

NASA Technical Memorandum 104640

Estimating the Thickness of Sea Ice Snow Cover in the Weddell Sea from Passive Microwave Brightness Temperatures

K. R. Arrigo
*NASA Goddard Space Flight Center
Greenbelt, Maryland*

G. L. van Dijken
*Department of Oceanography
Texas A&M University
College Station, Texas*

J. C. Comiso
*NASA Goddard Space Flight Center
Greenbelt, Maryland*



National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

1996

This publication is available from the NASA Center for Aerospace Information,
800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934, (301) 621-0390.

Estimating the Thickness of Sea Ice Snow Cover in the Weddell Sea from Passive Microwave Brightness Temperatures

K. R. Arrigo, G. L. van Dijken, and J. C. Comiso

ABSTRACT

Passive microwave satellite observations have frequently been used to observe changes in sea ice cover and concentration. Comiso et al. (1989) showed that there may also be a direct relationship between the thickness of snow cover (h_s) on ice and microwave emissivity at 90 GHz. Because the in situ experiment of Comiso et al. (1989) was limited to a single station, the relationship is re-examined in this paper in a more general context and using more extensive in situ microwave observations and measurements of h_s from the Weddell Sea 1986 and 1989 winter cruises. Good relationships were found to exist between h_s and the emissivity at 90 GHz–10 GHz and the emissivity at 90 GHz–18.7 GHz when the standard deviation of h_s was <50% of the mean and when h_s was <0.25 m. The reliance of these relationships on h_s is most likely caused by the limited penetration through the snow of radiation at 90 GHz. When the algorithm was applied to Special Sensor Microwave/Imager (SSM/I) satellite data from the Weddell Sea, the resulting mean h_s agreed within 5% of the mean calculated from >1400 in situ observations.

INTRODUCTION

The emissivity of sea ice and its associated snow cover is much greater at some microwave frequencies than those of seawater. Consequently, passive microwave sensors have proven to be very useful for mapping the extent of the sea ice cover. To date, several sensors have been launched aboard satellites and have provided a nearly continuous record of sea ice distribution since 1972. These include the single band Electrically Scanning Microwave Radiometer (ESMR, Nimbus-5 satellite, 1972-1977), the Scanning Multichannel Microwave Radiometer (SMMR, Nimbus-7 satellite, 1978-1987) with bands at 5 frequencies (6, 10, 18, 21, and 37 GHz) at dual, horizontal (H) and vertical (V) polarization, and the Special Sensor Microwave/Imager (SSM/I, Defense Meteorological Satellite Program, 1987-present), a radiometer with frequencies at 19 GHz (H and V polarization), 37 GHz (H and V polarization), 85 GHz (H and V polarization), and 22 GHz (V polarization only). The spatial resolution of these sensors is approximately 30 km^2 .

In order to provide in situ measurements which can be compared with satellite observations, Comiso et al. (1989) used surface-based sensors to measure local variability in the microwave signature of sea ice in the Weddell Sea. Comiso et al. (1989) also examined the effect of snow thickness on the emission of microwaves. To do so, they mounted a radiometer ~1.5 m. above the sea ice in an area of substantial snow cover. Radiometric measurements were made of the snow surface when it was undisturbed and as the snow was carefully scraped off in layers of 0.05 m. Significant increases in brightness temperature (T_B) at 90 GHz were observed when the snow was removed, while at other frequencies the signal remained relatively constant (Fig. 1). Comiso et al. (1989) demonstrated a nearly linear decrease in T_B with increasing h_s at 90 GHz (V) when the instrument was oriented 50° from nadir, the approximate viewing angle of the SSM/I. This suggested that it might be feasible to estimate the thickness of snow cover within the ice pack using satellite mounted sensors.

The decrease in T_B at 90 GHz with increasing h_s has been postulated as caused by greater attenuation of radiation emitted from the snow/ice interface by the thicker snow pack. It was argued by Comiso et al. (1989) that the absence of the decrease in T_B at lower frequencies was because of the smaller influence of volume scattering on T_B , since the wavelengths are large compared to the size of the snow particles. Modeling results of the effect of snow cover on sea ice show similar behavior. It must be noted, however, that the microwave signal is not only influenced by h_s but by other characteristics of the snow pack as well, such as the wetness, granularity, density, and presence of informalities like ice lenses, as well as the underlying sea ice itself.

Unfortunately, the preliminary findings reported by Comiso et al. (1989) were limited to only a few measurements made at a single location. The objective of the present study is to re-examine the relationship between h_s and its associated microwave signature using surface-based data, and if possible, to develop an algorithm appropriate for estimating h_s from space. The surface-based data used in this study were collected during the cruises ANT V/2 (1986) and ANT VIII/2 (1989) to the Weddell Sea aboard the R/V Polarstern. Also, satellite TBs are correlated with in situ snow measurements where no ship observations were available.

ANT V/2 (1986)

Observations of both h_s and microwave TB were made during the 1986 Winter Weddell Sea Project at 32 out of a total of 37 stations. A ship-mounted radiometer was positioned approximately 17 m above the sea ice and measured TB at frequencies of 6, 10, 18.7, 37, and 90 GHz at various angles from nadir. The change in polarization from vertical to horizontal were made by rotating the antenna 90°. Only data measured at an angle 50° from nadir were used in the present study, because this is the approximate angle at which SSM/I data are collected (i.e., 53°).

The mean value for h_s at each of the 32 stations was determined from about 26 individual measurements. The mean value for h_s for all stations ranged from 0 to 0.4 m, with 3 stations having $h_s = 0$ m, 27 stations with $h_s < 0.25$ m and 2 stations with $h_s > 0.25$ m (0.26 and 0.40 m). The standard deviation of h_s ranged from 20-130% of the mean.

Emissivity (ϵ) at the sea ice surface, calculated as

$$\epsilon = \frac{T_B - T_{sky}}{T_I - T_{sky}}$$

(Comiso et al 1989), was highly correlated with TB in the 1986 data (Fig. 2), where T_I is the snow-ice interface temperature and T_{sky} is the radiance caused by the atmosphere and free space. For example, the regression of TB10 GHz (V and H polarization) against ϵ 10 GHz (V and H polarization) at the same station yielded a correlation coefficient of >0.99 (Fig. 2A). This was also true at 90 GHz (V and H polarization) (Fig. 2B).

A plot of ϵ 90 GHz (V) versus ϵ 8.7 GHz (V) (Fig. 3) illustrates that the latter is reduced at $h_s=0$ m (i.e., the three data points in the lower right quadrant). When snow was present on the surface of the sea ice, the signal at 18.7 GHz remained approximately constant, while the micro-wave signal at 90 GHz varied from 0.75 to 0.98 (Fig. 3). This relationship was shown previously by

Comiso et al. (1989) who attributed the variability at 90 GHz to differences in either h_s or properties of the snow cover. A similar relationship also was apparent when the 90 GHz (ϵ and T_B , V and H polarization) band was plotted against 10 or 37 GHz bands, but not the 6 GHz band which exhibited more scatter.

Plots of h_s versus ϵ or T_B at 6, 10 (Fig. 4A), 18.7, and 37 GHz remained relatively flat (no slope), indicating that there was little sensitivity in the passive microwave signal at these frequencies to variation in h_s within the snow pack. The obvious exception was the case where $h_s=0$ m which exhibited much lower values for both ϵ and T_B . On the other hand, the 90 GHz (V) frequency exhibited much greater variability with respect to h_s , although there was no significant correlation between the signal at 90 GHz and h_s (Fig. 4B).

However, when stations where the standard deviation of h_s was greater than 50% of the mean were removed from the analyses, the relationship between ϵ_{90} GHz (V) and h_s improved dramatically (Fig. 5). Two types of outliers in Fig. 5 can be identified; stations where $h_s = 0$ m ($n = 2$) and stations where $h_s > 0.25$ m ($n = 2$). When those stations were omitted, a good linear relationship between h_s and the 90 GHz (V) frequency was obtained (Fig. 7). The equations and goodness of fit of the least-squares linear regression between h_s and ϵ_{90} GHz (V) and T_B 90 GHz (V) are:

$$\epsilon_{90} \text{ GHz (V)} = 1.08 - 0.019 * h_s \text{ (cm)} \quad (n = 10, r^2 = 0.78) \quad (1)$$

$$T_B_{90} \text{ GHz (V)} = 290.24 - 5.21 * h_s \text{ (cm)} \quad (n = 10, r^2 = 0.77) \quad (2)$$

Measurements with vertical polarization were more strongly correlated with h_s than those with horizontal polarization, which had higher (by ~10%) standard deviations. The number of stations where measurements at vertical polarization were taken was higher as well. The linear regression of the h_s data from Comiso et al. (1989) was

$$T_B_{90} \text{ GHz (V)} = 257.89 - 1.06 * h_s \text{ (cm)} \quad (n = 4, r^2 = 0.99) \quad (3)$$

and is shown in Fig. 6 along with the data used to generate Eq. (2). Equation (2) has a much steeper slope than Eq. (3), suggesting that predictions of h_s made using Eq. (2) will be more sensitive to changes in T_{90} GHz (V). Also, if the measured T_B is below 250°K, Eq. (2) will

predict lower values of h_s , while at T_B above 250°K Eq. (2) will give higher values. At T 250°K, both algorithms produce a similar value for h_s (~0.08 m).

If the relationship between h_s and microwave signal is expanded to include two frequencies, 90 GHz (V) and either 18.7 GHz (V) or 10 GHz (V), the regression improves further still

$$\epsilon_{90 \text{ GHz (V)}} - \epsilon_{10 \text{ GHz (V)}} = 0.20 - 0.0227 * h_s \text{ (cm)} \quad (n=11, r^2=0.92) \quad (4)$$

$$T_{B90 \text{ GHz (V)}} - T_{B10 \text{ GHz (V)}} = 55.56 - 6.20 * h_s \text{ (cm)} \quad (n=12, r^2=0.92) \quad (5)$$

$$\epsilon_{90 \text{ GHz (V)}} - \epsilon_{18.7 \text{ GHz (V)}} = 0.13 - 0.0197 * h_s \text{ (cm)} \quad (n=12, r^2=0.89) \quad (6)$$

$$T_{B90 \text{ GHz (V)}} - T_{B18.7 \text{ GHz (V)}} = 35.91 - 5.43 * h_s \text{ (cm)} \quad (n=12, r^2=0.90) \quad (7)$$

The advantage of this approach was that, in contrast to Eqs. (1) and (2) where snow-free stations were omitted, stations where $h_s = 0$ m fitted the resulting regression well (Fig. 7). Thus, the algorithms shown in Eqs. (4-7) apply to all cases where $h_s < 0.25$ m. This restriction is because of the fact that at higher values of h_s , the penetration depth of radiation at 90 GHz is smaller than the snow depth itself (Hall & Martinec 1985).

Only Eqs. (6) and (7) can be applied to SSM/I satellite data to generate estimates of h_s because unlike SMMR, SSM/I does not have a 10 GHz channel. SSM/I does not have a 90 GHz channel either, but it is expected that the differences between the data generated from the 85 GHz frequency of the SSM/I and the 90 GHz field data will be small enough to allow substitution of the 85 GHz SSM/I data into Eqs. (6) and (7).

Foster and Chang (1993) developed a simple algorithm to predict h_s on land using the microwave brightness temperatures at 18 and 37 GHz. Their equation was

$$h_s = 1.59 * [T_{B18 \text{ GHz (H)}} - T_{B37 \text{ GHz (H)}}] \quad (8)$$

However, this algorithm provided a poor fit to the sea ice data, perhaps because of the different emissivities of land and ice.

ANT VIII/2 (1989)

During the Weddell Sea Experiment, h_s and surface based radiometer measurements were taken simultaneously at 18 stations at an angle 50° from nadir from September 16 to October 6, 1989. Unlike 1986, only 10 GHz (V and H polarization) and 85 GHz (V and H polarization) frequencies

were measured. Although more detailed information of the snow cover was reported (grain size, vertical structure of the snow layer, presence of ice lenses, etc.), mean h_s at each station was determined from, at most, four measurements within the radiometer footprint. Snow depths ranged from 0.08 to 0.61 m and were generally less variable than in 1986. Most of the thick snow cover was observed in the western Weddell Sea where the ice cover is generally thicker. Standard deviations for a specific station could be >100% of the mean h_s , but were generally <40%.

Plotting the 85 GHz versus the 10 GHz frequency conformed to expectations; T_B at 10 GHz was fairly constant, while the signal at 85 GHz was highly variable. Also, T_B and ϵ for the 10 GHz channel were highly linearly correlated ($r^2 > 0.99$) (Fig. 8A). However, T_B and ϵ were poorly correlated for the 85 GHz band for both H and V polarization (Fig. 8B). This observation was in direct contrast to measurements made in 1986 which showed a highly linear relationship (Fig. 2) and suggests that the sky calibration of the radiometer in 1989 was not as good as those in 1986. However, some of the 1989 data conform to the relationship between T_B and ϵ found in the 1986 data. When the line of best fit from 1986 (Fig. 2) is plotted with the 1989 data, some of the points lie along the regression (Fig. 8B), suggesting that the calibration for these points may be correct. It is interesting to note that all of the suspect data lie to the right of the 1986 regression line.

Because of the calibration problem, h_s was poorly correlated with the quantity $(\epsilon_{85} - \epsilon_{10})$ GHz (V) in the 1989 data set (Fig. 9). However, if the line of best fit of this relationship from the 1986 data is plotted with the data from 1989, it can be seen that some of the 1989 data points lie on or near the 1986 regression line. Interestingly, the 1989 data points that conform to the 1986 relationship between T_B 85 GHz and ϵ 85 GHz also conform to the 1986 relationship between h_s and the quantity $(\epsilon_{85} - 10)$ GHz (V) (see circled solid black data points on Figs. 8 and 9). There were four other stations in 1989 which conform to the 1986 relationship between T_B 85 GHz and ϵ 85 GHz but do not fit the 1986 relationship between h_s and the quantity $(\epsilon_{85} - 10)$ GHz (V). Therefore, the fact that T_B and ϵ at a particular station relate as expected cannot be used as a proxy for “good data” for the snow depth algorithm. On the other hand, the disagreement of those data with the algorithm could be caused by experimental or weather conditions as well. For example, the header of these data files contained comments such as: “probably moist snow surface,” “radiometers may not be warm enough yet,” “cloud broken/sun in and out station,” and “near white out start of angular scan, slow motion work to be done at the end”; conditions which would very likely affect the microwave signature.

Comparisons with SSM/I data

Eqs. (6) and (7) were used to predict h_s in the Weddell Sea from SSM/I imagery. The mean value for h_s estimated from SSM/I data was nearly identical to that calculated from >1400 in situ measurements. However, the frequency histograms exhibited different distributions, with the in situ data exhibiting a lognormal distribution and the estimates from SSM/I tending toward a more normal distribution (Fig. 10). The differences in the two distributions is not surprising, however. The Central Limit Theorem states that the sampling distribution of the mean approaches the normal distribution as the sample size increases, regardless of the shape of the distribution of the raw data. In our case, the SSM/I averages the snow depth over an area of 625 km², which is essentially the same as increasing the sample size, resulting in a normal distribution. Despite the differences in distribution, the agreement between the means of the two data sets suggests that the algorithm is able to provide a reasonable estimate of h_s from SSM/I satellite data over a large area.

ACKNOWLEDGMENTS: This work was supported by a Maryland Sea Grant College/NASA fellowship in Remote Sensing of the Oceans to G. van Dijken.

REFERENCES

1. Carsey, F.D., R.G. Barry and W.F. Weeks. 1992. Introduction. In: F.D. Carsey [ed.], *Microwave Remote Sensing of Sea Ice, Geophys. Monogr. Ser. 68:1-7*, AGU, Washington, D.C.
2. Comiso, J.C., T.C. Grenfell, D.L. Bell, M.A. Lange and S.F. Ackley. 1989. "Passive microwave in situ observations of winter Weddell Sea ice," *J. Geophys. Res.* 94(C8): 10,891-10,905.
3. Foster, J.L. and A.T.C. Chang. 1993. "Snow cover," In: R.J. Gurney, J.L. Foster and C.L. Parkinson [eds.], *Atlas of satellite observations related to global change*. Cambridge University Press, New York, p. 361-370.
4. Grenfell, T.C., J.C. Comiso, M.A. Lange, H. Eicken and M.R. Wensnahan. 1994. "Passive microwave observations of the Weddell Sea during austral winter and early spring," *J. Geophys. Res.* 99(C5): 9,995-10,010.
5. Hall, D.K. and J. Martinec. 1985. *Remote Sensing of Ice and Snow*, Chapman and Hall, New York. 189 pp.

FIGURES

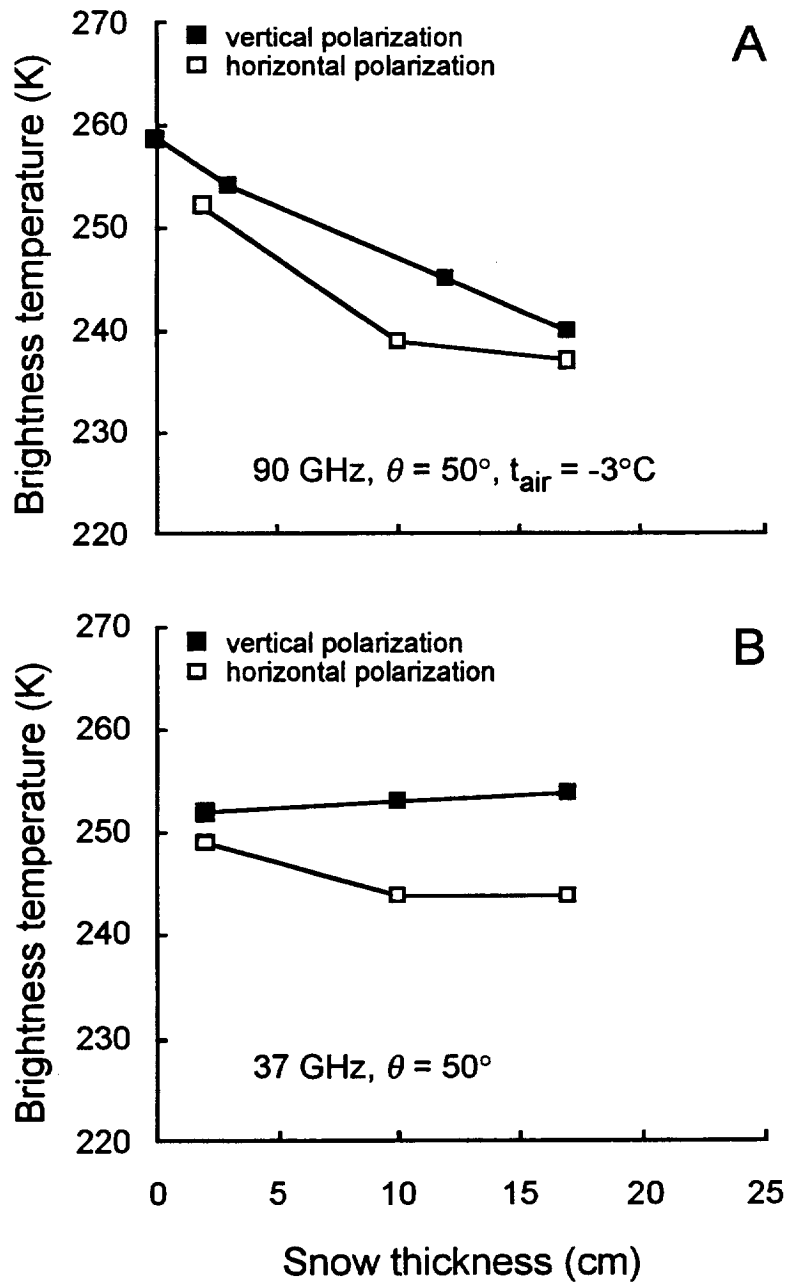


Figure 1. Brightness temperature at 90 and 37 GHz as a function of snow depth. Data was collected using a microwave radiometer mounted ~ 1.5 m. above the sea ice in an area of substantial snow cover. Radiometric measurements were made as the snow was carefully scraped off in layers of 0.05 m.

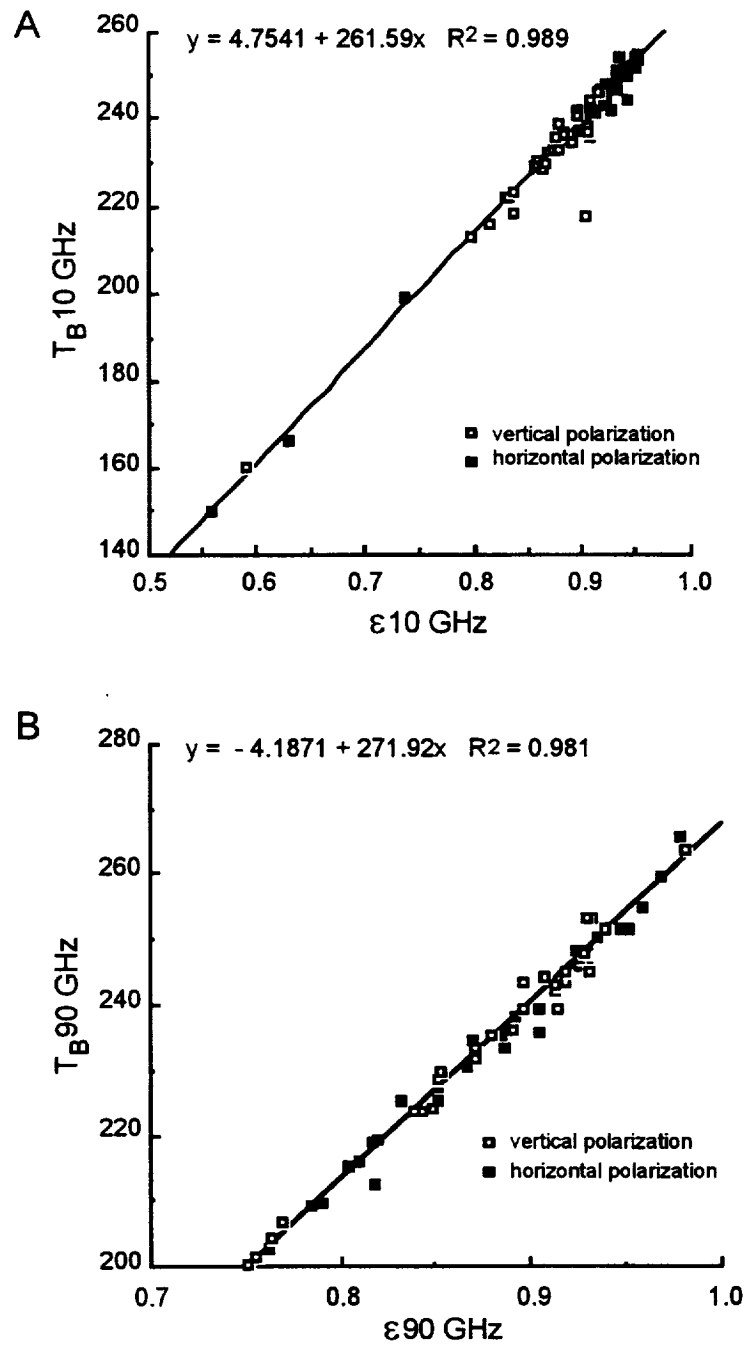


Figure 2. Brightness temperature versus emissivity at frequencies of (A) 10 GHz and (B) 90 GHz. Data was collected in 1986 as described in Fig. 1 with the exception that the radiometer was mounted on the RV Polarstern ~17 m above the ice surface.

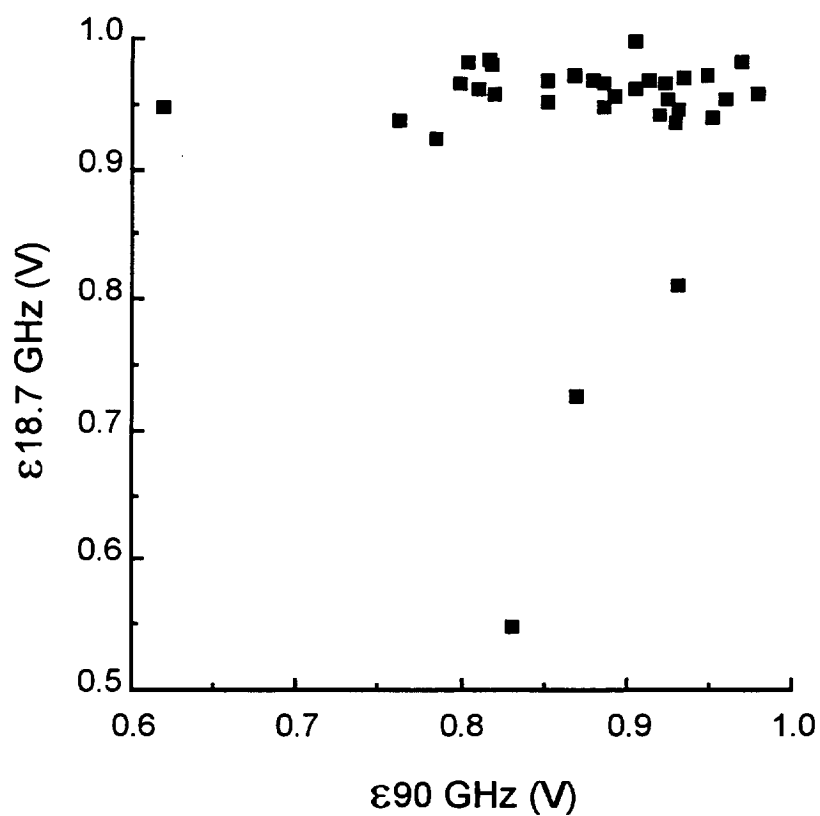


Figure 3. Emissivity at 18.7 GHz versus emissivity at 90 GHz. Data was collected as described in Fig. 2.

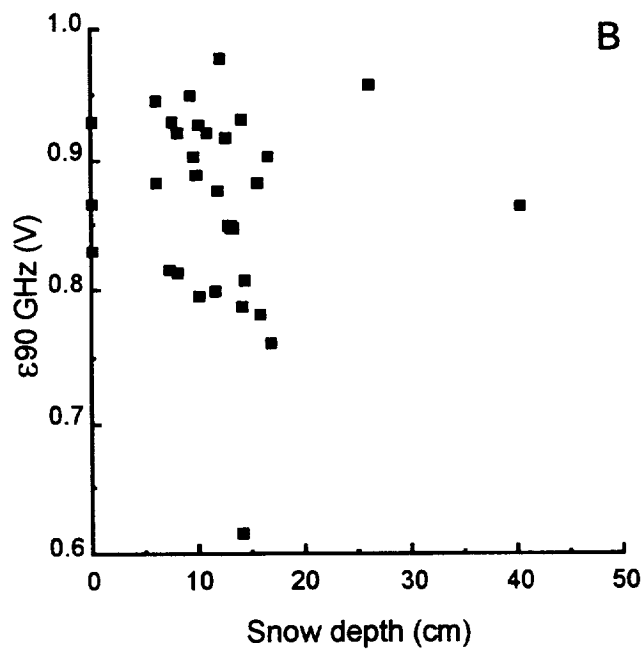
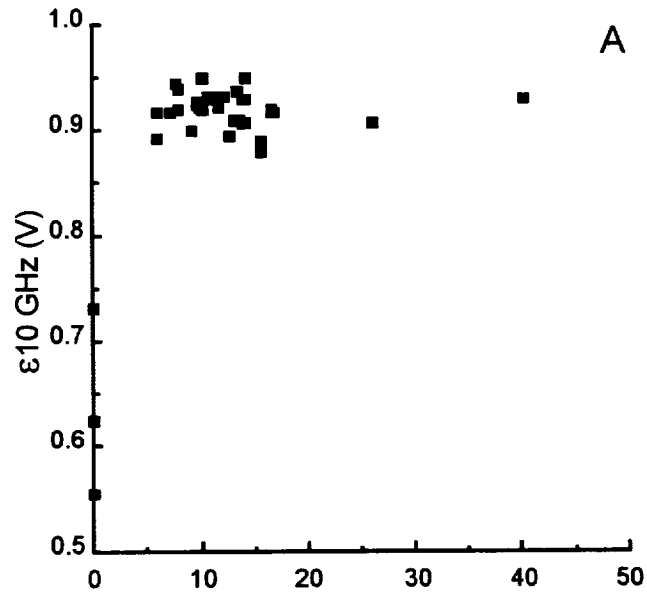


Figure 4. Snow depth versus emissivity at frequencies of (A) 10 GHz and (B) 90 GHz. Data was collected as described in Fig. 2.

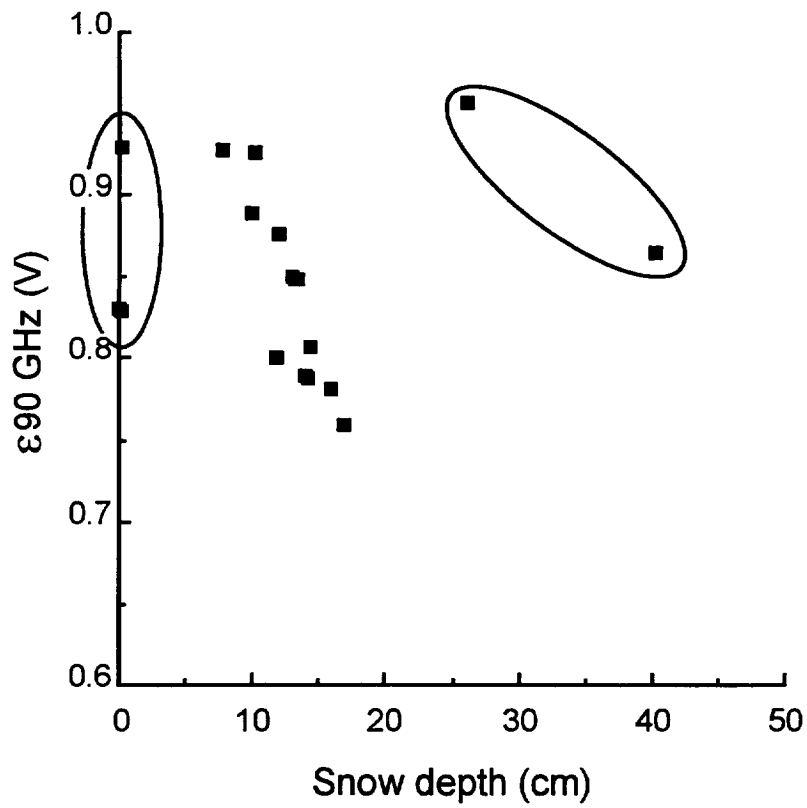


Figure 5. Snow depth versus emissivity at 90 GHz after removing data points where the standard deviation of the snow depth was $<50\%$ of the mean. Circled data points indicate where $h_s = 0$ and $h_s > 0.25$ m. Data was collected as described in Fig. 2.

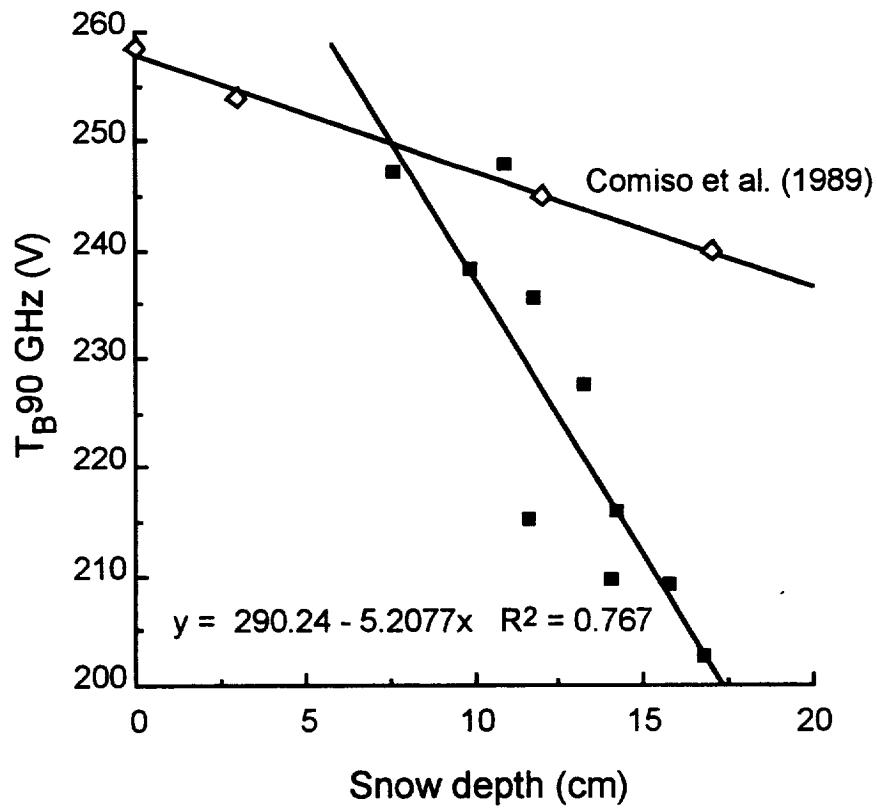


Figure 6. Least-squares regression of brightness temperature at 90 GHz versus snow depth (closed squares). Data points where the standard deviation of the snow depth was $<50\%$ of the mean, and where $h_s = 0$ and $h_s > 0.25$ m were also omitted. The best fit line of the data from Comiso et al. (1989) is shown for comparison (open diamonds). Data was collected as described in Fig. 2.

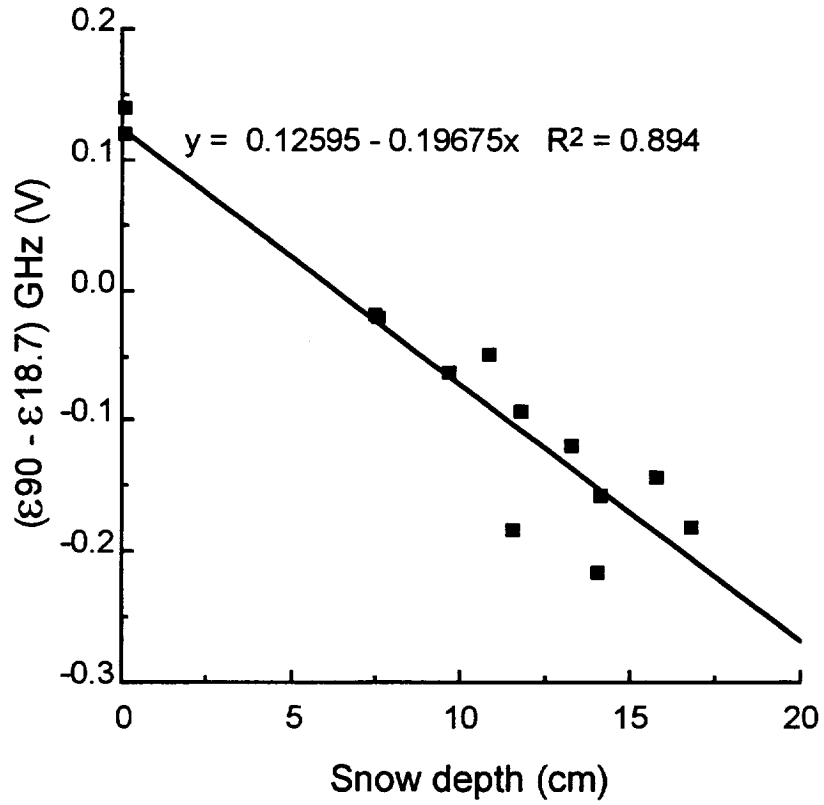


Figure 7. Snow depth versus the difference in emissivity at 90 GHz and 18.7 GHz. Note that data points where $h_s = 0$ m have now been included. Data was collected as described in Fig. 2.

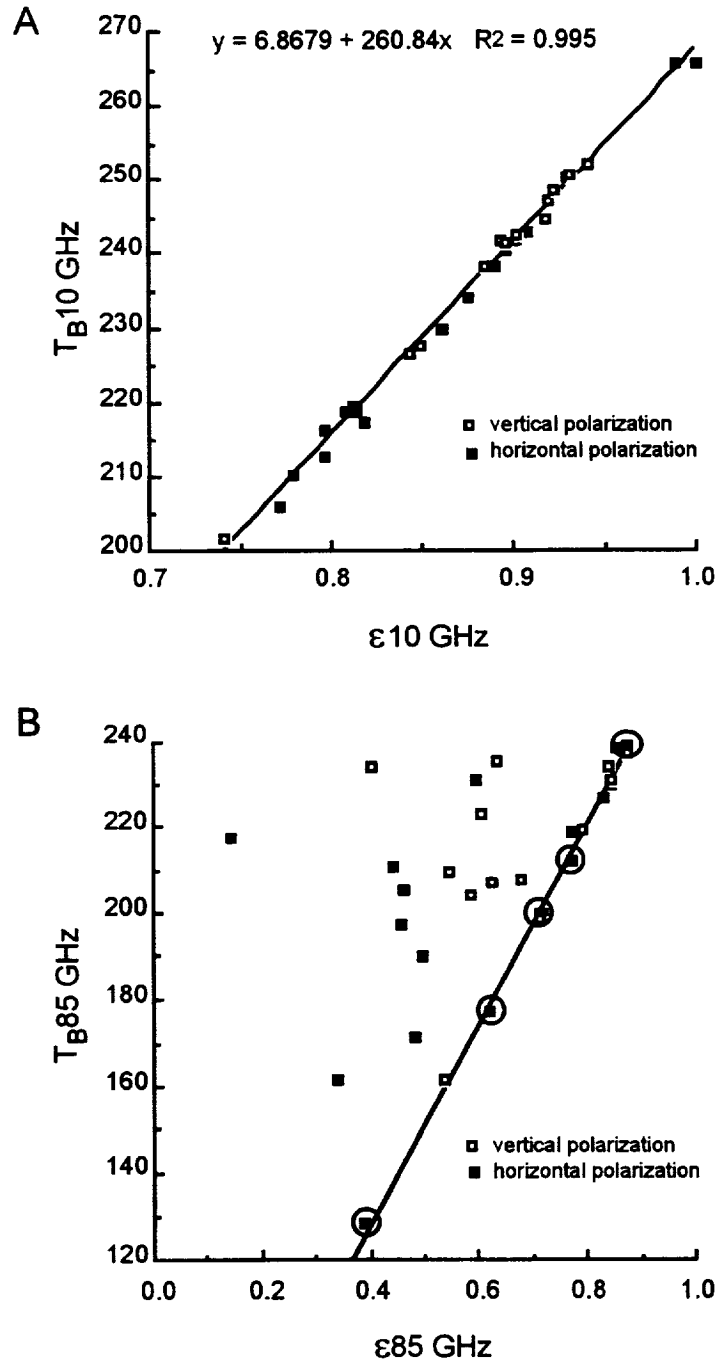


Figure 8. Brightness temperature versus emissivity at frequencies of (A) 10 GHz and (B) 90 GHz. Data was collected in 1989 as described in Fig. 1 with the exception that the radiometer was mounted on the RV Polarstern ~17 m above the ice surface. The line in (B) is the least squares fit to the 1986 data shown in Fig. 2B. Circled data points in (B) correspond to circled data points in Fig. 9 and indicate data which may be salvageable.

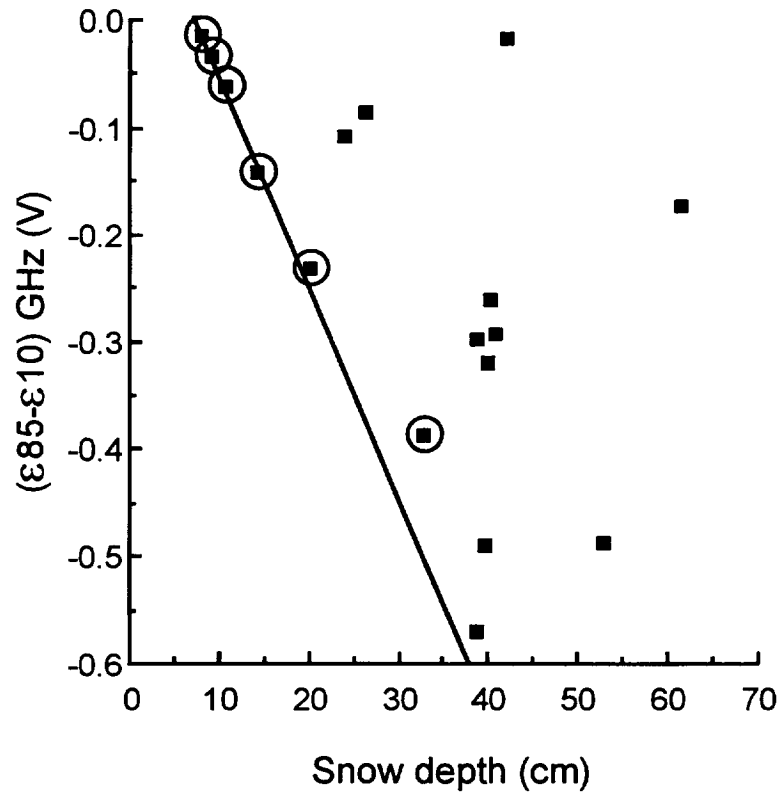


Figure 9. Snow depth versus the difference in emissivity at 85 GHz and 10 GHz. The line is the least squares fit to the 1986 data shown in Fig. 7. Data was collected as described in Fig. 8.

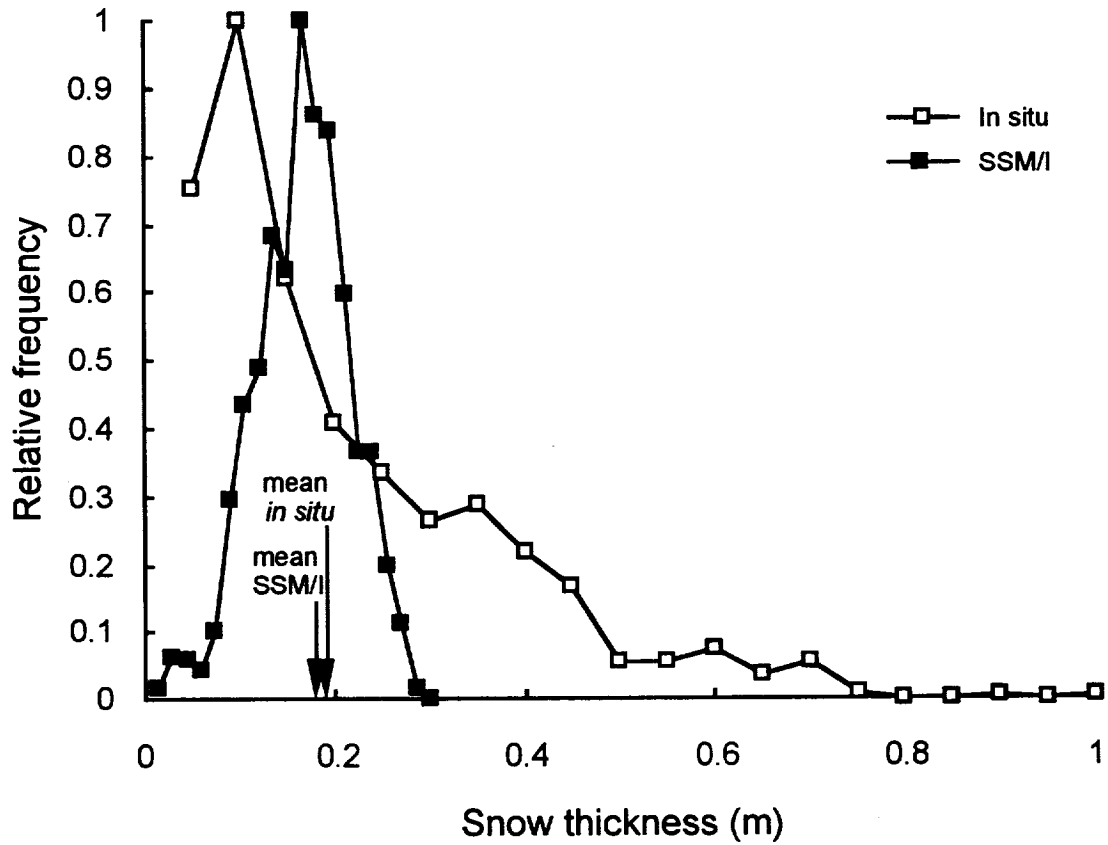


Figure 10. Comparison of the relative frequency distributions of snow depth as determined from in situ data and from estimates made using SSM/I data as input to Eq. (6). Note that the means for the two methods are almost identical. Differences in the distributions are explained in the text.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 1996	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Estimating the Thickness of Sea Ice Snow Cover in the Weddell Sea from Passive Microwave Brightness Temperatures			5. FUNDING NUMBERS Code 971	
6. AUTHOR(S) K. R. Arrigo, G. L. van Dijken, and J. C. Comiso				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Laboratory for Hydrospheric Processes Goddard Space Flight Center Greenbelt, Maryland 20771			8. PERFORMING ORGANIZATION REPORT NUMBER 97B00003	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Goddard Space Flight Center National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER TM-104640	
11. SUPPLEMENTARY NOTES G. L. van Dijken: Department of Oceanography, Texas A&M University, College Station, TX 77843-3146				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 43 This report is available from the NASA Center for Aerospace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090; (301) 621-0390			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Passive microwave satellite observations have frequently been used to observe changes in sea ice cover and concentration. Comiso et al. (1989) showed that there may also be a direct relationship between the thickness of snow cover (h_s) on ice and microwave emissivity at 90 GHz. Because the in situ experiment of experiment of Comiso et al. (1989) was limited to a single station, the relationship is re-examined in this paper in a more general context and using more extensive in situ microwave observations and measurements of h_s from the Weddell Sea 1986 and 1989 winter cruises. Good relationships were found to exist between h_s and the emissivity at 90 GHz-10 GHz and the emissivity at 90 GHz-18.7 GHz when the standard deviation of h_s was < 50% of the mean and when h_s was < 0.25 m. The reliance of these relationships on h_s is most likely caused by the limited penetration through the snow of radiation at 90 GHz. When the algorithm was applied to the Special Sensor Microwave/Imager (SSM/I) satellite data from the Weddell Sea, the resulting mean h_s agreed within 5% of the mean calculated from > 1400 in situ observations.				
14. SUBJECT TERMS Antarctica, snow, SSM/I, passive microwave			15. NUMBER OF PAGES 20	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	