

Title: Physical and Radiative Characteristics and Long Term Variability of the Okhotsk Sea Ice Cover

Authors: Fumihiko Nishio¹, Josefino C. Comiso², Robert Gersten^{3,2}, Masashige Nakayama⁴, Jinro Ukita¹, Al Gasiewski⁵, Boba Stanko⁵, and Kazuhiro Naoki¹

¹Center for Environmental Remote Sensing, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba City

²Cryosphere Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771

³RSIS, Greenbelt, MD 20770

⁴Kushiro Children's Museum, 1--2 Saiwai, Kushiro City, Hokkaido, Japan

⁵NOAA Environmental Research Laboratory, 325 Broadway Ave., Boulder, Colorado, 80303

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Abstract:

Much of what we know about the large scale characteristics of the Okhotsk Sea ice cover comes from ice concentration maps derived from passive microwave data. To understand what these satellite data represents in a highly divergent and rapidly changing environment like the Okhotsk Sea, we analyzed concurrent satellite, aircraft, and ship data and characterized the sea ice cover at different scales from meters to tens of kilometers. Through comparative analysis of surface features using co-registered data from visible, infrared and microwave channels we evaluated how the general radiative and physical characteristics of the ice cover changes as well as quantify the distribution of different ice types in the region. Ice concentration maps from AMSR-E using the standard sets of channels, and also only the 89 GHz channel for optimal resolution, are compared with aircraft and high resolution visible data and while the standard set provides consistent results, the 89 GHz provides the means to observe mesoscale patterns and some unique features of the ice cover. Analysis of MODIS data reveals that thick ice types represents about 37% of the ice cover indicating that young and new ice represent a large fraction of the ice cover that averages about 90% ice concentration, according to passive microwave data. A rapid decline of -9% and -12 % per decade is observed suggesting warming signals but further studies are required because of aforementioned characteristics and because the length of the ice season is decreasing by only 2 to 4 days per decade.

Popular Summary: The Okhotsk Sea has the unique distinction of being the southernmost region in the Northern Hemisphere with sea ice cover. The variability of the sea ice cover is thus highly linked closely to the changing climate of the region. It is also among the world's most productive and richest fishing grounds, in part because of the presence of sea ice during the winter and spring period. With its high productivity, it is also regarded as a potential carbon sink. Through comparative analysis of surface features using co-registered data from visible, infrared and microwave channels we evaluated the general radiative and physical characteristics of the ice cover as well as quantify the distribution of different ice types in the region. Ice concentration maps from AMSR-E using the standard sets of channels, and also only the 89 GHz channel for optimal resolution, are compared with aircraft and high resolution visible data and while the standard set provides consistent results, the 89 GHz provides the means to observe mesoscale patterns and some unique features of the ice cover. Analysis of MODIS visible and infrared data reveals that thick ice types represents about 37% of the ice cover indicating that young and new ice types represent a large fraction of the ice cover that averages about 90% ice concentration according to passive microwave data. These results are consistent with large seasonal and interannual variability of the ice cover. The Okhotsk Sea ice extent and area are, however, declining at a rapid rate of about -9% and -12 % per decade, respectively, suggesting that global warming may be a factor. Further studies, however, are needed since trends of such magnitude have been observed and the trend of the ice season is declining by only 2 to 4 days per decade.

Significant Findings:

Through comparative analysis of surface features using co-registered data from visible, infrared and microwave channels we evaluated the general radiative and physical characteristics of the ice cover as well as quantify the distribution of different ice types in the region. Ice concentration maps from AMSR-E using the standard sets of channels, and also only the 89 GHz channel for optimal resolution, are compared with aircraft and high resolution visible data and while the standard set provides consistent results, the 89 GHz provides the means to observe mesoscale patterns and some unique features of the ice cover. Analysis of MODIS visible and infrared data reveals that thick ice types represents about 37% of the ice cover indicating that young and new ice types represent a large fraction of the ice cover that averages about 90% ice concentration according to passive microwave data. These results are consistent with large seasonal and interannual variability of the ice cover. The Okhotsk Sea ice extent and area are shown to be declining at a rapid rate of about -9% and -12 % per decade, respectively, suggesting that Global warming may be a factor. This is alarming considering that the Okhotsk Sea is the southernmost sea with an ice cover but further studies are needed since a rate of decline of such magnitude has been observed before and the ice cover as observed in this study is quite vulnerable to change.

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11 ¹Center for Environmental Remote Sensing, Chiba University, 1-33 Yayoi-cho, Inage-ku,
12 Chiba City

13 ²Cryosphere Sciences Branch, NASA Goddard Space Flight Center, Greenbelt,
14 MD 20771

15 ³Adnet/RSIS, Greenbelt, MD 20770

16 ⁴Kushiro Childres's Museum, Hokkaido, Japan

17 ⁵NOAA Environmental Research Laboratory, 325 Broadway Ave., Boulder,
18 Colorado, 80303
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Abstract

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34 comes from ice concentration maps derived from passive microwave data. To understand
35 what these satellite data represents in a highly divergent and rapidly changing
36 environment like the Okhotsk Sea, we analyzed concurrent satellite, aircraft, and ship
37 data and characterized the sea ice cover at different scales from meters to tens of
38 kilometers. Through comparative analysis of surface features using co-registered data
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40 and physical characteristics of the ice cover changes as well as quantify the distribution
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48 passive microwave data. A rapid decline of -9% and -12 % per decade is observed
49 suggesting warming signals but further studies are required because of aforementioned
50 characteristics and because the length of the ice season is decreasing by only 2 to 4 days
51 per decade.

52

53 1. Introduction

54 The Okhotsk Sea has the unique distinction of being the southernmost region in
55 the Northern Hemisphere with sea ice cover. The variability of the sea ice cover is thus
56 sometimes linked closely to the changing climate of the region. It is also among the
57 world's most productive and richest fishing grounds, in part because of the presence of
58 sea ice during the winter and spring period. With its high productivity, it is also regarded
59 as a potential carbon sink. Satellite data revealed the existence of latent as well as
60 sensible heat polynyas that can have considerable impacts on the physical characteristics
61 of the sea (Alfultis and Martin, 1987). Furthermore, sea ice is an integral part of the
62 culture and lives of inhabitants in the coastal regions that surround the sea as manifested

63 by the existence of several communities along the coastlines and radar stations for
64 monitoring the ice cover for several decades (e.g., Mombetsu, Japan). Such coverage,
65 however has been limited and it was not until the advent of satellite remote sensing that
66 the true nature and extent of the sea ice in the region was revealed. During the satellite
67 era, large interannual variability and significant decline has been observed (Parkinson et
68 al., 1999) while anomalies in some years have been associated with El Nino events
69 (Nishio et al., 1998). A recovery was observed in 2001 but from that time on, the ice
70 cover has been declining again.

71 Among the objectives of this study is to utilize data concurrently observed from
72 aircraft, ship, and sensors from different or the same satellite platforms during the 2003
73 winter season to provide as comprehensive a characterization of the sea ice cover in the
74 Okhotsk Sea as possible. Of special interest is the spatial distribution of the different ice
75 types, especially the different types of new and young ice as well as the thick first year
76 ice. The strategy is to start with the large scale characteristics as can be inferred from ice
77 concentration maps derived from passive microwave data. The ice concentration maps
78 are in turn compared with high resolution satellite data in the visible and infrared to
79 obtain a general idea how the mesoscale distributions of sea ice is represented in these
80 ice concentration maps. High resolution aircraft microwave data are analyzed
81 concurrently with high resolution visible and infrared data to better understand the
82 passive microwave signature of ice in the region and how and why the derived ice
83 concentration varies significantly within the pack. These results are in turn used to
84 interpret the large scale seasonal and interannual variability as observed from passive
85 microwave data. Long term changes and trends are also examined in the same context
86 with a view of gaining insights into what makes the ice cover in the region so variable.

87

88 **2. The Okhotsk Sea Ice Cover: Large scale and Mesoscale Characteristics**

89

90 *2.1 Satellite Observations*

91 The first Advanced Microwave Scanning Radiometer was launched on board the
92 EOS-Aqua satellite on 4 May 2002 and is called AMSR-E, while the second one, called
93 AMSR, was launched on board the Midori-2 satellite on 24 December 2002. The two

94 systems have very similar specifications, the biggest difference being that AMSR has an
95 additional 52 GHz channel that is used primarily for atmospheric sounding. Sea ice data
96 from the two have been compared and provide nearly identical results, the difference
97 likely associated with changes due to time difference in the equatorial crossing for the
98 ascending orbits being 13:30 and 22:30 for AMSR-E and AMSR, respectively. AMSR-
99 E is still in operation while the Midori-2/AMSR ceased operation on 23 October 2003
100 because of satellite hardware problems. The data used in the comparative study are those
101 from AMSR-E, only because AMSR was not in full operation when the aircraft and ship
102 measurements were made. The characteristics of AMSR-E are summarized in Table 1.
103 As indicated, the resolution varies with frequency with the 89 GHz data having the
104 highest resolution at 5.4 km. The sensor scans at a fixed incidence angle of 55° with a
105 swath width of 1445 km covering practically the entire polar region. For long term
106 variability studies, we make use primarily of historical SMMR and SSM/I data for
107 consistency but we take advantage of almost 5 years overlap of SSM/I and AMSR-E to
108 make the data from these two sensors compatible.

109 The large scale characteristics of the Okhotsk Sea ice cover on 7 February 2003 as
110 depicted by an ice concentration map derived from AMSR-E data is presented in Figure
111 1. Because of the strong contrast in the emissivity between sea ice and open water, the
112 ice concentration maps provide consistent locations of the ice edges, large divergence
113 areas, and polynyas (e.g., to the north at around 56° N). Because of day/night all weather
114 capabilities, the data is ideal for monitoring large scale seasonal and interannual changes
115 in the ice cover, as will be illustrated below. Several algorithms have been developed to
116 estimate ice concentration using different techniques and sets of channels (Svendsen et
117 al., 1984; Cavalieri et al., 1984; Swift et al., 1986; Comiso, 1986). In this study, we used
118 data derived from the Bootstrap Algorithm as described in Comiso (2004). AMSR-E
119 data at high latitudes have been gridded in polar stereographic format at 12.5 by 12.5 km
120 to take advantage of the improved resolution of the new system. The data have also been
121 gridded at 25 by 25 km resolution for compatibility with historical passive microwave ice
122 data. Furthermore, for studies that require optimal resolution, a special data set with 6.25
123 by 6.25 km resolution has been generated utilizing only the 89 GHz channels (H&V) and
124 the Bootstrap technique as described in Comiso (2004).

125 It is fortuitous that on board the Aqua satellite is the Moderate Resolution
126 Imaging Spectroradiometer (MODIS) which is a 36 channel sensor that covers the
127 electromagnetic spectrum from 0.405 to 14.385 μm with spatial resolutions of 1 km at
128 nadir for most channels and at 250 m and 500 m for some special channels. The sensor
129 scans crosstrack with a swath width of 2,330 km for optimal coverage and good temporal
130 resolution in the polar region. The visible channels provides the means to discriminate
131 different surface types including open water, various types of new ice, young ice and
132 thick ice with snow cover during daytime. The thermal channels provide day/night
133 capability and enable estimates of ice concentration as well as the thickness of ice
134 covered surfaces. During clear skies conditions, MODIS provides valuable information
135 about the ice cover and at the same time the means to properly interpret the passive
136 microwave data. The images in Figure 2 shows visible and infrared images from MODIS
137 for the same day. Unfortunately, for that day, only the Terra/MODIS provided good
138 clear sky coverage since by the time Aqua/MODIS passed over the same region four
139 hours later, there were more clouds in the region. The MODIS data, however, provides a
140 good overview of how the sea ice cover look like on that date. Compared to the ice cover
141 as depicted in Figure 1, the images in Figure 2 reveals a lot more details with the visible
142 and infrared channels providing complementary information. In Figure 1, the marginal
143 ice zone is represented by a progression of ice concentrations changing from near 100%
144 to zero % over approximately 100-150 km region. On the other hand, the MIZ is
145 represented by MODIS as consisting mainly of ice bands, the widths of which gets
146 narrower closer to the open sea. With the MODIS data, the unique distributions of
147 different ice types in the region are also more fully revealed. In this sense, the thermal
148 infrared data provide information about the thickness of new ice, especially in lead areas.
149 Figure 3 provides a blown up view of the ice conditions and shows additional details in
150 the coverage and indicating a different pattern in the infrared for consolidated ice (top
151 left) than in the relatively loose ice regions. Patterns of large leads in the top left and
152 thick ice floes in the top middle parts of the image are identified in the image. The
153 presence of snow cover causes surfaces of different ice types to have basically the same
154 albedo but the infrared image is able to capture the distribution of the various ice types
155 with the dark ones representing thick ice floes and the lighter ones representing thinner

156 ice floes. On the other hand, the banding structure that is revealed in great details in the
157 visible channel (top right) is not captured by the infrared data mainly because the surfaces
158 likely have similar temperatures.

159 Even more detailed information about the spatial distribution and surface
160 characteristics, of the ice cover can be obtained from Landsat-7 data. The Enhanced
161 Thematic Mapper Plus (ETM+) sensor aboard the satellite has a panchromatic band with
162 15-m resolution and a thermal infrared band at 60-m resolution. For comparison, the
163 highest resolution from a MODIS visible channel is 250 m while that for its infrared band
164 is 1 km. The panchromatic band allows detection of details and improved classification
165 of surface types especially in narrow lead areas. However, the swath width of Landsat is
166 only 185 km while that for MODIS is 2330 km providing much less coverage in a single
167 day. During the aircraft campaign, good Landsat images were obtained on 11 February
168 and some other days but not on 7 February. Thus, comparative studies with aircraft and
169 ship data during the 7 February campaign will be done mainly with MODIS data while
170 the Landsat image of 11 February will be compared with near simultaneous AMSR-E
171 data.

172

173 *2.2 P3 Aircraft Observations*

174 As part of a dedicated campaign to study the physical and radiative characteristics
175 of the Okhotsk Sea ice cover, we planned two missions using an instrumented NASA P3
176 aircraft over selected transects in conjunction with a dedicated ship program as described
177 below. The first of these missions was successfully implemented but the second one was
178 not because the aircraft suffered a hardware problem and the latter had to be canceled.
179 The flight track of the first and only mission over the sea is presented together with an ice
180 concentration map derived from AMSR-E data in Figure 1. The aircraft went north from
181 its staging station at the Yokota Airforce Base (near Tokyo) at high altitude (6000),
182 covered a relatively large area (i.e., 175 by 50 km) at the farthest end, for comparative
183 studies with satellite data, as shown, and on the way back it went south at low altitude
184 (1,000 m) to collect data at an even higher resolution. Camera equipments were mounted
185 for high resolution visible coverage but the most important sensor on board the aircraft is
186 the Polarimetric Scanning Radiometer (PSR-A) which has frequency channels from 10 to

187 89 GHz that matches most of those of the AMSR-E sensor. The field-of-view of the
188 radiometers varies with frequency and at 37 GHz channel, the size of the footprint is
189 about 240 m at the cruising altitude of 6,000 m while it is about 40 m at 1000 m altitude.
190 Data from PSR thus allows for more direct comparison with MODIS data and can be
191 used check the microwave signature of individual features of the pack and also to test the
192 accuracy of algorithms derived from passive microwave data.

193

194 2.3 *Ship Observations on board Soya*

195 The physical characteristics of the sea ice cover in the southern portion of the Sea
196 of Okhotsk (e.g., Ukita et al., 2000) and in other regions (Weeks and Ackley, 1986;
197 Tucker et al., 1992) have been studied previously. The general location and details of
198 ship observations in the Okhotsk Sea are described in Naoki et al. (2007). The enlarged
199 version of the MODIS image shows an ice cover that is made of many ice types including
200 those of thick first year ice, young ice, gray ice, nilas and pancake ice. It reflects the
201 dynamic nature of the sea ice cover. The ship study is meant to complement previous
202 studies and to make measurements that are coincident with measurements from the P3
203 aircraft and satellite AMSR-E observations.

204 The ship observation was carried out in the 100km range as shown in the general
205 location presented in Figure 3. When the ship was moving, sea ice conditions around the
206 ship were recorded with three camcorders installed on the mast, bow and broadside. The
207 camcorder installed broadside measured the sea ice thickness and other physical
208 properties of the ice. During periodic stops, ice samples and snow overlying sea ice were
209 collected directly using a basket.

210 Typical observations of the ice cover during the cruise are shown in Figures 5a
211 and 5b. In Figure 5a, rafted ice is shown in the foreground while nilas with some open
212 water is shown in the middle part. In the background, thick ice cover covers the region
213 up to the horizon. The image is similar to those observed from the aircraft but with more
214 details, especially in the rafting geometry. It also represents the usual scenario following
215 a wind forced event when new and young ice gets rafted and leads open up and turns to
216 new ice within a few hours. The image in Figure 5b was taken on the same day but for a
217 different part of the ice cover. In the foreground is the track of the ship that reveals

218 basically the state of the consolidated ice region. Qualitative analysis indicates that the
219 ice cover has moderate thickness and the brownish color in some floes reveals the
220 presence of algae in the underside. The presence of birds in the region indicates that it is
221 a biologically active region.

222 Thicknesses of the different types of ice cover were sampled during the and the
223 results were correlated in a separate paper (Naoki et al., 2007). The microwave signature
224 of ice of different thicknesses have been shown to be different in part because of varying
225 salinity and temperature, which were also measured during the cruise.

226

227 **3. Comparative Analysis using Concurrent Data**

228 *3.1 AMSR-E Ice Concentration versus Landsat-7 Data*

229 The most important geophysical parameter derived from passive microwave data
230 is likely sea ice concentration. It provides information about the location of the ice edge,
231 polynyas and divergence areas and is used in the estimates of the extent and area of the
232 ice cover. It can also be used to estimate how rapidly the ice advances in the winter and
233 how fast it retreats in the spring and summer. The use of Landsat-7 for process studies is
234 on the other hand very limited because of sparse coverage and the limit imposed by
235 daylight and cloud free conditions. When it is available, however, the Landsat-7 data at
236 15 m resolution provide a wealth of information about the sea ice cover (Steffen and
237 Maslanik, 1988).

238 The Landsat visible channel data presented in Figure 6a and taken on 11 February
239 2003 provides a detailed characterization of the sea ice cover in the Okhotsk Sea. The
240 albedo of sea ice in the region has been studied by Toyota et al. (1999). The image
241 indicates the complexity in the spatial distribution and composition of the ice cover at this
242 time of the year. The ice edge is characterized by the presence of ice bands as indicated
243 earlier that have been observed to consist mainly of pancake ice usually several cm to a
244 few meters in diameter. Into the ice pack, some very well defined and thick ice floes are
245 evident. These thick ice floes are likely the ones that are least altered during the ice
246 season becoming part of the consolidated ice as the grease ice between them gets totally
247 frozen. During divergent conditions, they are likely to survive as individual entities again
248 and during melt period, they are likely to be the last floes to melt in the region. The

249 presence of a large fraction of new ice (intermediate albedo) in the image is indicative
250 that the region is in a rapid growth state condition. The stages include the formation tiny
251 ice particles called frazil ice during super cooling in the upper ocean layer and the
252 accumulation of these particles at the top surface to form what is usually called "grease
253 ice." This ice soup solidifies to form nilas or pancake ice depending on sea surface
254 conditions, leading to either gray ice or larger pancakes and then young ice which is
255 about 20 to 30 cm in thickness. As the young ice gets thicker and acquires snow cover, it
256 becomes first year ice which is the dominant ice type during the ice season. Rafting and
257 ridging of the different ice types due to strong winds are also a natural part of the ice
258 cover.

259 The availability of such concurrent images provides the opportunity to examine
260 how the mesoscale characteristics and detailed distribution of different ice types are
261 represented in the passive microwave data. Ice concentration maps over the same general
262 area as that in the Landsat image were derived from AMSR-E passive microwave data
263 using the Bootstrap Algorithm in three grid formats as described earlier: (a) 6.25 km
264 resolution using the 89 GHz (H & V) data only (Figure 6b); (b) 12.5 km resolution using
265 the standard set of channels as described by Comiso (2004) (Figure 6c); and (c) 25 km
266 resolution which is the standard grid for the historical data Figure 6d). It is remarkable
267 that the basic spatial features are coherent. This is an indication that the visible and
268 microwave sensors are sensitive to same physical characteristics of the ice cover. It is
269 apparent that a lot of the detailed distribution of the ice cover provided by Landsat are
270 also revealed in the AMSR-E image at 6.25 km resolution. The ice edges and divergence
271 areas are captured by AMSR-E but not the ice bands, mainly because of lack of
272 resolution in the latter. This implies that for a full characterization of the ice cover,
273 visible channel data like those from Landsat-7 would be highly desired. The 12.5 km
274 map provides a respectable representation and shows some of the divergence region
275 while the 25 km map shows very little in terms of detail. Many of the mesoscale features
276 that are needed for heat and humidity flux studies are thus lost in the coarse resolution
277 images.

278 It is important to point out, however, that for large scale studies, the passive
279 microwave data provide as good a representation of the ice cover as you can get. A slight

280 smearing of the ice edge is apparent but the maps provide consistent representation of the
281 ice cover that is also accurate if resolution is not a factor. A quantitative comparative
282 analysis is done using the co-registered data sets. Ice concentration is derived from
283 Landsat-7 data within each of the AMSR-E pixel at the various grids and compared with
284 data from the latter in Figures 7a, 7b, and 7c for AMSR-E data at 6.25, 12.5 and 25 km
285 grid, respectively. Linear regression analysis was done on each of these plots and the
286 regression lines are as shown. Surprisingly, however, the set of data that provided the
287 best correlation is the 25 km data with the correlation coefficient being 0.90 while
288 corresponding value when the 12.5 and 6.25 data sets were used are 0.97 and 0.95,
289 respectively. The comparisons also show a large scatter of the data points with the
290 standard deviations being about 17.14, 16.0 and 14.2 % ice concentration between
291 Landsat data and AMSR-E data at 6.25 km, 12.5 km, and 25 km resolutions, respectively.
292 Part of the reason for the large standard deviation is the few hours difference between the
293 Landsat-7 coverage and the AMSR-E coverage. Thus, a slight mismatch of the location
294 of an ice floe affects the correlation and the impact is higher with 6.25 km grid than that
295 of the 25 km grid. The results of the comparative analysis, however, indicate that despite
296 the relatively coarse resolution, passive microwave provides a good representation of the
297 sea ice cover.

298 This also brings about the issue of what the ice concentration value, as derived
299 from passive microwave data, really represents. Because the emissivity of sea ice varies
300 with ice type, it is difficult to categorize the microwave footprint of ice covered areas as
301 either ice or water. Because new ice has lower emissivities at the different frequencies
302 and polarizations than thick ice, unless an ice typing can be done effectively, the
303 algorithm produces ice concentrations that are lower in new ice regions than in thick ice
304 regions. In the comparative analysis, ice concentration from Landsat was derived based
305 on the different albedo values with the highest being 100% ice and the lowest being
306 100% open water. It is apparent that albedo is even more sensitive to thickness than the
307 emissivity of sea ice.

308

309 *3.2 PSR versus MODIS*

310 The aircraft PSR data provide the means to compare data of approximately the
311 same resolution from passive microwave and MODIS. Figure 8 shows data from MODIS
312 and from PSR at 37 GHz(V), 18 GHz (V), 37 GHz (H), and 89 GHz (V) at the study area
313 in the north. The MODIS data indicate that the ice cover in the region is mainly
314 consolidated, with many large ice floes discernible, surrounded by either open water or
315 new ice. At the top right is part of the Marginal Ice Zone (MIZ) located at the eastern
316 part of the region (towards the Pacific Ocean, see aircraft track in Figure 1 and top right
317 in Figure 2). The region is shown to have much lower albedo than the rest of the region,
318 indicative of the presence of new or younger types of ice cover. The relatively elongated
319 areas of higher albedo in the region are likely bands of pancakes and surrounded by
320 newer ice types. Also at the top corner is a pattern suggestive of the presence of clouds
321 that could pass by the region anytime. It is apparent that the PSR is sensitive to same
322 general characteristics of the ice cover as the visible channel of MODIS. Except for the
323 89 GHz channel, a reduction in the brightness temperature in the MIZ is apparent,
324 especially in the horizontal channel (37 GHz) which exhibits larger contrast between
325 open ocean and ice covered areas. The 18 GHz channel also show more reduction in
326 brightness temperature than the 37 GHz channel at vertical polarization because of the
327 higher contrast in the emissivity of ice and water at lower frequencies. The pattern is not
328 so obvious with the 89 GHz channel which actually shows lower brightness temperature
329 within the pack (lower left) than the rest of the region. The aircraft went back and forth
330 in the region to form the mosaic pattern. Gaps are shown between tracks (see Figure 1)
331 because the aircraft was going at higher altitude than was originally planned. It took
332 about an hour for the aircraft to make each track. The 89 GHz data for the second track
333 (from the right) shows significantly lower brightness temperature than those of the other
334 tracks suggesting the possibility of an atmospheric effect passing by during the hour the
335 data were obtained. In the following track, the data apparently went back to normal.

336 The ice concentration algorithm was applied on the aircraft passive microwave
337 data and the results are shown in Figure 9. It is apparent that much of the region is
338 interpreted as basically consolidate (100%) ice with the MIZ and some leads being
339 retrieved as having concentrations generally between 80 %(light pink) and 95 % (dark
340 red). In this sense, the passive microwave data captures the basic characteristics of the

341 ice cover. Again, it does not provide complete information in that it does not capture
342 some of the features like the presence of large floes and refrozen leads. The “tie points”
343 for 100% ice can be adjusted in the algorithm (see Comiso, 2004) but it would depend on
344 what type of sea ice cover would be regarded as 100% ice. This is usually not so easy to
345 define, as indicated earlier, since during subfreezing temperatures in winter, ice can form
346 quickly and new ice has emissivity that changes from that of open water to that of thick
347 ice, depending on thickness.

348 To gain insights about the signature of the ice cover, several segments of the
349 northern study area are shown in terms of scatter plots between different channels in
350 Figures 10, 11, and 12. The specific segments shown in the scatter plots using of passive
351 microwave data from the PSR are indicated by rectangular boxes in the images at the
352 bottom. Low albedo values as determined by MODIS are plotted in red to determine how
353 the lead areas with different thickness of new ice cover are represented in the passive
354 microwave data. Some but limited variability is apparent at the 10, 19, and 37 GHz
355 channels at vertical polarization while significantly greater variability is shown for 37
356 GHz at horizontal polarization and for 89 GHz at both polarizations. The data from the
357 latter are especially interesting in Figure 11, suggesting that thickness information in lead
358 areas may be possible to obtain from these channels, especially with the linear trend of
359 the data from lead areas at the 89 GHz channels. In Figure 12, however, where a large
360 fraction of the data is of new types of ice, the patterns do not look so linear.

361 The images in Figure 13 show a comparison of PSR data taken at high altitude
362 (6000 m, when the aircraft was going north) and at low altitude (1000m, when the aircraft
363 was going south). The data in the latter provides even improved resolution at around (50
364 m) when compared to those of the former. The PSR data shown is for the 37 GHz
365 channel at horizontal resolution. It is apparent that at this resolution, much of the
366 mesoscale features observed with the MODIS data is captured by the higher resolution
367 PSR data. It is thus possible that if resolution is not a factor, passive microwave data can
368 capture much of the mesoscale features that are of interest in polar process studies.

369 To show relationships of passive microwave data as obtained by PSR with those
370 from AMSR-E, scatter plots of the various channels over the same ice covered regions
371 are presented in Figure 14. The column in the left represents plots of various channels

372 using aircraft data while those in the right represents plots for similar channels but using
373 AMSR-E data.

374

375 *3.3. PSR versus Ship Data*

376

377 The ship tract overlaid on a PSR data at 37 GHz (V) is shown in Figure 15. Ice floes
378 along the ship tract were sampled in terms of thickness, salinity, snow cover and
379 temperature. The brightness temperatures at all PSR channels were observed to increase
380 quite rapidly from near zero thickness to about 10 cm thickness. Between 10 and 20 cm,
381 the brightness temperatures also increase but more moderately. Beyond 20 cm, the
382 change in brightness temperature with thickness was no longer discernible. The changes
383 are more discernible with the horizontal channels than the vertical channels, which is
384 expected because of the larger contrast in the emissivity of water and ice with the former.
385 These information were used in conjunction with a model by Naoki et al. (2007), to show
386 that ice thickness can be inferred from passive microwave data in new ice areas. This
387 would be a most welcome development especially for heat flux studies.

388

389 **4. Ice Types, patterns and distribution of sea ice in the Okhotsk Sea**

390 To get a general idea about the distribution of the different types of surfaces in the
391 Okhotsk Sea, a classification scheme was applied on the MODIS data in Figure 2a based
392 on histograms taken in various study areas. The range of albedo for the various types
393 were assigned arbitrarily according to what was suggested in the histogram study and we
394 arrived at 11 classes that is displayed in different colors in Figure 16. In this scheme,
395 thick first year ice shown in reds and the pinks represents about 37% of the Okhotsk Sea
396 ice cover. Young ice shown as brown and yellows represents about 22 % while new ice
397 shown in greens and blues represents about 28 % of the ice cover. Grease ice and/or
398 open water shown in gray represent 13%. There was no validation done mainly because
399 ship data was too limited but the qualitative representation as indicated in Figure 16 looks
400 reasonable. If the classification is approximately right, it appears that thick ice has the
401 highest percentage but not a dominant ice cover. This would mean that there is no

402 sizable core for the ice cover and the extent and area can be easily influenced by
403 enviromental factors on a year-to-year basis.

404

405 **5. Seasonal and Interannual Variability and Trends**

406 Monitoring even just the Okhotsk Sea ice cover using concurrent ship, aircraft
407 and satellite data on a daily basis for about 30 years would be an overwhelming task that
408 would require a lot of manpower and money. A more practical way is to use satellite data
409 and ensuring that the latter are interpreted as accurately as possible. Through
410 comparative analysis of AMSR-E ice concentration data with co-registered and
411 concurrent Landsat and MODIS data and also PSR and ship data, we get to better
412 understand what the ice concentration derived from passive microwave data really means.
413 We also get a general idea about the distribution of the different ice types. We now try to
414 use these result to interpret the seasonal and interannual variability of the sea ice cover as
415 inferred from historical data. To make the latter relevant, we have reprocessed historical
416 satellite data (SMMR and SSM/I) with the same technique used to process the AMSR-E
417 data for compatibility in interpretation. During periods of overlap, the ice concentrations
418 derived from SSM/I and AMSR-E have been shown to be very similar. The same
419 technique were also used to process SMMR data (1978 to 1987) for a longer time series.

420 The most important variables that can be derived from these ice concentration
421 maps are sea ice extent and ice area. Sea ice extent is the integrated sum of all areas with
422 ice concentration of at least 15 % while ice area is the integrated sum of the product of
423 the area and the ice concentration over all ice covered regions. The daily ice extents and
424 monthly ice anomalies are presented in Figure 17 while the daily ice areas and monthly
425 ice area anomalies are presented in Figure 18. The daily extents show the yearly
426 seasonality of the sea ice cover and how this has varied over the past 28 years. There is
427 apparently a large interannual variability in the yearly peak values with lows in 1984,
428 1991, 1997 and 2006 and highs in 1979, 1988, and 2001. Because of large seasonal
429 variability, trends in the ice cover are difficult to infer from the daily data. A more
430 standard procedure is to subtract the climatology based on the interannual average of all
431 available data for each month (e.g., Bjorgo et al., 1997; Cavalieri et al., 1997). The
432 monthly ice extent anomalies as presented in Figure 17b show large positive anomalies in

433 the late 1970s and early 1980s and some negative anomalies in the last 3 years.
434 Regression analysis using this data yielded a trend in ice extent of -8.8% per decade.
435 Such a trend is quite substantial considering that the overall trends for the entire Arctic
436 region is about -3% per decade (Parkinson et al., 1999). Similar analyses using ice area
437 as defined earlier are presented in Figures 18a and 18b. The overall trend in the ice area
438 is even greater at -12.0 % per decade. Such trend is quite alarming and indicates that the
439 Sea of Okhotsk is even more vulnerable in loosing its ice cover than the perennial ice
440 cover in the Arctic as reported in Comiso (2002), and Stroeve et al.(2004) and updated in
441 Comiso (2006). To gain insights into this trend, the length of each ice season from 1979
442 to the present were inferred from daily data and the results are presented in Figure 19.
443 The trend is more modest showing declines of about 2 to 4 days per decade. The latter
444 may not mean much because the ice cover is seasonal ice and it takes only subfreezing
445 temperatures to create sea ice. The region is usually below freezing during the winter
446 period. An early or late start date is therefore not as significant as the observed decline
447 in ice extent and ice area since the latter suggest warmer winter temperatures. It is
448 warmer winter temperatures that could lead to lower rate of freeze-up which means less
449 extensive ice cover. There are other complications including the composition of the ice
450 cover as discussed in the next section.

451

452

453 **6. Discussion and Conclusions**

454 The Sea of Okhotsk has the potential of providing an important signal about the
455 changing global climate since it is the southernmost region in the Northern Hemisphere
456 with an ice cover. We have been using passive microwave ice concentration data to
457 monitor the ice cover in the region but the latter is difficult to interpret especially in a
458 very divergent and rapidly changing environment like the Sea of Okhotsk. In this study,
459 we examined the general physical and radiative characteristics of the sea ice cover in the
460 Okhotsk Sea using concurrent in situ, aircraft and satellite data. High resolution satellite
461 data reveal a complex distribution of the ice cover with only about 37% being covered by
462 thick ice types and the rest being young and new ice, the signature of which can be very
463 unpredictable. They show many complex features in the ice cover that cannot be

464 represented in the standard passive microwave data sets. With data from the recently
465 launched AMSR-E sensor, many of such mesoscale features are adequately represented,
466 especially in the 89 GHz images, making the latter a useful tool for polar process studies.
467 However, the data has to be used with care since data at this wavelength is sensitive to
468 atmospheric and snow cover effects. The standard sea ice data from passive microwave
469 at 12.5 km resolution shows some of the mesoscale features as well but much of the
470 features are lost in the 25 km grids. Our results, however, show that the 25 km grid
471 provides dependable ice cover data that can be combined with historical data to study the
472 state and future of the ice cover.

473 The results of our analysis of historical data show that the sea ice cover in the
474 Okhotsk Sea is declining at a rapid rate of -8.8 and -12.0 % per decade for sea ice extent
475 and ice area, respectively. Such trend is alarming especially since the region is a very
476 productive region in part because of the presence of sea ice. Since the Okhotsk Sea ice
477 cover has a relatively small fraction of thick ice (about 37%) and the average
478 concentration of ice in the Okhotsk Sea is about 90%, a large fraction of the consolidated
479 ice consists of young and new ice. The ice cover has actually declined in a similar way in
480 the 1990s. The lack of a strong dependable core of thick ice that provides stability in the
481 ice cover could mean that the year-to-year variability can easily be attributed by
482 environmental forcing such as wind strength and direction during winter and spring. The
483 higher decline in ice area compared to that of the ice extent also indicates that the region
484 is getting more divergent with the average concentrations getting lower with time. What
485 this implies in the context of a warming Arctic is not known and will be the subject for
486 future studies. What we know is that the length of the ice season has been declining but
487 only by about 2 to 4 days per decade. Such change is not sufficient to explain the high
488 rate of decline since the entire region is in sub-freezing temperatures during the winter
489 months. Further studies are needed especially since the observed high rate of decline in
490 ice extent and ice area may mean that the rate of ice production in the region is declining
491 on account of a warmer winter.

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495 **Table 1. AMSR-E Sensor Characteristics**

| | | | | | | |
|-----------------------|-----------|-----------|-----------|-----------|-----------|---------|
| Freq. GHz) | 6.9 | 10.65 | 18.7 | 23.8 | 36.5 | 89.0 |
| Wavelength | 4.3 cm | 2.8 cm | 1.6 cm | 1.27 cm | 0.82 cm | 0.34 cm |
| Polarization | H & V | H & V | H & V | H & V | H & V | H & V |
| IFOV (km) | 73.0x43.1 | 49.8x29.6 | 26.2x16.5 | 30.8x19.0 | 13.7x10.3 | 6.0x4.9 |
| Mean Res. (km) | 56 | 38 | 21 | 24 | 12 | 5.4 |
| Sens (K) | 0.3 | 0.6 | 0.6 | 0.6 | 0.6 | 1.1 |
| Int. time (msec) | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 1.3 |
| Beamwidth (°) | 2.2 | 1.4 | 0.8 | 0.9 | 0.4 | 0.18 |
| Swath Width | 1445 km | | | | | |
| Satellite Altitude | 705 km | | | | | |

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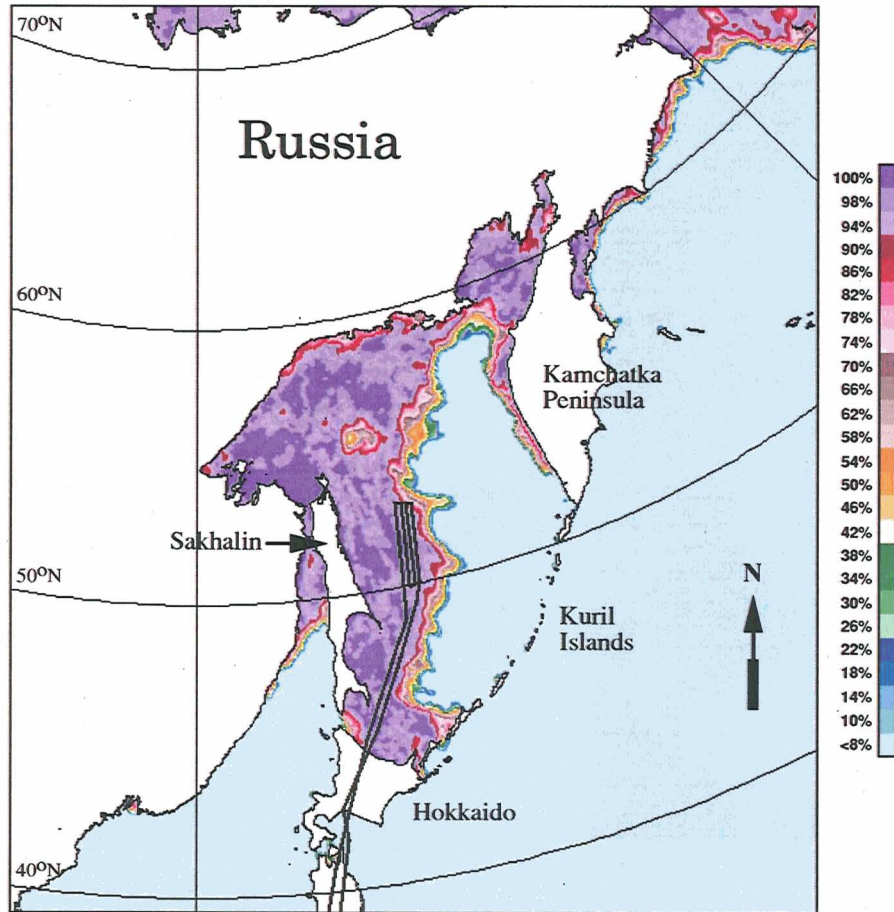
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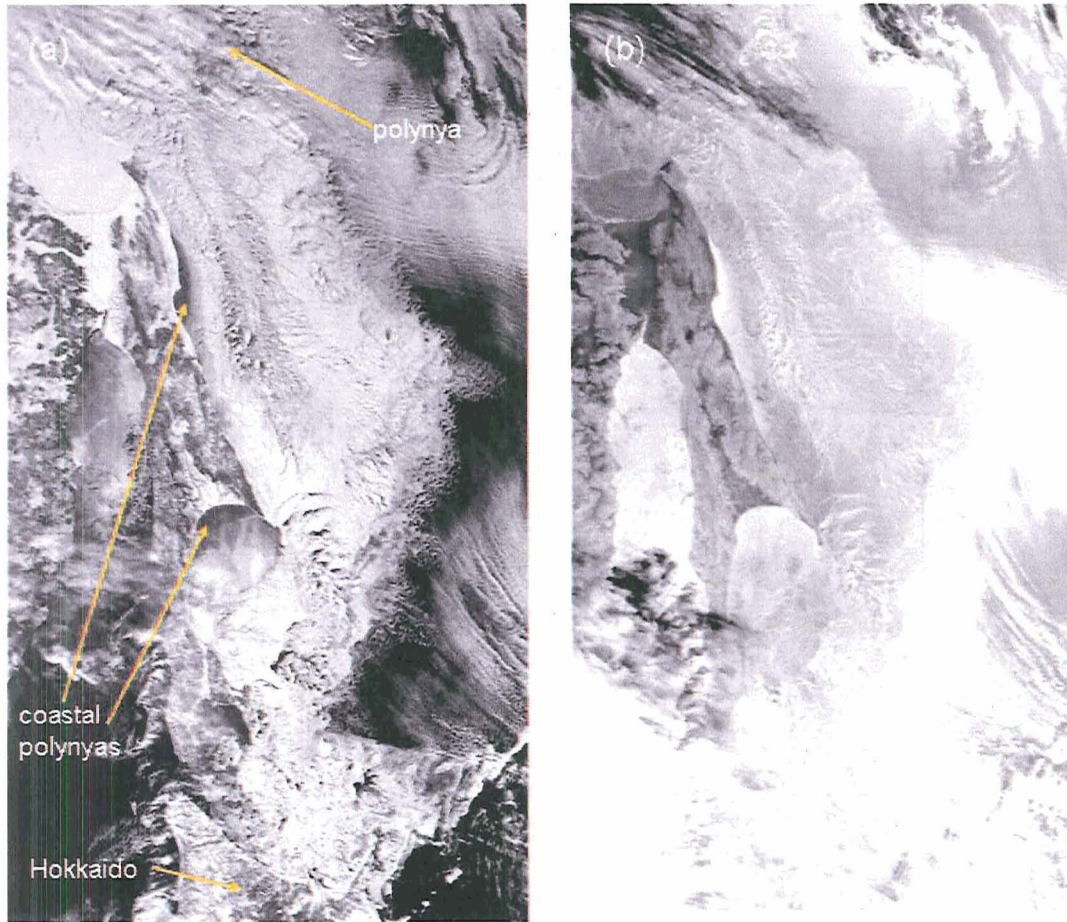
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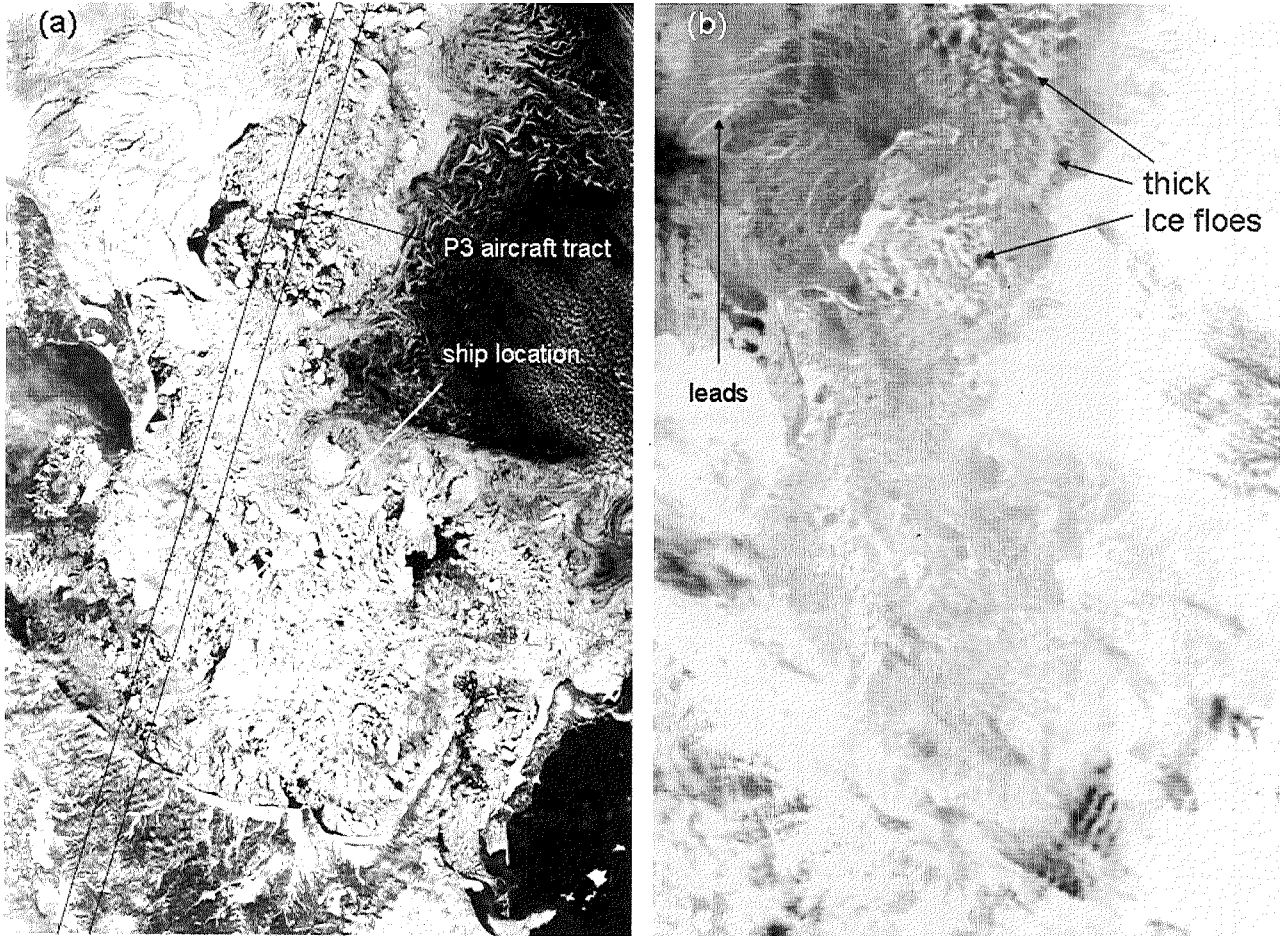
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Figure 1 AMSR-E ice concentration map of the Sea of Okhotsk on 7 February 2003 and flight track of the aircraft mission on the same day.



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Figure 2. MODIS image of the Okhotsk Sea ice cover on 7 February 2003 in the (a) visible (6 μm) and (b) thermal infrared (11 μm) channels of Aqua/MODIS sensor.



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Fig. 3 Enlarged MODIS image of the Okhotsk Sea ice cover in the (a) visible (6 μm) and (b) thermal infrared (11 μm) channels of Aqua/MODIS sensor.



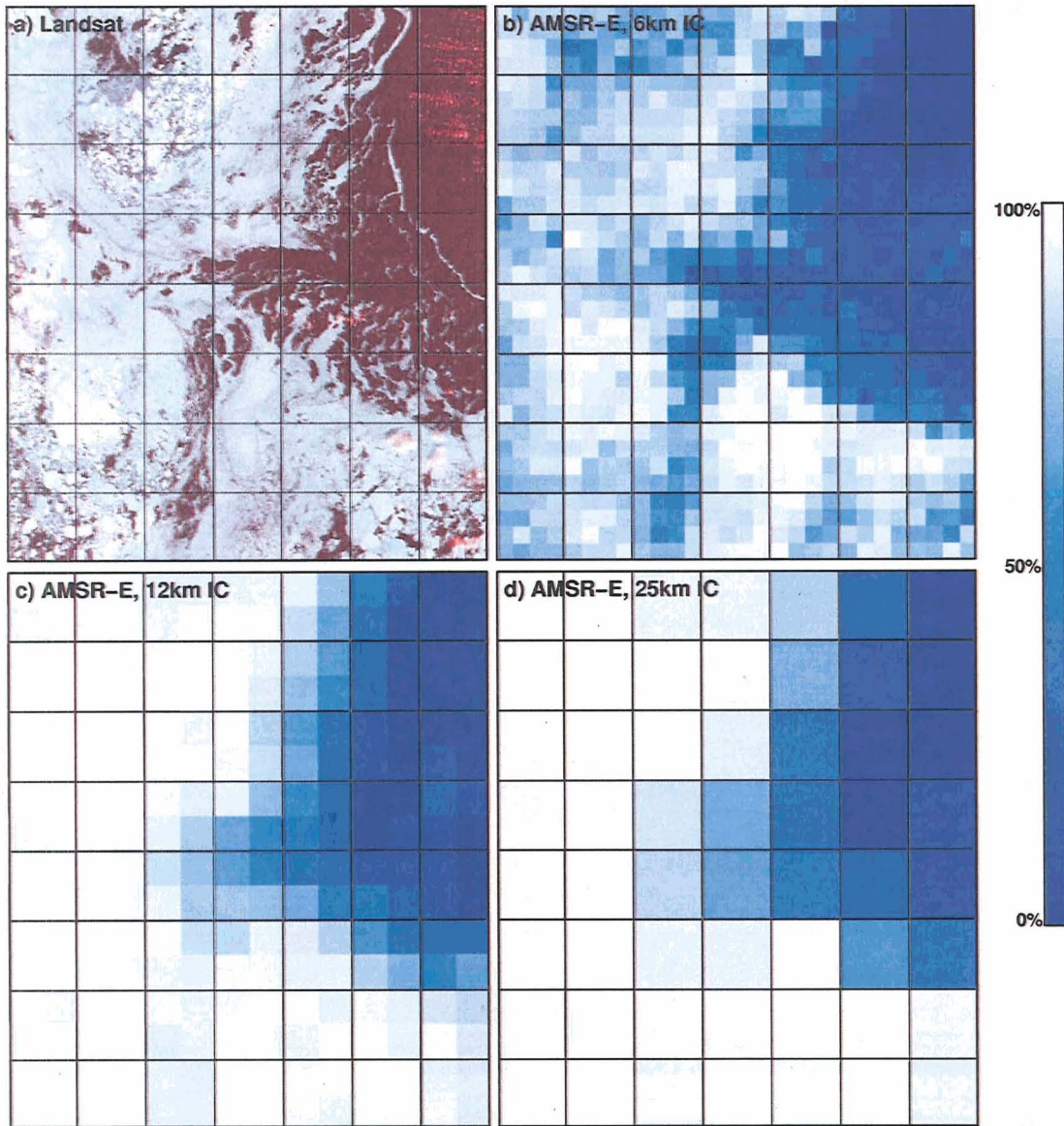
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Figure 4. Typical (a) new ice and (b) thick ice floes in the Okhotsk Sea as viewed from the P3 Aircraft



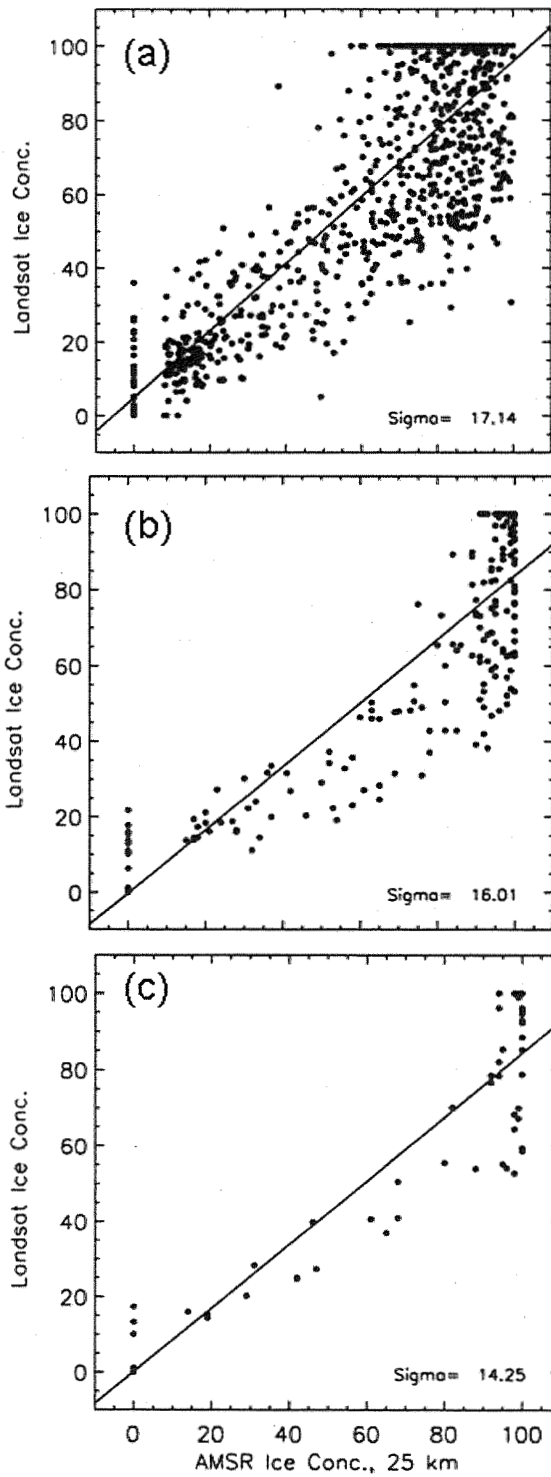
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Figure 5. Sample photographs of sea ice from ship of (a) rafted and grease ice; and (b) broken thick ice in the Okhotsk Sea



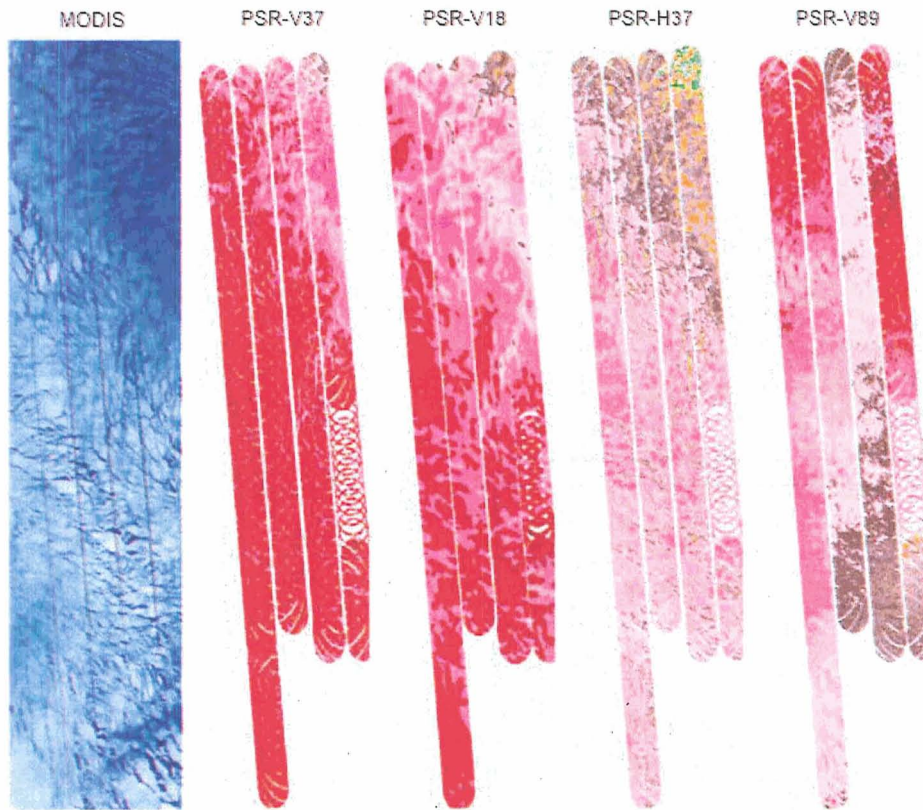
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Figure 6 Landsat-7 image of the Okhotsk Sea ice cover and corresponding AMSR-E ice concentration map at the (a) 6.25 km grid; (b) 12.5 km grid; and (c) 25 km grid.



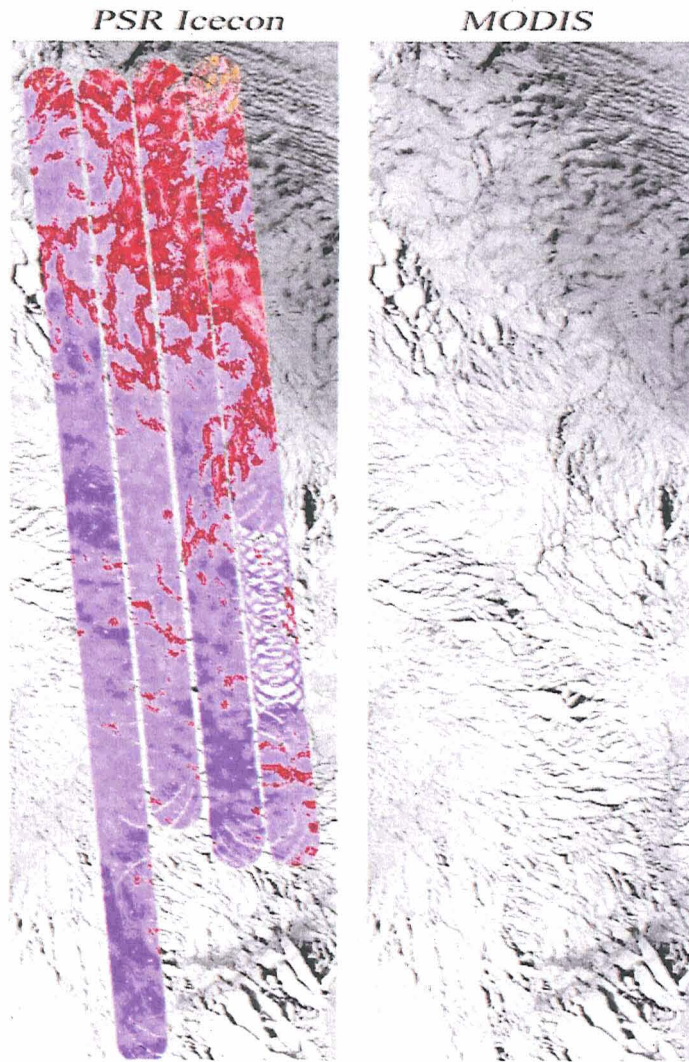
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Figure 7. Scatter plots of Landsat-7 ice concentration versus AMSR-E data at the (a) 6.25 km grid; (b) 12.5 km grid; and (c) 25 km grid.



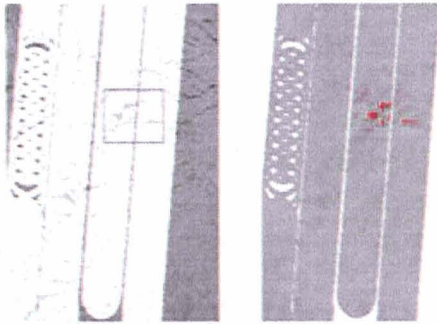
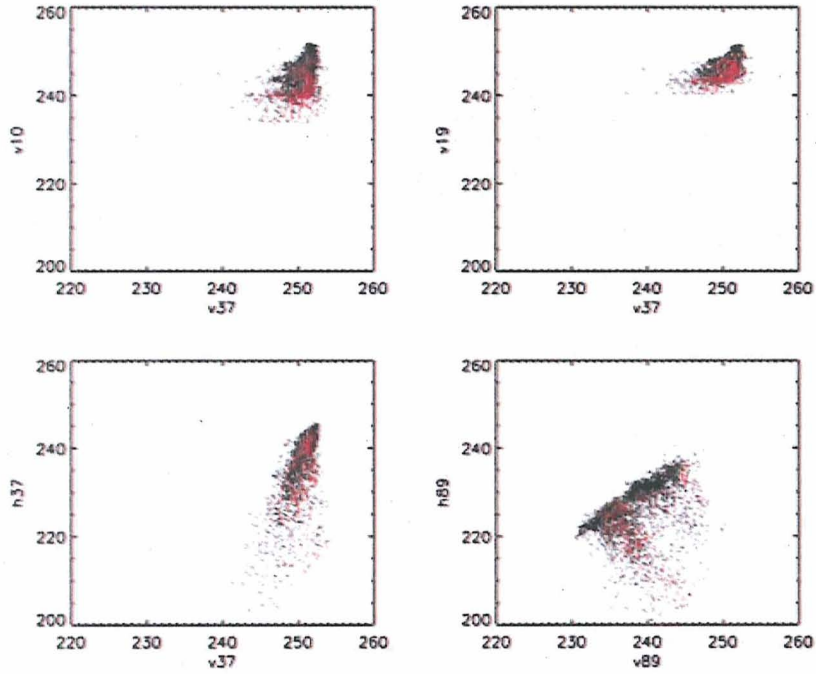
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Figure 8. MODIS image in the northern region and PSR data at 37 GHz(V), 18 GHz (V), 37 GHz (H) and 89 GHz (V).



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653 Figure 9. PSR ice concentration data (in color) derived using the Bootstrap Algorithm
654 and MODIS data (in black and white). Color scale is the same as in Figure 1.

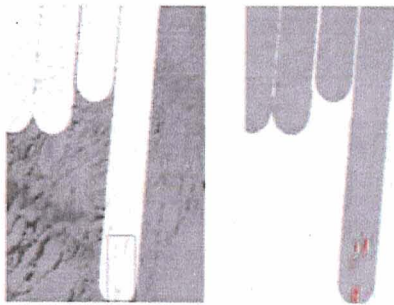
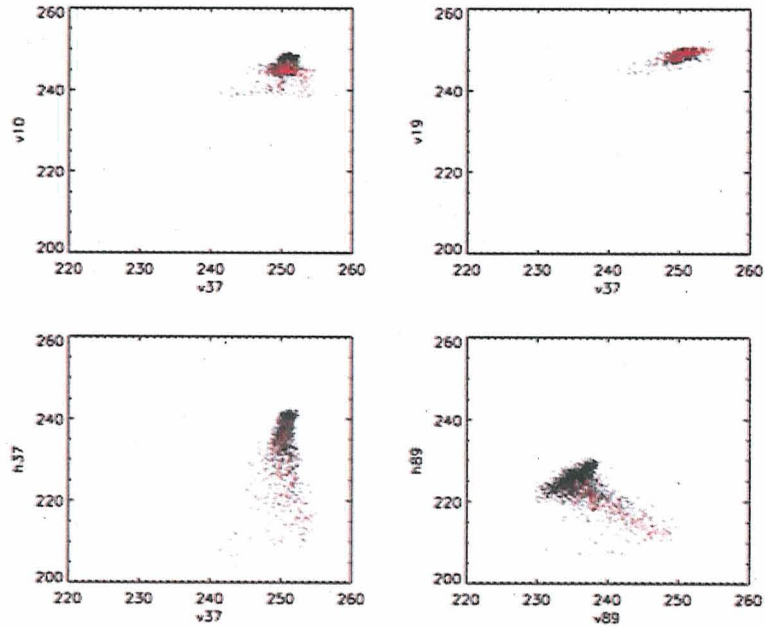
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Figure 10. Scatter plots of 10 GHz (V) versus 37 GHz (V); 19 GHz (V) vs 37 GHz (V); 37 GHz (H) vs 37 GHz (V) and 89 GHz (H) vs 89 GHz (V). The red data points represent low albedo areas inside the box in the image below the plots. The box is in a divergence region.

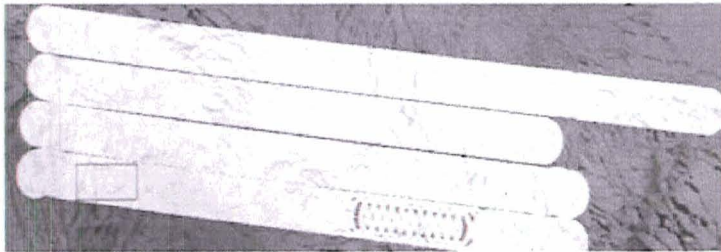
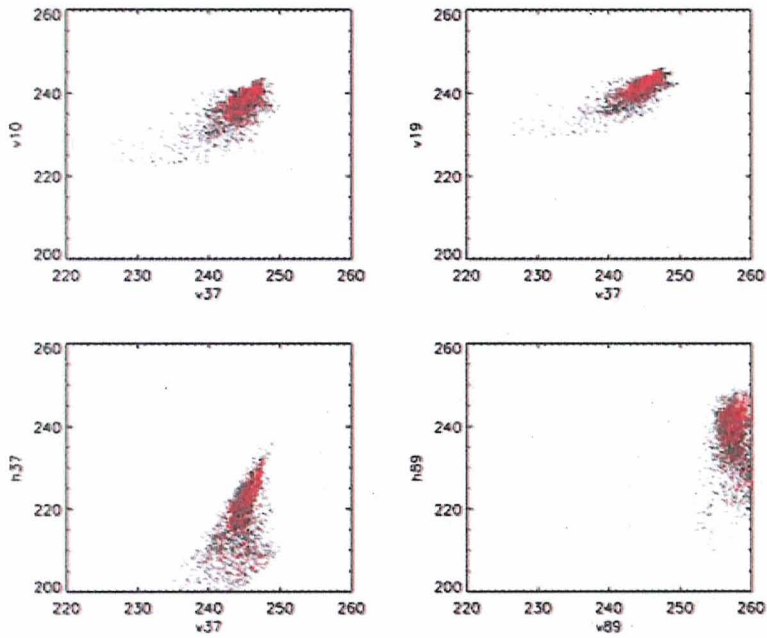
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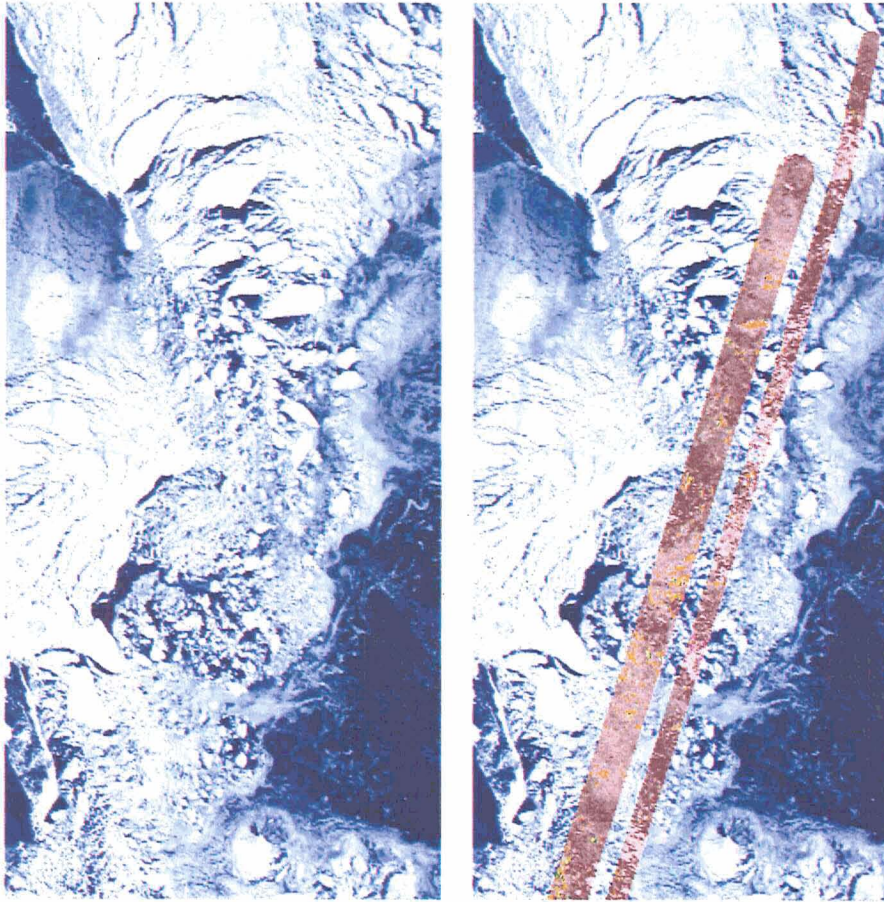
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Sea of Okhotsk (Feb 7, 2004)



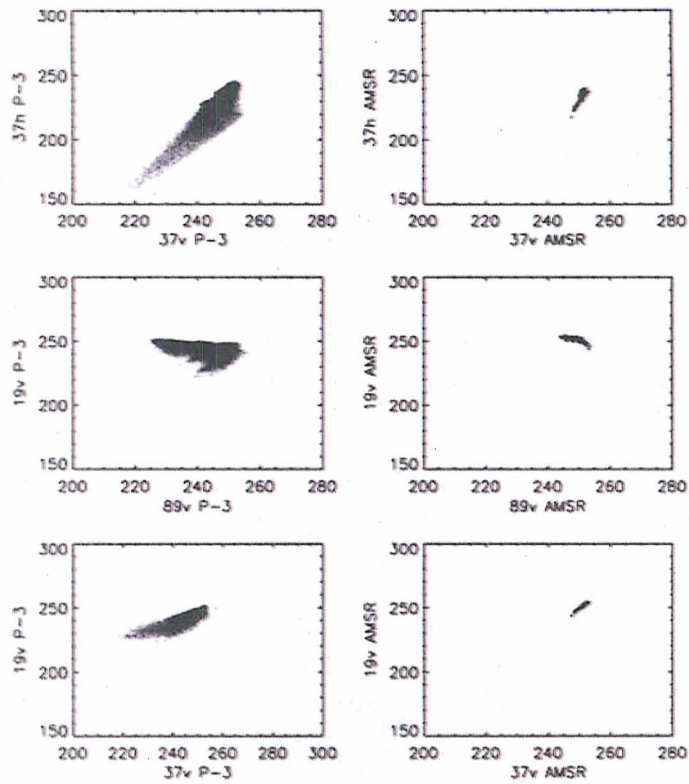
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Figure 12. Scatter plots of 10 GHz (V) versus 37 GHz (V); 19 GHz (V) vs 37 GHz (V); 37 GHz (H) vs 37 GHz (V) and 89 GHz (H) vs 89 GHz (V). The red data points represents low albedo areas inside the box in the image below. The box is in a marginal ice zone region.



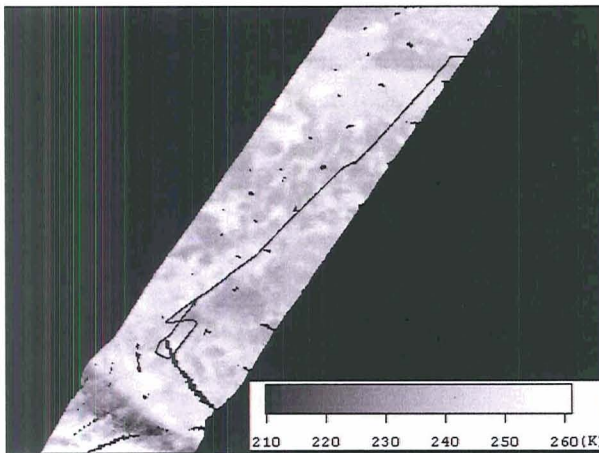
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Figure 13. (b) MODIS image over the Okhotsk Sea on 7 February 2003; and (b) MODIS image with PSR high (6000 m) and low altitude (1000 m) data at 37 GHz over Okhotsk Sea.



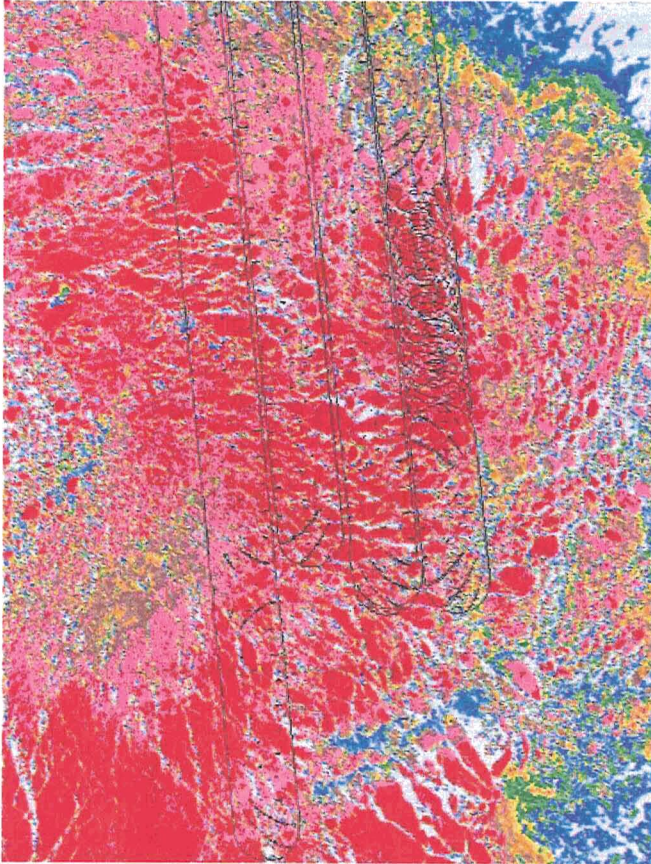
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Figure 14 Scatter plots comparing PSR and AMSR-E data



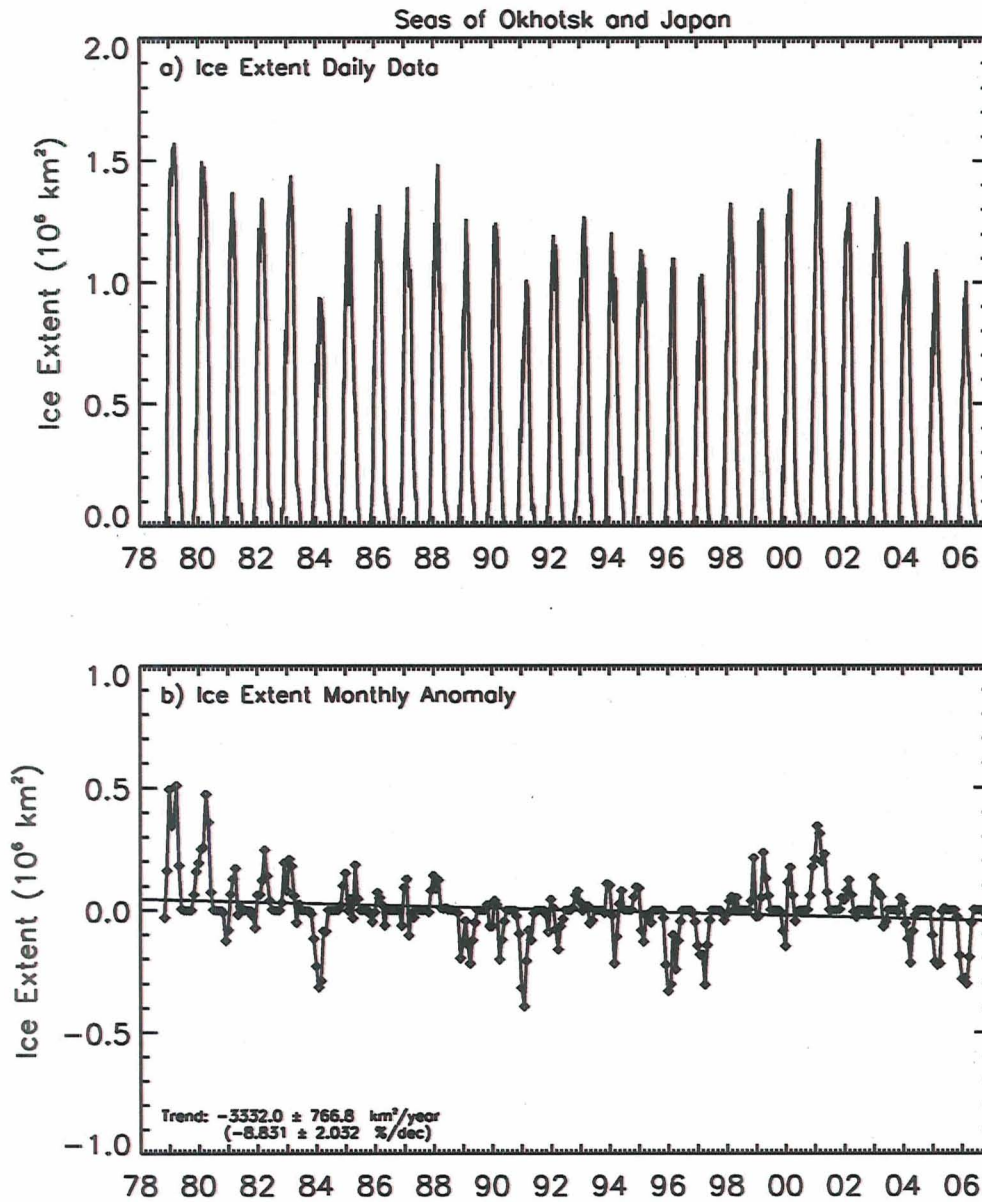
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Figure 15. Ship track on the PSR data on 7 February 2003



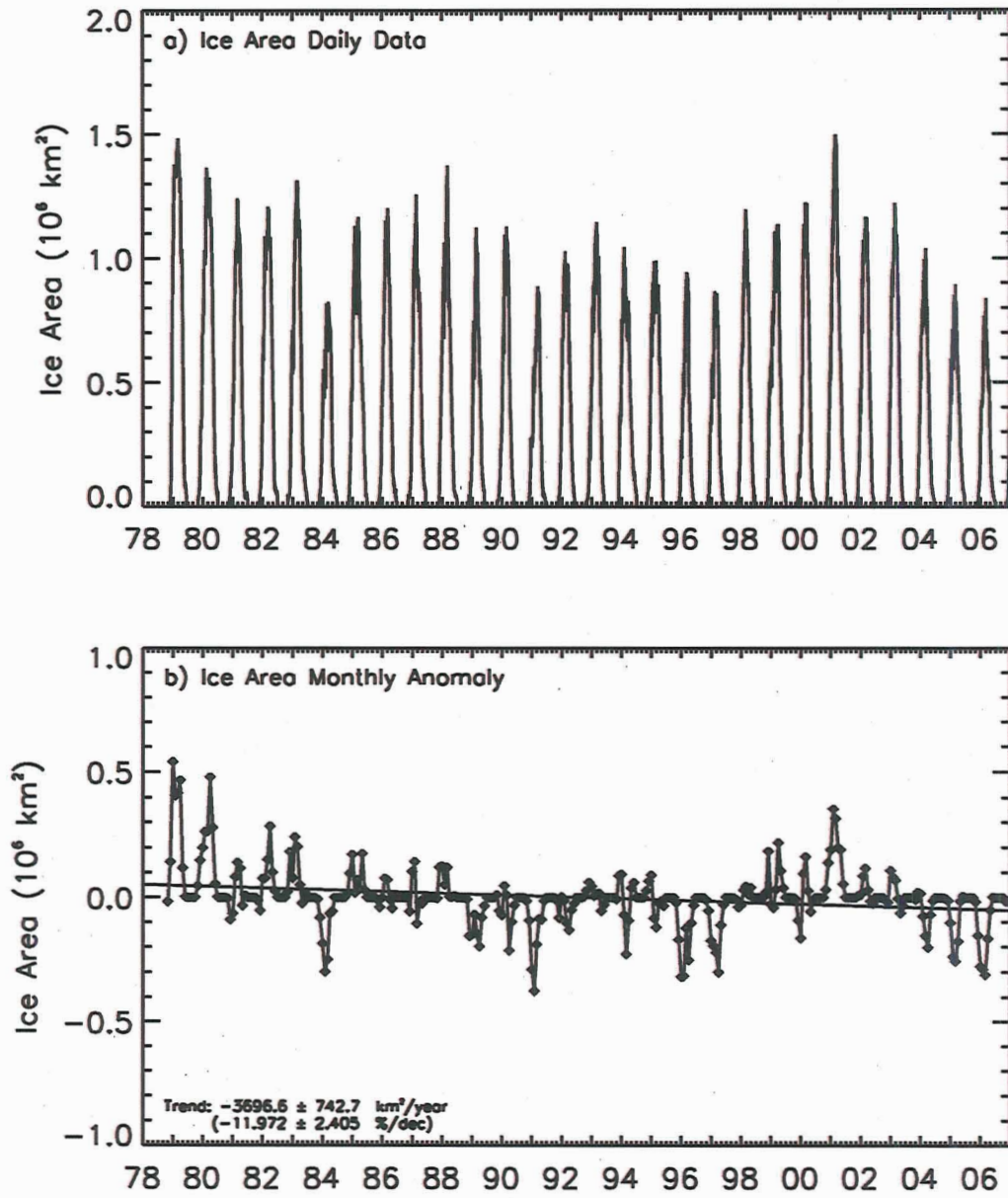
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Figure 16. Ice class map using MODIS visible channel data. Red and pink represent thick ice, brown and yellow represent young ice, while green and blues represent new ice. Gray represents either grease ice or open water.



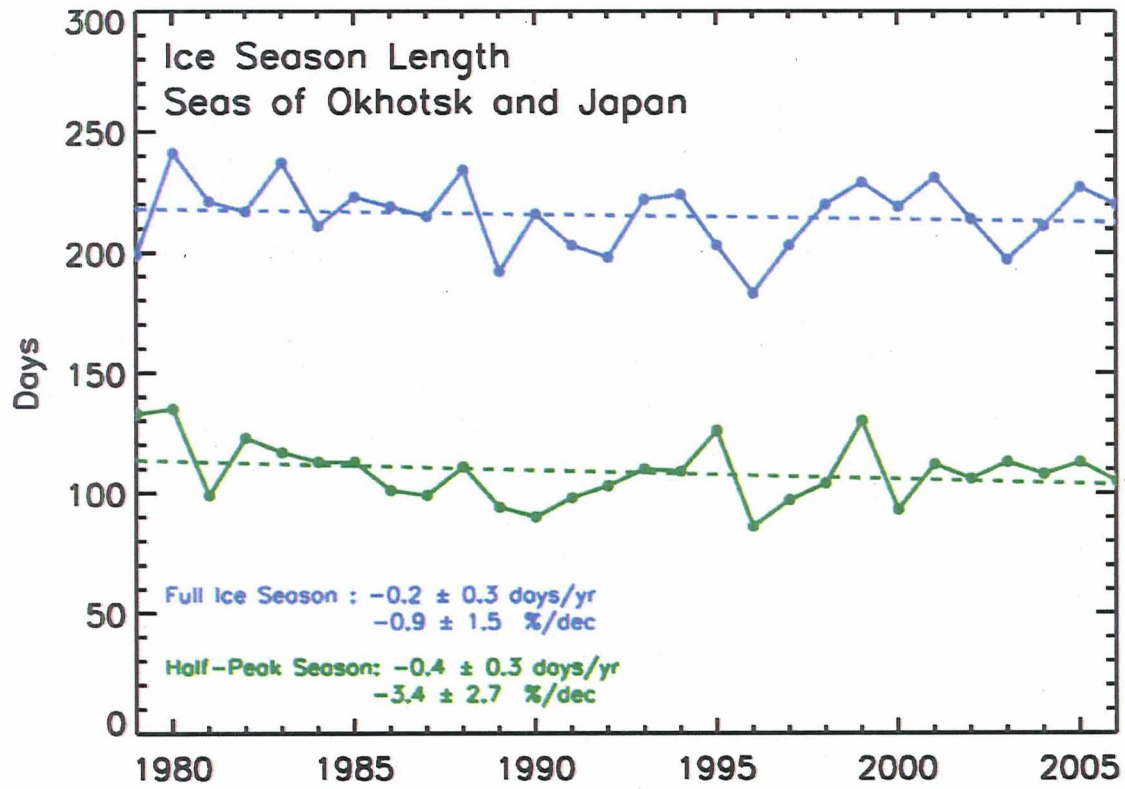
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Figure 17. (a) Seasonal and interannual variability of the ice extent of the Sea of Okhotsk and Sea of Japan from 1978 to 2006; (b) Anomalies and trends in the ice extent of the Sea of Okhotsk ice cover from 1978 to 2006.



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Figure 18. (a) Seasonal and interannual variability of the ice area of the Sea of Okhotsk and Sea of Japan from 1978 to 2006; and (b) Anomalies and trends in the ice area of the Sea of Okhotsk ice cover from 1978 to 2006.



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Figure 19. Length of the ice season in the Okhotsk Sea from 1978 to 2005 (blue) and the width at half-height of the plot in Figure 18a.