The East Greenland Current North of Denmark Strait: Part I[1]

K. AAGAARD AND L. K. COACHMAN[2]

ABSTRACT. Current measurements within the East Greenland Current during winter 1965 showed that above the continental slope there were large on-shore components of flow, probably representing a westward Ekman transport. The speed did not decrease significantly with depth, indicating that the barotropic mode dominates the flow. Typical current speeds were 10 to 15 cm. sec.$^{-1}$.

The transport of the current during winter exceeds 35 x 10^6 m.^{3} sec.$^{-1}$. This is an order of magnitude greater than previous estimates and, although there may be seasonal fluctuations in the transport, it suggests that the East Greenland Current primarily represents a circulation internal to the Greenland and Norwegian seas, rather than outflow from the central Polar basin.

RÉSUMÉ. *Le courant du Groenland oriental au nord du détroit de Danemark.* Au cours de l'hiver de 1965, des mesures effectuées dans le courant du Groenland oriental ont montré que sur le talus continental, la circulation comporte d'importantes composantes dirigées vers le rivage, ce qui représente probablement un flux vers l'ouest selon le mouvement d'Ekman. La vitesse ne diminue pas beaucoup avec la profondeur, ce qui indique que le mode barotropique domine la circulation. Les vitesses typiques du courant sont de 10 à 15 cm/s^{-1}.

Au cours de l'hiver, le débit du courant dépasse 35 x 10^6 m^3/s^{-1}. Cet ordre de grandeur dépasse les anciennes estimations et, malgré les fluctuations saisonnières possibles, il semble que le courant du Groenland oriental correspond surtout à une circulation interne des mers du Groenland et de Norvège, plutôt qu'à un émissaire du bassin polaire central.

РЕЗЮМЕ. *Восточно-гренландское течение к северу от Датского пролива.* При исследовании Восточно-гренландского течения, проведенного зимой 1965 г., выше континентального склона были обнаружены крупные потоки в направлении берега, которые, возможно, представляют собой перенос течений в западном направлении по теории Экмана. Скорость течений незначительно понижалась с глубиной, что указывает на преимущественно баротропический характер течений. Обычно, скорости течений изменялись в пределах 10 - 15 см/сек.

В зимний период перенос течений превышает 35 x 10^6 м^3/сек., что на один порядок величин выше предыдущих оценок. Допуская возможность сезонных изменений в скорости переноса, все же можно высказать предположение, что Восточно-гренландское течение представляет собой преимущественно внутреннюю циркуляцию в Гренландском и Норвежском морях, а не отток от центральной Полярной впадины.

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[2]Department of Oceanography, University of Washington.

INTRODUCTION

A southward-setting current carrying large amounts of ice runs along the east coast of Greenland (Fig. 1).

In Viking times, the vast extent of ice along the southeast Greenland coast was well known. Thus one reads in Konungs Skuggsjá (written about 1250) that upon proceeding west from Iceland: "As soon as one has passed over the deepest part of the ocean, he will encounter such masses of ice in the sea that I know no equal of it anywhere else in all the earth . . . They . . . extend so far out from the land that it may mean a journey of four days or more to travel across them. There is more ice to the northeast and north of the land than to the south, southwest, and west ["land" probably refers to the settled southern part of Greenland] . . . These ice floes have peculiar habits. Sometimes they lie as quiet as can be, though cut apart by creeks or large fjords; at other times they travel with a speed so swift and violent that a ship with a fair wind behind is not more speedy; and when once in motion, they travel as often against the wind as with it." (Larson 1917, p. 138.)

By the first half of the eighteenth century, knowledge of the ice movement and distribution of driftwood along the Greenland coast gave a firm basis for the belief that a current sets southwest along the entire East Greenland coast from near Spitsbergen to Cape Farewell (Kiilerich 1945).

In 1820, Scoresby's extensive account of the ice distribution and drift within

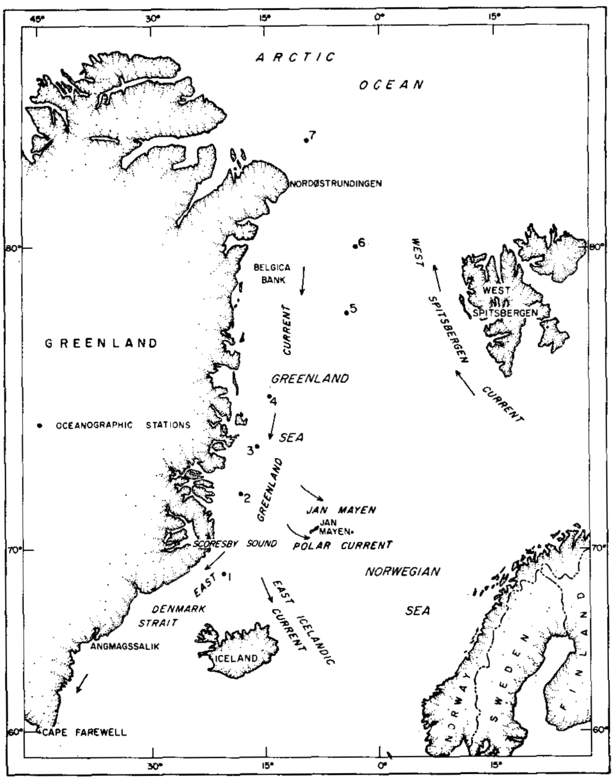

FIG. 1. The Greenland and Norwegian seas. Locations of major features and currents, and positions of 7 stations used in Fig. 4.

the East Greenland Current appeared. Scoresby, apparently, was the first writer to note that the current near the coast is less intense and regular than farther east: "Though the set of the current in the Greenland Sea be generally towards the southwest, yet near the shore, where there are eddies and tides, it is very irregular." (Scoresby 1820, p. 287.)

Beechey, in 1843, briefly discussed the flow along the Greenland coast as an example of the cold currents which he believed set southward along the east coasts of all arctic lands.

Petermann's chart in 1865 made two important contributions toward understanding the East Greenland Current. First, the current was represented as providing the outlet for a large Polar ocean and thus was not just an isolated phenomenon within the Greenland Sea. Second, north of Iceland a portion of the East Greenland Current was represented as separating from the main branch and turning southeast, contributing to the East Icelandic Current.

In 1869-70, the German North Polar Expedition under Koldewey obtained a few temperature measurements, as well as ice and drift observations, within the East Greenland Current (Koldewey 1874; Mohn 1887; Helland-Hansen and Nansen 1909).

However, it was not until the publication of Mohn's (1887) work on the Norwegian Ocean Expedition, that a systematic scientific account of the East Greenland Current became available. This account was based on the *Vøringen* cruises during the summers of 1876-78 and incorporated a large number of water-temperature and density measurements. Although the density measurements in particular were inaccurate by present-day standards (Helland-Hansen and Nansen 1909), Mohn computed the topography of the sea surface. He concluded that the western portion of the East Greenland Current originates in the interior of the Arctic Ocean, while farther east the ". . . Spitzbergen current, acted on by the prevailing easterly winds, passes gradually with its left border into the Greenland Polar Current." He believed the current speed to be greatest near the ice edge (32 cm. sec.$^{-1}$ east of Jan Mayen) and to decrease westward to 9 cm. sec.$^{-1}$ near the Greenland coast. He further believed that the greater part of the current flows along the Greenland coast through Denmark Strait, finally rounding Cape Farewell, whereas a lesser part sets toward Iceland, eventually contributing to the East Icelandic Current. This is in agreement with Petermann's chart from 1865.

Nansen (1890), in his account of the 1888 crossing of the Greenland ice cap, reviewed previous exploration and drift within the ice-belt of the East Greenland Current.

During 1891-92 Ryder, aboard the *Hekla,* made oceanographic observations within the East Greenland Current as far north as 76° N. He found ". . . a water layer with positive temperatures and large salt content along Greenland's east coast at 100-200 fathoms depth . . ." and believed it ". . . probable that this warm current must originate from a continuation of the warm current along Spitzbergen's west side." (Ryder 1895, p. 203-4).

Petermann's chart of 1865 had correctly assigned the origin of the Polar Water of the East Greenland Current to the Arctic Ocean. The oceanography of the Arctic Ocean, however, was not investigated until the drift of the *Fram* in 1893-96 when Nansen (1902) provided the first description of the source characteristics of the Polar Water of the East Greenland Current.

During the Nathorst expedition of 1898 aboard the *Antarctic,* a number of drift bottles released in the northern Greenland Sea appear to have drifted with the East Greenland Current. A chart of the supposed trajectories was prepared by Hamberg (1906).

The Nathorst expedition of 1899 occupied several hydrographic stations within the East Greenland Current between 70° and 75° N. However, once again the greatest interest is attached to the drift bottle experiments; a larger number of bottles were involved, many of which were released well within the East Greenland Current. A chart of the supposed trajectories was prepared by Åkerblom (1904).

A few pertinent hydrographic stations and some drift bottle releases during two expeditions in 1900 have been reported by Amdrup (1902), and by Pettersson and Ostergren (1901).

Temperature and salinity measurements of accuracy commensurate with modern standards were first made within the East Greenland Current by Amundsen from the *Gjøa* in 1901. The measurements were discussed by Nansen (1906), who found evidence for a branch of the East Greenland Current setting southeast and east in the area north of Jan Mayen, coinciding with the eastward-extending tongue of ice ("isodden") familiar to

In 1905, on the *Belgica* expedition, Koefoed obtained a series of stations within the East Greenland Current as far north as 78°13′ N. (Helland-Hansen and Koefoed 1907). For a half century these stations provided the bulk of hydrographic information on the East Greenland Current. From the steep inclination of the isopycnals over the shelf break and slope, contrasted to the nearly horizontal isopycnals over the continental shelf, Helland-Hansen and Koefoed concluded that the major portion of the East Greenland Current runs along the upper part of the continental slope. They computed the speed of the current at the sea surface near the edge of the continental shelf as about 30 cm. sec.$^{-1}$ between 75° and 78° N., and found that value to be in good agreement with the observed drift of ships within the current. They believed that the flow chiefly occurred within 200 m. of the surface. The flow west of the current axis was believed to set south in a broad, slow stream and even to be subject to directional reversal under the influence of the northward-setting tidal wave. To the east of the current axis, Helland-Hansen and Koefoed thought the current slight and variable. They further believed the effect of the wind to be important, the current decreasing in intensity under the influence of southerly winds. It was assumed that the melting of ice during the summer increased the current, and that winter freezing decreased it. The observed southward decrease of temperature and salinity within the warm water layer underlying the cold surface Polar Water was thought to support Ryder's contention that the warm water also moved southward.

Helland-Hansen and Nansen (1909), in their treatise on the physical oceanography of the Norwegian Sea, discussed at length the East Greenland Current.

They chiefly synthesized previous observations since only a few of the *Michael Sars* stations of 1901-04 were taken within the Current. They showed that the warm intermediate water (hereafter referred to as the Atlantic Intermediate Water) of the East Greenland Current was probably derived from the West Spitsbergen Current. This influx of warm water to the East Greenland Current was thought to occur at about 77° to 78° N. Helland-Hansen and Nansen further described the branch of the East Greenland Current which sets southeast and east to the north of Jan Mayen and which Nansen had described in discussing the *Gjøa* observations; they proposed the name Jan Mayen Polar Current. In addition, they described the connection between the East Greenland Current and the East Icelandic Current, as well as the course of the East Greenland Current in and to the south of Denmark Strait. Although the number of observations available from Denmark Strait south was limited, they believed that the main course of the current was along the edge of the continental shelf. They further believed that the current speeds were greater in the southern regions than along the Greenland coast north of Denmark Strait, probably attaining 50 cm. sec.$^{-1}$ near Angmagssalik.

Trolle (1913) made a few hydrographic observations within the East Greenland Current from about 75° to 78° N. during the *Danmark* expedition of 1906-08. In contrast to Helland-Hansen and Nansen (1909), Trolle believed that the current was more intense during the winter than during the summer, but his evidence is not conclusive. In other respects, his conclusions support the views of previous authors.

Mikkelsen (1922) constructed a current chart, from observations of the distribution of ice and driftwood, during the *Alabama* expedition of 1909-12. He represented the East Greenland Current north of 75° N. as being composed of two major branches, the westernmost branch passing west of Belgica Bank. This is in direct contrast to earlier work, which indicated that the currents over the western portion of the shelf were weak and irregular. It would appear that Mikkelsen's conclusions were based on rather meagre evidence.

In July and August 1923, the *Conrad Holmboe* obtained a number of hydrographic stations within the East Greenland Current. The ship entered the ice at 71°30′ N. and proceeded northwest to within 55 km. of the Greenland Coast at about 74° N. From there it drifted south with the current until October. The observations were discussed by Kvinge (1963), who estimated the temperature and salinity of the Atlantic Intermediate Water as 2.65°C. and 35.01‰ before it mixes with the Polar Water.

Nielsen (1928) discussed the hydrography of Greenland coastal waters including the East Greenland Current, but presented no new observations.

A few stations taken within the East Greenland Current at about 77°40′ N. from aboard the *Veiding* during August 1931 were reported by Kvinge (1963); observations from the coastal region at 72° to 73° N. during the Danish Three Years Expedition of 1931-34 were reported by Spärck (1933); and two stations in the vicinity of Scoresby Sound made from the *Meteor* in 1933 were reported by Schulz (1936).

In 1931-32 the *Polarbjørn* obtained hydrographic observations within the East

Greenland Current between 72°30′ and 75° N. The observations were discussed by Jakhelln (1936), who carefully investigated the dynamic topography, using both the *Belgica* and the *Polarbjørn* data. He estimated the volume transport of the current to be about 1.3 x 10^6 $m.^3$ $sec.^{-1}$. Jakhelln found the Atlantic Intermediate Water to be unusually warm and saline (2.1°C. and 35‰) in 1931-32. He related this occurrence to similar conditions off the Norwegian coast in 1928.

Synthesizing observations from 1905-31, including those of the *Godthaab* expeditions of 1924 and 1930, Riis-Carstensen (1938) studied the dynamic topography of the East Greenland Current between 74° and 79° N. North of 75° N., he found that the water near the coast moved northward, in agreement with ice drift observations.

The drifting ice station North Pole 1 presented in 1937-38 the first opportunity for continuous observations of the East Greenland Current from its source in the central Arctic Basin and thence along the east coast of Greenland (Shirshov 1938, 1944; Shirshov and Fedorov 1938; Shuleikin 1938). North Pole 1 was abandoned at about 71° N., after the observers had obtained a series of 38 hydrographic stations extending south to about 76°30′ N. Unfortunately the observational material does not appear to be available, except insofar as portions can be gleaned from various articles.

In 1945, Kiilerich's paper on the hydrography of the Greenland Sea appeared. While Kiilerich did not present any significant new observational material, he critically combined previous material into a coherent unit, describing in as much detail as possible the course and hydrography of the East Greenland Current along nearly the entire east coast of Greenland. Kiilerich's work is probably still the best available review of the physical oceanography of the East Greenland Current.

Koch's comprehensive work on the East Greenland ice also appeared in 1945. Of particular interest is his study of the fluctuations of the ice drift. He also discussed some features of the hydrography that he believed pertained to the ice distribution.

Several hydrographic stations near the eastern edge of the East Greenland Current at the latitude of Jan Mayen were made during the winter of 1954 from the *Atka* (U.S. Navy Hydrographic Office 1956).

In 1956, the *Ob'* took a large number of stations within the East Greenland Current between 78° and 83° N. (Balakshin 1958). Unfortunately, these data have never been made available, so that the validity of the current chart presented by Laktionov, Shamontev and Yanes (1960), based on the *Ob'* data, cannot be ascertained. The chart indicates that between 78° and 82° N., the surface water moves about 10 cm. $sec.^{-1}$. Two anticyclonic gyres are shown: one ESE of Nordøstrundingen (Fig. 1) and another near the eastern part of Belgica Bank.

Chaplygin (1959, 1960) also incorporated the *Ob'* data in discussions of the speed and water properties of the East Greenland Current as functions of latitude. He concluded from dynamic computations that in summer the mean speed of the East Greenland Current increased from 7 cm. $sec.^{-1}$ at 80° to 41 cm. $sec.^{-1}$ at 60° N.

The extensive cruises of the *Johan Hjort* in 1958 included stations along the eastern edge of the East Greenland Current between 71° and 80° N. (Eggvin 1961).

American icebreakers have in recent summers made several oceanographic cruises in the Greenland Sea. In 1961 the *Edisto* made a traverse of the East Greenland Current off Scoresby Sound (N.O.D.C. cruise 688). The 1962 cruise of the *Atka* included several stations within the East Greenland Current, and these data have been presented by Gladfelter (1964). In 1964 the *Edisto* surveyed the northern Greenland Sea and completed five traverses of the East Greenland Current between 78° and 81° N. (Palfrey 1967; Codispoti 1968). In 1965, the *Edisto* made 49 stations during a cruise to investigate the East Greenland Current between 70° and 80° N. (unpublished data). The 1965 cruise included a few direct current measurements over the northern portion of the Greenland continental shelf.

During 1964-65, the drift of the floating ice island Arlis II from the Arctic Basin into the East Greenland Current and thence along the east coast of Greenland to Denmark Strait provided a platform for oceanographic investigations. Direct current measurements were made during the Arlis II drift, along with standard hydrographic measurements (Tripp and Kusunoki 1967).

In summary, the East Greenland Current north of Denmark Strait was believed, prior to the present paper, to have the following characteristics:

1) It is composed chiefly of water colder than 0°C. (Polar Water) and is the major egress of water from the Arctic Ocean.

2) Its speed decreases rapidly with depth: at the surface the speed may be as much as 50 cm. sec.$^{-1}$, but below 200 m. depth it is nearly negligible.

3) Its speed is greatest near the upper part of the continental slope; over the western part of the continental shelf the current is erratic in intensity and direction.

4) The transport of the East Greenland Current is about 2 to 3 x 10^6 m.^{3} sec.$^{-1}$.

5) Water from the East Greenland Current moves eastward north of Jan Mayen to form the Jan Mayen Polar Current.

6) Below the Polar Water, i.e., below about 200 m. depth, water warmer than 0°C. (Atlantic Intermediate Water) moves southward at 2 cm. sec.$^{-1}$ or less. This relatively warm water is derived from the West Spitsbergen Current which sets northward along the west coast of Spitsbergen.

7) The transport of the Atlantic Intermediate Water is only a small fraction of that of the Polar Water.

A pictorial summary of the circulation is seen in Fig. 2, which is taken from Kiilerich (1945). In this and subsequent figures, the 1,000 m. isobath is taken to represent the continental slope.

The present investigation deals primarily with the data from the *Edisto* cruises during the summers of 1964 and 1965 and from the drift of Arlis II in 1965, since these data provide the most nearly complete quasi-synoptic coverage and the only direct current measurements within the East Greenland Current north of Denmark Strait.

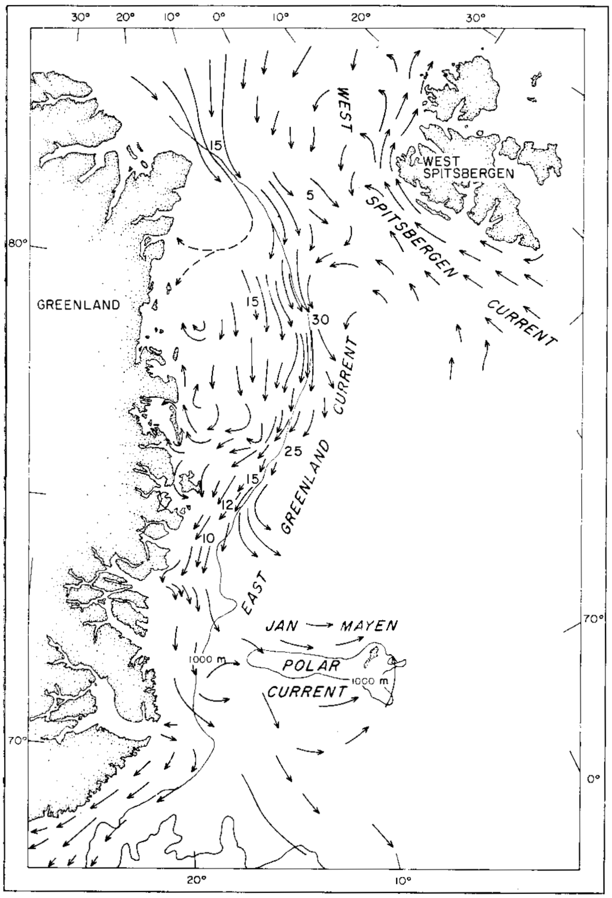

FIG. 2. Currents in the upper 10 m. according to Kiilerich (1945). Speeds in cm. sec.$^{-1}$.

Some bathymetric features

The East Greenland Current occupies the western Greenland Sea, the bathymetry of which is shown in Fig. 3. The figure is a composite of a bathymetric chart of the northern Greenland Sea (Johnson and Eckhoff 1966) and one of the southern part of the sea (Adams 1967). In the northern area, there is a broad continental shelf, up to 300 km. wide. North of 77°30′ N., the shelf features a system of banks of less than 200 m. depth, including Belgica Bank. At 77° N., the shelf turns southwest, narrowing at 75° N. to less than one-third of its former width and remaining thus to Denmark Strait. The shelf is marked by several deep indentations, particularly in the southern part.

At about 79° N., the Greenland Sea below a depth of 2,500 to 2,600 m. is separated from the Polar Basin by a slight rise. South of the rise, the Greenland Sea contains two deep (more than 3,400 m.) basins. At 71° N., the Jan Mayen Ridge extends toward Greenland, with a maximum depth between Greenland and Jan Mayen of about 1,500 m., while in Denmark Strait the sill depth is about 600 m.

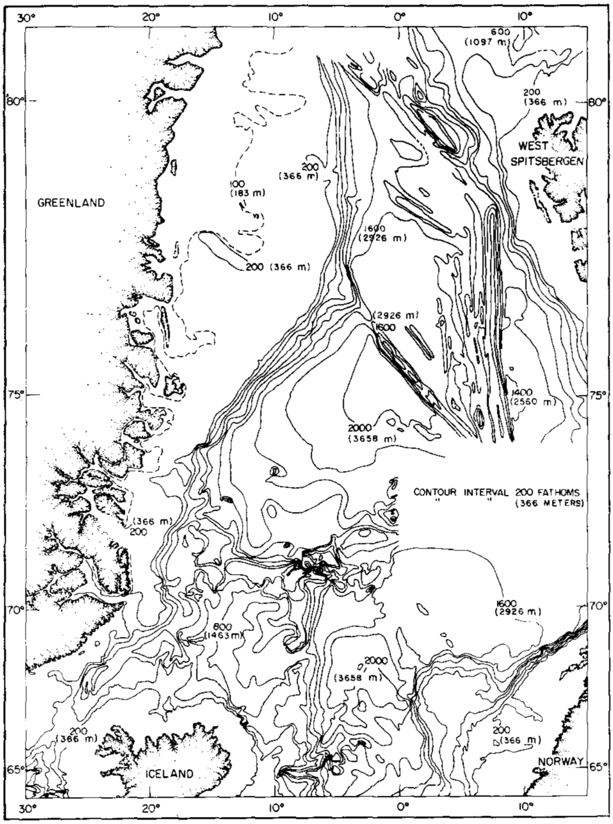

FIG. 3. Bathymetry of the Greenland and Norwegian seas (after Johnson and Eckhoff 1966; Adams 1967).

TABLE 1. Selected hydrographic stations.

Designated number in Fig. 1	*Vessel and station number*	*Date*	*N. latitude*	*W. longitude*	*Sounding in m.*
1	Arlis II — 354	18 April 1965	69°01′	20°25′	1390
2	Polarbjørn — 28	21 August 1932	72°27′	18°24′	268
3	Conrad Holmboe — 15	2 August 1923	74°16′	16°10′	224
4	Belgica — 32	24 July 1905	75°58′	14°08′	300
5	Edisto ’65 — 31	5 September 1965	78°20′	4°12′	1463
6	Edisto ’64 — 33	9 September 1964	80°00′	3°00′	2274
7	Arlis II — 290	20 January 1965	82°07′	9°36′	290

The water masses

Seven hydrographic stations have been selected to delineate the major water masses within the East Greenland Current. Their locations are shown in Fig. 1, and their sources, dates, geographical coordinates, and soundings given in Table 1. These stations were taken over a period of sixty years, between January and September; they cover the western Greenland Sea from just north of Denmark Strait to northeast of Nordøstrundingen; and they were taken on the continental shelf, on the slope, and seaward of the slope. Despite this considerable diversity of time and position, there is a remarkable similarity between the various stations in the vertical distributions of temperature and salinity. This similarity is apparent in Fig. 4, in which the observations at the 7 stations are presented.

It is useful to recognize 3 water masses within the East Greenland Current north of Denmark Strait. (Some exceptions to the differentiating criteria may occur at the eastern edge of the current.) These water masses are similar to those found in the Arctic Ocean (Coachman 1963):

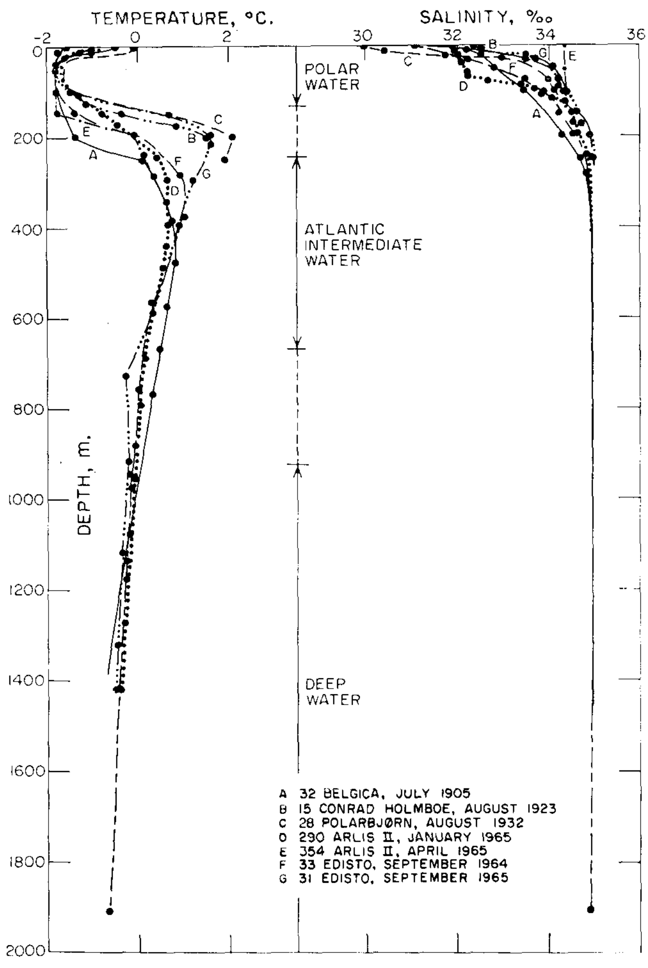

FIG. 4. Vertical distributions of temperature and salinity for 7 stations in the East Greenland Current.

1) The Polar Water extends from the surface down to a mean depth somewhat greater than 150 m. The temperature varies between about 0°C. and the freezing point. During the summer there is usually a temperature minimum at about 50 m., while in winter the temperature is uniformly near the freezing point from the surface to about 75 m. Normally a strong halocline is present: the salinity at the surface may be less than 30‰, but at the bottom of the layer of Polar Water, the salinity is nearly 34‰ or more. (At these relatively low temperatures, the water density is principally a function of the salinity. For example, the effect on density of changing by one part per thousand the salinity of Polar Water is about seventeen times greater than the effect of changing the temperature one degree Celsius.)

2) The Atlantic Intermediate Water underlies the Polar Water, extending down to approximately 800 m. The temperature remains greater than 0°C., and a temperature maximum, which lies between 200 and 400 m., is present throughout the year. The salinity increases from the Polar Water downward until it attains a value between 34.88 and 35‰, which usually occurs above 400 m. Below 400 m. the salinity remains practically constant.

3) The Deep Water is found below about 800 m. The temperature of this water is less than 0°C., and the salinity is between 34.87 and 34.95‰.

GENERAL FEATURES OF THE VELOCITY FIELD

Direct current measurements: methods and limitations

The current observations made during the drift of the ice island Arlis II constitute the first set of direct measurements of water motion made within the East Greenland Current north of Denmark Strait. The data and observational methods have been presented by Tripp and Kusunoki (1967).

The motion of the water in relation to the ice island was determined by the use of impeller-type current meters, and the motion of the ice island in relation to the sea floor was determined by the use of a specially-constructed drift meter. The drift meter employed a transducer resting on the sea floor and three hydrophones located on the ice island. The drift of the ice island in relation to the sea floor was computed from the differences in receiving time of the transducer signal at the three hydrophones. The motion of the water in relation to the sea floor was then estimated by vectorial addition of the relative current and the drift.

The uncertainties associated with the relative current and drift measurements are less than 1 cm. sec.$^{-1}$ and respectively about 10 and 3 degrees of arc. The greatest uncertainty associated with the resultant current vectors, however, is caused by the relative current and drift measurements not having been made simultaneously; the time interval between the two measurements varied from a few minutes to a few hours. The drift rate and direction at the time of each current measurement was therefore linearly interpolated between 2 drift measurements that had usually been made about 4 hours apart. The accuracy of this interpolation cannot be stated with certainty, but it is believed that at least 83 per cent of the 176 interpolated drift vectors are accurate to within 3 cm. sec.$^{-1}$

and 20 degrees of arc, and that at least 61 per cent are accurate to within 1 cm. sec.$^{-1}$ and 15 degrees of arc. Therefore, the motion of the water in relation to the sea floor has probably been determined in the majority of instances to within at least 2 to 4 cm. sec.$^{-1}$ and 25 to 30 degrees of arc.

The current measurements suffer from what is probably a more serious limitation however: they were made neither from an Eulerian nor from a Lagrangian viewpoint, i.e., the ice island did not remain stationary nor did its motion coincide with that of the water. Therefore, without additional information the time- and space-dependent portions of the velocity field cannot be separated.

Furthermore, each set of measurements was made only once a day and usually at the same time of day, between 1000 and 1200 GMT. This procedure has introduced the possibility that the measurements may have been biased by currents with periods of 24 hours or less, e.g., tidal and inertial motions. The few sets of measurements during the afternoon (1500 to 1600 GMT) do not show velocities differing greatly from the normal southerly or westerly set, however. Furthermore, the measurements extended over several months, during which time biasing effects would tend to be reduced because of the gradual phase shift of the biasing currents, whose probable periods would differ slightly from 12 hours. The data have therefore been interpreted on the assumption that biasing can be neglected, but it must be recognized that interpretation of the measurements is somewhat hazardous.

Mean velocities

The data indicate that short-period fluctuations over 10 minutes or so may be quite large. For example, over the continental shelf at 76°N. on 8 March, the current at 194 m. at 1010 GMT was 10 cm. sec.$^{-1}$ toward 60°T., whereas at 145 m. 12 minutes later it was 2 cm. sec.$^{-1}$ toward 290°T. In view of this, satisfactory velocity profiles cannot be constructed from the data, as a misleading picture of the current field might result. The only reliable data are time and space averages which can be tested statistically.

In an attempt to suppress partially at least the short-term time dependence of the velocity, the mean velocities of the different water masses were, whenever possible, computed for every 30 minutes of latitude. The number of observations and the time interval over which the mean was computed ranged from a single measurement to 20 measurements extending over 7 days, so that the time dependence has probably not been equally supressed at all positions. The averaging interval was in general longest north of 74°N.

These mean velocities are shown graphically in Fig. 5. The computed mean velocity field cannot be considered definitive and, indeed, may in certain respects be misleading, as indicated above; nevertheless, there are three notable features that merit attention:

1) The speed of the current appears to increase toward the south, from about 4 cm. sec.$^{-1}$ southeast of Belgica Bank to about 14 cm. sec.$^{-1}$ east of Scoresby Sound. The difference in mean speed north and south of 75°N. was tested statistically and found to be significant at the 2 per cent level, so that the effect does not appear to be spurious. That the speed increases with decreasing latitude

accords with the suggestion of Chaplygin (1960) mentioned on page 9. However, it should not be concluded that the greater speeds observed at the southern positions, compared to those at the northern positions, are conditioned solely by the decrease in latitude. It is possible that the effect is at least in part a time-dependent one which was not suppressed by the averaging procedure. It is also possible that the speed increase is largely due to a variation of the cross-stream position of the ice island. The precise influence of each of these factors cannot be determined, but it seems very likely that at least part of the increase may be due to the last factor, namely a movement of the measurement platform laterally across the current toward its eastern side, where the speeds have long been considered to be greater than farther inshore. This movement of the measurement platform across the current may well have been associated with the prevailing northerly winds. The wind from 18 February to 10 April set in the mean toward 175°T. while Arlis II drifted toward 200°T. and the current at 25 m. depth was directed toward 250°T. The drift of the ice 25 degrees to the right of the wind set is in good agreement with the 22° angle computed from the observations of Sverdrup (1928) over the Siberian shelf during the same time of year; the set

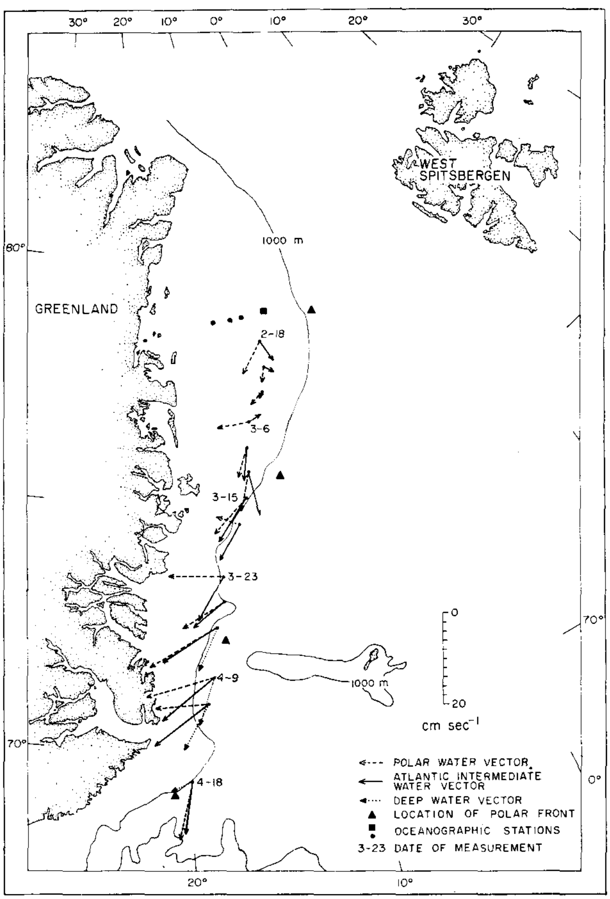

FIG. 5. Mean velocity vectors from Arlis II observations, location of the Polar front (after Kiilerich 1945), and positions of 4 stations.

of the current at 25 m. to the right of the ice drift is in qualitative agreement with the Ekman wind-drift theory.

Three series of current measurements made from aboard the *Edisto* in September 1965 reinforce the belief that at least in the northern Greenland Sea the current speed decreases westward over the continental shelf. The ship was anchored on the Belgica Bank in depths between 130 m. and 205 m. at the positions indicated in Fig. 5 by solid circles. Each series of measurements was separated by about four hours. At the westernmost station no current was found down to 40 m. over a period of 40 minutes. At the middle station the mean current speed was less than 5 cm. sec.$^{-1}$, and this was probably a measurement at least in part artificially induced by the ship's yaw. At the easternmost station, the current at 20 m. was monitored for 1 hour. During the first 6 minutes, the current increased from 17 cm. sec.$^{-1}$ to 26 cm. sec.$^{-1}$ and then during the next 3 minutes decreased to or near zero, and remained at that low intensity for the rest of the hour. The ship was motionless in relation to the ice during these anchored periods. Eleven hours earlier and 55 km. farther east, at the location indicated in Fig. 5 by a solid square, and under nearly unchanged wind conditions, the ship drifted with the ice toward SSW at an estimated speed of 75 $\pm$ 25 cm. sec.$^{-1}$. These measurements strongly indicate a speed decrease toward the west within the East Greenland Current at the latitude of Belgica Bank.

It also appears to be likely that the mean Arlis II observation locations shown in Fig. 5 are farthest from the eastern edge of the East Greenland Current in the northern part, for which the indications are twofold. First, the position of the eastern edge of the East Greenland Current according to the composite chart of Kiilerich (1945), which is indicated in Fig. 5 by solid triangles, lies well to the east of the track of Arlis II at 78°N. (about 120 km.), but approaches the track farther south, to within 20 km. at 72°N. latitude. Second, the mean thickness of the Polar Water, as observed from Arlis II, shows significant variation with latitude. (Crossing the East Greenland Current from west to east, the thickness approaches zero at the eastern edge.) For the Arlis II stations, the thickness is least between 74°45′ and 70°45′N., being as small as 82 m. at 73°15′N. whereas between 75°15′ and 77°45′N. it varies between 186 and 226 m.

It thus appears to be likely that at least part of the observed southward increase in speed, indicated in Fig. 5, is a result of the southerly measurements having been made closer than the northerly measurements to the eastern edge of the current where the speeds are greater than farther inshore.

However, the large onshore velocity component (Fig. 5) also requires that the speed increases toward the south (see section on volume transports).

2) In the majority of instances, the mean current vectors for the various water masses at any one point do not appear to differ greatly in magnitude, i.e., there does not, in general, appear to be a large decrease in speed with depth. This effect is also corroborated statistically. For example, no difference in speed between the 20 to 50 m. and the 184 to 340 m. levels north of about 75°N. could be found even at the 52 per cent significance level. This is in contrast to the views expressed by previous investigators who felt that "the current decreases very rapidly with the depth, and . . . it is only a small quantity of the water which . . . has the

same rate as the main current" (Kiilerich 1945, p. 60). However, these earlier views were not supported by direct current measurements, but were based on dynamic computations relative to an assumed surface of no motion, usually taken to lie at about 200 to 300 m., so that the low speeds at depth existed by assumption.

3) With increasing depth there appears to be an eastward rotation of the mean current vectors. This rotation north of about 75°N. was tested statistically both as a function of time and of depth. Below a depth of about 140 m., rotation as a function of time was not significant at the 39 per cent level, and rotation as a function of depth was not significant at the 24 per cent level. Similarly, the rotation between the 20 to 50 m. and 184 to 340 m. layers as a function of time was not significant at the 50 per cent level. The westerly velocity components in these two layers differed at the 0.04 per cent level, however. Furthermore, the vectorial difference in mean velocity between the two layers was about 6 cm. sec.$^{-1}$ toward 282°T., which is 90° to the right of the mean wind vector over the same period (6 m. sec.$^{-1}$ from 012°T.). The conclusion therefore seems to be that the only significant rotation of the velocity vector was that which occurred, as a function of depth, between the Ekman layer and the deeper water, and this was a result of a westward Ekman transport created by the prevailing northerly winds. The difference in direction of the Atlantic Intermediate and Deep Water velocity vectors is probably spurious.

Volume transports

The existence of significant currents below 200 m. leads to some interesting estimates of the volume transport of the East Greenland Current.

The drift of Arlis II from 78° to 69°N. can be approximated by a line directed 200°T., which will be referred to as the station line. In the section on mean velocities, evidence was presented that suggested this station line was a partial traverse of the East Greenland Current, the ice island being closer to the eastern edge of the current during the southern part of the drift than it was farther north. On the basis of the mean extent of the East Greenland Current shown in Fig. 5 a reasonable conjecture might be that 75 per cent ± 10 per cent of the flow had been traversed during the drift from 78° to 69°N. The total volume transport across the station line might therefore be expected to give a minimum estimate of the transport of the East Greenland Current from mid-February to mid-April.

Over 175 current observations were made along the station line, extending from near-surface to 1,220 m. These observations have been used to compute mean cross-line volume transports of the three water masses. The lower limit of the Polar Water was assumed to be the 0°C. isotherm, and the lower limit of the Atlantic Intermediate Water to be 900 m. (approximate depth of 0°C. isotherm at the deep current stations). The transport estimates are given in Table 2.

Nearly 80 per cent of the transport of Atlantic Intermediate Water across the station line and nearly 50 per cent of the Polar Water transport occurs between 72°30′ and 70°30′N. Again, however, it is impossible satisfactorily to separate the space- and time-dependent transport components, i.e., distinguish between the effects of changes in latitude, cross-stream position, and time.

TABLE 2. East Greenland Current minimum transport estimates, winter 1965.

Water masses	*Cross-line volume transport in sverdrups (sv)**
Polar Water	7.7
Atlantic Intermediate Water	21.3
Deep Water	2.5
Total	31.5

*One sv = 10^6 m.^{3} sec.$^{-1}$, following the suggestion of M. J. Dunbar at the Arctic Basin Symposium in 1962.

The most striking characteristic of this transport estimate is its large magnitude. If the term East Greenland Current designates the flow in the Greenland Sea occurring west of the 0°C. surface isotherm, then it appears to be likely that in the late winter of 1965 the volume transport of the East Greenland Current was well in excess of 35 sv (1 sverdrup = 10^6 m.^{3} sec.$^{-1}$), i.e., about one-half that of the Gulf Stream. This is at least an order of magnitude greater than previous transport estimates of this current. For example, Vowinckel and Orvig (1962) thought it probable that the mean transport was 3.4 to 3.7 sv, and Mosby (1962) estimated it as about 2 sv. Such estimates have usually been based on mass and heat budget calculations for the Arctic Ocean and adjacent seas and have included the advective effects of the East Greenland Current in transporting Polar Water, and the West Spitsbergen Current in transporting Atlantic Water.

If the mass and heat budget computations and the Arlis II current measurements are both accepted as reasonably correct, then it follows that the major portion of the East Greenland Current represents a circulation internal to the Greenland Sea, or to a Greenland Sea — Norwegian Sea — North Atlantic Ocean system. The outflow from the central Arctic Ocean thus represents only a minor portion of the total flow in the western Greenland Sea. However, since the Polar Water is the least dense of the three water masses and therefore constitutes the surface layer and to a large extent controls the ice distribution, its presence is manifested out of all proportion to its relatively small contribution to the total transport.

Another point is that the East Greenland Current transport computed on the basis of the mass and heat budgets represents an annual mean, whereas the transport estimate made from the Arlis II measurements is representative of a two-month period in late winter. It is quite possible that there are significant variations in transport during the year. Such variations are indicated by the relatively large transport of Polar Water (nearly 8 sv) computed above. It is probable that the major portion of this Polar Water represents outflow from the Arctic Ocean, rather than a circulation internal to the Greenland Sea. However, it is larger by a factor of 2 to 4 than the annual mean outflow computed from heat and mass budgets.

Chaplygin (1960) and Laktionov, Shamontev, and Yanes (1960) have stated that the East Greenland Current is most intense during winter, under the influence of strong northerly winds; however, they did not substantiate their statements.

Lee (1961, 1962), reporting on eleven years of hydrographic measurements across the West Spitsbergen Current at about 74°N., found that in the mean there were strong seasonal fluctuations in the transport volume between 0 and 400 m. The maximum transport occurred in February and the minimum in April, the latter transport being about one-tenth that in February. In addition, there was a secondary maximum and minimum. Lee's transport estimates were based on dynamic computations relative to the 750 decibar surface; the computed speeds were in good agreement with the observed drift rate of cod larvae. He found that in winter a positive correlation existed between the transport and the strength of the southerly wind component during the preceding period.

Timofeyev (1962), reporting on 13 years of hydrographic measurements across the West Spitsbergen Current at 78°N., found a single annual maximum and minimum. The maximum occurred in December-January and the minimum in May-June, the latter transport being about one-half that of the former.

Two different opinions on the coupling of the West Spitsbergen and East Greenland currents have been offered. One is that of Laktionov, Shamontev, and Yanes (1960, p. 57): "From our data it can be reckoned that fluctuations in the intensity of the West Spitsbergen and East Greenland currents are fairly considerable, whilst, with the strengthening or weakening of one of them, the other conversely slackens or becomes stronger, as if they are linked together." Again, they offered no substantiating evidence. If their viewpoint is taken, then, based on Lee's mean transport curve for the West Spitsbergen Current, the intensity of the East Greenland Current might be expected to increase from a minimum in February to a maximum in April. The mean observed currents from the Arlis II drift (Fig. 5) are compatible with such a scheme, but they do not, of course, provide substantiation.

An opinion contrary to that of Laktionov, Shamontev, and Yanes has been offered by Timofeyev (1962) who believed that the two currents were in phase. In support of this, he presented computations of ice drift rate in the northern part of the East Greenland Current, which in the mean show a maximum in January-February and a minimum in July-August-September. However, there appear to be discrepancies between the observational points and the purported mean. Furthermore, these computed ice drift rates are not necessarily an accurate index of the mean speed of the East Greenland Current, so that Timofeyev's argument is not entirely convincing.

The conclusion seems to be that significant seasonal transport variations in the East Greenland Current are possible, even likely, but that the phase, period, magnitude, and cause of these variations are at present unknown. Therefore, it is quite possible that the volume transport estimate in excess of 35 sv, based on the Arlis II observations, is not a reliable estimate of the annual mean, although its order of magnitude is probably correct. Thus the conclusion that the major portion of the East Greenland Current is not composed of outflow from the central Arctic Ocean is probably also correct.

There is another implication of the large transport across the station line. If one assumes that all the water inshore of the station line moves southward rather than northward, then, in order to maintain continuity, the mean speed inshore of the station line must increase from 77°45′ to 69°15′N. by about 44 cm. sec.$^{-1}$. This increase is considerably greater than Chaplygin's (1960) estimate; he concluded from dynamic computations that the mean speed of the 0 to 50 m. layer increases by 9 cm. sec.$^{-1}$ between these same latitudes, and that of the 50 to 150 m. layer by 2 cm. sec.$^{-1}$.

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