Precipitation characteristics in Greenland-Iceland-Norwegian Seas determined by using satellite microwave data

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Abstract. Precipitation characteristics and their connection with atmospheric conditions are studied for the Greenland-Iceland-Norwegian (GIN) Seas during wintertime using satellite microwave (Special Sensor Microwave/Imager) and SSM/T2 data. A snowfall algorithm using SSM/T2 data is presented, which makes it possible to estimate the total precipitation and the relative contribution of each precipitation component (rain or snow) over open water. The monthly mean snowfall rate distribution compares well with the snowfall frequency derived from shipboard present weather reports although no data are available for direct snowfall rate validation. The retrieved results show that more than half of the precipitation falls as snow in the GIN Seas during winter and that the monthly mean horizontal distributions of rain and snow have different patterns. By examining the relationship between surface wind and precipitation and conducting case studies, it is found that rainfall and snowfall are associated with different weather types: rainfall occurs mainly in low pressure systems, while snowfall is more likely associated with cold air outbreaks.

1. Introduction

Observations of the Great Salinity Anomaly (GSA) in the North Atlantic during 1960s to 1980s [e.g., Dickson et al., 1988] have focused attention on the processes that determine surface salinity in the Greenland-Iceland-Norwegian (GIN) Seas. An increased freshwater flux into these regions acts to stably stratify the water column and can cause a reduction or even a complete shutdown in the amount of deep water that is produced in this region.

As described by Schmitz [1994], the ocean freshwater cycle is determined by the amplitude and distribution of freshwater exchange from the atmospheric, cryospheric, and terrestrial reservoirs. Freshwater inflows from rivers in the western North Atlantic are a significant source of fresh water, especially to the Labrador Sea. The melting of sea ice that is exported from the Arctic Ocean provides a source of fresh water. The relative importance of continental runoff, surface freshwater flux, and transport of sea ice in forcing surface salinity anomalies remains uncertain. Pollard and Peu [1985] suggest that interannual variability in surface freshwater fluxes (i.e., precipitation minus evaporation) is of sufficient magnitude to produce measurable surface salinity anomalies.

Understanding precipitation in the North Atlantic is needed to sort out the relative contributions of surface fluxes, river runoff, and sea ice transport to surface salinity variations. Using the "present weather" observations obtained from ships, Dorman and Bourke [1981] estimated rainfall rates in the North Atlantic and Petty [1995] studied the precipitation frequency. Sheu and Curry [1992] used European Centre for Medium-Range Weather Forecasting (ECMWF) initialized analyses to determine precipitation in the North Atlantic as the residual in a moisture budget analysis. Walsh [1995] used a similar technique but used atmospheric soundings directly, rather than analyses from a numerical weather prediction center.

For large-scale diagnostic and modeling studies that require precipitation, satellite retrievals are the only platform from which precipitation can be determined observationally. Rainfall rates have been determined from satellite using either microwave or visible/infrared radiance. Infrared methods [e.g., Arkin and Xie, 1994] have been derived for tropical regions by using an assumed relationship between precipitation amount and cloud top temperature. Infrared techniques have not been carefully scrutinized at high latitudes, and relationships derived for tropical convective precipitation are not expected to perform well at high latitudes. A variety of microwave algorithms have been developed (see Wilheit et al. [1994] for a summary), although many of the microwave-derived precipitation estimates have not been applied north of 60° latitude to avoid snowfall among other reasons. Curry et al. [1990] and Liu and Curry [1996a] have specifically addressed the remote sensing of precipitation in the North Atlantic, although validation of satellite-derived rainfall products over ocean remains problematic.

Of particular concern in the determination of high-latitude precipitation from satellite is the presence of snow. In an analysis of present weather reports obtained from ships, Petty [1995] showed that there is significant frequency of snowfall in oceanic regions north of 40° latitude during winter months (December, January, and February). Curry et al. [1996] suggest that in addition to the freshwater flux associated with snowfall, snow may further influence the ocean surface buoyancy flux through its influence on the surface sensible heat flux. Snow temperature as it reaches the ocean surface may be considerably colder than the ocean, and an additional contribution arises from the latent heat required from the ocean to melt the snow. Curry et al. [1996] thus emphasize that the phase of the precipitation must be determined to assess its impact on the ocean, in addition to determining the amount of the precipitation.

During winter a substantial portion of precipitation in GIN Seas falls in the form of snow. To the authors' knowledge, no satellite microwave snowfall algorithm has been proposed. The main reason is thought to be that the snowfall signals are not strong enough in the currently available microwave data. Using newly available high-frequency microwave satellite data,
we develop a microwave snowfall algorithm that is applicable to high-latitude oceanic regions. We use the retrievals of rainfall and snow to examine precipitation in the Gin Seas during winter and their connection with weather systems.

2. Data Sources and Satellite Retrieval Algorithms

In this study we analyze the period from January 14 to February 13 in 1993 in the region of 55°- 80°N, 60°W - 30°E. This period is chosen because of data availability. Special Sensor Microwave Imager (SSMI) and Special Sensor Microwave water vapor sounder (SSM/T2) data are the primary data sources used in this study. The SSM/I has seven separate total-power radiometers at frequencies of 19.35, 22.235, 37, and 85.5 GHz (hereinafter referred to as 19, 22, 37, and 85 GHz). Dual-polarization measurements are taken at 19, 37, and 85 GHz, while only vertical polarization is observed at 22 GHz. The spatial resolution ranges from 69 x 43 km at 19 GHz to 15 x 13 km at 85 GHz. Nine 85 GHz pixels are averaged to match one 19 GHz pixel whenever both frequencies are used simultaneously. Two DMSP satellites (F-10 and F-11) provide SSM/I data, which results in local sampling frequency of 2 to 4 times per day. The SSM/T2 has five channels at 91.655, 150, 183.31+/-7, 183.31+/-3, and 183.31+/-1 GHz (hereinafter referred to as 92, 150, 183.7, 183.3, and 183.1 GHz). SSM/T2 is a cross-track scanning radiometer, making 28 measurements across a scan line at 3° increments with a swath width of 1480 km. Only the center 20 pixels are used here to avoid possible interference by the glare obstruction panel as well as large scan angles. The spatial resolution at nadir is 88 km for 92 GHz and 34 km for 150 GHz. SSM/T2 data are only on board the F-11 satellite, providing a local sampling frequency of once to twice per day.

The SSM/I and SSM/T2 satellite data are used to retrieve rainfall and snowfall rates over the open water of the Gin Seas. Sea ice concentration is retrieved from SSM/I data based on Cavalieri et al. [1991] to determine surface type (water or ice). Physical parameters are not retrieved over land or sea ice. Figure 1 shows the SSM/I retrieved monthly mean ice concentration in the North Atlantic Ocean during January 1993. In practice, we first calculate ice concentration from SSM/I data, and atmospheric parameters would not be retrieved if ice concentration is greater than 0. In the interpretation of precipitation in the context of weather systems the following additional parameters are retrieved from the microwave satellite data: surface wind speed, precipitable water, cloud liquid water path, and ice water path. The rainfall algorithm used in this study is described in section 2.1. The snowfall retrieval algorithm is developed in this study and described in detail in section 2.2. Retrievals of other physical parameters follow techniques in the literature, and are briefly discussed in section 2.3.

To provide ancillary information and to assist in the interpretation of the retrievals, analyses from European Centre for Medium-Range Weather Forecasting (ECMWF) model are also used. These data have a 2.5° (latitude/longitude) spatial resolution and are available at 0000 and 1200 UT. The sea surface temperatures from the Reynolds and Smith [1995] analysis are also used.

2.1. Rainfall

The rainfall algorithm used in this study was developed by Liu and Curry [1992] and modified slightly by Liu and Curry [1996a]. The SSM/I rainfall algorithm described by Liu and Curry [1992] has been applied over most regions of the global oceans. Horizontally polarized brightness temperatures at 19 and 85 GHz are used in the algorithm. This algorithm combines emission and scattering from cloud and precipitation particles, has a correction for the error caused by the inhomogeneity of the rain field in a satellite pixel, and is less sensitive to the height of the freezing level than the emission-based algorithms. The use of the emission signal from the liquid hydrometeors picks up the signal from low to mild precipitation, while the ice scattering signal (mainly due to the presence of large ice particles) is sensitive to heavy precipitation.

The Liu and Curry [1992] algorithm was originally developed for atmospheric conditions more typical of lower latitudes and warmer seasons than are found in the North Atlantic during winter. In the high latitudes during winter there is a smaller amount of water vapor and cloud liquid water in the atmosphere. Therefore the 85 GHz brightness temperature does not saturate until the rainfall becomes heavy enough so that the brightness temperature difference between 19 and 85 GHz cannot represent rainfall rate unambiguously. To solve this problem, we use the microwave index $f$ as defined by Liu et al. [1995]

$$f = (1 - D/D_{\text{sat}})+2f(1-PCT/PCT_{\text{sat}})$$

where $D$ represents the polarization difference at 19 GHz given by $D = T_{\text{BHV}} - T_{\text{BSV}}$ and $T_{\text{BHV}}$ and $T_{\text{BSV}}$ are, respectively, vertically and horizontally polarized brightness temperatures at 19 GHz; $D_{\text{sat}}$ is $D$ at the threshold for the onset of rain. PCT is the 85 GHz polarization-corrected temperature defined by Spencer et al. [1989] as $\text{PCT} = 1.818T_{\text{BSV}} - 0.818T_{\text{BHV}}$ where $T_{\text{BSV}}$ and $T_{\text{BHV}}$ are, respectively, vertically and horizontally polarized brightness temperatures at 85 GHz; and $\text{PCT}_{\text{sat}}$ is PCT at the threshold for the onset of rain. $D$ represents the microwave emission signal from liquid water drops in an atmospheric column, while PCT reflects the ice scattering signal by dense ice. Therefore as for the brightness temperature difference between 19 and 85 GHz used by Liu and Curry [1992], $f$ also combines emission and scattering microwave signals. The following relationship between rainfall rate ($R$) and microwave index ($f$) is determined to be [Liu and Curry, 1996a]:

$$R = 10.6 f^{1.63}$$
A detailed description of the development of this equation can be found in the work of Liu and Curry [1996a]. This new form of the algorithm is more suited to the high-latitude regions because it avoids multiple values for low rainfall rates.

The Liu and Curry [1992] algorithm has been validated during the Global Precipitation Climatology Project Algorithm Intercomparison Projects that used radar and rain gauge data in the region surrounding Japan [Liu and Curry, 1992] and the tropical western Pacific Ocean [Liu et al., 1995; Sheu et al., 1996]. The modified version (2) was derived by comparing $f$ and retrieved rainfall rate in the tropical region [Liu and Curry, 1996a] although it has not been validated for the high latitudes. One of the major uncertainties of (2) for high-latitude rainfall could be the effects of high surface wind. High surface wind speed ($> 17$ m s$^{-1}$) increases the brightness temperature of the surface, which in turn may be misidentified by the algorithm as a rain signal.

### 2.2 Snowfall

During winter in the GIN Seas a substantial amount of precipitation falls as snow. To retrieve snowfall rate, we follow a similar approach to the ice water path retrieval method described by Liu and Curry [1996a]. By examining the radiative transfer equation, they found that the parameter $\beta$ is approximately proportional to the integral of volume-scattering cross section of ice particles:

$$\beta = \frac{(T^w_{B100} - T^w_{B150})}{(T^w_{B150} - T^w_{B0})}$$

(3)

where $T^w_{B100}$ and $T^w_{B150}$ are, respectively, the brightness temperatures at 150 GHz under conditions with and without ice. $T^w_{B150}$ is determined from the scatterplot of $T^w_{B150}$ versus $T^w_{B0}$ (brightness temperature at 92 GHz) of SSM/T2 data and is expressed as a function of $T^w_{B0}$. $T^w_{B0}$ is the typical brightness temperature emitted solely by the atmosphere. We found 150 K to be suitable for this region.

In order to relate $\beta$ to snowfall rate, radiative transfer simulations are performed for high-latitude winter snowfall conditions. The microwave retrieval of ice and snow characteristics is made difficult by the nonsphericity of the snowice particles. The microwave scattering by nonspherical particles has been studied by Magni and Wiscombe [1986] and Evans and Stephens [1995]. In view of the lack of information on the habit and orientation of high-latitude ice clouds and how they interact with microwave radiation, we assume that the ice/snow particles are equivalent mass spheres.

Figure 2 shows the simulated results of the relationship between $\beta$ and snowfall rate using a radiative transfer model [Liu and Curry, 1993], assuming a 45°N standard atmosphere during winter. The ice particle sizes are assumed to range from 100 to 3000 \(\mu\)m in radius with size distribution given by Schaefer and Srivastava [1970]. The cloud top changes from 1 km to 6 km as snowfall rate increases from 0 to 1.5 mm h$^{-1}$ (water equivalent). A constant cloud liquid water (50 g m$^{-3}$) is assumed in the cloud. Five ice densities (0.1, 0.2, 0.3, 0.4, and 0.5 g cm$^{-3}$) are used to represent different ice/snow types. A terminal velocity of 0.5 m s$^{-1}$ is assumed for calculating snowfall rate near the ground. It is seen that there is clear relationship between snowfall rate and $\beta$ although there exists significant scatter due to the variations in ice density and cloud structure.

The best fit curve derived from these calculation results is expressed by the following equation:

$$R_s = 1.4 \beta^{0.42}$$

(4)

where $R_s$ is snowfall rate in millimeters per hour (water equivalent). When the air temperature near the surface is warm, snowflakes may melt before reaching ground. To take this effect into account, surface air temperatures from ECMWF analysis are used to determine whether snowfall reaches the ground. If surface air temperature is higher than 5°C, snowfall rate is set to be 0 even though SSM/T2 data show scattering signatures. There is no obvious threshold temperature to be used for snowfall, and the threshold undoubtedly depends on atmospheric humidity as well. The 5°C threshold we used here is felt to be a "loose" criterion that allows most snowfall events to be included, although non-snow cases may also be included occasionally.

In applying this algorithm, it must be kept in mind that the microwave scattering signal roughly reflects the total mass of ice particles in the atmospheric column, while snowfall rate is the snow water flux at the surface. Therefore the snowfall algorithm must be based on the assumption that a larger amount of snow in the atmospheric column is associated with a heavier snowfall rate at the surface. Although this is not an unreasonable assumption statistically, the detailed relationship between ice water path and snowfall rate may vary from storm to storm. Major uncertainties involved in the algorithm include vertical structure of the snow layer, the size distribution, the density, and the terminal velocity of snow particles. In developing the snowfall algorithm, we varied the vertical structure and snow density over a reasonable range and kept the size distribution and terminal velocity unchanged using our best knowledge of these variables. In Figure 2 it is seen that there would be larger errors for heavier snowfall rates solely due to the changes in vertical snow layer structure and snow density. Improvement to the algorithm using ground and/or aircraft measured snowfall
data is needed in the future. Using a similar method, Liu and Curry [1996b] studied the possibility of using SSM/I data to retrieve ice water path in tropical cirrus clouds. For limited comparison with data measured by aircraft, ice water path retrieve from SSM/I data shows no significant bias against the in situ measured values.

There are no in situ snowfall rate measurements over open ocean to directly validate this algorithm. In this study we compare the satellite estimates with snowfall frequency from shipboard present weather reports in Comprehensive Ocean-Atmosphere Data Set (COADS) [Woodruff et al., 1986] to evaluate the algorithm qualitatively. The analysis of the COADS data set follows the method described by Petty [1995]. Figure 3a shows rainfall rate, Figure 3b snowfall rate, Figure 3c frequency of “moderate/heavy” precipitation (see Petty [1995] for definition), and Figure 3d frequency of snowfall. Rainfall rate is calculated using SSM/I data during January 1-31, 1993; snowfall rate is calculated using SSM/I data from January 14-31, 1993; moderate/heavy precipitation, and snowfall frequencies are generated from COADS shipboard present weather reports for January 1993. It is seen that rainfall has a similar pattern to moderate/heavy precipitation, the maxima occurring over the warmer water along Gulf Stream - North Atlantic Drift. Snowfall, on the other hand, has larger values near the east coasts of Newfoundland and south of Greenland, similar to the pattern of snowfall frequency of the climatology. Note that the large “white” areas in the east of Greenland in the frequency figures indicate no observations. Therefore we can conclude that the snowfall algorithm described in this study agrees at least qualitatively with in situ observations, although it is difficult to validate the snowfall retrievals quantitatively because of the lack of in situ observations of snowfall rate.

2.3 Additional Parameters

In the analysis of rainfall and snowfall in the context of different weather systems, we employ additional parameters that are determined from satellite microwave measurements: surface wind speed, precipitable water, cloud liquid water content, and cloud ice water content.

Figure 3. Comparison of microwave retrievals of (a) rainfall and (b) snowfall rates derived from satellite with the frequencies of (c) moderate/heavy rainfall and (d) snowfall events derived from shipboard present weather reports.
Surface wind speed and precipitable water are retrieved using algorithms by Goodberlet et al. [1989] and Petty [1994]. Both algorithms were derived statistically by comparing SSM/I brightness temperatures with in situ observations and are only valid for nonraining conditions. In this study, values of surface wind speed and precipitable water at rainy areas are interpolated from retrievals in nearby nonraining areas. A validation study by Cober et al. [1995] showed that results from these two algo-

**Figure 4.** Mean distributions of (a) sea surface temperature, (b) precipitable water, (c) liquid water path, (d) rainfall rate, (e) ice water path, and (d) snowfall rate for the period January 14 to February 13, 1993.
rithms agree with aircraft data for the North Atlantic region dur-
ing winter within the experimental error of the aircraft observa-
tions.

Liquid water path is calculated using the algorithm described
by Liu and Curry [1993], which uses SSM/I 19 and 37 GHz
brightness temperatures. Comparisons of satellite retrievals
with aircraft-measured liquid water path were done by Cober et
al. [1995] and Liu and Curry [1996a] using data collected during
the Second Canadian Atlantic Storm Program (CASPII). The re-
results showed that the satellite and aircraft measured liquid water
paths are well correlated (correlation coefficient is equal to 0.8)
and there are no systematic biases between them.

Ice water path is derived from SSM/T2 data using algorithm
proposed by Liu and Curry [1996a]. The ice water path is cal-
culated based on the brightness temperature depression at 150
GHz, which is caused by scattering by large ice particles in the
atmosphere. Brightness temperature at 92 GHz was also used to
determine the “background radiation” due to surface, liquid wa-
ter clouds, and atmospheric gases. This algorithm has not been
validated due to a lack of validation data.

3. Results

The algorithms described in section 2 are used to study the
precipitation characteristics in the GIN Seas during the period
of January 14 to February 13, 1993. The algorithms are not
applied over land or sea ice.

3.1. Mean conditions

Figures 4a-4f show the mean distributions of sea surface
temperature, precipitable water, liquid water path, rainfall rate,
icewaterpath,andsnowfallrate during the period from January
14 to February 13, 1993. Sea surface temperature data are from
Reynolds and Smith [1995]. The sea surface is warmer in the
southeast than in the northwest portion of the region due to the
warm current of North Atlantic Drift. Precipitable water has a
similar pattern to that of the sea surface temperature, having a
maximum in the southeast portion of the region. Liquid water
path and rainfall rate are higher along the warm drift. Ice water
path and snowfall rate, however, show larger values on the west
side of the region. In other words, the liquid precipitation
mainly occurs along the North Atlantic Drift, while the solid
precipitation largely takes place near the south and east coasts
of Greenland. This suggests two weather regimes in the GIN
Seas: one is favorable to rainfall along the Drift and another to
snowfall in the western portion of the region.

The total precipitation (rain plus snow) and the relative con-
tribution of snowfall to the total precipitation are shown in
Figure 5. The result shows that the total precipitation is higher
in the southern part of the region, particularly lower than 60°N.
On the average, about 70% of precipitation falls as snow in this
region during this winter month, the highest percentage along
the Greenland coasts and above 65°N. This high percentage of
snowfall amount emphasizes the importance of measuring
snowfall in this region.

3.2. Cold and Warm Episodes

From Figure 5b it is noticed that the western region has an
extremely high contribution of snowfall to the total precipita-
tion, while in the east region, rainfall becomes more impor-
tant. In order to investigate the weather conditions under which
snowfall or rainfall is more likely to occur, we divide the GIN

Seas into two regions (west and east) by a curve connecting
points 60°N, 30°W; 70°N, 5°W; and 80°N, 20°E. The time se-
ries of daily averaged parameters are shown in Figure 6 for the
western region and in Figure 7 for the eastern region. V1 and
V2 are averaged meridional surface wind speeds in the west and
east regions, respectively. The wind speed is retrieved from
SSM/I data, and the wind direction is determined from ECMWF
analysis.

In Figure 6a the arrows indicate the days on which relatively
strong north/northwest wind events were observed within the
GIN Seas region in the surface wind field. Most of these events
coincide with negative V1 (north wind on average). Liquid wa-
ter path and rainfall rate do not show a clear response to the
north wind events, while precipitable water slightly decreases,
presumably because the northerly winds bring in a colder and
drier air mass. On the other hand, ice water path and snowfall
rate usually increase during the northerly wind events; this is
especially evident during the three strongest snowfall events
on days 21 (January 21), 36 (February 5), and 40 (February 9).
The increase of snowfall during the north wind episodes could
indicate the presence of convective clouds that give rise to
snowfall, which occur under the extremely unstable atmos-
pheric conditions associated with cold air being advected over a
relatively warm ocean.
precipitable water is lower than 10 kg m⁻²; liquid water paths are close to zero in most of the region; and almost no rainfall occurs. The retrieved ice water path shows large values in the region of strong north winds. Snowfall with maximum values of about 0.5 mm h⁻¹ are observed above 65°N. An additional region of high snowfall is observed to the south of Greenland, in the Labrador Sea.

3.2.2. January 29 case. Figure 9 shows a warm episode that occurred on January 29. A low at 850 mbar is located south of Greenland and southerly winds are predominant in the entire GIN Seas region. Precipitable water in the large area south of Iceland exceeds 20 kg m⁻². A band of high-liquid water path is aligned in a southwest-northeast direction. Rainfall exceeding 1.5 mm h⁻¹ is observed within the large system south of Iceland. Ice water path is relatively low and its local maxima do not coincide exactly with those of liquid water path. This may reflect the different horizontal distributions of liquid and ice particles in the storm. Little snowfall is present in the storm partially due to the surface air temperature exceeding 5°C south of 62°N. Snowfall was not observed in the northern part of the GIN Seas in this system.

3.2.3. February 5 case. Two low pressure systems were observed in the region on February 5, 1993 (Figure 10), one having its 850 mbar center north of 75°N and another near 60°N. The northern low brought cold air to its rear region (southwest of the low) by a northwest wind, resulting in snowfall (maximum about 0.5 mm h⁻¹) above 70°N, while the southern...
ern low brought in warm and moist air from the south. A large area of rainfall is observed near the south low with maximum rainfall rate exceeding 1 mm h\(^{-1}\). Again, maxima of ice water path and liquid water path are not observed in the same locations. This case shows a mixture of cold and warm episodes. Cold and warm episodes are also simultaneously observed on several other days (see Figures 6 and 7).

4. Conclusions

In this study we made the following efforts toward understanding precipitation in GIN Seas: (1) estimation of both liquid and solid precipitation, including development of a new satellite snowfall algorithm; and (2) investigation of the atmospheric conditions favoring each of the two precipitation types.

**Figure 8** January 22 case. (a) surface air temperature and 850 mb geopotential heights are shown by isobars; surface winds by arrows. (b) precipitable water, (c) liquid water path, (d) rainfall rate, (e) ice water path, and (f) snowfall rate.
This study provides the first attempt to derive snowfall rate from satellite. Comparison of the snowfall retrievals with shipboard weather report shows that the areas of large snowfall rate correspond to the areas of high snowfall frequency. Although further refinements in the algorithm are needed, the satellite snowfall algorithm shows potential in obtaining the solid component of the total precipitation in high-latitude oceanic regions. Validation of this algorithm using aircraft data will be pursued in future studies.

In the LiN Seas during winter, our results show that about 70% of the total precipitation falls as snow, and the percentage is higher on the west side than on the east side of the region. Rainfall occurs mainly in the southeast part of the region, caused by the passage of low-pressure systems. Snowfall is usually associated with cold air advection from the north or northwest. It is thought that the snowfall is produced by the convective clouds under unstable conditions of cold air advecting over warmer water. As a result of the different causes of

Figure 9. Same as Figure 8, but for January 29 case.
the two precipitation types, the monthly mean rainfall and snowfall display different distributions; rainfall is higher along the North Atlantic Drift and snowfall is higher near the coast of Greenland.

Retrieval of precipitation in high latitude oceanic regions is a difficult task and validation of the algorithms is equally difficult because of the lack of adequate validation data. For this reason, we focused primarily on the distributions and relative changes in this study. We will continue to validate, investigate, and improve our retrievals using both theoretical studies and observational data that we anticipate will be available in the future. In addition, precipitation over sea ice is also very valuable to climatological research. Satellite retrieval of precipitation may be possible over uniformly distributed multiyear ice. However, snow cover over the ice sheet would complicate the retrieval problem, because the scattering signal of falling

Figure 10. Same as Figure 8, but for February 5 case.
snow is similar to that of the snow cover. Satellite retrieval of precipitation over younger ice is even more difficult due to the ice horizontal inhomogeneity.

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