Statistical Analysis of Observed Iceberg Drift[1]

ROBERT ERWIN ETTLE[2]

ABSTRACT. Eight iceberg trajectories observed by the U.S. Coast Guard during 1965, 1967, and 1968 have been subjected to preliminary analysis. The data were obtained by tracking the icebergs relative to fixed reference markers using visual bearings and radar ranges. Speed ratios and drift angles were calculated for each half hour of iceberg trajectory. It was found that at low wind speeds the effects of permanent currents, older wind-driven currents, and tidal currents predominate over wind drag and new wind-driven currents, whereas at wind speeds of over 10 knots the wind has a significant effect on the drift of an iceberg. The ratio of the drag coefficient for the iceberg's above-water portion to the drag coefficient for its submerged portion was found to range from 1.5 to approximately 7.

RÉSUMÉ. *Analyse statistique de la dérive observée des icebergs.* On a soumis à une analyse préliminaire les trajectoires de huit icebergs observés par la Garde côtière des E.U. en 1965, 1967 et 1968. On a recueilli les données en suivant les icebergs par rapport à des repères fixés, au moyen de levés visuels et du radar. On a calculé les rapports de vitesse et les angles de dérive pour chaque demi-heure de trajectoire. On a trouvé que pour des vitesses du vent faibles, les effets des courants permanents, des courants anciens d'origine éolienne et des courants de marée prédominent sur la traînée du vent et sur les courants récents d'origine éolienne, alors que pour des vitesses du vent de plus de 10 nœuds, le vent a un effet significatif sur la dérive de l'iceberg. Le rapport du coefficient de la traînée pour la partie de l'iceberg au-dessus de l'eau au coefficient de la traînée pour la partie au-dessous de l'eau se situe de 1.5 à environ 7.

РЕЗЮМЕ. *Статистический анализ дрейфа айсбергов.* Проведен предварительный анализ траекторий движения восьми айсбергов, наблюдение которых проводилось Береговой Службой США в 1965, 1967 и 1968 годах. Движение айсбергов относительно неподвижных объектов определялось визуально и с помощью радара. Коэффициенты скорости и углы дрейфа вычислялись для каждого получаса траектории айсберга. Было обнаружено, что при небольшой скорости ветра, движение айсбергов определяется комплексом постоянных, ветровых и приливных течений. Если же скорость ветра больше 10 узлов, дрейф айсберга определяется этим ветром. Выяснилось, что отношение коэффициента торможения надводной части айсберга к коэффициенту торможения его подводной части меняется от 1,5 до приблизительно 7.

INTRODUCTION

Since 1914, the U. S. Coast Guard has operated the International Ice Observation and Ice Patrol Service in the North Atlantic Ocean (Ice Patrol). During the iceberg season (March-July), the southern and eastern limits of known ice are patrolled regularly using Coast Guard aircraft and, when necessary, Coast Guard cutters. During the iceberg season, the Coast Guard Oceanographic Cutter *Evergreen* (WAGO-295) conducts oceanographic surveys to calculate ocean cur-

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[2]Coast Guard Oceanographic Unit, Washington, D.C.

rents by using the geostrophic method (Neumann and Pierson 1966). These calculated currents and forecast wind conditions are routinely used to predict iceberg drift during periods between sightings by patrol aircraft or cutters.

To better understand the relationship between the relevant forces (i.e. wind, waves, and currents) and the resultant iceberg movement, iceberg drift studies were scheduled. These studies consisted of accurately tracking an iceberg's movement while wind and current velocity were observed. While these data will be used to develop and verify mathematical models for iceberg drift, it is felt that publication of a basic statistical analysis of the data is valuable.

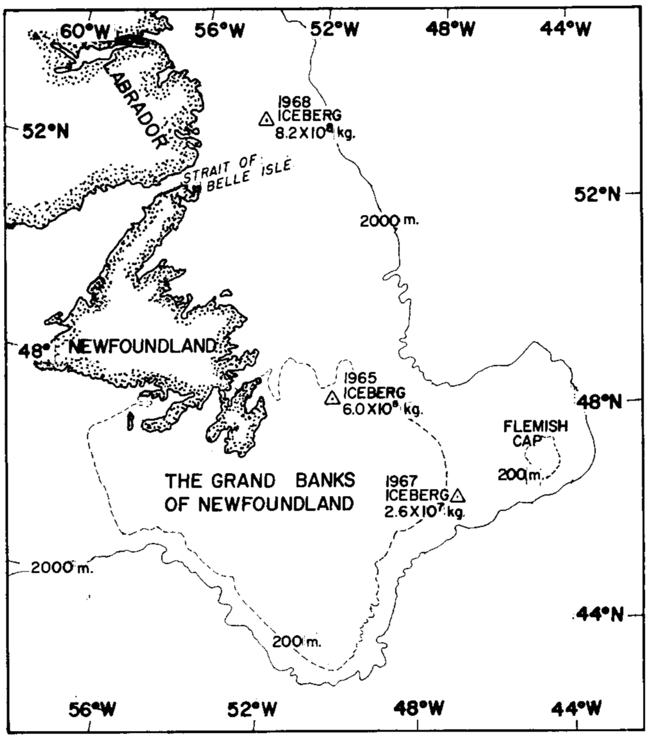

FIG. 1. Iceberg drift study area.

The observations were made on the Grand Banks of Newfoundland and over the Labrador continental shelf (Fig. 1). The most prominent feature of the oceanic circulation in this region is the Labrador Current flowing southeastward along the continental shelf and slope of Labrador (Smith *et al.* 1937). At about 48°N, latitude, a part of the Labrador Current turns eastward and passes north of Flemish Cap; most of the current, however, turns southward and follows the continental slope along the eastern edge of the Grand Banks of Newfoundland. Current speeds in this region are generally between 1 and 2 knots, but greater speeds have been observed (Soule 1964; Ettle and Wolford 1972).

Eight separate iceberg drift trajectories obtained from three icebergs, tracked on Ice Patrol cruises during 1965, 1967, and 1968, respectively, were of suitable quality for further analysis.

TABLE 1. Iceberg drift observations.

Date	Approximate location	Average mass (kg.)	Hours tracked	Current drogue depth (m.)
2-4 May, 1965	47-56°N 50-52°W	6.0 x 10^8	47	9.1 (35 hours) 54.6 (12 hours)
1-4 June, 1967	46-08°N 47-27°W	2.6 x 10^7	72	9.1 (59 hours) 60.0 (13 hours)
3-8 August, 1968	53-11°N 53-48°W	8.2 x 10^8	90	45.5 (70 hours) 54.6 (20 hours)

Mass determinations were made by taking photographs of the icebergs along equally-spaced radial directions. The subaerial (i.e. above-water) topography was plotted at 25 foot (7.6 m.) intervals and the subaerial volume was calculated. Using an assumed iceberg density of 0.9 gm./cm.^{3} and Archimedes Principle, the iceberg mass was calculated. These mass determinations are estimated to be accurate to ± 10% (Kollmeyer *et al.* 1965). Average iceberg mass, approximate location, date and duration of observation, and depth of current drogue are shown in Table 1.

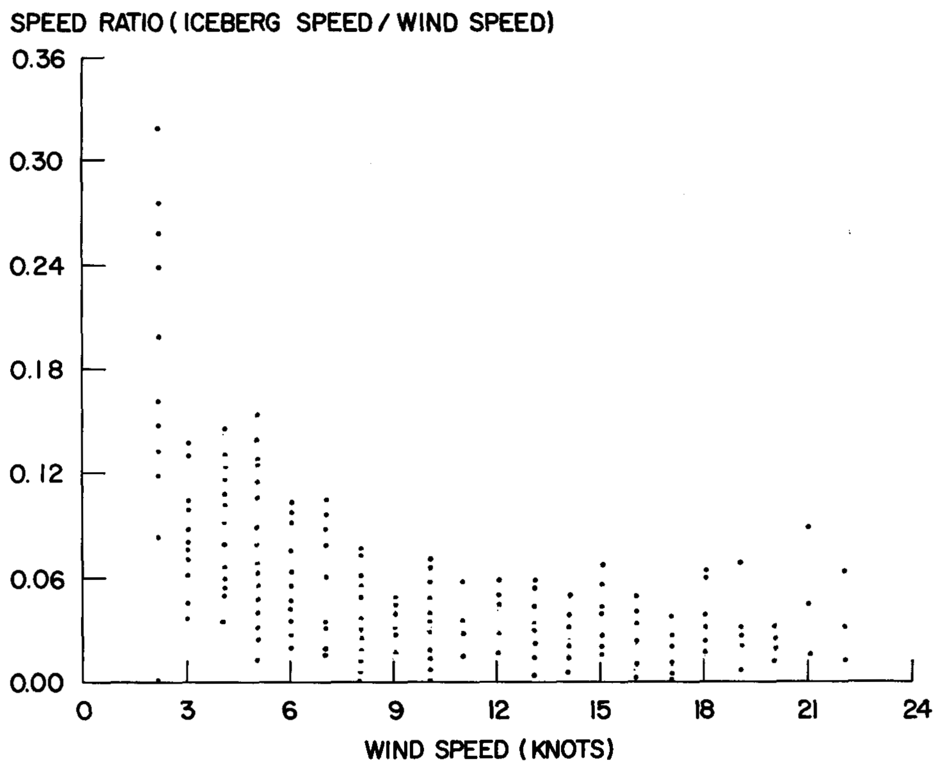

FIG. 2.

It should be noted that the 1967 berg was located near the high velocity axis of the Labrador Current (up to 2 knots). The 1965 berg was located on the Grand Banks where the currents are weaker and more variable (Soule 1964), while the 1968 berg was over the Labrador continental shelf where the currents, though generally southeastward, are also somewhat weak and variable (Andersen 1968).

Wind velocity was observed using an installed shipboard anemometer and was corrected for ship motion. The icebergs under study as well as the subsurface current drogues were tracked relative to a fixed reference marker using visual bearings and radar ranges. These procedures are described in greater detail by Wolford (1966).

Since berg, wind, and drogue observations were made at irregular intervals that varied from 20 to 60 minutes, a computer program was developed to interpolate values for each parameter to the even hour and half hour. The result was 396 half-hourly sets of data, with each set containing iceberg velocity, wind velocity, and generally, current velocity.

ANALYSIS

A speed ratio and a drift angle were calculated for each half-hourly data set. The speed ratio (V_i/V_a) was defined as the ratio of iceberg speed (V_i) to wind speed (V_a). Drift angle was defined as iceberg drift direction minus downwind

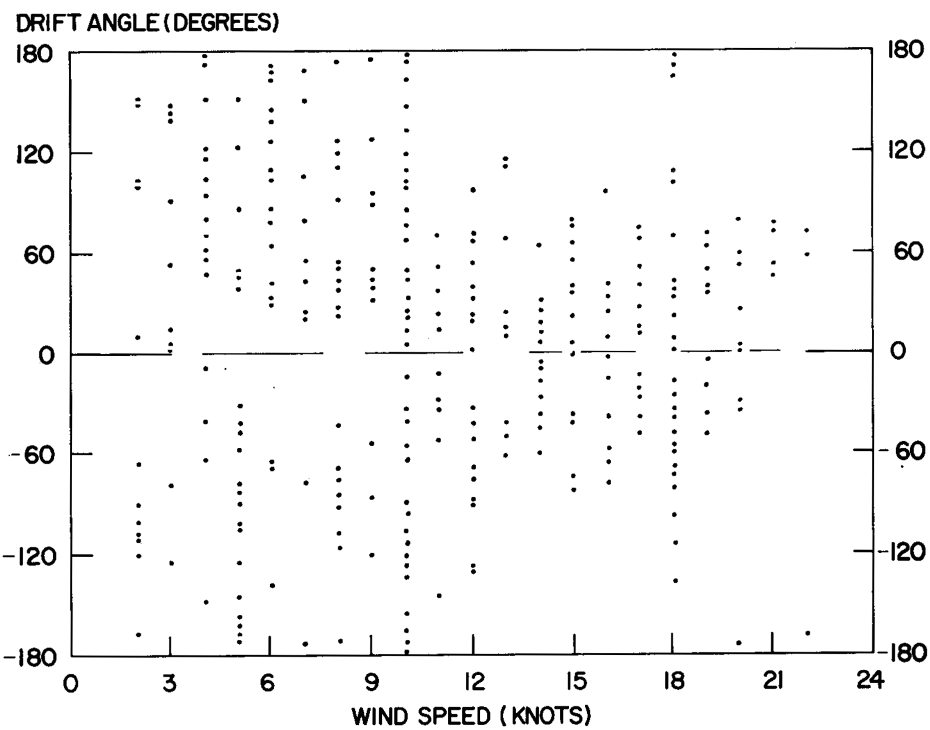

FIG. 3.

TABLE 2. Mean speed ratios and mean drift angles.

Wind speed class (knots)	Mean speed ratio	Speed ratio: standard deviation	Mean drift angle	Drift angle: standard deviation	Samples in class
0-5	0.123	0.124	−1	104	73
6-10	0.041	0.064	9	102	144
11-15	0.030	0.015	2	53	90
16-20	0.019	0.014	5	63	82
21-25	0.039	0.029	29	88	7
6-25	0.032	0.044	6.5	81	323

direction. Thus a positive drift angle means the iceberg drift was to the right of downwind, while a negative drift angle means the iceberg drift was to the left of downwind.

Speed ratio (ordinate) has been plotted against wind speed (abscissa) for all 396 data sets (Fig. 2). At wind speeds above 10 knots the speed ratios varied from 0.00 to 0.07, while at wind speeds below 10 knots the speed ratios were occasionally much larger. This occurs because, at low wind speeds, the effects of permanent currents, older wind-driven currents and tidal current predominate over the effects of wind drag and new wind-driven currents.

Drift angle (ordinate) has been plotted against wind speed (abscissa) for all 396 data sets (Fig. 3). At wind speeds of less than 10 knots the bergs moved in random directions up to 180 degrees either side of downwind. Above 10 knots of wind speed the bergs drifted within about 60 degrees of downwind (Fig. 3). In both cases the majority drifted to the right of downwind.

The data were grouped by year, and thus by current regime, but there were no significant differences in mean speed ratio or mean drift angle from year to year. The 396 data sets were grouped by wind speed into 5 classes and the mean speed ratio and mean drift angle were calculated for each class (Table 2). The mean speed ratio for the 0 to 5 knot wind speed class has been distorted by permanent or tidal currents; this may also be the case for the 6 to 10 knot class.

Murray (1968) reports that theoretical wind-driven current factors developed by 8 different investigators range from 0.015 to 0.036. The grouped mean speed ratio for the classes from 6 to 25 knots wind speed was 0.032 (standard deviation was 0.044). It is logical that this observed mean speed ratio should lie at the upper end of the theoretical range, since it includes the effect of direct wind drag as well as wind-driven current. For predicting iceberg drift, Ice Patrol now uses speed ratios that range from 0.025 to 0.035 with increasing wind speed (Murray 1968).

With the exception of the 21 to 25 knot wind speed class, which had only 7 samples, the mean drift angles were nearly downwind. The grouped mean drift angle for the classes from 6 to 25 knots wind speed was 6.5 degrees to the right of downwind (standard deviation was 82 degrees). Note that the variability from the mean, as indicated by standard deviation, is quite high for both speed ratio and drift angle.

We can compare the drag coefficient for the subaerial portion of the iceberg (C_{Da}) with the drag coefficient for the submerged portion of the iceberg (C_{Dw}) if mean relative speed ratios are calculated based on the iceberg's movement relative to the water (r) rather than relative to the earth (V_i). The mean relative speed ratios (r/V_a) were substantially the same as the mean speed ratios (V_i/V_a).

Two rather gross simplifying assumptions are required to make the comparison: first, coriolis effect must be neglected, and secondly, steady state or equilibrium drift must be assumed. We may then equate the drag force due to the air with the drag force due to the water, as follows:

$$\tfrac{1}{2}\, \rho_a\, C_{Da}\, V_a^2\, S_a = \tfrac{1}{2}\, \rho_w\, C_{Dw}\, r^2\, S_w \qquad (1)$$

The various terms are:

ρ_a = Density of air
ρ_w = Density of sea water
C_{Da} = Drag coefficient for subaerial portion
C_{Dw} = Drag coefficient for submerged portion
V_a = Wind Speed
r = Iceberg speed relative to water
S_a = Cross-sectional area perpendicular to air flow
S_w = Cross-sectional area perpendicular to water flow

By rearranging, we obtain:

$$\frac{C_{Da}}{C_{Dw}} = \frac{\rho_w\, r^2\, S_w}{\rho_a\, V_a^2\, S_a} \qquad (2)$$

If we assume the ratio of water density to air density to be 10^3 and use 3.5 to 1.0 for the ratio of S_w to S_a (Budinger 1960), we obtain:

$$\frac{C_{Da}}{C_{Dw}} = 3.5 \times 10^3 \left[\frac{r}{V_a}\right]^2 \qquad (3)$$

TABLE 3. Drag coefficient ratio.

Wind speed class (knots)	Mean relative speed ratio	Drag coefficient ratio (C_{Da}/C_{Dw})
0-5	0.102	36.4
6-10	0.045	7.1
11-15	0.031	3.4
16-20	0.021	1.5
6-20	0.035	4.3

The resulting drag coefficient ratios are displayed in Table 3. Unfortunately, observational errors are magnified by squaring the relative speed ratio to get the drag coefficient ratio. At low wind speeds, a small error in wind speed observations will cause a large error in relative speed ratio which will be magnified by squaring to get drag coefficient ratio. This is a likely cause of the large ratio for the 0 to 5 knot wind speed class.

The drag coefficient ratios for the remaining wind speed classes ranged from 1.5 to approximately 7 and had a mean value of 4.3. This result is not surprising, since the Reynolds Numbers for the submerged flow and the subaerial flow can be shown to be of the same order of magnitude, and also since field observations indicate that the subaerial roughness is usually much greater than the submerged roughness.

CONCLUSIONS

At low wind speeds (<10 knots) the effects of permanent currents, tidal currents, and older wind-driven currents predominate over wind drag and new wind-driven currents. At wind speeds of over 10 knots the wind has a significant effect on the drift of an iceberg. The calculated mean values of speed ratio (0.032) and drift angle (6.5 degrees to the right of downwind) represent reasonable estimates. The ratio of the drag coefficient for the iceberg's subaerial portion to the drag coefficient for its submerged portion was found to range from 1.5 to approximately 7.

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