# Mesoscale Oceanographic Processes Beneath the Ice of Fram Strait

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**A major component of the Fram Strait Marginal Ice Zone Experiment was the investigation of air-sea-ice interactions, processes, and circulation patterns found behind the local ice edge and on scales greater than 10 kilometers (mesoscale and large scale). Neutrally buoyant floats, ice-tethered cyclesondes, and helicopter-based measurements were used to obtain uniquely integrated and consistent views of the mesoscale ocean features beneath the ice cover of Fram Strait. Within the vicinity of the Yermak Plateau, three distinct regions of mesoscale motion were observed that coincided with the shallow topography of the plateau, the northward flowing Atlantic water over the western flank of the plateau, and the strong current-shear zone of the East Greenland Polar Front. A subice meander of the front was also observed, which was probably occluded subsequently.**

Fram Strait, which lies between Greenland and Spitzbergen, is an area of primary exchange between the Arctic and Atlantic Oceans. Within this region, strong open-ocean and ice-edge mesoscale activity between the southward flowing, ice-covered polar waters of the East Greenland Current and the warmer, northward flowing waters of Atlantic origin (West Spitsbergen Current) has been linked to substantial cross-frontal transfers of heat, salt, biomass, and chemical constituents (*1*). Observations of such activity beneath the ice-covered surface of the Arctic Ocean and its peripheral seas have been rare (*2*), and even more detailed work within Fram Strait before 1984 (*2, 3*) provided only slightly improved results.

The Marginal Ice Zone Experiment (MIZEX-84) provided detailed information about subice mesoscale oceanography within a 50,000-$km^2$ sector of Fram Strait from mid-June to mid-July 1984. Within this region, three different techniques were used to monitor mesoscale processes. Neutrally buoyant (nearly isobaric) drifting floats at depths of about 100, 200, and 250 m (decibars) were tracked hourly by underwater acoustic ranging. Cyclesondes acquired data on conductivity, temperature, and depth (CTD) as well as on velocity, light transmission, and downwelling irradiance while vertically cycling every hour within the upper 200 m of the water column on a taut wire rope attached to a free-drifting ice floe (Argos positioning). Two rapidly deployed helicopter-based CTD systems nominally provided continuous data to depths of 600 m. Although differing widely in measuring characteristics, these techniques provided unique, consistent, and complementary views of the subice mesoscale.

The helicopter-based CTD data provided a view of mesoscale activity beneath the ice cover shown in the map of dynamic topography of the sea surface (synoptic over a 5-week data interval; Fig. 1, top). The contours of dynamic height represent streamlines of surface geostrophic currents relative to an assumed level of no motion at 200 m. The larger scale feature trending north-northeast is the East Greenland Polar Front (EGPF), which defines the major division between the warmer, more saline water of Atlantic origin to the east and the cooler, less saline southward flowing waters of Arctic origin to the west.

Superimposed on the EGPF is a frontal meander (about 80.7°N, 1.0°E) that has a nominal diameter of 30 km. The isolated features to the east and west were typically smaller (<20 km) and represent discrete eddies having both clockwise and counterclockwise rotation with core depths ranging from near-surface to several hundred meters. More of these features appear on the eastern side of the front. Although this zonal variation may reflect a lack of more densely spaced data in the west, it may also indicate very different generating mechanisms or the influence of the mean circulation patterns on either side of the EGPF (or both). Representations of surface dynamic topography obtained by using deeper reference levels of no motion (>200 m) increased the number of mesoscale features observed and in one case (no motion at 500 m) reversed an eddy's sense of rotation. Thermal mapping of the EGPF south of 79.5°N identified two additional eddies that were not resolved by dynamic topography because of masking by the stronger signal of the front. One eddy was identified as it passed two instrumented moorings on the East Greenland slope (*4*).

In contrast to the Eulerian mapping of purely geostrophic baroclinic motion deduced from horizontal density variations within the ocean, float trajectories depicted a Lagrangian view of the circulation patterns beneath the ice (Fig. 1, bottom) resulting from both baroclinic and barotropic motion (currents due to sea surface tilt). Although the float trajectories are complicated, the prevalence of the mesoscale activity superimposed on the larger scale motion is readily apparent, especially north of 80.25°N. South of this latitude, average trajectories were to the southwest. A divergence zone centered at 80.0°N and 1°E was indicated by both float and ice-moored cyclesonde drift tracks. This may be due to a strong destabilization of the EGPF as it leaves the western slope of the Yermak Plateau and travels over deep water toward the Greenland Shelf. An analogy to this would be the observed increase in meandering of the Gulf Stream as it leaves the continental slope region off the North American coast (*5*).

Anticyclonic behavior of one of the southern floats (80°N, 2°W) could not be directly accounted for in the surface dynamic topography because of temporal disparity in the data sets. Frequently, however, eddies with similar rotational characteristics have been observed embedded in the EGPF (*4*).

Detailed analysis of float trajectories north of 80.25°N showed three distinct patterns of movement (denoted by I, II, and III in Fig. 1) that were strongly related to sea bottom topography. The first pattern (group I) was exhibited by floats over the Yermak Plateau, where trajectories reflect bottom-trapped motion. Two of these floats were situated over and remained close to small bathymetric highs that rose about 300 m above the surrounding depths. The third float was located within the intervening 800-m-deep saddle and cycled between the other two floats. Typical fluid motions were elliptical and preferentially cyclonic, with much larger oscillations in the north-south direction (tens of kilometers) than in the east-west direction (a few kilometers). The most southerly of these floats was trapped in cyclonic movement for 36 days over the topographic high where it was intentionally deployed (Fig. 1, bottom, point A). Hydrographic data indicated a weak dynamic signature (anticyclonic) over the southern edge of this same bathymetric high (Fig. 1, top, point A), on 24 June, but it was replaced by

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weakly cyclonic motion several days later. Although this specific motion cannot be accounted for by tidal motion rectified into a clockwise mean flow over a local topographic high (*6*), it can be interpreted as the entrapment of a nonlocally generated cyclonic eddy that had an appreciable barotropic component of flow over the weak baroclinic field. The observed confinement of floats over the central Yermak Plateau seems to indicate that eddies, once trapped, may eventually decay entirely in this region. If so, this area may represent a sink for heat, salt, and chemical constituents.

Group II is a transition region between groups I and III that defines those trajectories having steady drift to the north. Small east-west oscillations (at tidal frequencies) are common and may become large enough to shift a float into the region of trapped motion (group I) over the Yermak Plateau or into the region of larger scale (20 to 30 km) meandering (group III). Although surface dynamic topography does not show this northward flow, mean circulation patterns in the region (*7*) support this concept.

Directly west of group II larger meander-

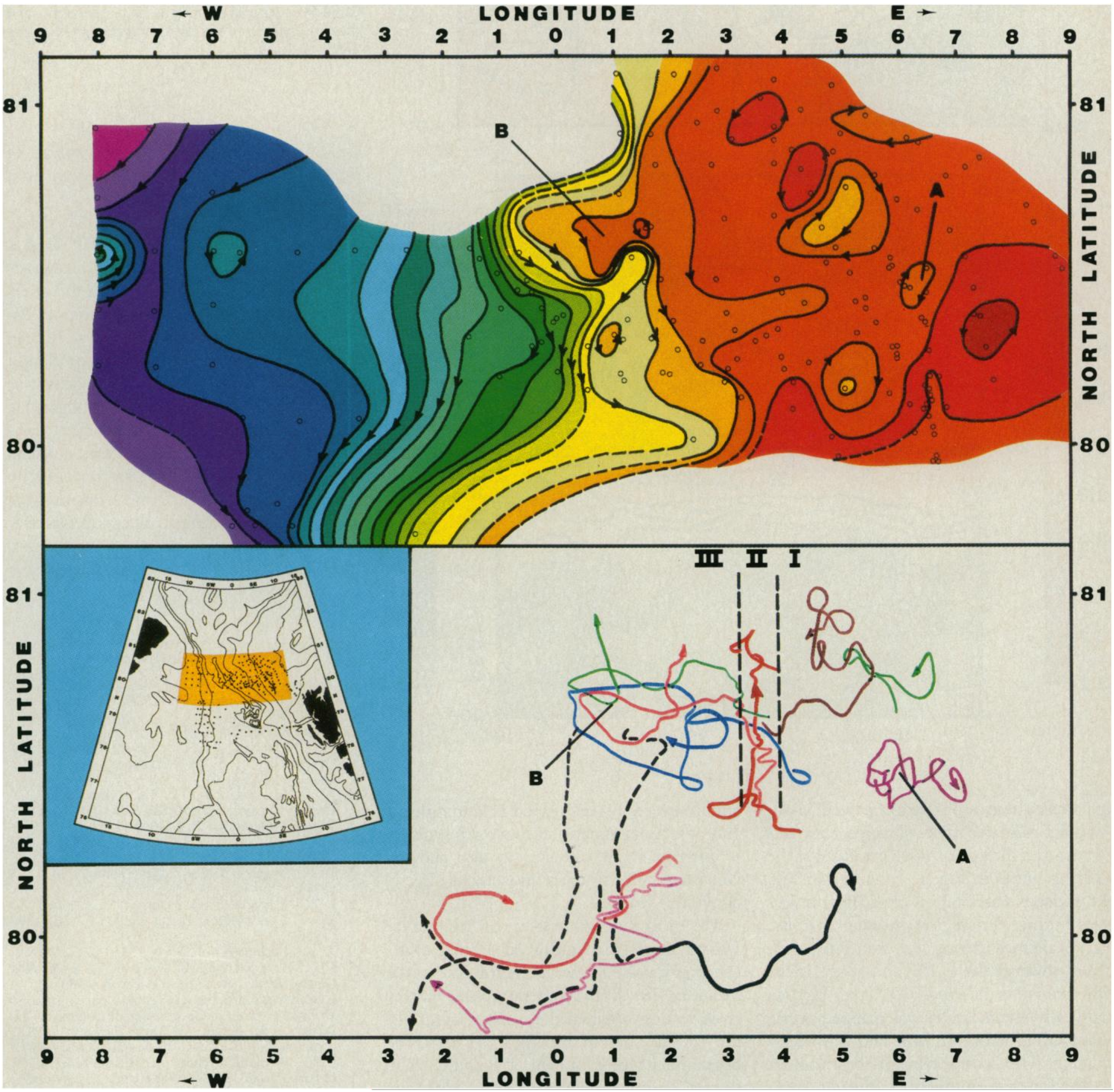


**Fig. 1.** Mesoscale circulation patterns observed beneath the ice-covered portion of Fram Strait. (**Inset**) Position of the survey area relative to Greenland and Spitsbergen. (**Top**) Shaded area of inset map, showing surface dynamic topography with 200 m as the level of no motion. The contour interval is 1 dynamic centimeter. Arrows indicate the direction of geostrophic flow. Small open circles are positions of helicopter CTD stations. The EGPF is defined by close spacing of contours extending north between 1° and 4°W from 79.7°N. Isolated features (closed contours) are eddies. (**Bottom**) Trajectories of neutrally buoyant floats (solid lines) and selected cyclesonde drift tracks (dashed lines). Arrows indicate the direction of movement. Eastward drift of the R.V. *Polarqueen* is shown by a solid black line drawn from the end of the most easterly cyclesonde drift track. Point A defines an area of long-term trapping of a float and point B defines the central position of the EGPF meander.

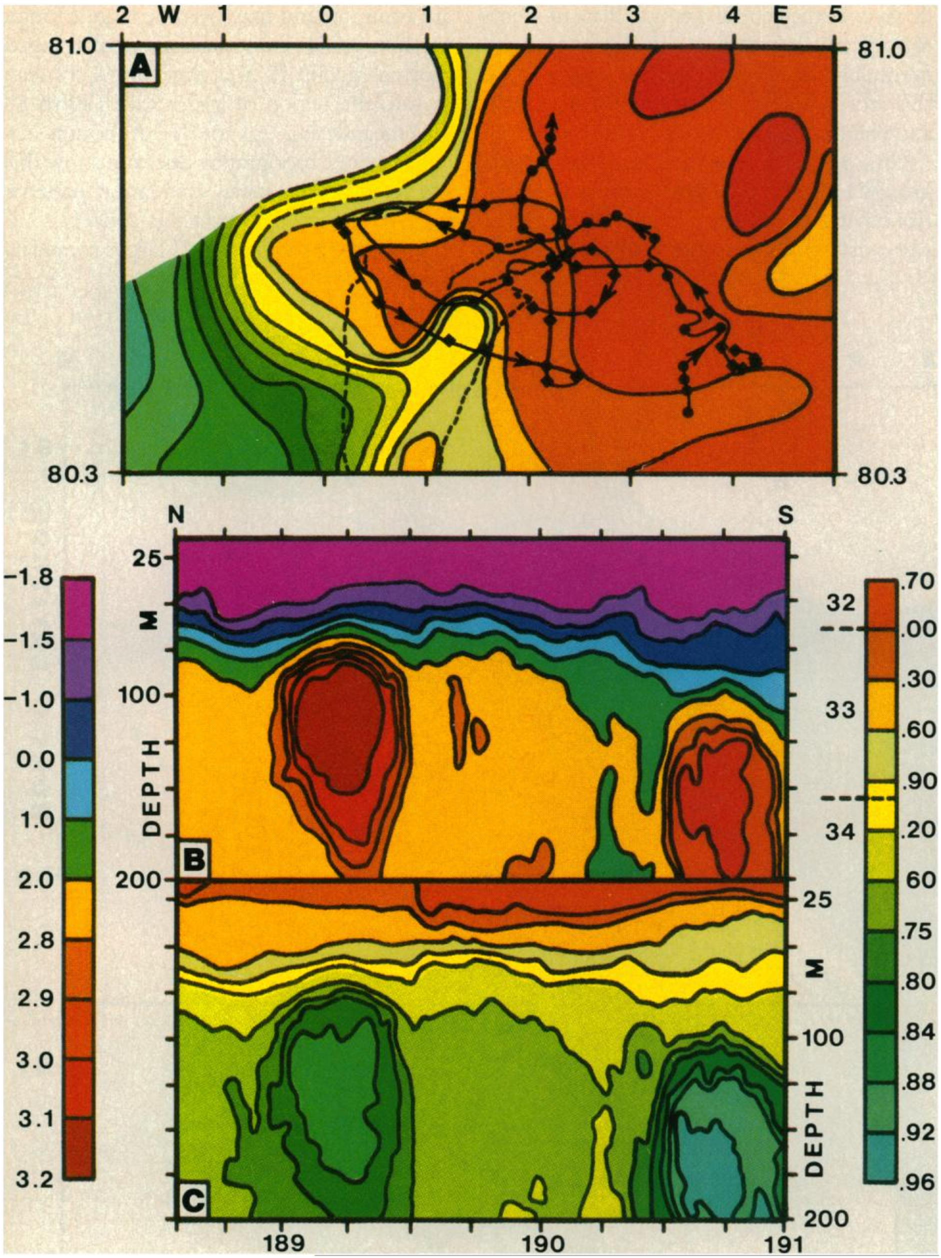


**Fig. 2.** Detailed views of the EGPF meander. (**A**) Float trajectories (solid lines) and cyclesonde drift tracks (dashed lines) superimposed on an expanded view of the meander in surface dynamic topography (point B in Fig. 1). Arrows indicate the direction of float movement. Diamond and dot patterns define daily positions of floats at 200 m and 100 m, respectively. Detailed cross sections of temperature (**B**) and salinity (**C**) along the southerly drift of the most westerly cyclesonde show the isolated core of the meander near the beginning of the drift. The temperature scale (−1.8° to 3.2°C) is given to the left, the salinity scale (32.70 to 34.96 parts per thousand) is to the right, and the time axis (in Julian days) is at the bottom (day 189 = 7 July).

ing patterns of group III are observed, and it is within this area that all three data sets documented the same subice meander of the EGPF (point B in Fig. 1; enhanced in Fig. 2A). Independent analysis of the float trajectories within this region showed that the larger scale meandering was associated with current-shear of the EGPF and is consistent with helicopter-based CTD data. Hydrographically, the meander was mapped over a 5-day period before 30 June and was nearly occluded. The central core of the meander was atypical of the ambient conditions, completely isolated, and composed of very warm (>3°C) water of Atlantic origin. Evidence that the meander evolved later to form a cyclonic eddy can be seen in the closed loop patterns of the two floats and four independently drifting cyclesondes that bounded the feature over a 2-week period beginning on 1 July (*8*). Ice kinematic studies from synthetic aperture radar mosaics (*9*) also showed consistent patterns of ice movement directly above this feature.

The most detailed transect of this feature was obtained by a southward drifting cyclesonde as it passed near the central core of the meander (*10*). Both temperature and salinity cross sections defined the isolated nature of the central part of the meander near the beginning of the drift (Fig. 2, B and C). The second, deeper core near the right side of the transect may represent a filament of Atlantic water being recirculated to the south as part of the Return Atlantic Current. The position of the meander also coincided with a spur-trough complex of similar spatial scale on the western flank of the Yermak Plateau and may suggest further involvement of bottom topography in the mesoscale motion.

From these data it is evident that mesoscale activity within the Fram Strait MIZ is diverse, encompassing eddies, fronts, meanders, and motions associated with the interrelated effects of tides and topography. Although not every feature is described fully in this report, there is a striking correlation among the available data sets. Baroclinic or barotropic instability (or both), topographic generation through potential vorticity conservation, and production of mean currents through tidal rectification over topography are all possible generating mechanisms. Further questions relating to the processes that govern the evolution, existence, interaction, and eventual decay of mesoscale phenomena are still unresolved.

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