local wind direction  $\theta$ ; maximum leeway values ~3.4 cm/sec occur at a local wind direction around 65° from the bow, which corresponds to a relative wind direction around 30°. This is because relative wind is larger for  $\theta < 90$  than for  $\theta > 90$  due to the ship-induced apparent wind. If we apply these results to an ocean route or trackline oriented at an angle  $\theta < 90$  to the local wind and assume that an equal number of ships travel in both directions along the trackline, then the asymmetry disappears. This is because we must average leeway values for both of the directions ships are traveling. In this case the maximum modelled leeway is obtained when the local wind is normal to the trackline  $\theta = 90^\circ$ . The leeway for a trackline as a function of its orientation  $\theta$  is very closely approximated by

$$v = (v_{\theta = 90^{\circ}})\sin\theta. \tag{6}$$

Both the maximum downwind leeway and the average downwind leeway increase nonlinearly with increasing wind speed; the average downwind values are equal to approximately half of the leeway values for a wind abeam,  $\theta = 90^{\circ}$  (Fig. 3d).

## Leeway versus ship speed

The leeway-versus-ship-speed curve is relatively flat for typical ship speeds of 5 m/s to 10 m/s, showing that variations of ship speed are not very important to leeway (Fig. 3c). An uncertainty of 1 m/s in the mean ship speed would cause an uncertainty of roughly 0.1 cm/ sec in maximum modelled leeway values.

## Leeway of ship with no way on

These results show that the leeway of a ship underway at normal cruise speed is generally much less than the leeway of a ship with no way on and lying normal to the local wind direction  $\theta = 90^{\circ}$ . The leeway of the latter ship can be modelled by balancing the hydrodynamic drag of the hull,  $Y = \rho_w/2 \ Cd_w \ A_w \ V^2$ , with the aerodynamic drag of the



Fig. 3a. Modelled leeway as a function of local wind direction  $\theta$  relative to the bow. The hydrodynamic force due to the rudder angle which is required to balance the aerodynamic and hydrodynamic moments (equation 4) reduces leeway compared to the case where a zero rudder angle was assumed (equation 5). Maximum leeway amounts to 3.4 cm/sec for an assumed zero rudder angle and 3.0 cm/sec when rudder deflection is included. On average the rudder force reduced leeway by 15%. The 5.9 m/s wind speed was chosen to match the mean speed used later in the analyses of shipdrift data. The 6.2 m/s (12 knots) ship speed is the estimated typical value for cargo ships in the 1920-1940 period, when most shipdrift measurements were made. Figure 3b: Modelled leeway as a function of local wind speed and direction  $\theta$ . The curves were calculated using equation 4,  $\rho_o/\theta$  $\rho_w = 1.15 \times 10^{-3}$  and  $A_a/A_w = 1.0$ . Note that the largest leeway values are obtained for local winds slightly forward of the beam,  $\theta \sim 65^\circ$ . The corresponding relative wind angle  $\alpha$  for maximum leeway is around 30°. Figure 3c: Plot of modelled leeway versus ship speed using equation 4 and a 5.9 m/s wind beam ( $\theta = 90$ ). For ship speeds u < 1 m/sec where the hydrodynamic angle of attack  $\beta > 5^{\circ}$ , the assumptions used to derive equation 4 become less valid. In this regime (u < 1 m/s) leeway was estimated from  $Y' + Y'_{a} = 0$  using the relationship between Y' and  $\beta$  given by Hughes (1930). A ship with no way on and with a 5.9 m/s wind blowing from abeam drifts downwind with a speed of  $\sim$  20 cm/sec (equation 7). Figure 3d: Modelled leeway as a function of local wind speed. The curve showing leeway generated by a local wind from abeam ( $\theta = 90^\circ$ ) represents the maximum downwind lecway encountered along a ship trackline if ships steam in both directions along it. The average downwind leeway curve was calculated by averaging the downwind components of leeway over the angles of  $\theta = 0$  to 180°. This curve represents the average leeway encountered by ships in a certain region if their course directions or tracklines are randomly oriented with respect to the local mean wind direction. Note that the average curve is very close to one half of the wind abeam curve.

hull and superstructure,  $Y_a = \rho_a/2 C d_a A_a W_L^2$ , where  $C d_w$  and  $C d_a$  are the drag coefficients and leeway is assumed to be much smaller than the wind speed. In this case leeway is given by

$$V = \sqrt{\frac{\rho_a}{\rho_w} \frac{Cd_a}{Cd_w} \frac{A_a}{A_w}} W_L. \tag{7}$$

Assuming  $\rho_a/\rho_w = 1.15 \times 10^{-3}$ , the ratio of drag coefficients  $Cd_a/Cd_w = 1.0$  and  $A_a/$  $A_w = 1.0$ , then  $V = 0.034 W_L$  or 3.4% of the wind speed. A wind speed of 5.9 m/s gives a leeway of 20 cm/sec. This is around eight times larger than the 2.6 cm/sec leeway for the ship steaming at 6.2 m/s. Interpreted in terms of a ship with no way on (eq. 7) the effective drag area ratio  $(Cd_a A_a)/(Cd_w A_w)$  of a 6.2 m/s ship steaming perpendicular to a 5.9 m/s local wind would be around 1/60, which is similar to the ratio of some of the best drogued surface drifters (although their drogues are usually much deeper than a ship's hull). Clearly, hydrodynamic lift is capable of strongly limiting the leeway of ships steaming at full speed. The linear relationship between the leeway of a ship with no way on and the wind speed has been verified by numerous tests at sea by the Coast Guard (Allen, 1996; Nash and Wilcox, 1991) and others (Hiraiwa et al., 1967) although most ships do not lie perfectly normal to the wind direction and tend to drift downwind through the water at an angle relative to the wind. Leeway has been measured to be several percent of the wind speed depending on the type of boat or ship. Although it is fairly straightforward to measure the leeway of a ship with no way on, it is very difficult to measure the leeway of a ship steaming at full speed because its speed  $\sim 6$  m/s is 200 times greater than leeway  $\sim 3$  cm/sec.

#### Limitations of modelled leeway

The many approximations and assumptions used in deriving and applying equation 4 to model leeway suggest that it is very approximate. Even the functional relationship between leeway and wind speed is considered to be approximate, at least at higher wind speeds where waves become important. Probably the largest source of error in using the results of equation 4 to model the real leeway of ships in the ocean is the neglect of ocean waves, which were omitted because their effect on leeway is so complex (Beck *et al.*, 1989). Large waves induce significant time-dependent lateral forces and yawing moments, which require rudder action to counter. One can easily imagine that a downwind and downwave leeway could be caused by a rectification of wave effects. Therefore the modelled leeway in equation 4 could be an underestimate of real leeway due to the neglect of waves, especially at higher wind speeds. It was for this reason that the plots in Fig. 3 were cut off at wind speeds of 10 m/s. Large waves can also cause a significant Stokes drift, a downwave Lagrangian surface velocity (not leeway), which would also be measured by ships (Kenyon, 1969).

The coefficients used to derive equation 4 were obtained with model ships, which raises the issue of scale changes in applying model data to full-scale ships. The model data were obtained with Froude numbers similar to those encountered by ships at sea, but the Reynolds numbers were by necessity not simultaneously matched. Fortunately, additional studies have shown that there is very little scale effect on lift coefficients (Crane *et al.*, 1989) in the small angle of attack range of typical underway ships. The lateral aerodynamic coefficient is probably less well known because of both scaling effects (different Reynolds numbers) and because of the difficulties in reproducing with models the combination of ship-induced apparent wind velocity, which is not sheared vertically, and the local wind velocity, which is sheared vertically. The source of the transverse aerodynamic coefficients (Crane *et al.*, 1989) did not explain how the values were obtained, so we cannot evaluate how accurately  $Y'_a = \sin \alpha$  models real ships. The presence of vertical shear in the real wind raises the further issue of how representative a given wind speed is if its height above the sea level is not specified or known.

Also poorly known is the average size, shape and speed of the ships that measured shipdrifts in the 1920–1940 period, when most shipdrifts were measured. It was assumed that typical ships steamed at 6.2 cm/s (12 knots), that they had a  $A_a/A_w = 1.0$  and that their hulls were similar to the Series 60 cargo hulls, that have been well tested in tow tanks (Crane *et al.*, 1989). These assumptions may not match reality very closely and could cause unknown errors in the modelled leeway. However, these assumptions probably have little effect on the shape of the curves relating leeway to wind velocity, or at least a smaller effect than that caused by neglecting waves.

#### LEEWAY ESTIMATED FROM SHIPDRIFTS

#### General method

Leeway was estimated from shipdrift measurements by using data from four major Atlantic ship tracklines, or commonly used routes, that crossed at nearly right angles in a region of generally weak surface current and moderate, steady tradewinds. The average winds were roughly parallel to two of the tracklines and roughly normal to the other two. It was assumed that the trackline parallel to the wind direction would have little leeway since any change in the ship speed due to wind would have been recorded by the ship's speed log. As we will see, the results suggest that the tracklines roughly parallel to the wind do indeed have little or no leeway. This issue is further discussed in the Appendix. The tracklines normal to the wind would have unknown leeway caused by uncorrected downwind sideslip of the ship through the water normal to the steered course. The leeway can thus be obtained by subtracting the surface current velocity calculated for the tracklines parallel to the wind (no-leeway case) from that calculated from the normal tracklines (leeway case). Since the surface velocity measured on both tracklines where they cross should be equal, the residual velocity gives an estimate of leeway.

The crossing tracklines do not need to be aligned parallel and normal to the mean wind for the technique to work, although it is easier to understand if they are. If the tracklines are not parallel and normal to the wind, then both tracklines could have leeway components. The magnitude of the leeway calculated by the differential method would be correct, although the direction of the calculated leeway would not necessarily be downwind. To understand this, first consider two tracklines crossing at right angles, one oriented northsouth, the other east-west. A wind blowing from the north would cause a leeway L toward the south on the east-west line but no leeway on the north-south line. The leeway L is easily obtained by simply subtracting the surface current calculated from the north-south line from that calculated from the two lines would be L/2. Now consider a wind blowing from a small angle  $\theta$  clockwise from north (Fig. 4). The wind causes a westward leeway on the north-south line and a southward leeway on the east-west line. The magnitude of the resultant leeway is L and the direction is downwind at an angle  $\theta$  clockwise from south. In



Fig. 4. Schematic diagram illustrating leeway on tracklines where the local wind  $W_L$  blows from a direction  $\theta$  relative to one of two perpendicular tracklines. The leeway component on each trackline is proportional to the across-line component of wind velocity. The resultant leeway vector L calculated by combining the two leeway components is in the same direction as the wind and equal in magnitude to the leeway on a trackline perpendicular to the wind velocity. The subtraction method used to estimate leeway in this paper rotates the leeway, called modelled leeway here, counterclockwise ( $\theta$ ) relative to trackline 1 because  $L_1$  is vectorially subtracted from  $L_2$  instead of added to it, as shown by the resultant leeway vector. In principle the correct resultant leeway direction could be obtained by rotating the modelled leeway 2 $\theta$  clockwise.

order to calculate the leeway, we subtract the surface current vector calculated from the north-south line from that calculated from the east-west line. Because of the subtraction, the westward leeway component on the north-south line is reversed, resulting in an apparent leeway direction of  $\theta$  counterclockwise from south. If the two lines do not cross at right angles, the direction of the induced leeway would not necessarily be in a downwind direction and the apparent direction would not necessarily be rotated counterclockwise an equal angle.

The reader may wonder why this analysis did not use the wind and surface current measurements observed by each ship as it steamed along, but instead used averages along tracklines. The answer is that historically the wind and current observations were split into different data files and the job of trying to match them up again seemed too daunting. The use of average data along tracklines gives an estimate of leeway that is representative of average shipdrift data.

An important assumption is that the distribution in time of shipdrifts along each trackline gives a good sampling of the long-term mean surface currents. That four different major tracklines crossing at three different locations give similar results suggests the distributions are probably adequate.

#### Data analysis

The worldwide shipdrift data set consisting of  $4.2 \times 10^6$  surface current observations was obtained from the National Oceanographic Data Center. We calculated  $1^\circ \times 1^\circ$  box

averages of current velocity and various statistics. A plot of the number of observations in each  $1^{\circ} \times 1^{\circ}$  box revealed four tracklines suited for the analysis crossing near 20 N, 45 W in the Atlantic (Fig. 5, Table 1). The  $1^{\circ} \times 1^{\circ}$  boxes along these four tracklines contain much larger numbers of observations than in the boxes nearby the tracklines except in the northwestern and southwestern regions, where numerous other lines contribute large numbers of observations. The four tracklines cross at four points, three of which were chosen to calculate leeway (points A, B, C). The fourth point was located farther north, in weaker winds and much larger numbers of background observations, which could have seriously contaminated the results. The effect of the contamination, which tends to decrease the apparent leeway, is discussed later.

The orientation of tracklines 1 and 2 from Europe to South America is roughly parallel to the mean wind velocity (Figs 5 and 6). These will be referred to as the no-leeway tracklines, although there could be some leeway on them. The two other lines, trackline 3 from eastern Brazil to New York and trackline 4 from South Africa to New York, are roughly normal to the mean wind velocity. These will be referred to as the leeway tracklines, although the wind velocity is not exactly normal to them. This region lies under the Northeast Tradewinds (Fig. 6b), which are quite steady in the sense of having small seasonal and synoptic scale variations (Isemer and Hasse, 1985). The mean wind velocity for the three points is 6.1 m/s for A, 6.7 m/s for B, and 4.9 m/s for C, based on the Comprehensive Ocean-Atmosphere Data Set (COADS) climatology (Woodruff *et al.*, 1987; Mayer and Weisberg, 1993) provided by D. Mayer. Points A and C are on the northern side of the high velocity region; point B is near the center of the region of largest mean wind velocity and highest directional stability. The angles between the wind and lines 1 and 2 are 19° at point A, 20° at point B, and a rather large 41° at point C. The angles between the wind and lines 3 and 4 are 63° at point A, 70° at point B, and 60° at point C.

The main surface current (Fig. 6a) is the North Equatorial Current, which is relatively slow (10–15 cm/sec), with little seasonal or mesoscale variation (Wyrtki *et al.*, 1976; Richardson and McKee, 1984; Richardson and Walsh, 1986). Thus the region near 20 N, 45 W is a good one to search for the effects of leeway.

Boxes that contained the largest numbers of observations along the tracklines were selected for analysis, excluding the  $2^{\circ} \times 2^{\circ}$  boxes where the tracklines crossed and boxes located in regions where the number of background observations was a significant fraction of those along the tracklines (Fig. 5b). In order to calculate the surface current velocity at the crossing points, *u* and *v* velocity components from  $1^{\circ} \times 1^{\circ}$  boxes lying along the tracklines were plotted as a function of distance along the trackline from the southernmost box and a linear regression line was fitted through each set of components (Fig. 7). The mean surface velocity was then calculated for both tracklines at each crossing point using the linear regression line. The standard error of the mean velocity components was estimated from the standard errors of the intercept and slope of each regression line.

#### Leeway magnitude and corrections

The main results are given in Figs 8 and 9 and Tables 2-4. Since the calculated surface currents and leeway values for the three points agree closely, averages of the three will be discussed below. That the three agree well suggests the results are not merely due to noisy data. In addition, the estimated standard errors based on the results of linear regression analysis are significantly smaller than the mean currents and leeway values.





Table 1. Trackline Data					
Trackline	Direction	Lat Limits	Number of Observations	Number of $1^{\circ} \times 1^{\circ}$ Boxes	Observations Per Box
1	233°	11 N-26 N	5129	18	285
2	222°	15 N-28 N	5285	13	407
3	323°	11 N-20 N	2732	9	304
4	315°	11 N-21 N	1657	12	138

The shipdrift velocity observations in  $1^{\circ} \times 1^{\circ}$  boxes were used to calculate current velocity for each line. A total of 14,803 observations was used.

The average surface current at points A, B, and C on tracklines 1 and 2, the no-leeway tracklines, is 11.9 cm/sec toward 293° (Table 2). The effect of leeway on tracklines 3 and 4, the leeway tracklines, is to increase the apparent magnitude of the surface current to 13.5 cm/sec and to rotate the velocity toward 284°. This is an increase of 1.6 cm/sec and a 9° downwind rotation of the current vector. The mean vector difference between the two sets of tracklines, the leeway L, is 2.7 cm/sec toward 235° (Tables 2 and 3). The magnitude of leeway amounts to  $(2.7/11.9) \times 100 = 23\%$  of the surface current in this region.

The velocity observations in the boxes along the tracklines are contaminated by some values from ships traveling in other directions (Fig. 5b). This contamination would tend to diminish the estimated leeway, which implies that the real leeway is larger than that calculated. The contamination of the main trackline velocities by cross-trackline velocities is estimated to be around 12% (Table 3). To obtain this value, the numbers of observations along tracklines were compared to the numbers of background observations attributable to crossing tracklines. Background observations that lay several boxes away from the tracklines were assumed to be distributed equally between ships steaming parallel to the two crossing tracklines. Corrections for the contamination along each trackline were estimated. Applying these to the leeway values increased them around 31% to an average corrected leeway  $L_c$  of  $3.5 \pm 0.4$  cm/sec (Table 3).

The mean current vectors at A, B, and C were similarly corrected, giving a corrected mean current velocity from tracklines 1 and 2 (no leeway) of 11.7 cm/sec toward 295° and from tracklines 3 and 4 of 13.8 cm/sec toward 282° (see Fig. 9). Leeway increases the no-leeway current velocity by 2.1 cm/sec and rotates it 13° downwind. The magnitude of the corrected leeway (3.5 cm/sec) amounts to  $(3.5/11.7) \times 100 = 30\%$  of the no-leeway current, a sizeable percentage.

Another possible error in the magnitude of the estimated leeway is caused by the  $64^{\circ}$  average angle between the wind velocity and tracklines 3 and 4, which contain the major leeway as implied by the leeway vector being almost perpendicular ( $85^{\circ}$ ) to these lines. The average cross-line component of wind for tracklines 3 and 4 at the three points is 0.90 of the mean wind velocity, which suggests that the calculated leeway could underestimate the real leeway by around 10%. We would need to increase the calculated leeway by this amount to reflect what the leeway would have been if the wind vector had been exactly perpendicular to tracklines 3 and 4. Since we do not know the exact relationship between the cross-trackline component of wind and the leeway, we have not corrected the leeway for this possible error.

It is important to note that the average corrected leeway of  $3.5 \pm 0.4$  cm/sec is primarily due to the leeway on the tracklines normal to the wind direction (Fig. 8). The average



Fig. 6a. Map of shipdrift current velocity. Vector means were calculated using all data in each  $1^{\circ} \times 1^{\circ}$  box and plotted on a  $2^{\circ} \times 2^{\circ}$  grid to avoid clutter. Vectors in boxes that contained fewer than 50 observations were also omitted. Figure 6b: Map of mean wind velocity from Isemer and Hasse (1985). Points A, B, and C are indicated.

corrected leeway expressed as a percentage of the mean wind speed of 5.9 m/s is  $0.60 \pm 0.10\%$  (Table 3). In general, for the regions without major tracklines running through them, velocities in  $1^{\circ} \times 1^{\circ}$  boxes were obtained by ships steaming along lines oriented at various directions relative to the mean wind. For lines oriented randomly with



Fig. 7. Plot of u and v shipdrift velocity components along each trackline using  $1^{\circ} \times 1^{\circ}$  box average velocities. Zero distance is centered in the most southern box along each trackline (see Figure 5b). Linear regression lines through the data have been added. Calculated mean velocity values at trackline crossing points A, B, and C are indicated by small dots surrounded by circles.

respect to the wind direction, the leeway would be reduced to half of that for the lines normal to the wind direction or 1.8 cm/sec. Therefore this value, 1.8 cm/sec or  $0.30 \pm 0.05\%$  of the wind speed, is the estimated leeway for regions characterized by ships traveling in numerous different directions and without a major trackline.

#### Leeway direction

The estimated leeway direction is almost perpendicular (average of  $85^{\circ} \pm 4^{\circ}$ ) to the leeway tracklines 3 and 4 and 21° counterclockwise from the downwind direction (Fig. 8). This direction is not surprising since the differential method tends to rotate L counterclockwise from the wind direction. What is surprising is the small size of the angle  $(21^{\circ} \pm 7^{\circ})$  compared to the larger angle  $(52^{\circ} \pm 13^{\circ})$  of the modelled leeway using equation 4. This is surprising, because any leeway to the left of tracklines 1 and 2 would have been subtracted from the leeway on tracklines 3 and 4, resulting in an apparent leeway component to the right of tracklines 1 and 2. That the estimated direction of L is nearly perpendicular to tracklines 3 and 4 implies nearly zero leeway on tracklines 1 and 2.



Fig. 8. Plot of the relative orientation and direction of tracklines, wind velocity, and leeway (see Table 4). Tracklines 1 and 2, which lie closest to the wind direction, are oriented up in this figure. Also shown is the direction of the modelled leeway based on equation 4. The modelled leeway is rotated counterclockwise from tracklines 1 and 2 because the method used to calculate leeway subtracts the modelled component of leeway (reverses its direction) on tracklines 1 and 2 from the component on tracklines 3 and 4. The lower right panel shows average directions obtained by averaging the values at points A, B, and C.

Two possible explanations of this result are: (1) that real ships responded to wind and waves in a way fundamentally different from equation 4 when steaming nearly parallel to the direction of the wind (versus normal to its direction) and that a rectification of the ship's response to the variable wind and wave forces somehow resulted in a reduced leeway; (2) that a small systematic steering error on this course somehow compensated for the real



Fig. 9. Plot of corrected current velocity and leeway based on averages from the three points A, B, and C.

	u (cm/sec)	v (cm/sec)	Speed (cm/sec)	Direction
Point A				
Trackline 4	$-12.20 \pm 0.55$	$0.80 \pm 0.33$	$12.23 \pm 0.55$	274 <u>+</u> 2
Trackline 1	$-10.12 \pm 0.28$	$2.90 \pm 0.35$	$10.53 \pm 0.29$	286±3
Leeway	$-2.08 \pm 0.62$	$-2.10\pm0.48$	$2.96 \pm 0.55$	$225 \pm 11$
Point B				
Trackline 3	$-15.68 \pm 0.46$	$4.48 \pm 0.33$	16.31 ± 0.45	$286 \pm 1$
Trackline 1	$-13.40 \pm 0.43$	$5.60 \pm 0.53$	$14.52 \pm 0.45$	$293 \pm 2$
Leeway	$-2.28 \pm 0.63$	$-1.12\pm0.62$	$2.54 \pm 0.63$	$244 \pm 14$
Point C				
Trackline 3	$-11.47 \pm 0.86$	$4.26 \pm 0.61$	$12.24 \pm 0.83$	$290 \pm 3$
Trackline 2	$-9.33 \pm 0.43$	$5.66 \pm 0.50$	$10.91 \pm 0.46$	$301 \pm 3$
Leeway	$-2.14 \pm 0.96$	$-1.40\pm0.79$	$2.56 \pm 0.91$	237 <u>+</u> 18
Averages, A, B, C				
Trackline 3 and 4	$-13.12\pm1.59$	3.18 ± 1.46	$13.50 \pm 1.58$	$284 \pm 6$
Trackline 1 and 2	$-10.95 \pm 1.50$	$4.72 \pm 1.11$	$11.92 \pm 1.45$	293±6
Leeway	$-2.17 \pm 0.07$	$-1.54 \pm 0.36$	$2.66 \pm 0.55$	$235 \pm 6$

Table 2. Current Velocity and Leeway Calculations

Surface current velocity components were calculated from the regression lines (two per trackline) at point A 19 N 40 W, point B 13 N 47 W, and point C 21 N 53 W. Tracklines 3 and 4 are roughly normal to the wind velocity (leeway lines); tracklines 1 and 2 are roughly parallel to the wind velocity (no-leeway lines). Leeway is defined to be the vector difference between the current velocity from the leeway lines 3 and 4 and the current velocity from the no leeway lines 1 and 2. The indicated uncertainty of the velocity components is the standard error estimated from the standard errors of the slope and intercept of the regression lines. Averages of velocity and leeway based on values at the three points are also given. Uncertainty in these values was estimated from  $\sigma/\sqrt{n-1}$ , where  $\sigma$  is the standard deviation of the three values about the mean and n=3.

	Point A	Point B	Point C	Average
Leeway L:	<u> </u>			
Speed	$2.96 \pm 0.55$ cm/sec	$2.54 \pm 0.63$ cm/sec	$2.56 \pm 0.91 \text{ cm/sec}$	$2.69 \pm 0.17$ cm/sec
Direction	$225^{\circ} \pm 11^{\circ}$	$244^{\circ} \pm 14^{\circ}$	$237 \pm 18^{\circ}$	235° ± 7°
Percent contamination	$15 \pm 5\%$	9±3%	11±4%	$12 \pm 2\%$
Correction factor	$1.43 \pm 0.21$	$1.22 \pm 0.09$	$1.28 \pm 0.14$	$1.31 \pm 0.08$
Corrected leeway $L_c$	$4.23 \pm 1.00$ cm/sec	$3.10\pm0.80$ cm/sec	$3.28 \pm 1.22$ cm/sec	$3.54 \pm 0.43$ cm/sec
Wind velocity:				
Speed	6.09 m/s	6.74 m/s	4.91 m/s	5.91 ± 0.66 m/s
Direction	252°	253°	263°	$256 \pm 4$
Corrected leeway/ Wind velocity × 200	0.35±.08%	0.23±.06%	0.33±0.12%	$0.30 \pm 0.05\%$

Table 3. Summ	ary of Leeway	Values and	. Corrections
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The leeway values were calculated in Table 2. The percent contamination of data on each main trackline was estimated from the number of observations along the trackline and the number of background observations (outside of the trackline limits) attributed to other lines crossing the trackline. The values given here are the average percent contamination for the two lines crossing at each point. The errors of the percent contamination were estimated subjectively from the distribution of background numbers of observations. Corrected leeway is the leeway multiplied by the correction factor for trackline contamination. Wind velocity is a vector average of the COADS climatology for each location (see Mayer and Weisberg, 1993). These wind speeds and directions differ only a few percent from those given by Isemer and Hasse (1985, chart 160) and by Hastenrath and Lamb (1977). The corrected leeway as a percentage of the wind velocity is given in the last row of the table. The quantities listed in the last column are averages of the values at the three points A, B and C. The listed uncertainty in the last column was estimated from  $\sigma/\sqrt{n-1}$ , where  $\sigma$  is the standard deviation of the three values about the mean and n=3.

	Point A	Point B	Point C	Average
Line 1 or 2 (no leeway)	233	233	222	 229±4
Line 3 or 4 (leeway)	315	323	323	320 + 3
Wind velocity W	252	253	263	256 + 4
Leeway L	225	244	237	$235 \pm 7$
Modelled Leeway ML	206	213	192	$204 \pm 9$
W-L	27	9	26	21 + 7
W-ML	46	40	71	$52 \pm 13$
W-Line 1 or 2	19	20	41	27 + 9
L-ML	19	31	45	$32 \pm 11$
Line 3 or 4-L	90	79	86	$\frac{-}{85+4}$
Line 3 or 4-W	63	70	60	$64\pm4$

Table 4. Summary of Directions

Modelled Leeway ML is the leeway obtained by using equation 4 to calculate the leeway components on the two tracklines and using the differential method with these components to obtain the leeway. The quantities in the last column are averages of the three values obtained at points A, B, and C. The uncertainty values are the standard errors estimated by  $\sigma/\sqrt{n-1}$ , where  $\sigma$  is the standard deviation of values about the mean and n=3. induced leeway. These and some additional explanations are discussed further in the Appendix.

#### Shipdrift velocities

These results suggest that the effect of the leeway error on surface current estimates can be significant where velocities are calculated primarily from lines that are oriented normal to the wind direction, where the mean wind velocities are large, and where the surface currents are weak. A good example is where the South Africa–New York and the Brazil–New York tracklines cross the Northeast Trades in the North Equatorial Current. The (corrected) leeway along these lines is around 30% of the surface current measured on the Europe to South America lines, and rotates the current vector 13° downwind. Even though this leeway is a substantial percentage of the measured current, leeway causes only a small leeward angular deviation ( $\sim 0.3^\circ$ ) of a 12 knot ship from its steered course.

The relative effect of leeway is reduced in the equatorial band (5 S-10 N) where currents are much swifter. The near-equatorial currents have mean velocities as large as 30-50 cm/sec and the amplitudes of the seasonal variations are typically 10-20 cm/sec (Richardson and Walsh, 1986). Although the seasonal variations of winds could have caused (through leeway) some of the apparent seasonal variations of surface currents, the mean leeway values ( $\sim 1.8 \text{ cm/sec}$ ) would be on the order of 10%-20% of the seasonal variation of the dominant currents, significant but not overwhelming.

The effect of leeway on Eddy Kinetic Energy (EKE) calculated from shipdrifts is small. This is because relatively large random errors ( $\sim 20 \text{ cm/sec}$ ; see Richardson, 1983) in the shipdrift technique coupled with the usual energetic eddy field in the ocean result in large calculated EKE values (Wyrtki *et al.*, 1976). The lowest shipdrift EKEs in the ocean are located in the subtropical gyres and are around 300 cm<sup>2</sup>/sec<sup>2</sup>, which implies an rms velocity about the mean of around 25 cm/sec. An additional 2–3 cm/sec variation in currents due to leeway would be practically undetectable in the EKE distribution.

The 12 cm/sec current velocity reported here for the North Equatorial Current is around half of the prevailing current ( $\sim 25$  cm/sec) shown in the U.S. Pilot Charts and in many atlases of ocean currents, although the origin of the data is the same. This is because a prevailing current combines the direction of the vector average velocity with the scalar average speed. Note that the magnitude of the prevailing current, 25 cm/sec, is approximately equal to the rms velocity. Random errors, which can be large in shipdrift measurements, tend to cancel in vector averages of velocity, but usually do not cancel in the calculation of scalar average speeds. Thus part of the difference between a vector average velocity and a prevailing current speed is measurement error. Because of its inflated value, the prevailing current speed is relatively less influenced by leeway than the vector average current.

The leeway estimated here is fairly close to a value estimated by comparing velocities from moored current meters (13 months) and historical shipdrift velocities near 6 N 28 W (Richardson *et al.*, 1992). In that study the downwind velocity from shipdrifts relative to the downwind velocity from a current meter at 20 m (both averaged coherently with respect to the wind direction) was 8.1 cm/sec  $\pm$  1.5 cm/sec for winds around 6.6 m/s at a height of 3 m. This value (8.1 cm/sec) includes both leeway and unknown shear in the upper 20 m. An estimate of the wind-induced downwind shear over the mixed layer for the 6 N location is 3 cm/sec (Price, personal communication) which suggests the leeway was around 5 cm/sec.

This is larger than the 1.8-3.5 cm/sec estimated leeway for the North Equatorial Current near 20 N. However, if the ships experienced a downwind and downwave Stokes drift of a few cm/sec, which is consistent with estimates of Stokes drift averaged over the upper 5 m, where the ship hulls are located (Kenyon, 1969), then the estimates of leeway could be brought into conjunction. The two values of leeway agree fairly well considering (1) the size of the errors in the estimates, (2) the mismatch in timing of current meter (1984-85) and shipdrift (~1920-1941) measurements and in their locations (a point for current meter, a 300-400 km swath for shipdrift), (3) the unmeasured downwind shear between 20 m and the ships' hulls (the usual problem in comparisons between shipdrifts and other current measurements) and (4) the unknown magnitude of Stokes drift. Because of the unknown (unmeasured) downwind shear in the upper 20 m including Stokes drift and the mismatch in timing and location, the leeway estimated from the differential method is considered to be the more realistic one.

## CORRECTION OF SHIPDRIFT VELOCITY

If we assume that the corrected leeway  $L_c$  calculated from the shipdrift data is representative of the true leeway, then we can use  $L_c$  to predict real leeway and to correct shipdrift velocities. The predicted leeway is defined here to be the modelled leeway curve (equation 4) multiplied by 1.35 to make it pass through the average estimated leeway value  $L_c = 3.54$  cm/sec at  $W_L = 5.91$  m/s (Fig. 10). The resulting relationship can be approximated by a polynomial

$$L_c = 0.0027 + 0.0025 W_L + 0.00051 W_I^2 \tag{8}$$



Fig. 10. Plot of predicted leeway versus local wind speed. The small circle and error bar show the mean leeway and standard error estimated using shipdrifts and the subtraction technique and including the correction term (see Table 3). The linear fit passes through the origin and the estimated mean leeway value 3.54 cm/sec at 5.91 m/s. The predicted leeway curve is a combination of the modelled leeway from equation 4 using  $p_a/p_w = 1.15 \times 10^{-3}$ ,  $A_a/A_w = 1.0$ , a ship speed of 6.2 m/s, a local wind abeam  $\theta = 90^\circ$  of 5.9 m/s, and a factor of 1.35 chosen so the curve passes through the estimated mean leeway value.

which is a least squares best fit to the modelled leeway adjusted to match the estimated leeway  $L_c$ . The polynomial is a good fit to the predicted leeway for wind speeds of 1-17 m/s. Also shown in Fig. 10 is a linear fit whose equation is  $L_c = 0.0060 W_L$ .

It is tempting to explain the 1.35 factor as being the ratio  $A_a/A_w$  of real ships at sea versus the 1.0 estimated here. However part of the factor might be caused by waves, which could partially balance the hydrodynamic moment, reduce the mean downwind rudder deflection, and increase leeway. For the case of zero rudder deflection, the factor required to force the modelled leeway (eq. 5.0,  $\theta = 90^\circ$ ) to match the estimated leeway is reduced to 1.12. For this case the modelled and estimated leeway closely agree (within 12%). A third possibility (discussed later) is the nonlinearity of leeway coupled with wind variations.

For fairly small wind speeds, <7 m/s, the predicted leeway curve and the linear fit agree within a few tenths of a cm/sec in leeway. In this low wind regime the linear fit seems to be a reasonable approximation of the predicted leeway. At higher wind speeds the linear fit diverges from the predicted leeway curve reaching a difference of 1.8 cm/sec at a wind speed of 10 m/s. Because the predicted leeway curve is extrapolated at wind speeds over 5.9 m/s, and because there is no verification of it at higher wind speeds, corrections to shipdrift velocity using the extrapolated curve should be applied with caution. Fortunately, the annual mean wind velocity in the North Atlantic is generally less than 7 m/s (Fig. 6b), where the predicted leeway curve is probably a pretty good representation of leeway.

The only direct measurements of the leeway of a ship at sea that I could find to verify the predicted leeway were of a 60 m long Japanese fisheries training ship (Hiraiwa et al., 1967). The ship steamed at various speeds on a course at right angles to the local wind, and the leeway was measured relative to the drift of a gill net, which was assumed to represent the water velocity. Measurements made with a ship speed of 12 knots in a wind speed of 8 m/s clustered near a leeway of 10 cm/sec, which is about twice the leeway predicted by the curve in Fig. 10. There are two explanations for this difference. First, the fisheries ship had a larger  $A_a/A_w = 1.8$  compared to cargo ships and it encountered a larger  $\rho_a/\rho_w = 1.23 \times 10^{-3}$  in the Bering Sea compared to the tradewinds. When multiplied together, the two values for the fisheries ship are 1.9 times larger than the values for the cargo ships in the tradewinds. Thus the predicted leeway for the fisheries ship would be almost twice that of the cargo ships. Second, the gill net extended from the surface down to roughly 10 m and drifted with a velocity averaged over this depth range. If the water in the upper few meters drifted downwind relative to the gill net, which seems likely, then the measured leeway would be biased too large. Therefore the fisheries ship leeway appears to be consistent with predicted leeway (Fig. 10) when the relevant details of the measurements are included.

In correcting shipdrift velocities the simplest case is one in which numerous tracklines cross each other at various directions. In this case the expected mean leeway is in a downwind direction and equal to  $L_c/2$ . The factor of 2 is needed because two tracklines were used to estimate  $L_c$ , so the per trackline average leeway is  $L_c/2$ . In addition Fig. 3d shows that the modelled average downwind leeway is one half the leeway for  $\theta = 90^{\circ}$ . The leeway correction for a box-averaged shipdrift velocity is given by  $-L_c/2$ , where  $L_c$  is equal to  $1.35 \times v$  (equation 4) evaluated at  $\theta = 90^{\circ}$  or to the expression given by equation 8.

The second, more complicated case is where most data lie along a specific trackline, as in the North Equatorial Current region considered here. Correcting shipdrift mean velocity values for leeway is difficult because both the angle  $\theta$  of the wind velocity relative to the trackline and the contamination by crossing lines could be important and both need to be considered in the correction. The leeway correction is not obvious because of the ambiguous relationship between the estimated leeway and wind velocity for various angles between trackline and wind velocity. The problem is the near-zero implied leeway on tracklines 1 and 2 despite angles up to  $\theta = 41^{\circ}$  at point C. The implication is near-zero leeway for low angles  $\theta \le 41^{\circ}$  and significant leeway for large angles  $\theta \ge 60^{\circ}$  up to 90°. An unresolved issue is how leeway varies throughout the range of angles, especially for angles between 41° and 60°. For large angles  $\theta \ge 60^{\circ}$  we can estimate the leeway correction using the curve of  $L_c$  versus wind speed in Fig. 10 as described in last paragraph. The direction of leeway correction for a single trackline would be normal to it and upwind. If the contamination by ships travelling on different courses was significant, it would need to be included in order to adjust the leeway correction to be representative of the actual contaminated leeway on the line. For the case of tracklines 3 and 4 the leeway correction is  $(-2.69/3.54) L_c = -0.76 L_c$ .

#### Wind fluctuations

It is important to remember that the modelled leeway represents an instantaneous value based on the local wind, whereas the estimated leeway is an average of data obtained under a variety of wind velocities. Since leeway is a nonlinear function of wind velocity, the estimated leeway could be somewhat larger than the real instantaneous leeway-versus-windspeed relationship. We can estimate the size of the difference between the average leeway and instantaneous leeway by using the measured wind fluctuations in the Tradewind region, which have a standard deviation near 3 m/s (Isemer and Hasse, 1985; their charts 171 and 176). Assuming that the fluctuations in wind speed are normally distributed about the mean wind velocity and using the predicted leeway curve  $(1.35 \times \text{equation 4}, \text{Fig. 10})$ , we estimate that the average leeway could be around 0.4 cm/sec larger than the 3.5 cm/sec value predicted by the curve using the mean wind velocity of 5.9 m/s. This result might explain why the leeway estimated from data was larger than the modelled leeway. This calculation suggests that, in the tradewind region, the instantaneous leeway curve and the leeway measured under typical wind fluctuations agree quite well (within around 10%). In regions where the wind variations are much larger, we would expect the agreement to be poorer. In principal one could improve the leeway correction in these regions by combining measurements of wind fluctuations there with the predicted leeway curve.

The documentation that accompanies the shipdrift data states that shipdrift values measured in high winds  $\geq$  33 knots (17 m/s) and waves  $\geq$  12 feet have been omitted from the file. Since any high wind speeds > 17 m/s have been included in estimates of the mean wind velocity, there is a resulting incompatibility of shipdrifts and wind velocities when some high winds measurements are included. For a calculated average wind velocity that included some values over 17 m/s, the corresponding average leeway would be biased low compared to the real leeway-versus-wind-speed relationship because the shipdrift measurements with the largest leeway values would have been excluded from the average. The magnitude of the bias would depend on number and size of the leeway values excluded. If one knew the frequency distribution of winds for certain regions and times one could crudely estimate the size of this bias. In order to obtain predicted leeway in such a high wind regime the curve in Fig. 10 would have to be extrapolated far from the data (5.9 m/s) and such an extrapolation would result in a very large uncertainty in the predicted leeway.

#### SUMMARY

The relationship between the leeway of a ship and the local wind velocity was modelled using the equations of motion and results of laboratory measurements of the transverse forces and yawing moments of model ships at various angles of attack. The modelled leeway is 2.6 cm/sec for ships encountering a mean wind speed of 5.9 m/s, typical of the Tradewind region of the North Atlantic. This is much smaller than the 20 cm/sec leeway modelled for similar ships drifting with no way on. The modelled leeway for underway ships was found to increase nonlinearly with wind speed, very different from the linear relationship obtained for ships with no way on. The modelled leeway may underestimate the leeway of real ships in the ocean because of the neglect of waves, which could cause additional leeway, especially in high winds when the waves are large. The many approximations and sources of error suggest that the modelled leeway has a large uncertainty. Considering this uncertainty, it is remarkable that the modelled leeway agrees quite closely with the leeway estimated from shipdrift data (for tracklines oriented approximately normal to the local wind velocity).

The amount of leeway of real ships underway was estimated using the historical shipdrift data. For the area of the Northeast Trades near 20 N, 45 W, where the mean wind velocity is 5.9 m/s, the leeway is  $2.7 \pm 0.2$  cm/sec. This is an average of three values, each calculated by subtracting the surface current velocity determined from a trackline oriented roughly parallel to the mean wind (no-leeway case) from the current velocity determined from a trackline oriented at nearly right angles to the mean wind. The three values agree well with each other, suggesting they are not merely a result of noisy data. The 2.7 cm/sec value is considered to be an underestimate, because data from both sets of tracklines were somewhat contaminated by vessels steaming normal to them. An estimate of the contamination error suggests the real leeway is  $3.5 \pm 0.4$  cm/sec. Expressed as a percentage of the mean wind velocity, this leeway is  $0.60 \pm 0.09\%$ . Corrections to shipdrift velocity were estimated by fitting the modelled leeway-versus-wind-speed curve to the data.

The effect of leeway on a shipdrift-determined current velocity depends strongly on the orientation of the trackline used to calculate the velocity. The effect is greatest ( $\sim 30\%$ ) where the mean wind velocity is large and nearly normal to the trackline, such as along the South Africa-New York and Brazil-New York tracklines in the Northeast Trades. The effect is diminished by the additional presence of other tracklines (Europe-South America) oriented nearly parallel to the wind. For the cases of lines oriented randomly with respect to the mean wind direction, or where two perpendicular lines cross each other, the mean corrected leeway is reduced by half, to around  $1.8 \pm 0.2$  cm/sec.

The size of the estimated mean leeway, 1.8 cm/sec, is around 15% of the mean current velocity in regions of low velocity (10–15 cm/sec) like the North Equatorial Current near 20 N, 45 W. This estimated leeway is significantly smaller than the swift seasonally varying currents observed within about 10° of the equator. For example, the amplitude of the seasonal variation of the countercurrent is 20 cm/sec, roughly ten times larger than the leeway.

One puzzling result is the implied near-zero leeway on tracklines 1 and 2, which have angles of  $19^{\circ}-41^{\circ}$  with respect to the wind direction. The reason for this is not known, but may be the different transverse response of a ship steaming nearly parallel to the wind and wave direction (versus normal to it) plus a possible small systematic steering error which could have compensated for any induced leeway. The implication is that the modelled

leeway is suspect for tracklines that are oriented fairly close to the wind direction  $(\theta < 45^{\circ})$ .

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#### APPENDIX

#### DISCUSSION OF LEEWAY DIRECTION

This discussion is an attempt to reconcile the difference in direction between the modelled leeway and the leeway estimated from shipdrift data. Two significant differences encountered by a ship steaming along a trackline closely aligned with the wind velocity (tracklines 1 and 2) compared to a trackline nearly normal to the wind (tracklines 3 and 4) are the relative wind acting on the ship and its motion in the seas. Consider a ship steaming northward at 12 knots into a local wind blowing at 12 knots from a direction of 20° to the right of the ship's course (tracklines 1 and 2 at point B). The ship-induced wind (12 knots) is added to the local wind (12 knots) to give a relative wind of 24 knots at an angle of 10° to the right of the course. Now consider a ship on the reciprocal course, steaming southward at the same speed in the same local wind. The relative wind blowing against the ship would be 4 knots from a direction almost abeam. The resulting leeway calculated from this hypothetical trackline would be an average of the values from the upwind and downwind courses, values that are very different from each other. This example is contrasted with a ship steaming at 12 knots with a 12 knot wind abeam somewhat like tracklines 3 and 4. The relative wind is 17 knots at a direction of 45° off the bow and is similar on the reciprocal course.

The motion of a ship would be different along the two sets of tracklines, further complicating the response of a ship to the wind. A ship steaming into the wind and seas pitches, a ship steaming normal to the wind and seas rolls, and a ship steaming downwind and in the same direction as the seas or with quartering seas pitches, yaws, and rolls. A rectification of wave forces could be very different depending on the direction of the ship relative to the wind and seas. Wind gusts and waves continually vary a ship's yawing tendency. An inability of the helmsman or autopilot to maintain the correct average course in the presence of wind and waves could lead to a small but systematic (with respect to the mean wind velocity) steering error that would be indistinguishable from leeway but could possibly act to counter the leeway on the course most closely aligned with the wind. A systematic upwind steering error of only 0.1° on tracklines 1 and 2 is all that would be required to counter the modelled leeway on these tracklines.

The lack of apparent leeway on tracklines 1 and 2 may be merely a result of the captains' better leeway corrections on these lines. Since we concluded that most captains did not correct for leeway because they did not know its size, this explanation is probably not correct.

We should also reconsider whether the along-trackline leeway could be important. Earlier we assumed that it was zero because any along-trackline change in ship's speed due to the wind would be included in the speed given by the ship's log. If, however, there was an unknown along-trackline leeway that was proportional to the along-trackline component of mean wind velocity and equal to the rate of across-trackline leeway, then two crossing tracklines would have equal leeway no matter what the direction of wind. These leeways would exactly cancel when the current velocities were subtracted. Since we do calculate a reasonable leeway, this cannot be the explanation. Allowing for different relative rates of along-trackline and across-trackline leeway does not seem to give the correct observed leeway, the along-track leeway rate on tracklines 1 and 2 (most closely aligned with the wind) would have to be much less than that on tracklines 3 and 4, which would have to be just the correct magnitude to counter the cross-track leeway on 1 and 2. This seems intuitively wrong because we would expect the greatest along-track leeway on 1 and 2 (not the least) since they are most closely aligned with the wind. Data from the mariner class cargo ship (Beck *et al.*, 1989 their Fig. 10) show that the largest decrease in speed due to winds and waves is for a course heading into

them. The relative reduction in ship speed by winds and waves is approximately proportional to  $\cos(\theta/2)$  where  $\theta$  is the angle between the ship heading and direction from which the waves and winds are travelling. The alongtrack components of leeway calculated using this relationship do not rotate the estimated leeway vector normal to tracklines 3 and 4.

Another possibility is that under certain circumstances, errors in the ship's speed log could cause apparent leeway in the along-track direction. A speed log mounted on the hull might respond differently to a ship pitching (and maybe even pounding) into the seas compared to a ship rolling on a course normal to the seas. This could result in errors in the indicated ship speed. Slightly different responses by the speed log along the two different sets of tracklines could have contributed to rotating the calculated leeway vector in a downwind direction. For this explanation to work, however, the along-trackline error on lines 3 and 4 would have to be much greater than the error on tracklines 1 and 2 and of the right magnitude and direction to just counter the predicted cross-trackline leeway on tracklines 1 and 2. This seems a bit farfetched.

To conclude this speculation on leeway direction, the most reasonable explanations of why the estimated leeway direction does not match the modelled direction are (1) that the cross-track component of leeway on tracklines 1 and 2 was very small due to the reduced (compared to the model) response of a ship to the wind and seas for courses most closely aligned with the wind, and (2) a small  $(0.1^\circ)$  but systematic steering error compensated for any leeway on these tracklines.