N84 27310

METHOD TO ESTIMATE DRAG COEFFICIENT AT THE AIR/ICE INTERFACE OVER DRIFTING OPEN PACK ICE FROM REMOTELY SENSED DATA

Uri Feldman

Department of Geography, Bar-Ilan University
Ramat-Gan 52100, Israel

ABSTRACT

A knowledge in near real time, of the surface drag coefficient for drifting pack ice is vital for predicting its motions. And since this is not routeinly available from measurements it must be replaced by estimates. Hence, a method for estimating this variable, as well as the drag coefficient at the water/ice interface and the ice thickness, for drifting open pack ice was developed. These estimates were derived from three-day sequences of Landsat-1 MSS images and surface weather charts and from the observed minima and maxima of these variables. The method was tested with four data sets in the southeastern Beaufort sea. Acceptable results were obtained for three data sets. Routine application of the method depends on the availability of data from an all-weather air or spaceborne remote sensing system, producing images with high geometric fidelity and high resolution.

1. INTRODUCTION

The study of drifting pack ice depends on the knowledge of numerous parameters related to its motion (Feldman and Howarth, 1979). And since data vital for determining these parameters are not routinely available for the polar oceans they must be estimated (Feldman et al., 1979, 1982). The purpose of this study is to present a method for estimating ice thickness and drag coefficients at the air/ice and the water/ice interfaces for groups of detached ice floes. To this end, a reduced form of the general equation of motion for drifting pack ice was employed, assuming wind stress, water drag and Coriolis force to be at equilibrium.

Data were obtained from three sources:

(1) Pack ice speed and direction of motion, which were measured fr[illegible] three-day sequences of sidelapping Landsat-1 multispectral scanner (MSS) [illegible]ges.

(2) Surface wind speed and direction, at 10 m above the ice and air density, which were obtained from three-day sequences of surface weather charts, following the work by Feldman et al. (1979, 1981).

(3) Minimum and maximum values of pack ice thickness and drag coefficients of its surface and subsurface, which were obtained from observations previously conducted in the Arctic ocean.

The method developed in this study is based upon employing three ratios between pairs of the unknown parameters, which could be calculated from the pack ice velocity vector and the wind field data, in conjunction with the known minima and maxima of the same parameters. The procedure to obtain the estimates was tested by four groups of open pack ice, consisting of three or four data sets within each group, which drifted in the Beaufort sea during October 1973, July and August 1974.

Acceptability of the results was determined from the corresponding values of the cross isobar angle.

2. PHYSICAL BACKGROUND

The general equation of motion for a unit area of drifting pack ice is given by Campbell (1965) as

$$\vec{\tau}_a + \vec{\tau}_w + \vec{C} + \vec{P} + \vec{I} = \rho_{ice}\, h\, d\vec{V}/dt \qquad (1)$$

where $\vec{\tau}_a$ is the horizontal air stress at the air/ice interface, $\vec{\tau}_w$ is the horizontal water stress at the water/ice interface, $\vec{C}$ is the horizontal Coriolis deflecting force, $\vec{P}$ is the horizontal marine pressure gradient force, $\vec{I}$ is the horizontal internal ice stress, ρ_{ice} is the ice density, h is ice thickness and $d\vec{V}/dt$ is the horizontal ice acceleration. Thorndike (1973) has shown that the horizontal acceleration term is usually much smaller than all other terms in equation (1). Therefore, a steady state drift can be assumed (Nansen, 1902; McPhee, 1982) and equation (1) can be rewritten as

$$\vec{\tau}_a + \vec{\tau}_w + \vec{C} + \vec{P} + \vec{I} = 0 \qquad (2)$$

If this equation is applied to drifting open pack ice, consisting of detached ice floes, where internal ice stress cannot be transmitted among the floes (Hibler, 1979; McPhee, 1980) then equation (2) can be reduced to

$$\vec{\tau}_a + \vec{\tau}_w + \vec{C} + \vec{P} = 0 \qquad (3)$$

Using data reported by Newton (1973, p.23) it can be shown that mean speed of ocean currents in the Beaufort sea is less than $2\,\mathrm{m\ day^{-1}}$. In addition, Hibler and Tucker (1979) stated that geostrophic currents and ocean tilt have a negligible effect on short term, weekly drifts. Hence, it may be concluded that in the area of study motions of drifting open pack ice can be determined from a simple steady state equation, written as

$$\vec{\tau}_a + \vec{\tau}_w + \vec{C} = 0 \qquad (4)$$

Nansen (1902), Sverdrup (1928), Shuleiken (1938), Fel'zenbaum (1958), Campbell (1965), Thorndike (1973), Neralla et al. (1980), Feldman et al. (1981) and McPhee (1982) applied equation (4) in their studies.

Under conditions of neutral equilibrium within the atmospheric boundary layer

$$\tau_a = \rho_a\, C_d^a\, U^2 \qquad (5)$$

where ρ_a is the air density, C_d^a the drag coefficient at the air/ice interface and U the horizontal surface wind speed at 10 m above the ice surface. Under similar conditions beneath the ice (Johannessen, 1970)

$$\tau_w = \rho_w C_d^w V^2 \tag{6}$$

where ρ_w is the ocean water density, C_d^w is the drag coefficient at the water/ice interface and V is the speed of the centre of gravity of a drifting group of ice floes. The Coriolis force may be derived from

$$C = \rho_{ice} f h V \tag{7}$$

where h is the ice thickness and $f(=2\omega \sin\phi)$ is the Coriolis parameter, ω ($=7.292\ 10^{-5}\ s^{-1}$) is the Earth's angular speed and ϕ is latitude.

Resolving the x and y components of $\vec{\tau}_a$, $\vec{\tau}_w$ and $\vec{C}$ from equations (5), (6) and (7), allows equation (4) to be written as

$$\rho_a C_d^a U^2 \cos \Delta\gamma = \rho_w C_d^w V^2 \tag{8}$$

and

$$\rho_a C_d^a U^2 \sin \Delta\gamma = \rho_{ice} f h V \tag{9}$$

where $\Delta\gamma$, the angle of sea ice deflection (Feldman et al., 1981) is defined as

$$\Delta\gamma = \theta_{ice} - \theta_u \tag{10}$$

and θ_{ice} and θ_u are the directions of motion of the pack ice and the surface wind respectively.

The cross isobar angle, $\Delta\theta$ is defined as

$$\Delta\theta = \Theta_G - \theta_u \tag{11}$$

where θ_G is the geostrophic wind direction. $\Delta\theta$ may be obtained from the difference between equations (11) and (10), written as

$$\Delta\theta = \Delta\gamma + \theta_G - \theta_{ice} \tag{12}$$

3. PACK ICE VELOCITY FROM LANDSAT MSS IMAGES

A number of techniques have been used to calculate the velocity of drifting pack ice from sequential Landsat MSS imagery (Crowder et al., 1973; Hibler et al., 1974; Wendler and Jayaweera, 1974; Nye and Thomas, 1974; Nye, 1975 and Sobczak, 1977). The orbits of Landsat converge in high latitude thereby producing sequences of four sidelapping images over the Beaufort sea. In this study, velocities of four groups of drifting ice floes were calculated over three-day sequences. A group could consist of any number of single ice floes in close proximity, but in these cases they ranged from 3 to 26. To determine the velocity it is necessary to measure the co-ordinates of each ice floe in a group and to know the exact mean time of imaging, t_i, on each day. The co-ordinates, x_i; y_i, of the ice floes were measured with a digitizer and were related to an origin and several control points located on land. The exact mean scanning time, t_i, was determined from the orbital information.

The area, A_i, of each floe was calculated from 1:250,000 scale enlargements of the images, using the dot grid method. The co-ordinates of the estimated centre of gravity of each group, X_{gr}; Y_{gr}, were calculated from

$$X_{gr} = \Sigma A_i x_i / \Sigma A_i \quad (13) \qquad \text{and} \qquad Y_{gr} = \Sigma A_i y_i / \Sigma A_i \quad (14)$$

This procedure eliminated effects due to collisions which could occur within a group while in motion.

The component mean velocities of drifting centres of gravity, V_x; V_y, were calculated for the intermediate scanning time, T_{11i+1} ($=t_{12}$, t_{23}, t_{34}.....) from

$$V_x = \Delta X_{gr}/\Delta t \quad (15) \qquad \text{and} \qquad V_y = \Delta Y_{gr}/\Delta t \quad (16)$$

where Δt is the time increment between sequential paths of Landsat-1 and ΔX_{gr} or ΔY_{gr} are the component distance increments during Δt.

4. RATIOS AND MEAN RATIOS BETWEEN ICE PARAMETERS

The first step towards estimating h, C_d^a and C_d^w consisted of determining the ratios M, N and B and their means M, N and [illegible]ues of M and N, defined as

$$M = h/C_d^a \quad (17) \qquad \text{and} \qquad N = C_d^w/C_d^a \quad (18)$$

were calculated from available data, for the four groups, at t_{11i+1}, by rewriting equations (17) and (18) from equations (9) and (8) respectively, as

$$M = (\rho_a U^2 \sin\Delta\gamma)/(\rho_{ice} f V) \quad \text{and} \quad (19)$$

$$N = (\rho_a U^2 \cos\Delta\gamma)/(\rho_w V^2) \quad (20)$$

The variable U was obtained from the geostrophic wind speed G by the formula

$$U = 0.54G + 1.68 \quad (21)$$

adopted by Feldman et al. (1979) from Hasse's (1974a, 1974b) work. G and ρ_a were derived from surface weather charts.

$\Delta\gamma$ was replaced by values of the mean angle of ice deflection $\overline{\Delta\gamma}$, defined and calculated by Feldman et al. (1981) in the area of study for t_{11i+1}. V was calculated from equations (15) and (16). Finally, the constants ϕ (required for calculating f in $f = 2\,\omega \sin\phi$) ρ_w and ρ_{ice} were replaced by $\phi = 70°$, $\rho_w = 1.03\ 10^3$ kg m^{-3} and $\rho_{ice} = 0.91\ 10^3$ kg m^{-3} respectively.

The means $\overline{M}$ and $\overline{N}$ were calculated for the four data sets at t_{12} & t_{23}, at t_{23} & t_{34}, at t_{12} & t_{34} and at t_{12}, t_{23} & t_{34}. Means of B, defined as

$$B = h/C_d^w \qquad (22)$$ were calculated from: $$B = M/N \qquad (23)$$

by replacing M and N in equation (23) with $\overline{M}$ and $\overline{N}$. Values of $\overline{B}$, $\overline{M}$ and $\overline{N}$ are presented in Table 1.

5. ACCEPTABILITY OF RESULTS FOR $\overline{B}$, $\overline{M}$ AND $\overline{N}$

Results presented in Table 1 indicate that two fully acceptable ratio sets of $\overline{B}$, $\overline{M}$ and $\overline{N}$ are available for cycle 26a, as well as one for cycle 26b, one for cycle 41 and none for cycle 43. And although the acceptable ratio sets obtained are sufficient for deriving the estimates of h, C_d^a and C_d^w, for three out of the four cycles tested, it is evidently necessary to account for the frequent occurrence of ratio sets or ratios which were either not available or rejected in Table 1.

5.1 Availability of Landsat-1 MSS images

Ratio sets numbers 4.2, 4.3 and 4.4 could not be determined because the Landsat-1 image, required for obtaining the variables V and $\overline{\theta}_{ice}$ for cycle 43 at t_4, was not available. This might occur in cases where a dense cloud cover prevents identification of ice floes on an image or in cases where floes drift outside the area covered by the corresponding image.

5.2 Ratios rejected by $\overline{\Delta\theta}$

Ratio sets number 2.1, 2.2, 2.3, 3.2, 3.3 and 3.4 were rejected where values of $\overline{\Delta\theta}$, calculated from equation (12) were either less than 0° or greater than 60°. This range of $\overline{\Delta\theta}$ was chosen as the criterion of acceptability for the ratio sets, firstly because corresponding observed data, required for calculating M and N from equations (19) and (20) respectively, were not available for comparison and secondly, because this range, which was determined from observations, is relatively small. The limits of $\overline{\Delta\theta}$ (0° and 60°) were determined from studies by Gordon (1952), Reynolds (1956), Aagaard (1969), Hasse (1974a, 1974b) and Lavrov (1974) conducted over sea surfaces, which have drag coefficients similar to those over pack ice (Roll, 1965) and from studies by Smith et al. (1970), Banke and Smith (1973), Feldman et al. (1979) and Albright (1980) conducted over pack ice.

Data of V and θ_{ice}, used in this study, are considered to be highly accurate, because Landsat-1 MSS images are nearly free of distortions and because the technique employed to obtain these data produces accurate results. Hence, rejection

Table 1: Means of the Ratios, B, M and N

Data Set No.	Cycle No.	Date	Period	$\overline{B}$ m	$\overline{M}$ m	$\overline{N}$
1.1	26a	23/24 & 24/25.10.73	t_{12} & t_{23}	886.64	638.38	$\underline{0.72}$
1.2	26a	24/25 & 25/26.10.73	t_{23} & t_{34}	$\underline{970.94}$	980.65	1.01
1.3	26a	23/24 & 25/26.10.73	t_{12} & t_{34}	837.14	795.28	0.95
1.4	26a	23/24, 24/25 & 25/26.10.73	t_{12}, t_{23} & t_{34}	864.02	777.62	0.90
2.1	26b	25/26 & 26/27.10.73	t_{12} & t_{23}	262.46	1225.71	4.67
2.2	26b	26/27 & 27/28.10.73	t_{23} & t_{34}	*	*	*
2.3	26b	25/26 & 27/28.10.73	t_{12} & t_{34}	*	*	*
2.4	26b	25/26, 26/27 & 27/28.10.73	t_{12}, t_{23} & t_{34}	*	*	*
3.1	41	24/25 & 25/26.07.74	t_{12} & t_{23}	156.09	543.19	3.48
3.2	41	25/26 & 26/27.07.74	t_{23} & t_{34}	*	*	*
3.3	41	24/25 & 26/27.07.74	t_{12} & t_{34}	*	*	*
3.4	41	24/25, 25/26 & 26/27.07.74	t_{12}, t_{23} & t_{34}	*	*	*
4.1	43	24/25 & 25/26.08.74	t_{12} & t_{23}	127.10	$\underline{7945.24}$	$\underline{62.51}$
4.2	43	25/26 & —— .08.74	t_{23} & ——	(–)	(–)	(–)
4.3	43	24/25 & —— .08.74	t_{12} & ——	(–)	(–)	(–)
4.4	43	24,25, 25/26 & —— .08.74	t_{12}, t_{23} & ——	(–)	(–)	(–)

$\underline{0.72}$ Rejected ratios: Where $\overline{B}$, $\overline{M}$ and $\overline{N}$ are outside the acceptable range.

* Rejected ratios: Where the corresponding value of $\overline{\Delta\theta}$ is outside the acceptable range.

(–) Ratios not given: Where data on pack ice velocity are not available.

of a ratio may result either from errors in the variables $\overline{\Delta\gamma}$, ρ_a and U^2 (equations 19 and 20) and/or from errors in $\overline{\Delta\gamma}$ and $\overline{\theta_G}$ (equation 12). And since variations in $\overline{\Delta\gamma}$ (Feldman et al., 1981) and ρ_a are relatively small, and U is linearly related to G (equation 21), it follows that rejection of a ratio set is mainly due to errors in G^2 and/or $\overline{\theta_G}$. Employment of interpolated values of G and $\overline{\theta_G}$, which were needed to replace gaps in the data sequences obtained from the surface weather charts, could be the main source of error.

6. MINIMA AND MAXIMA OF RATIOS BETWEEN OBSERVED ICE PARAMETERS

The second step towards estimating h, C_d^a and C_d^w consisted of determining the observed minima and maxima B_o, M_o and N_o from the observed minima and maxima h_o, C_{do}^a and C_{do}^w, which had previously been measured in the Artic ocean by other investigators. The ranges of h_o, C_{do}^a and C_{do}^w were summarized by Feldman et al. (1981) as

$$0.00 = h_{o\,min} \leqslant h_o \leqslant h_{o\,max} = 3.00 \text{ m} \tag{24}$$

$$0.95 = 10^3\, C^a_{do\,min} \leqslant 10^3\, C^a_{do} \leqslant 10^3\, C^a_{do\,max} = 4.00 \quad \text{and} \tag{25}$$

$$3.32 = 10^3\, C^w_{do\,min} \leqslant 10^3\, C^w_{do} \leqslant 10^3\, C^w_{do\,max} = 57.17 \tag{26}$$

Minima and maxima of B_o, M_o and N_o were determined by replacing h, C_d^a and C_d^w in equations (22), (17) and (18) with the observed minima and maxima of these parameters, given in equations (24), (25) and (26). These were

$$0.00 \leqslant B_o \leqslant 903.61 \text{ m} \tag{27}$$

$$0.00 \leqslant M_o \leqslant 3157.89 \text{ m} \quad \text{and} \tag{28}$$

$$0.83 \leqslant N_o \leqslant 60.18 \tag{29}$$

7. ESTIMATING ICE THICKNESS AND DRAG COEFFICIENTS

The final stage of estimating ice thickness and drag coefficients in the area during the period of study consisted of rewriting equations (22) and (17) for h, using the observed minima C_{do}^w, C_{do}^a and h_o from equations (26), (25) and (24), respectively, and the calculated means $\overline{B}$ and $\overline{M}$, written as

$$h = C^w_{do}\, \overline{B} \geqslant 3.32\ 10^{-3}\ \overline{B} \text{ m} \tag{30}$$

$$h = C^a_{do}\, \overline{M} \geqslant 0.95\ 10^{-3}\ \overline{M} \text{ m} \quad \text{and} \tag{31}$$

$$h = h_o \geqslant 0.00 \text{ m} \tag{32}$$

hence

$$h \geqslant \max.\ \{3.32\ 10^{-3}\ \overline{B},\ 0.95\ 10^{-3}\ \overline{M},\ 0.00\} = h_{LL} \text{ m} \tag{33}$$

where h_{LL}, the lower limit of h, was given by the maximum (max.) among the three values of h in equation (33). In the same way h_{UL}, the upper limit of h was given by the minimum (min.) among the three values of h in equation (34).

$$h \leqslant \text{min.} \quad \{57.17\ 10^{-3}\ \ \overline{B},\ 4.00\ 10^{-3}\ \ \overline{M},\ 3.00\} \ = h_{UL} \text{ m} \tag{34}$$

The range of h was defined as

$$h_{LL} \leqslant h \leqslant h_{UL} \text{ m} \tag{35}$$

Ranges of h were determined for each data set from equations (33) and (34) with $\overline{B}$ and $\overline{M}$ from Table 1. Results are presented in Table 2.

Ranges of C_d^a and C_d^w were derived from (17) and (22) after replacing M and B by their means and h by its lower and upper limit, written as

$$h_{LL}/\overline{M} \leqslant C_d^a \leqslant h_{UL}/\overline{M} \qquad (36) \qquad \text{and} \qquad h_{LL}/\overline{B} \leqslant C_d^w \leqslant h_{UL}/\overline{B} \qquad (37)$$

Ranges of C_d^a and C_d^w were determined for each data set from equations (36) and (37) respectively with $\overline{B}$ and $\overline{M}$ from Table 1 and h_{LL} and h_{UL} from Table 2. The results were presented in Table 2.

8. EVALUATING THE ESTIMATES OF h, C_d^a AND C_d^w

When the calculated values $\overline{B}$, $\overline{M}$ and $\overline{N}$ (Table 1) are either less than the corresponding minimum or greater than the corresponding maximum of B_o, M_o and N_o (equations 27, 28 and 29 respectively), then the estimated values of the lower limit of h, C_d^a and C_d^w are greater than the upper limit of these variables. In these cases the results are unacceptable as estimates for h, C_d^a and C_d^w. Hence, the results for cycle 43 in Table 2 were considered unacceptable.

The best results were those obtained for cycles 26b and 41, where $\overline{B}$, $\overline{M}$ and $\overline{N}$ (Table 1) are either greater than the minimum or less than the maximum of B_o, M_o and N_o (equations 27, 28 and 29 respectively). For the same reasons the results for cycle 26a are partially acceptable (i.e., the results for t_{12} & t_{34} and for t_{12}, t_{23} & t_{34} are acceptable while those for t_{12} & t_{23} and for t_{23} & t_{34} are not).

The calculated values of the ranges of h obtained for cycles 26a and 26b do not agree with those measured at the nearest coastal stations (Table 2). Freeze up along the west coast of the Mackenzie bay occurred about 8 October 1973 (interpreted from Landsat-1 image 1442-20295) and at Tuktoyaktuk, N.W.T. on 9 October 1973 (AES, 1974). Since only 0.25 - 0.50 m of ice could be formed during a period of 2-3 weeks (Pounder, 1965), it was suggested that values of h, measured during cycles 26a and 26b, provide a better approximation to the actual values than the calculated one. The calculated value of h_{LL} for cycle 26b is less than h_{LL} for cycle 26a and provides, therefore, a better estimate for the actual value of h. The calculated values of h for cycle 41 were within the range of values measured at Sachs Harbour, N.W.T. (1.80 m) on 14 June 1974 and at Cape Parry, N.W.T. (1.07 m) on 5 July 1974 (AES, 1974).

ORIGINAL PAGE IS
OF POOR QUALITY

Table 2: Estimates of Range and Mean Values of h, C_d^a and C_d^w for the Cycles

Data Set No.	Cycle No.	Date	Period	Thickness, h of Pack Ice and Fast Ice		Drag Coefficient at Surface $10^3C_d^a$		Drag Coefficient at Subsurface $10^3C_d^w$	
				Range, m	Mean, m	Range	Mean	Range	Mean
1.1	26a	23/24 & 24/25.10.73	t_{12} & t_{23}	2.93-2.55 (0.30-0.35)	2.74 (0.33)	4.58-4.00	4.29	3.32-2.90	3.11
1.2	26a	24/25 & 25/26.10.73	t_{23} & t_{34}	3.23-3.00 (0.30-0.35)	3.12 (0.33)	3.30-3.06	3.18	3.32-3.08	3.20
1.3	26a	23/24 & 25/26.10.73	t_{12} & t_{34}	2.78-3.00 (0.30-0.35)	2.89 (0.33)	3.49-3.77	3.63	3.32-3.59	3.46
1.4	26a	23/24, 24/25 & 25/26.10.73	t_{12}, t_{23} & t_{34}	2.87-3.00 (0.30-0.35)	2.94 (0.33)	3.69-3.86	3.78	3.32-3.47	3.40
2.1	26b	25/26 & 26/27.10.73	t_{12} & t_{23}	1.16-3.00 (0.30-0.35)	2.08 (0.33)	0.95-2.45	1.70	4.44-11.44	7.94
3.1	41	24/25 & 25/26.07.74	t_{12} & t_{23}	0.52-2.17 (1.07-1.80)	1.35 (1.44)	0.95-4.00	2.48	3.32-13.93	8.63
4.1	43	24/25 & 25/26.08.74	t_{12} & t_{23}	7.55-3.00 (— - —)	5.28 (—)	0.95-0.38	0.67	59.39-23.60	41.50

4.58 Rejected estimates, where their values are outside the corresponding observed ranges, h_o, C_{do}^a & C_{do}^w.

(0.30) Thickness of fast ice, measured at nearest coastal stations (AES, 1974)

9. CONCLUSIONS

It has been demonstrated that ice thickness and drag coefficients, associated with drifting open pack ice and vital for predicting its motions, which are not routinely available for the polar oceans, can be estimated from three-day sequences of satellite images and wind field data. Unfortunately, the method used could not be tested by a larger number of data sequences, since Landsat-1 has an 18 day repeat cycle and data recorded on cloudy days are useless.

Images recorded by weather satellites, within the visible or the thermal infrared regions of the electromagnetic spectrum were considered for application to this study. They were rejected because their images are geometrically distorted and have a relatively low resolution.

It is recommended that for a routine application of this method an all weather air or spaceborne remote sensing system, producing high geometric fidelity and high resolution images, should be employed.

10. ACKNOWLEDGEMENTS

The author would like to thank P.J. Howarth and J.A. Davies for their counsel during the preparation of the manuscript, to M.G. Sonis for his helpful comments and to Z. Drezner for his aid with the calculations. This work was supported by the Natural Science and Engineering Research Council, Canada and the Research Directorate, Atmospheric Environment Service, Canada.

11. REFERENCES

Aagaard, K., 1969: Relationship between geostrophic and surface winds at weather ship M. J. Geophys. Res., 74, 3440-3442.

AES, 1974: Ice thickness data for Canadian selected stations, freeze-up 1973 - break-up 1974. ICE 1-74. Atmos. Environ. Serv., Ottawa, Ont.

Albright, M., 1980: Geostrophic wind calculations for AIDJEX. Sea Ice Processes and Models, 402-409, Univ. of Wash. Press, Seattle, WA.

Banke, E.G. and S.D. Smith, 1973: Wind stress on arctic sea ice. J. Geophys. Res., 78, 7871-7883.

Campbell, W.J., 1965: The wind driven circulation of ice and water in a polar ocean. J. Geophys. Res., 70, 3279-3301.

Crowder, W.K., H.L. McKin, S.F. Ackley, W.D. Hibler III and D.M. Anderson, 1973: Mesoscale deformation of sea ice from satellite imagery. Advanced Concepts and Techniques in the Study of Snow and Ice Resources, 563-573, Nat. Acad. Sci., Washington, DC.

Feldman, U. and P.J. Howarth, 1979: Predicting the motions of drifting open pack ice. J. Glaciol., 24, 501-502.

Feldman, U., P.J. Howarth and J.A. Davies, 1979: Estimating the surface wind speed over drifting pack ice from surface weather charts. Boundary Layer Meteorol., 16, 421-428.

Feldman, U., P.J. Howarth and J.A. Davies, 1981: Estimating surface wind direction over drifting open pack ice. J. Geophys. Res., 86, 8117-8120.

Fel'zenbaum, A.I., 1958: The theory of steady drift of ice and the calculation of the long period drift in the central part of the Arctic basin. Problemy Severa, 2, 16-46. Translated from Russian in Problems of the North, 1961, 2, 13-44.
Gordon, A.H., 1952: The relationship between the mean vector surface wind and the mean pressure gradient over the oceans. Geofiscia Pura e Applicata, 21, 49-51.
Hasse, L., 1974a: Note on the surface to geostrophic wind relationship from observations in the German bight. Boundary Layer Meteorol., 6, 197-201.
Hasse, L. 1974b: On the surface to geostrophic wind relationship at sea and the stability dependence of the resistance law. Contrib. Atmos. Phys., 47, 45-55
Hibler, W.D. III, S.F. Ackley, W.K. Crowder, H.L. McKim and D.M. Anderson, 1974: Analysis of shear zone ice deformation in the Beaufort sea using satellite imagery. The Coast and Shelf of the Beaufort Sea, 285-296, Artic Instit. N. Am., Arlington, VA.
Hibler, W.D. III, 1979: A dynamic thermodynamic sea ice model. J. Phys. Oceanogr., 9, 815-846.
Hibler, W.D. III and W.B. Tucker III, 1979: Some results from a linear-viscous model of the Arctic ice cover. J. Glaciol., 22, 293-304.
Johannessen, O.M., 1970: Note on some vertical current profiles below ice floes in the gulf of St. Lawrence and near the North Pole. J. Geophys. Res., 75, 2857-2862.
Lavrov, N.A., 1974: Analysis of experimental data on the wind on the Baltic sea. Meteorologiya i Gidrologiya, 10, 102-104. Translated from Russian in Meteorol. and Hydrol., 1974, 10, 130-133.
McPhee, M.G., 1980: An analysis of pack ice drift in summer. Sea Ice Processes and Models, 62-75, Univ. of Wash. Press, Seattle, WA.
McPhee, M.G., 1982: Sea ice drag laws and simple boundary layer concepts, including application to rapid melting. CRREL, Hanover, NH.
Nansen, F., 1902: The [illegible] of the north polar basin and the influence of the wind upon the dr[illegible] north polar ice. The Norwegian North Polar Expedition 1893-1896, Scientific Results, Vol. 3, 357-386, Longmans, Green and Co., London, UK.
Neralla, V.R., W.S. Liu, S. Venkatesh and M.B. Danard, 1980: Techniques for predicting sea ice motion. Sea Ice Processes and Models, 197-206, Univ. of Wash. Press, Seattle, WA.
Newton, J.L., 1973: The Canada basin, mean circulation and intermediate scale flow features. Ph.D. thesis, Univ. of Wash., Seattle, WA.
Nye, J.F. and D.R. Thomas, 1974: The use of satellite photographs to give the movement and deformation of sea ice. AIDJEX Bull., 27, 1-21.
Nye, J.F., 1975: The use of ERTS photographs to measure the movement and deformation of sea ice. J. Glaciol., 15, 429-436.
Pounder, E.R., 1965: The Physics of Ice. Pergamon Press, Oxford, UK.
Reynolds, G., 1956: A wind analysis for the Northern Irish sea. Quart. J. Roy. Meteorol. Soc., 82, 469-480.
Roll, H.U., 1965: Physics of the Marine Atmosphere. Academic Press, New York, NY.
Shuleikin, V.V., 1938: The drift of ice fields. Comptes-Rendus (Doklady) de l'Academie des Sciences de l'URSS, 19, 589-594.
Smith, S.D., E.G. Banke and O.M. Johannessen, 1970: Wind stress and turbulence over ice in the gulf of St. Lawrence. J. Geophys. Res., 75, 2803-2812.

Sobczak, L.W., 1977: Ice movements in the Beaufort sea 1973-1975, determination by ERTS imagery. J. Geophys. Res., 82, 1413-1418.
Sverdrup, H.U., 1928: The wind-drift of the ice on the north Siberian shelf. The Norwegian North Polar Expedition with the "Maud" 1918-1925, Scientific Results, Vol. 4, 1-46, John Grieg, Bergen, Norway.
Thorndike, A.S., 1973: An integrated system for measuring ice motions. Ocean 73, 496-499. IEEE, New York, NY.
Wendler, G. and K.O.L.F. Jayaweera, 1974: A technique to obtain ice movement. J. Geophys. Res., 79, 3476-3479.