Variations of Mesoscale and Large-Scale Sea Ice Morphology in the 1984 Marginal Ice Zone Experiment as Observed by Microwave Remote Sensing


During the summer 1984 Marginal Ice Zone Experiment in the Fram Strait and Greenland Sea (MIZEX '84), passive and active microwave sensors on five aircraft and the Nimbus 7 scanning multichannel microwave radiometer (SMMR) acquired synoptic sequential observations which when combined give a comprehensive sequential description of the mesoscale and large-scale ice morphology variations during the period June 9 through July 16, 1984. The high-resolution ice concentration distributions in these images agree well with the low-resolution SMMR distributions. For diffuse ice edges the 30% SMMR ice concentration isopleth corresponds to the ice edge, while for compact conditions the ice edge falls within the 40 to 50% SMMR isopleths. Throughout the experiment, ice edge meanders and eddies repeatedly formed, moved, and disappeared, but the ice edge remained within a 100-km-wide zone. The ice pack behind this alternately diffuse and compact edge underwent rapid and pronounced variations in ice concentration over a 200-km-wide zone. The aircraft microwave images show the complex structures and ephemeral nature of the mesoscale sea ice morphology. The difference in oceanographic forcing between the eastern and western sectors of the experiment area generated pronounced ice morphology differences. On the Yermak Plateau, from 3°E to 10°E, the weak ocean circulation allowed the wind to be the dominant force in determining the ice morphology. To the southwest of this region, over the Molloy Deep and the Greenland continental shelf break, from 3°E to 8°W, the ice morphology was dominated by the energetic East Greenland Current with its associated eddies and meanders.

1. INTRODUCTION

The Marginal Ice Zone Experiment (MIZEX) field programs in the East Greenland Sea (MIZEX East) and Bering Sea (MIZEX West) studied the air–sea ice–ocean interactions occurring in these regions that strongly influence local and hemispheric weather and climate [Johannessen et al., 1983]. A key aspect of these MIZ studies has been the use of satellite and aircraft remote sensing to observe the morphology of the MIZ and its temporal and spatial variations along with simultaneous meteorological and oceanographic observations. Because MIZ locations are in the dark about half the year and usually cloudy when not, the MIZEX plans put special emphasis on passive and active microwave remote sensing.

The sole satellite microwave sensor operating during the MIZEX experiments has been the scanning multichannel microwave radiometer (SMMR) on Nimbus 7, and it has provided essential large-scale ice observations. Remote-sensing aircraft obtained detailed microwave observations of the MIZ mesoscale areas (~100 km x 100 km) in which comprehensive dielectric, meteorological, and ocean observations took place [Cavalieri et al., 1986; Shuchman et al., 1987]. The design of the MIZEX mesoscale microwave aircraft programs was based on instrumental and logistical techniques used in earlier MIZ remote sensing studies: the joint U.S./USSR Bering Sea Experiment (BESEX) in winter–spring 1974 [Kondratyev et al., 1975; Gloersen et al., 1982], in the southern Beaufort Sea in winter 1975 [Campbell et al., 1976] and winter–spring 1978 [Campbell et al., 1980], and in the east Greenland Sea during the Norwegian Remote Sensing Experiment (NORSEX) in winter 1979 [NORSEX Group, 1983]. However, the MIZEX '84 remote sensing program differed from these preceding experiments in one fundamental and important aspect: the aircraft and satellite data were used in a near-real time mode to direct investigators in ships and aircraft to rapidly evolving ice-ocean phenomena, especially eddies.

The most comprehensive MIZ aircraft program performed to date took place during MIZEX '84 in the Fram Strait–east Greenland Sea area during the period June 9 through July 16, 1984. Five microwave remote sensing aircraft performed sequential mesoscale mapping with a variety of passive and active microwave sensors. The NASA CV-990 airborne laboratory had 19- and 92-GHz imagers, a 6-channel radiometer operating at three wavelengths from 0.8 to 1.7 cm with both horizontal and vertical polarizations except without horizontal polarization for 1.4 cm, and a metric aerial camera. The Canadian Center of Remote Sensing (CCRS) CV-580 had the Environmental Research Institute of Michigan (ERIM) digital X and L band synthetic aperture radar (SAR). The Institut Géographique National B-17 used the digital X band side-looking airborne radar (SLAR) of the Centre National d'Etudes Spatiales (CNES). The U.S. Navy Naval Research Laboratory (NRL) P-3 flew a 90-GHz imager and other radiometers, and the National Oceanographic and Atmospheric Administration (NOAA) P-3 had an X band SLAR and gust probes. These aircraft flew joint and individual missions over the mesoscale MIZEX array of ships, and all flights were made with simultaneous or near-simultaneous (within 1 day) radiometric measurements from the Nimbus 7 SMMR and surface-based sensors.

The active and passive microwave data acquired by the
ICE CONCENTRATIONS FROM SMMR

Fig. 1. Ice concentrations during MIZEX '84 derived from Nimbus 7 SMMR radiances, June 8–30, 1984. Boxes indicate the location of the mesoscale microwave observations made from each remote sensing aircraft. The shaded areas indicate parts of Svalbard (east) and Greenland (west).
ICE CONCENTRATIONS FROM SMMR

Fig. 2. Ice concentrations during MIZEX '84 derived from Nimbus 7 SMMR radiances, July 4-16, 1984. Boxes indicate the location of the mesoscale microwave observations made from each remote sensing aircraft. The shaded areas indicate parts of Svalbard (east) and Greenland (west).

NASA CV-990, the Canadian CV-580, and the French B-17 provide a comprehensive synoptic sequential description of the mesoscale sea ice morphology of the Fram Strait MIZ and its variations throughout a melt season. This summer MIZ had complex and ephemeral ice structures, with pronounced variations in ice concentration, floe size distribution, and ice edge shape and position. This paper presents an analysis of the data acquired with these three aircraft and from the SMMR to describe the varying large-scale and mesoscale ice morphology and then discusses aspects of the atmospheric and ocean forcing involved in determining their temporal and spatial variations.

2. SMMR SEA ICE DISTRIBUTIONS

The Nimbus 7 SMMR provided near-real time ice observations for an area much larger than the actual experiment region, and this information not only aided in the initial site selection and buoy deployment of MIZEX '84 but also was used in directing the microwave aircraft flights through the 38 days of flight operations. During the experiment, the SMMR was on for every even Julian day and imaged the entire sea ice cover between Greenland and Svalbard (west Svalbard) extending from the sea ice edge to 85°N.

These data, processed using the SMMR Team sea ice algorithm [Cavalieri et al., 1984] including a weather filter [Gloersen and Cavalieri, 1986], yielded sea ice concentration maps covering the period June 8 to July 16, 1984 (Figures 1 and 2). Multifrequency observations for cold ice give ice concentrations with accuracies of 3–5% [Cavalieri et al., 1984; Swift and Cavalieri, 1985; Suenssen et al., 1983]. These 14 maps show the large-scale ice concentration distribution for every day that one or more of the three aircraft performed a
Fig. 3. Mesoscale maps of sea ice morphology derived from radar observations made by the ERIM SAR onboard the Canadian CV-580 and the CNES SLAR onboard the French B-17: (a) June 29 by the CV-580, (b) June 30 by the CV-580, (c) June 30 by the B-17, and (d) July 5 by the CV-580. The ice concentration and median floe size for the legend are as follows: 1, large individual floes; 2, ice-free ocean and polynyas; 3, concentration of < 20%; 4, concentration of 20 to 45%, median floe size of 125 m; 5, concentration of 45 to 70%, median floe size of 1 km; 6, concentration of 70 to 90%, median floe size of 100 m; 7, concentration of 90 to 100%, median floe size of 1 km.

The SMMR ice concentration maps (Figures 1 and 2) give both the ice extent and the ice concentration, with concentration isopleths for 20, 30, 50, 70, and 90%. These contours were drawn from the direct output of the SMMR ice algorithm which produces grid print maps on 4% ice concentration intervals, a technique also used to analyze SMMR data of the same area acquired during summer 1983 [Gloersen

mapping mission. The area mapped during each flight is shown in each SMMR ice concentration map, with the name of each aircraft. Of the 18 mesoscale maps acquired by the aircraft, six were acquired on odd days (June 9 and 30; July 5, 7, 9, and 11). In this case the area mapped is shown in the SMMR map for the preceding or following day with the observation date in parentheses under the aircraft name.
and Campbell, 1984]. In these maps, many areas have nearly coincident or coincident 20 and 30% ice concentration isopleths; this situation occurs frequently with compact ice edges. A key question asked by those unfamiliar with interpreting SMMR ice concentration maps is what ice concentration isopleth coincides best with the actual ice edge position determined by high-resolution images obtained by aircraft and observations from ships. This question, of course, has nothing to do with ice algorithm accuracy, but rather is concerned with the convolution of the large SMMR footprint with the small
Fig. 5. Mesoscale maps of sea ice morphology derived from radar observations made by the CNES SLAR onboard the French B-17: (a) July 11, (b) July 14, and (c) July 16. The ice concentration and median floe size for the legend are as follows: 1, large individual floes; 2, ice free-ocean and polynyas; 3, concentration of <20%; 4, concentration of 20 to 45%, median floe size of 125 m; 5, concentration of 45 to 70 percent, median floe size of 1 km; 6, concentration of 70 to 90%, median floe size of 100 m; 7, concentration of 80 to 100%, median floe size of 1 km.

The spatial resolution of the SMMR is approximately 30 km [Cavalieri et al., 1984], while that of the aircraft passive microwave imager (electrically scanning microwave radiometer, or ESMR) is approximately 0.5 km and that of the ERIM and CNES radars is about 10 m. The SMMR observations, which give ice concentrations averaged over a footprint, make...
the ice edge appear more diffuse than it actually is. A further spreading results from the gridding of the data onto 1° by 1° maps. For example, consider a consolidated ice pack in which ~100% concentration ice extends close to the edge, say, to within several kilometers. In this case the SMMR map would show an apparently diffuse edge with an ice concentration going from 0 to ~100% over a distance of at least 30 km. Therefore the SMMR ice concentration maps shown in Figures 1, 2, 7, and 8 and the SMMR transect data shown in Figures 9 and 10 give concentration gradients near the ice edge that are considerably less than the observed. Also, the actual ice edge lies not along the 20% SMMR isopleth but somewhere along a higher concentration isopleth. The question is, which isopleth?

A comparison of SMMR-derived ice concentrations with high-resolution aircraft observations and ship observations acquired during NORSEX [Svendsen et al., 1983] showed that in the Greenland Sea for the fall–winter period the actual ice edge position correlated best with the 50% SMMR ice concentration isopleth. These results used the NORSEX algorithm [Svendsen et al., 1983] which yields sea ice concentration determination accuracies in the same range as does the SMMR Team algorithm [Cavalieri et al., 1984]. During MIZEX ’84, a summer experiment, both compact and diffuse ice edges were observed by high-resolution aircraft microwave sensors, shown in Figures 3–5 and Plates 1 and 2. (Plates 1 and 2 are shown here in black and white. The color versions can be found in the separate color section in this issue.) These ice edge positions and ones obtained visually from the aircraft indicate that for diffuse ice edges the 30% SMMR isopleth...
Plate 2. Mesoscale microwave radiometric maps made from data obtained with the ESMR on board the NASA CV-990 airborne laboratory for June 12, 18, 22, 24, and 26, 1984. (The color version and a complete description of this figure can be found in the separate color section in this issue.)

closely approximates the observed edge positions, whereas compact ice edge positions correlate best within the 40–50% SMMR isopleths. This finding is discussed in detail later in this paper.

The problem of the limited SMMR spatial resolution and large ice concentration gradients also applies within the ice pack. None of the polynyas which appear in the high-resolution aircraft mesoscale maps (Figures 3–5 and Plates 1–2) appear in the SMMR maps because they are of a size not resolvable by SMMR. However, the occurrence of many polynyas within a SMMR footprint will reduce the SMMR ice concentration of that SMMR pixel. The only polynya that appears in the SMMR maps is the very large one off northeast Greenland.

The SMMR ice concentration maps amply illustrate the fact that the sea ice cover of the east Greenland Sea underwent pronounced rapid large-scale and mesoscale variations. These variations occurred not only in the MIZ but also over the entire inner ice pack. For example, from July 10 to 16, the entire north-central sector changed from >90% ice concentration to between 70% and 90%. The reduced ice concentrations associated with a well-known polynya that occurs each summer off northeast Greenland appear in all SMMR maps; the size and minimum ice concentration of this polynya varied greatly, especially during July. Because the SMMR footprint is the same size as the typical ice-ocean eddies observed in the Fram Strait region [NORSEX Group, 1983; Shuchman et al., 1987; Johannessen et al., this issue], these eddies are not resolvable in the SMMR maps. However, throughout MIZEX ’84, meanders several footprints in size appear, disappear, and then reappear. Some of these meanders, such as the one on June 26 at 79°30’N and 3°E, will be shown to have been associated with eddies.

The picture of the behavior of this summer MIZ that emerges from the SMMR maps is one of a long (~800 km) ice edge upon which meanders repeatedly formed, moved, and disappeared, with all of this activity taking place in a 50- to 100-km-wide band. Behind this edge the ice pack rapidly and frequently compacted and expanded throughout a 200-km-wide zone.

3. Mesoscale Ice Morphology by Passive Microwave

During the period June 9–30, the NASA CV-990 airborne laboratory mapped the MIZEX ’84 experiment area seven times. A list of the aircraft instrumentation is given in Table 1,
TABLE 1. NASA CV-990 Instrumentation

<table>
<thead>
<tr>
<th>Passive Microwave Instrument</th>
<th>Frequency, GHz</th>
<th>View Angle, deg</th>
<th>Polarization</th>
<th>Beam Width, deg</th>
<th>Resolution, altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrically scanned microwave radiometer</td>
<td>19.35</td>
<td>50 L to 50 R</td>
<td>H</td>
<td>2.8</td>
<td>1/20</td>
</tr>
<tr>
<td>Aircraft multichannel microwave radiometer</td>
<td>18.0</td>
<td>45 (right of nadir)</td>
<td>H/V</td>
<td>6</td>
<td>1/7</td>
</tr>
<tr>
<td></td>
<td>21.0</td>
<td>45 (right of nadir)</td>
<td>V</td>
<td>6</td>
<td>1/7</td>
</tr>
<tr>
<td></td>
<td>37.0</td>
<td>45 (right of nadir)</td>
<td>H/V</td>
<td>6</td>
<td>1/7</td>
</tr>
<tr>
<td>Aircraft uplooker</td>
<td>21.0</td>
<td>22 (right of zenith)</td>
<td>...</td>
<td>6</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>37.0</td>
<td>22 (right of zenith)</td>
<td>...</td>
<td>6</td>
<td>...</td>
</tr>
<tr>
<td>Advanced microwave moisture</td>
<td>92.0</td>
<td>45 L to 45 R</td>
<td>mixed</td>
<td>2</td>
<td>1/30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar altimeter</td>
<td>13.7-GHz Rutherford Appelton</td>
</tr>
<tr>
<td>Infrared radiometer</td>
<td>PRT-5 10.7-GHz nadir viewing</td>
</tr>
<tr>
<td>Cartographic camera</td>
<td>(1) KS-87B 5-inch format nadir viewing</td>
</tr>
<tr>
<td></td>
<td>(2) KS-87B 5-inch format 45° right of nadir viewing</td>
</tr>
</tbody>
</table>

and the electrically scanning microwave radiometer, operating at a frequency of 19.35 GHz (1.55 cm), produced the images shown in Plates 1 and 2. All seven mapping missions were flown at about 9550 m, which gives a resolution of about 0.5 km. Each image is presented with a color scale (to the right of the image) that relates the microwave radiances to the ice concentration. Note that the scales vary, because during the observational period the ice surface went through alternating freeze-thaw periods, and the microwave emissivities of sea ice responded accordingly. Therefore, different radiance-ice concentration relationships apply depending on the wet or dry surface conditions at the time of each flight. Since the ESMR scans cross-track and takes data at varying incidence angles, the calibration of each beam position yields approximately nadir values of the radiances, to avoid limb darkening in the images. The calibration consisted of a two-point linear calibration of each beam position, using model values for the radiances of consolidated sea ice near the melt point and calm open water with clear skies. The data taken at the ends of the flight lines, during aircraft turns, must be ignored because the view angle of the ESMR was canted 30°-40° left or right of nadir.

The two different concentration scales in Plates 1 and 2 correspond to (1) the situation where the ice is at the melting point over the entire MIZEX '84 area and (2) that where the ice surface temperatures are partially or completely below the freezing point. The melt (wet) ice case is the most straightforward for deducing ice concentrations, since both first-year and multiyear ice have about the same microwave signature (~270 K), at the melt point. Thus 100% ice concentration is set at this value for June 22 and 24, when the MIZEX '84 area was cloud-covered and the entire ice surface wet. On June 9, 12, 18, 26, and 30, for the frozen or partially frozen case, there are areas with fully consolidated ice where the radiance is about 225-235 K, typical of multiyear ice below the freezing point at this time of the year. Thus the 100% concentration mark is at this value, and all radiances above 235 K are also interpreted as 100% ice cover, because radiances of fully compact mixtures of first-year and multiyear ice can range from about 225 to 270 K. The open water point of 125-135 K is used for the 0% ice concentration point on both scales. The 10 K steps on the two ESMR color scales were chosen to be consistent with the rms noise of the instrument (about 6 K). The value of the bottom of the scales was chosen to be 10 K less than the minimum radiances observed over the oceans. The top value of the scales was chosen to be 10 K more than the maximum radiances observed over the sea ice.

The ice concentration scale for the melt (wet) cases is shown in Plate 2 to the right of the July 22 and 24 images, which were days on which all the ice was wet. The scale for frozen (dry) cases is shown in Plate 1 to the right of the June 9 and 30 images, which were days on which all the ice was frozen (dry). The situation for June 12, 18, and 26 is more complex than the above because on these days the mesoscale areas had both clear and cloudy regions, with low-level stratus and stratocumulus, and therefore wet and dry surface conditions. Thus on these days both the ice concentration scales shown in Plate 2 apply. On June 12 a stratocumulus layer covered the area in the center of the image, and the surface of the ice under it melted, which accounts for the center band ~270 K radiances in this image. On June 18, stratocumulus clouds covered the area north of 81°50'N latitude, again causing melt and ~270 K radiances, while the area to the south was cloud-free with a dry ice surface. On June 28, a stratus layer covered the area north of 80.5°N latitude, where once again the high radiances of wet ice appear in the mesoscale image.

Gloersen et al. [1974] and Zwally and Gloersen [1977] estimated that the accuracy of ice concentration from ESMR radiances without a priori knowledge of surface temperatures, ice types, and atmospheric conditions is ±15%. With such knowledge, the end points of the linear interpolation are more precise, and therefore the accuracy of the concentration determination is set by the radiance interval used in the color scale. In the present case, such a priori knowledge was available from numerous observations from ships and helicopters. This means that the accuracy for estimates using the scale for dry conditions is about 10%, corresponding to the 10 color steps between the end points of the dry ice scale, while that for wet conditions is about 6%, corresponding to the 16 color steps between the end points of the wet ice scale.

The ice concentration distributions given in the passive microwave maps (Plates 1 and 2) and those given in the SMMR maps (Figures 1 and 2) closely agree. Figure 9, which will be discussed later, shows temporal variation of the 50% SMMR ice concentration isopleth along 6°E and the ice edge location from aircraft observations. The aircraft ice edge is consistently 10 to 20 km north of the SMMR edge, well within the scale of the SMMR footprint (30 km).

Two aspects of the mesoscale MIZ morphology are unambiguously revealed in these mosaics, the distribution of polynyas and the complex ice structures near the ice edge, especially those associated with ice-ocean eddies ( Plates 1 and 2). Many large floes are clearly resolved in each image where they were surrounded by zones of reduced ice concentration and/or differing ice type. For example, note the large (~15 km) floe centered at 81°10'N, 8°50'E in the June 12 ESMR.
image (Plate 2) which has a signature of $\sim 265$ K while the ice around it has a signature of $\sim 225$ K.

4. MESOSCALE ICE MORPHOLOGY BY ACTIVE MICROWAVE

The high-resolution capability of radar makes it the ideal sensor to observe sea ice morphology and motion under all meteorological and lighting conditions. Radar observations can accurately determine floe size distributions, and repetitive mapping of a given area can be used to obtain the detailed ice kinematic and deformation fields needed for ice forecasting and model studies. Therefore repetitive radar observations of the MIZEX '84 area were a key part of the remote sensing program, and 11 mesoscale maps derived from radar observations were obtained during the period June 29, to July 16 with the ERIM digital X and L band SAR flown on the CCRS CV-580 and the CNES VARAN-S digital X band SLAR (Figures 3, 4, and 5).

An important aspect of the remote sensing program in MIZEX has been to discover if sea ice concentration can accurately be measured with radar. The dynamic range and resolutions of radars used in earlier mesoscale mapping experiments in the Beaufort Sea during the Arctic Joint Dynamics Experiment (AIDJEX) in 1975-1976 [Campbell et al., 1978; Leberl et al., 1979] and the Bering Sea Experiment in 1974 [Ramseier et al., 1982] were insufficient to permit ice concentration estimates. The improved radars used in MIZEX '84 permit such estimates [Burns et al., 1986].

The ensemble of aircraft data obtained on June 30 over the same MIZ area provides an excellent base to compare the ice concentration estimates derived from passive and active images with metric camera photography. This was the key day of the remote sensing program, with the CV-990, CV-580, and B-17 aircraft flying on this cloud-free day at the same time over the same area of the MIZ containing mesoscale ice-ocean eddies. The map for June 30 in Figure 1 shows the mesoscale areas flown by each aircraft. The ESMR image (Plate 1) and photomosaic (Figure 6) obtained by the CV-990 overlaps 100% of the B-17 SLAR image (Figure 3c) and 75% of the CV-580 SAR image (Figure 3b).

Experience gained during AIDJEX [Campbell et al., 1978; Gloersen et al., 1978] shows that great care must be taken in comparing active and passive microwave images and photographs of sea ice. The problem is that new ice (nilas, pancakes) which forms in leads and polynyas has a radiometric signature quite distinct from that of open water in the 19- to 37-GHz passive microwave range, while in radar images and nadir-pointing photographs a distinction between open water and new ice forms is frequently impossible. Therefore during the June 30 aircraft overflights, emphasis was placed on lead and polynya observations. Of the three aircraft, the B-17 flew at the lowest altitude (2400 m), and during each of the six parallel flight lines, oblique visual and photographic observations were made in the direction of the sun. The sharp glint from ice-free leads, usually covered with capillary and small gravity waves, is quite distinct from the flat glare of those with new
Plate 3. (left) Visible and (right) infrared NOAA AVHRR images of the Fram Strait-Greenland Sea region on July 4, 1984. Numbers indicate the location of two ice-ocean eddies (1 and 2) and three ocean eddies (3, 4, and 5) that appear in both images. (The color version of this figure can be found in the separate color section in this issue.)

ice, which effectively damps out these waves. These observations confirmed that all of the leads and polynyas within the ice pack area covered by the B-17 mosaic were ice-free. Therefore an unambiguous comparison of the ice concentrations deduced from simultaneous active and passive microwave and photographic observations made on this day is possible.

Shuchman et al. [1987] developed a radar-ice concentration algorithm using coincident ERIM SAR data and mapping-quality aerial photographs acquired during MIZEX East '83. Burns et al. [1986] have used an ensemble of aircraft remote sensing data from MIZEX East '83 and MIZEX '84 to develop algorithms to deduce ice concentration, floe size distribution, and ice kinematics from SAR observations. The accuracy of this ERIM technique as applied to the MIZEX '84 data was determined by Burns et al. [this issue], who used it to compare simultaneous SAR and mapping-quality aerial photographs obtained on June 30 by the CV-580, ESMR data acquired by the CV-990, and 90-GHz image data from the NRL P-3. These studies show that highly accurate estimates of ice concentration and floe size can be derived under these summertime conditions from SAR and SLAR sea ice observations, with the radar ice concentrations agreeing with those from aerial photography to within 5% for concentrations ranging from 30% to 80% and floe size measurements agreeing to within 10% on average. All of the MIZEX '84 SAR and SLAR data were processed at ERIM using this technique to yield the 11 mesoscale ice morphology maps given in Figures 3, 4, and 5. The digital SLAR images used to make these mesoscale maps are shown by Lannelongue et al. [1985]. The digital SAR images for July 5, 7, and 9 are shown by Johannesen et al. [this issue]. The CV-580 images for June 29, 30, and July 6 are as yet unpublished. These estimates of accuracy are not necessarily valid in the winter, when thin ice rather than open water is frequently present between the larger floes.

These mesoscale maps of the summer MIZ derived from radar images give a high-resolution view of the distribution and variation of the key aspects of ice morphology (ice concentration, ice edge structures and positions, and floe size distribution) throughout the latter half of MIZEX '84. Of all the complex ice features revealed in these 11 maps, obtained within the western sector (3°E to 8°W longitude) of the experiment over the Molloy Deep and the Greenland continental shelf break, the most salient are those associated with eddies. Indeed, 10 of the maps clearly show the ice plumes, bands, and streamers of ice-ocean eddies.

A comparison of the ice concentration distributions given in these mesoscale maps with those given in the SMMR maps (Figures 1 and 2) shows that they agree closely. On June 30 the mesoscale map (Plate 1) revealed a high concentration gradient extending from a compact ice edge into the main
Fig. 7. Wind stress fields during MIZEX '84, June 9-30, 1984. Vectors originating at a cross indicate stress derived from observations aboard ships.
pack (50%/50 km). The SMMR map for June 28 also shows a high concentration gradient of 50%/50 km in the area of the radar map.

A very different ice morphology occurred just south of this area on June 30 and was observed by all three aircraft. The SMMR map (Figure 1) shows the overlap of the aircraft maps (Figure 3) and that they were made over an area of low ice concentrations (30-50%). All three maps show many large polynyas in a pack with many large floes, as if a compact pack had rapidly diverged. The radar ice concentration gradients averaged over SMMR footprint (30 km) scales compare well with the SMMR ones. Note that in the overlapping passive (ESMR) and active (SAR, SLAR) microwave maps there is a ~10% agreement between ice concentration estimates in the areas of high and low concentration, and in areas of intermediate concentrations the agreement is of the order of 20%. The CV-990 (Plate 1) and B-17 (Figure 3c) images clearly show the complex structure of a long (~70 km) plume of ice associated with an eddy located at 79°15′N, 2°30′E in the vicinity of the Molloy Deep [Johannessen et al., this issue].

In the mesoscale map of July 5 (Figure 3d), ice-ocean eddy plume structures of low concentration (~20%) were adjacent to the main ice pack with many large floes and an ice concentration of 80-90%, which agrees with the SMMR concentrations in that area on July 6. The eddy, shown in the center of the July 5 image, also appears in the advanced high resolution radiometer (AVHRR) images of July 4 (Plate 3) and is labeled "I". (Plate 3 is shown here in black and white. The color version can be found in the separate color section in this issue.) Just north of this area on this following day a similar morphology existed (Figure 4a), but the ice plume and band zone associated with eddies was much wider (~80 km). The radar map of July 7 (Figure 4c), obtained in essentially the same area as that of July 5, shows a very different MIZ structure than that of 2 days earlier. The MIZ became compact, and the main pack with high ice concentrations (80-90%) was close to the edge. Long bands of compact ice with high concentrations of 80-90% made up of small floes (8-500 m) appeared along the ice edge, and the zone of low-concentration ice between the edge and main pack was narrow (~10 km). This high ice concentration gradient agrees well with the SMMR for July 8.

By July 9 (Figure 4d) in the area just north of the July 7 mesoscale map area, the ice edge became more diffuse, with low-concentration bands and streamers extending ~50 km from the main pack. From this date until the last microwave mapping mission of July 16, a pronounced change took place from the earlier mesoscale and large-scale morphologies, which is clearly shown in the SMMR maps for July 10, 14, and 16 (Figure 2) and B-17 SLAR maps for July 11, 14, and 16 (Figures 5a, 5b, and 5c). These data show that at the end of MIZEX '84 the ice in the MIZ and the interior pack rapidly opened up and/or melted. The mesoscale maps show large areas of diffuse ice associated with eddies and only small amounts of high-concentration ice. The SMMR maps show very low concentration gradients in the MIZEX area with rapidly decreasing concentrations in the interior pack adjacent to it, which became as low as 20% on July 16.

Section 6 will discuss the ocean current and wind forces that created these complex and rapidly changing ice morphologies.

5. WIND STRESS

The observed MIZ ice morphology results from the combined effects of atmospheric and oceanographic forcing, and of these two, daily synoptic information is available only for the atmospheric forcing. Figures 7 and 8 give the wind stress fields for the day on which each aircraft microwave map was obtained. The wind stress maps were made using direct stress measurements from the various ships, when available, or computed wind stress from wind observations, and finally, where there were no observations, the large-scale pressure maps [Lindsay, 1985].

The direct wind stress measurements were made from bow masts on the Polar Queen and Hakon Mosby and were made using the dissipation method of Shacher et al. [1981]. Also, profile and eddy correlation measurements from towers on ice floes adjacent to the Polar Queen yielded stress values. When direct stress measurements were unavailable, the bulk method estimated the stress using the drag coefficient and the 10-m wind. Wind measurements, when available, from Polarstern, Kvitbjorn, Valdivia, and Lynch gave additional stress information using the bulk technique.

The value of the drag coefficient C_d over areas with sea ice was determined from the SMMR ice concentration maps using the technique of Guest and Davidson [this issue], which relates C_d to ice morphology. In open ocean regions, the value of C_d during neutral stability was set to 2.0 × 10^{-3}, which was the average obtained from the Hakon Mosby stress measurements. During unstable conditions, C_d was adjusted for stability using the method of Large and Pond [1981].

Where no stress or wind observation existed, the stress was calculated from the gradient wind. These calculations used the surface weather maps prepared by the National Meteorological Center contained in the work of Lindsay [1985]. Maps prepared specially for the MIZEX region using all available data, including satellite information (Picard, unpublished data, 1984), were used during the periods June 18-24 and July 4-6. The ratio of the friction velocity, from ship surface measurements, and the gradient wind, u_{rms}/G, as well as the turning angle z between G and U_{10} were calculated at the ship locations. The magnitude and direction of the wind stress was then determined at locations away from the ships using the u_{rms}/G and z relationships from the nearest ship. If the stability or surface roughness changed significantly away from the ships, then u_{rms}/G and z were altered according to the model results from Overland [1985] over ice regions or from Brown and Liu [1982] for the open ocean. The gradient wind speed was the dominant factor affecting wind stress, while stability and roughness effects were of secondary importance.

The wind stress fields, Figures 7 and 8, used the vector-averaged wind stress in the period 0000 to 1200 UT on the day of the aircraft flights. These wind stress maps show large-scale (>20 km) wind stress and do not reflect local variations in wind stress caused by the mesoscale ice variations as observed with ESMR, SAR, or SLAR. The terms light, moderate, or strong winds refer to wind speeds of <5 m s^{-1}, 5-10 m s^{-1}, and >10 m s^{-1}, respectively. The vectors indicate the direction and magnitude of the wind stress at the base of the vector. If this value was from a directly measured surface wind from a ship, it is indicated by a cross at the vector base.
SURFACE WIND STRESS

Fig. 8. Wind stress fields during MIZEX '84, July 5-16, 1984. Vectors originating at a cross indicate stresses derived from observations aboard ships.
6. Ice Morphology Affected by Wind Stress and Ocean Circulation

The sequential synoptic microwave observations shown in Figures 1–5 and Plates 1–2 show the general ice conditions that occurred during MIZEX '84 as well as the rapid response of the ice morphology to variations in ocean current and wind forces. The SMMR observations give the large-scale ice conditions, while the aircraft observations give the detailed mesoscale conditions as the experiment area moved from east to west at approximately 8 km d\(^{-1}\), or with the mean ice drift.

The combination of the SMMR maps and the surface wind stress fields for the entire region (Figures 7 and 8) shows the variations of the large-scale ice morphology in response to changing meteorological conditions, which are now discussed before a similar discussion of the mesoscale morphology variations. In general, the ice edge and the pack close to it, the region between the 30% and the 70% ice concentration lines, have undulations whose amplitudes vary depending on the strength of the wind. After periods of low wind stress, \(<0.05\) N m\(^{-2}\), large undulations form with two dominant protuberances that result from the mean oceanographic conditions. One repeatedly forms at approximately 77ºN, 2ºW as a result of the East Greenland Current that transports ice eastward as it follows the curving shelf break in this region. Another one repeatedly forms at approximately 79.2ºN, 2ºE, in the vicinity of the Molloy Deep, a region of eddy generation and activity [Johannesen et al., this issue]. These protuberances disappear and are replaced by a smooth ice edge with only small-amplitude undulations immediately after large-scale strong wind stress events, \(>0.15\) N m\(^{-2}\), that overwhelm the mesoscale oceanographic forcing. Figures 7 and 8 give the wind stress fields only for the aircraft radar observation days and have gaps of up to 4 days between observations. Lindsay [1985] and Figures 9 and 10 give the daily sequential wind conditions. These data show that the relatively straight edge of July 5 resulted from the moderate winds that occurred during July 2 to 4.

These observations show that regardless of the wind direction, strong winds tend to smooth the large-scale and MIZ morphology, primarily as a result of wind generated shear in the ice pack. The wind-driven ice transport is seldom purely on or off ice, it usually contains a strong component along the ice edge, and Shuchman et al. [1987] show from buoy drifts that strong shear occurs in the MIZ during strong winds. In addition, ice transport normal to the ice edge also tends to smooth large-scale features. On-ice transport compact the ice and produces internal ice stresses that tend to smooth these large scale protrusions. The off-ice component combines with rapid melting as the ice drifts across the polar front into warm North Atlantic water to limit the seaward ice drift, and the ice extent will be influenced by the large-scale upper ocean temperature distribution. Measurements by Josberger [this issue] show that in the MIZ the heat transfer from the upper ocean to the ice can melt 2-m-thick ice in less than 2 days. Hence the warm ocean acts as a barrier that restricts southerly ice transport, and the ice edge position will indicate the ocean thermal structure in this situation. This occurred on June 24 and 26, two days with moderate protuberances, during a wind regime that would produce more off-ice transport than transport along the edge.

Several examples of the transformation between the two configurations can be seen in Figures 7 and 8. On June 9, two large protuberances dominated the large-scale MIZ morphology. The moderate to strong winds during June 9 to 11 yielded the smooth edge of July 12. During June 18 to 22, light winds or no wind occurred, and by June 22 the two large protuberances reappeared. During June 23 and 24, strong on-ice winds over the Fram Strait region smoothed the protuberance associated with the Molloy Deep. Strong southerly winds parallel to the ice edge on June 26 produced a nearly straight edge with only a small protuberance near the Molloy Deep, which expanded during the light and variable winds of June 28 and 29. The strong off-ice winds of July 7 to 9, the strongest during the experiment, resulted in a very smooth ice edge.

The complete mesoscale and large-scale data ensemble, Figures 1–8 and Plates 1–3, for the MIZ area covered during the experiment, 10ºE to 8ºW, shows that the ice responds to different forcing in the eastern and western sectors. The eastern sector, from 10ºE to 3ºE, is over a bathymetric plain called the Yermak Plateau. The western sector, from 3ºE to 8ºW, in-
cludes the Molloy Deep and the Greenland continental shelf break. In the eastern sector the ice edge zone generally was aligned east to west for the entire experiment, and the ice concentration gradients remained moderate to high, 70%/80 km to 70%/150 km. However, in the western sector the ice edge zone undulates widely and repeatedly, and the ice concentration gradients fluctuate from low (50%/150 km) to high.

To discuss the ocean and wind forcing in the eastern and western sectors in relation to both the large-scale and mesoscale variations in morphology, we have constructed a time series of SMMR ice concentration isopleths along transects in each region and the wind stress for the center of each region, Figures 9 and 10. These transects are perpendicular to the average ice edge and extend from the open ocean into the ice pack for about 200 km, and they are shown in the SMMR map of June 8 (Figure 1) labeled “E” for the eastern sector and “W” for the western sector. The ordinate in Figures 9 and 10 gives the distance from the arbitrary seaward end of each transect, which for the eastern transect is 79°N, 6°E and for the western transect is 78.5°N, 2.5°E. These figures include data from all of the SMMR observations, not only those from the 15 maps shown in Figures 7 and 8. The daily wind stress vectors shown are for the center of each transect, which for the eastern sector is at 80.5°N, 6°E and for the western sector is at 79°N, 0°E. The wind stress vectors in Figure 10 have been rotated to show the stress relative to the section line; that is, a vertical vector is parallel to the section line and a horizontal vector is normal to the section line.

Before proceeding with the discussion of the morphology variations in these two sectors, we next discuss the accuracy of the ice edge determinations by SMMR. The simultaneous aircraft and SMMR observations provide unique data to make this comparison. All but the final passive microwave imaging took place in the eastern sector, while all of the radar imaging took place in the western sector. The six passive microwave images obtained in the eastern sector show ice edges extending generally east-west, with those of June 9, 12, and 18 having diffuse edge zones and those of June 22, 24, and 26 having compact edge zones. The 11 radar images, with the exception of that of July 7, show very diffuse and irregular ice edges. In addition to the microwave observations from each aircraft, visual observations were made when possible. The ice edge position was observed during all B-17 and CV-990 flights, even though low cloud cover was present most of the time. The great albedo difference between ice and water and the thin low-level stratus and stratocumulus layers made it possible to visually map the ice edge position, including large plumes and bands. For compact ice edges the edge positions are readily determined, but for diffuse edges, determining the edge positions involves subjective criteria. In this study we take the seaward limit of large bands and plumes, such as those shown in the radar images of June 29 and 30 and July 5, 6, 9, 11, 14, and 16, for the ice edge position. The 18 ice edge positions obtained from the aircraft radar, ESMR, and visual observations show that, for diffuse ice edges, the 30% SMMR concentration isopleth best correlates with the ice edge position, while for compact ice edges, the ice edge falls between the 40 and 50% SMMR ice concentration isopleths.

The Eastern Sector

In the eastern sector, two strong off-ice and on-ice wind events occurred during the experiment, as shown in Figure 9. The following describes the effects of these events on the ice conditions, referring first to the SMMR data and then the mesoscale aircraft data. The following discussion also uses the term “ice concentration gradient,” which is the percent change in ice concentration divided by the distance over which the change occurs. Hence a compact ice pack will have a concentration gradient greater than that of a diffuse ice pack.

From June 9 to 12, the wind stress time series in Figure 9 shows that strong to moderate off-ice winds occurred. These winds generated seaward motion of the high-concentration ice as shown by the 50-km southward progression of the 90% SMMR ice concentration isopleth and the 50-km decrease in the distance between the 90 and 50% ice concentration isopleths. However, the ice edge advanced southward only 20 km; the advance was limited by rapid melting as the ice entered warm water. The mesoscale maps (Plates 1 and 2) show that on June 9 a very diffuse ice edge existed with a 40-km-wide zone of ice bands and plumes that had ice concentrations ranging from 10 to 30%. Within the main pack there were many polynyas 5 to 20 km in length with microwave signatures that indicate ~50% ice concentrations. Three days later, on June 12, the width of the diffuse ice edge had increased to ~60 km, with many polynyas in the main pack. This morphology resulted from the off-ice winds that occurred during this 2-day period, some of the strongest winds of the experiment. Between June 13 and 18 the winds were light and variable, with little effect on the ice morphology, and the ice edge continued to be diffuse.

During the period June 20 to 27, compact conditions replaced the diffuse conditions of June 8 to 20 as a result of changing wind conditions. As Figure 9 shows, a moderate wind blew towards the southwest on June 20 and diminished to almost no wind on June 22. The SMMR ice concentration gradient increased when compared with the previous 20 days. The mesoscale map (Plate 2) shows no polynyas and a compact ice edge region. During June 23 to 27 the passage of a cyclone south of this sector generated the strong on-ice winds. The SMMR ice concentration gradients increased to 60%/75 km. The mesoscale maps for June 24 and 26 (Plate 2) show compact ice packs, with ice concentrations of >90% and no polynyas. The edge zone was compact and nearly linear. The portions of these two images that cover areas west of 3°E will be discussed in the western sector section.

During July 6 through 10, an intense cyclone that moved northward to the east of Svalbard generated the strongest off-ice winds experienced in the eastern sector during the experiment. As Figure 9 shows, these winds caused a rapid decrease of the SMMR ice concentration gradients and advanced the ice edge southward by 35 km. The ice divergence, in the absence of strong ocean currents, results from greater aerodynamic roughness in the edge region than in the interior. Guest and Davidson [this issue] show that the bulk drag coefficient is 40–100% greater near the ice edge than deep within the pack. The on-ice winds of July 10–11 caused the MIZ to shift northward ~15 km. The strong decrease in ice concentration throughout the eastern sector after July 14 results from low winds and the regional ice melt which reaches its peak at this time.

The above describes a MIZ whose internal morphology rapidly responds to the wind, and the fact that little change is observed during light wind conditions implies weak oceanographic forcing. Observations by Johannessen et al. [this
issue] and Manley et al. [1987] found ocean currents of approximately 10 cm s⁻¹ in the eastern sector during the experiment. The insensitivity of the 30% SMMR isopleth to winds that would transport ice to the south, except for the extreme wind event of July 6 to 10, shows that the warm water to the south prevents the southerly transport of ice in most cases.

The Western Sector

Throughout the experiment, the ice morphologies in the western sector (3°E to 8°W) and their response to ocean and wind forces were distinctly different from those in the eastern sector. Figure 10 gives the time series of the SMMR ice concentrations along the transect shown in the June 8 SMMR map in Figure 1, as well as the wind stress for this sector. In the west, the distance between the 30% and 70% SMMR ice concentration isopleths was typically twice that in the east. Also, within 100 km of the ice edge, ice concentrations of 90% or more rarely occurred, whereas in the east this high concentration always existed within 80 to 100 km of the ice edge. Another large-scale difference is that the entire western ice pack, the area having >50% SMMR ice concentrations, underwent major changes in ice concentration. From the beginning of the experiment to June 28, the interior had ice concentrations of 80%. From June 28 to July 10, these high concentrations disappeared and then reappeared.

The wind forcing in the west differed from that in the east. As Figures 9 and 10 show, the winds in the western sector were usually more parallel to the ice edge and not as strong as the winds in the eastern sector. However, these wind differences do not explain the different large-scale and mesoscale ice morphologies which occurred in each sector: it is the difference in ocean circulation that is responsible. In the west the vigorous East Greenland Current flows south over the Molloy Deep and along the continental shelf break, rapidly transporting ice to the southwest. The various eddies and meanders that result from this closely coupled current-bathymetry system dominate in determining the structures and variations of the ice morphologies. This complex and rapidly varying current system, described by Johannessen et al. [this issue], causes the formation of equally complex and dynamic ice structures, as will be shown in the following discussion.

Unfortunately, the typical size of the ocean eddies in the Molloy Deep region (~30 km) is the same size as the SMMR footprint; thus the individual effects of the eddy circulation on the mesoscale ice morphologies are visible only in the aircraft images. Radiometric mapping of this area started on June 24 (Plate 2) with passive microwave imagers. In the southwest corner of this image there are ice plumes and bands ~60 km from the main pack, just east of the Molloy Deep. The ESMR image of June 26 shows similar structures, and the complex ice structures associated with an eddy located near the Molloy Deep centered at 79°15′N, 3°E. Johannessen et al. [this issue] and the plumes and bands observed in this area 2 days earlier were also associated with this eddy. During this period the winds were weak and variable, which allowed the ice to follow the ocean circulation.

On June 29 the CV-580 obtained the first mesoscale high-resolution radar image, covering an area of the MIZ just north of the Molloy Deep (Figure 3a) during a period of light and variable winds. Numerous large polynyas occurred within the pack, from which several low ice concentration plumes extended southward into the open sea toward the Molloy Deep.

On June 30 the CV-580, CV-990, and B-17 imaged the Molloy Deep area, and all three overlapping mesoscale images (Plate 1, Figure 3b, and Figure 3c) show ice structures associated with ocean eddies. An extended ice plume which was advected from the diffuse ice pack by the cyclonic circulation of an ocean eddy centered at 79°15′N, 3°E is clearly shown in both the SLAR and ESMR images. The ESMR image shows ice structures indicating smaller eddies centered at 79°15′N, 1°W and 78°45′N, 1°W. All three of these ice-ocean eddies can be seen in great detail in the photomosaic (Figure 6) of this area obtained from the CV-990. Because of the persistent cloudiness during the experiment, this was the only photomosaic obtained which covered the entire mesoscale area viewed by the microwave sensors. In the SAR image (Figure 3b), the bands and plumes which existed south of the diffuse pack appear to have been generated by a fourth eddy which was centered just out of the south image.

The SAR image acquired during the light wind conditions on July 5 (Figure 3d) of a part of the MIZ southwest of the area covered on June 30 shows that a very diffuse ice edge zone some 20–30 km wide and made up of small floes extended along the MIZ, and within this zone an eddy centered at 78°45′N, 2°30′W created many plumes in a cyclonic rotation. In the southwestern corner of this map there are plumes associated with a second eddy which appears to have been centered at about 78°N, 4°W. A pair of visible and infrared images acquired on July 4 from the NOAA AVHRR satellite (Plate 3), covering a large MIZ area including that of the July 5 SAR image shows the ice structures and ocean thermal structures associated with five eddies. Those labeled 1 and 2 are the same eddies shown in the SAR image.

Nearly overlapping SAR and SLAR images of the Molloy Deep region, acquired on July 6 (Figures 4a and 4b), show a diffuse MIZ structure with many bands and plumes extending 60 km from the pack. Where the images overlap, the upper right of Figure 4a and the lower right of Figure 4b, nearly identical morphologies are seen. They result from an eddy located just north of the Molloy Deep, which can be seen in the NOAA AVHRR image of July 4 (Plate 3).

On July 7 the passage of a cyclone east of Svalbard generated strong off-ice winds in the western sector that overwhelmed the mesoscale oceanic forcing. This was the only day of the 11 days on which mesoscale observations of the western sector were acquired (June 24 to July 16) that ocean forces did not dominate in determining the ice morphology. These winds, the strongest during the entire experiment, produced the most linear MIZ and compact ice edge observed in the western sector during the experiment (Figure 4c), and Johannessen et al. [1983] reported a similar occurrence in this area during the NORSEX program. The mesoscale structure shows an ice edge straightened by a combination of melting and the ice shear of the ice transport parallel to the ice edge. Almost all of the eddy signatures which existed 2 days earlier in the same area had disappeared, except for a semicircular ice-free region which bounds an eddy at 78°40′N, 2°W. From the center part of the map of the southwest corner, wind and wave forces formed long ice bands along the ice edge with high ice concentrations (~80%) and composed of small floes (10–500 m) with numerous ice streamers trailing from the edge. These features may indicate the presence of an ice edge jet, as was
observed in this area by Johannessen et al. [1983] during NORSEX. Roed and O'Brien [1983] predict a jet in these conditions using a coupled ice-ocean model. The interior ice pack also responded to this wind event, the SMMR observations, Figures 2 and 10, show the reappearance of 80 to 90% ice concentrations in the western sector.

As the cyclone moved eastward, the winds diminished to moderate levels by July 9. The relaxation of the atmospheric forcing once again allowed the ocean circulation to determine the ice morphology. The mesoscale image of this day (Figure 4d) shows that the linear and compact ice edge of 2 days earlier had rapidly diffused, and bands and plumes associated with eddies appeared.

From July 10 until the end of the experiment, only light on-ice winds blew in the western sector (Figures 8 and 10). The SMMR data (Figures 2 and 10) and the SLAR mesoscale maps for July 11, 14, and 16 (Figures 5a, 5b, and 5c) show a pronounced and continuous decrease in ice concentration in both the MIZ and the interior ice pack associated with the peak of the summer melt season. The mesoscale morphologies on all 3 days were clearly determined by the ocean circulation. On July 14, many bands and plumes were advected cyclonically around an eddy centered at 78°50'N, 1°10'W. Ships, directed as this eddy as a result of this image, mapped its three-dimensional structure [Johannessen et al., this issue]. The circulation around this eddy was sufficiently strong to advect large multiyear floes out of the main pack to encircle it. On July 16 this eddy was in the same position and had continued to advect large amounts of ice around it. Tracking numerous identifiable ice floes in both the July 14 and 16 images yields mean orbital speeds of about 30 cm s⁻¹. From oceanographic measurements, Johannessen et al. [this issue] found that the orbital speed of the upper 50 m of this eddy was 30 to 40 cm s⁻¹; thus the equal ice and current speeds show that ocean forcing determined these morphologies.

The above discussion shows that during MIZEX '84 the mesoscale morphologies in the western sector were determined primarily by ocean circulation, with the one exception of July 7 when the strongest winds of the experiment occurred. The ocean forces also appear to be dominant in the determination of the large-scale morphologies in this sector. Häkkinen [1986, 1987] has modeled the Fram Strait–Greenland Sea area and finds that the ice motion is governed by three principal components: (1) the East Greenland Current following the continental shelf break and the currents associated with the eddies generated near the Molloy Deep, (2) local wind-generated currents, and (3) the direct wind stress of the wind on the ice. Häkkinen finds that the Coriolis force on the ice is small compared with the forces given above. During periods of very low wind stress, such as those that existed during MIZEX '84 on June 22, June 29, and July 5 (Figures 7 and 8), the model predicts that the ice will follow the externally generated ocean flows, i.e., those in the Molloy Deep area and the East Greenland Current. Note that on each of these days, the large-scale morphologies (Figures 1, 2, 7, and 8) show large protuberances in the Molloy Deep area and along the irregular break of the continental shelf at about 77°N.

7. SUMMARY

Large-scale passive microwave observations of the Fram Strait–Greenland Sea marginal ice zone during MIZEX '84 by the Nimbus 7 SMMR and simultaneous mesoscale passive and active microwave observations by microwave remote sensing aircraft provide a unique history of the complex and dynamic summer ice morphology. The emphasis in the experiment design on microwave remote sensing was well placed, since cloud cover over the MIZEX area was frequent. Indeed, on only 1 day of the 15 days flight operations occurred was the MIZEX area completely cloud free. The following are the key findings of the analysis of this microwave data set coupled with MIZEX wind and ocean observations:

1. The long (~800 km) ice edge between northwest Svalbard and central Greenland, which had meanders and eddies repeatedly form, disappear, and reform along it, moved within a narrow zone of 50–100 km, while behind this alternating diffuse and compact edge the ice pack underwent rapid, alternating, and pronounced variations in ice concentration over a wide zone (~200 km).

2. A comparison of aircraft microwave and visual observations with the SMMR ice concentration distributions indicates that for the summer MIZ the 30% SMMR ice concentration isopleth correlates best with actual ice edge positions for diffuse ice edges, whereas compact ice edge positions correlate best within the 40–50% SMMR isopleths.

3. The variations in mesoscale ice morphologies in response to wind and ocean forcing were distinctly different in the eastern and western sectors of the experiment. In the eastern sector, 3°E to 10°E, over the Yermak Plateau, the morphologies were determined by the wind. In the western sector, 3°E to 8°W, which includes the Molloy Deep, the Fram Strait, and part of the Greenland continental shelf break, the morphologies were determined by ocean current forcing, with the exception of July 7 when the strongest off-ice winds of the experiment determined the morphology.

4. The experimental objective of locating and mapping ice-ocean eddies was achieved. Eddies or parts of eddies were observed on 15 of the 18 aircraft mesoscale microwave flights. These eddies ranged in diameter from ~20 km to ~80 km. The typical diameter of the eddies was about 30 km.

5. The large-scale SMMR ice concentration distributions and the microwave mesoscale ones agree closely. Along the transect in the eastern sector, the positions of the SMMR and aircraft microwave 50% ice concentration isopleths agree within the range 8 km to 20 km.

6. In the eastern sector, the large-scale ice concentration distributions underwent pronounced variations in response to the winds, while the ice edge generally did not. With the exception of the period of intense melt at the end of the experiment, off-ice winds caused a decrease in the ice concentration gradients and on-ice winds caused an increase. The 30% concentration isopleth position varied only about 20 km in latitude, except during the extreme off-ice winds of July 6–10 and the following melt period.

7. Considering the highly dynamic nature of the MIZ observed in the sequence of microwave mesoscale maps, it appears that a time span of 2 or more days between such observations will result in an undersampling of the information needed to develop and test MIZ models. Repetitive mapping of selected areas at least once a day is recommended for future MIZ experiments.

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MICROWAVE RADIOMETRIC MAPS
1.55cm WAVELENGTH

Plate 1 [Campbell et al.]. Mesoscale microwave radiometric maps made from data obtained with the electrically scanning microwave radiometer (ESMR) on board the NASA CV-990 airborne laboratory for June 9 and 30, 1984. ESMR radiances are given in degrees Kelvin on the color scale. Approximate inferred ice concentrations are also shown on this scale.
Plate 2 [Campbell et al.]. Mesoscale microwave radiometric maps made from data obtained with the ESMR on board the NASA CV-990 airborne laboratory for June 12, 18, 22, 24, and 26, 1984. ESMR radiances are given in degrees Kelvin on the color scale. Approximate inferred ice concentrations are also shown on this scale. Two different concentration-radiance scales are given for observations made during differing surface conditions.
Plate 1 (Campbell et al., 1984). Visible and infrared NOAA AVHRR images of the Fim Fjord-Greenland Sea region on July 10, 1984. Numbers indicate the location of two ocean codons (3, 4, and 5) that appear in both images.