View metadata, citation and similar papers at core.ac.uk brought to you by CORE
provided by Electronic Publication Information Center

Analysis of Sea Ice Surface Roughness and Thickness Profiles for Improvement of SAR Ice Type Classification

Carola von Saldern(1), Thomas Busche(1), Christian Haas(1), Wolfgang Dierking(1)

(1)Alfred Wegener Institute for Polar and Marine Research, Bussestr. 24, D-27570 Bremerhaven, Germany
csaldern@awi-bremerhaven.de
tbusche@awi-bremerhaven.de
chaas@awi-bremerhaven.de
wdierking@awi-bremerhaven.de

ABSTRACT

Sea ice thickness and surface morphology obtained from airborne electromagnetic induction sounding have been investigated in order to improve SAR ice type classification. The stochastic properties of the surface profiles have been analysed using the parameters mean elevation, RMS height, skewness, kurtosis, fractal dimension and correlation length. A clustering algorithm has been applied to the roughness parameters, and the analysis has been iterated in order to find roughness parameters that are characteristic for different ice thickness classes. The set of best parameters was found to consist of mean elevation, RMS height, skewness and kurtosis, and the optimal number of clusters was found to be 6. The thickness of the profiles belonging to the same roughness clusters were analysed. It was found that there exists some relation between similar roughness parameters and similar ice thickness. In addition, the roughness parameters have been compared to normalized backscatter coefficients obtained from Radarsat-1 images.

1. INTRODUCTION

Classification of sea ice type is based on ice thickness and surface morphology. Since ice thickness measurements are considerably more difficult to accomplish by means of remote sensing than surface measurements, it is important to improve techniques for estimating thickness classes from surface characteristics. Surface roughness characteristics nonlinearly determine SAR backscattering coefficients; therefore a detailed knowledge of roughness parameters is crucial to improving SAR-based ice type classification. Ice thickness measurements contain information about the typical level ice thickness as well as the stage of deformation. Surface topography profiles contain similar information, since growth and deformation processes such as ridging, rafting etc. manifest themselves in the surface roughness.

Roughness can be defined on different length scales. In order to enable a comparison with SAR data, the length of the surface profiles is important. A short profile length is more homogeneous with respect to sea ice types, but is also affected more by statistical errors as it consists of fewer points. Longer profiles, on the other hand, fail to differentiate between smaller surface features such as for example leads and ice floes by averaging over them. In this study, all surface elevation profiles obtained by laser altimetry were divided into 2 km long sections. The stochastic properties of these sections were analysed in order to extract meaningful information on the surface characteristics and on the corresponding ice thickness. Characteristic roughness parameters were calculated for all surface profile sections and subjected to a cluster analysis, resulting in groups of similar profiles. These groups were analysed with respect to the mean thickness of the corresponding profile sections of the ice thickness data. The cluster analysis was iterated in order to obtain clusters for which the variation in ice thickness was minimal. In addition, normalized backscattering coefficients for selected profiles were analysed.

2. DATA ACQUISITION

The data used in this study were obtained during the winter cruise ARK XIX of the German research vessel *Polarstern* to the Barents Sea and Fram Strait around Svalbard in March and April 2003 [1]. Fig. 1 shows a map of the research area. Thickness and surface profiles were obtained by means of helicopter-borne electromagnetic induction sounding and laser altimetry. The sensors measuring the thickness and the surface elevation were mounted on the same platform, the HEM bird, which was towed over the ice by a helicopter at a height of 10-15 m above the surface. Flights were performed along triangles with 40 km side lengths. At each turning point, the helicopter ascended to 100 m for calibration purposes.

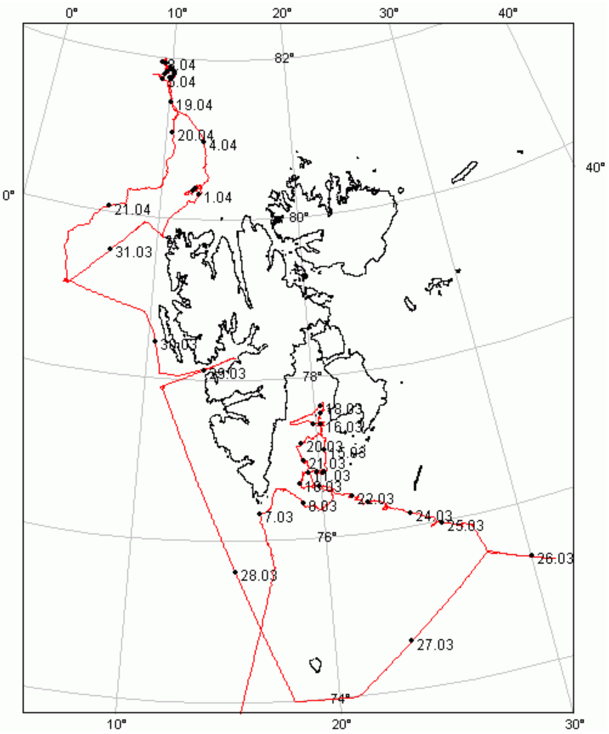

Fig. 1. Research area

The ice thickness data were obtained with a sampling frequency of 10 Hz, which, at a flight speed of 60-80 knots corresponds to a point spacing of 3-4 m. The surface elevation profiles were obtained with a Riegl LD90-3100HS laser altimeter. The infrared laser has a wavelength of 905 nm and a beam divergence of 2 mrad. The range is up to 150 m with an accuracy of 0.02 m. The measuring frequency is 100 Hz, which corresponds to a point spacing of 0.3-0.4 m. To remove the effect of altitude variation due to the helicopter motion, the raw laser data were processed with an automated three-step method using a combination of high- and low-pass filters [2]. The surface elevation thus obtained is not identical to the ice freeboard, but is measured relative to the level ice.

For all profiles, thickness and surface elevation data were obtained. For the stochastic analysis, a sample consisting of profiles from different regions and dates were used, containing mean ice thicknesses ranging from 0.1m to 4.1 m. Each profile was divided into 2 km long sections, yielding a sample size of 104 profile sections. The calculated roughness parameters from the sample are therefore characteristic on a macroscopic scale.

For selected profiles, normalized SAR backscattering coefficients σ_0 from Radarsat-1 (C-band) were available. The images were taken in descending orbit and in standard beam mode with a swath width of 100 km.

3. ROUGHNESS PARAMETERS

Past studies of sea ice surface roughness have been based on parameters such as mean elevation, RMS height, skewness, fractal dimension and correlation length to characterize roughness (e.g. [3]-[7]).

Ref. [6] showed that on large scales, sea ice appears to be smooth and that the fractal dimension appears not to be a useful parameter for differentiating between different ice types. Another widely used approach to characterize surface roughness is based on spectral analysis ([8], [9]). Reference [10] uses long- and shortwave coefficients to characterize different ice classes. In this study, in addition to the statistical parameters mean surface elevation, RMS height, skewness, fractal dimension and correlation length, the kurtosis has been calculated for all profile sections contained in the sample. The RMS height characterizes the average variation of the surface topography about the mean. The ratio of RMS height to mean elevation, often referred to as the coefficient of variation (e.g. [4], [5]), can be interpreted as an indicator of the deformation processes affecting the ice [4]. Sea ice growth is affected by two processes: Thermodynamic ice growth, which occurs over a large area, leads to a systematic thickening of the ice. Compressional deformation like ridging and rafting, on the other hand, occurs only locally and thus leads to the formation of topographic variation. Ref. [4] suggests that ice having a large coefficient of variation has therefore experienced a more active deformation history than ice with a small coefficient of variation.

The skewness is a measure of the asymmetry of a distribution around its mean [11]. For a distribution with positive skewness, the main part is concentrated on the left part of the distribution, while an asymmetric tail extends to more positive values. A typical surface profile with a positive skewness is therefore likely to contain more features that are higher than the surrounding topography, i.e. pressure ridges [3].

The kurtosis measures the relative peakedness or flatness of a distribution [11]. For a distribution with positive kurtosis (leptocurtic), the maximum extends higher than for a normal distribution, and the flanks (or shoulders) are steeper and narrower. For leptocurtic distributions, an excess of values is found near the mean and near the tails. A profile with a positive kurtosis and a positive skewness therefore contains more high features than a normal distribution.

In contrast to smooth curves or surfaces, fractals are objects which contain infinite detail on all length scales. Compared to a classical surface, a fractal surface therefore appears rough. The fractal dimension is a measure of this property.

The correlation length is given by the length at which the autocorrelation function between two points of a profile has dropped to 1/e.

4. CLUSTER ANALYSIS

In order to find a set of characteristic parameters for classification, a cluster analysis has been run with the

104 surface elevation profiles for every combination of the six parameters and for different numbers of clusters. The cluster algorithm applied is a hierarchical, complete-linkage method based on the Mahalanobis distance between cluster elements. This distance measure has the advantage of eliminating possible correlations between cluster variables and thus avoiding a bias in the analysis [12]. It is also scale-invariant, which implies that the variables do not have to be standardized.

The resulting cluster partitions have been analysed with respect to the variation in ice thickness of all profiles contained within each cluster. A partition was considered to be optimal if the sum of the thickness variance of all clusters was minimal. It was found that the optimal set of parameters consisted of the four parameters mean elevation, RMS height, skewness and kurtosis. The optimal number of clusters was found to be six.

4.1 Results

The six clusters formed contain 23 (cluster 1), 56 (cluster 2), 9 (cluster 3), 1 (cluster 4), 7 (cluster 5) and 8 (cluster 6) profile sections. Cluster 4 with only one element was retained since it was the cluster with the lowest values for the kurtosis and the skewness. It contained a profile which closest resembled a normal distribution. Figs. 2 and 3 show mean values for all four parameters for the different clusters.

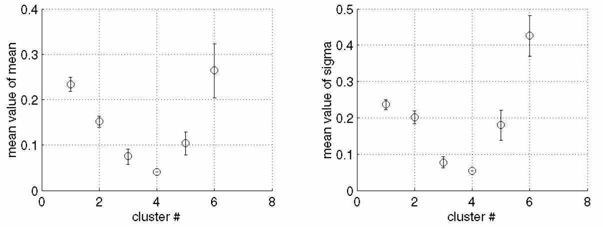

Fig. 2. Mean values for the parameters mean elevation and RMS height. Error bars indicate 95%-confidence intervals

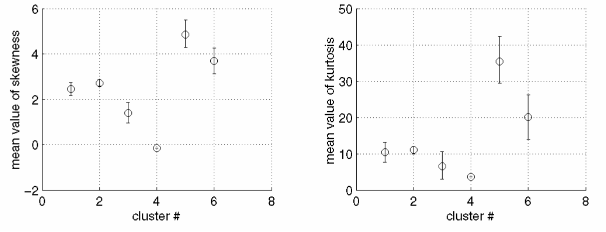

Fig. 1. Mean values for the parameters skewness and kurtosis. Error bars indicate 95%-confidence intervals

Cluster 1 contains 23 elements and is the second largest cluster. The mean elevation for profiles belonging to cluster 1 is 0.23 m; the RMS height is 0.24 m. The values for skewness and kurtosis are 2.45 and 10.35, respectively. The moderate values for mean, skewness and kurtosis suggest that the profiles contain several pressure ridges. The value for the RMS height indicates that the ice between the ridges is not very level, but rather deformed. A typical surface profile section from cluster 1 is displayed in Fig. 4 a.

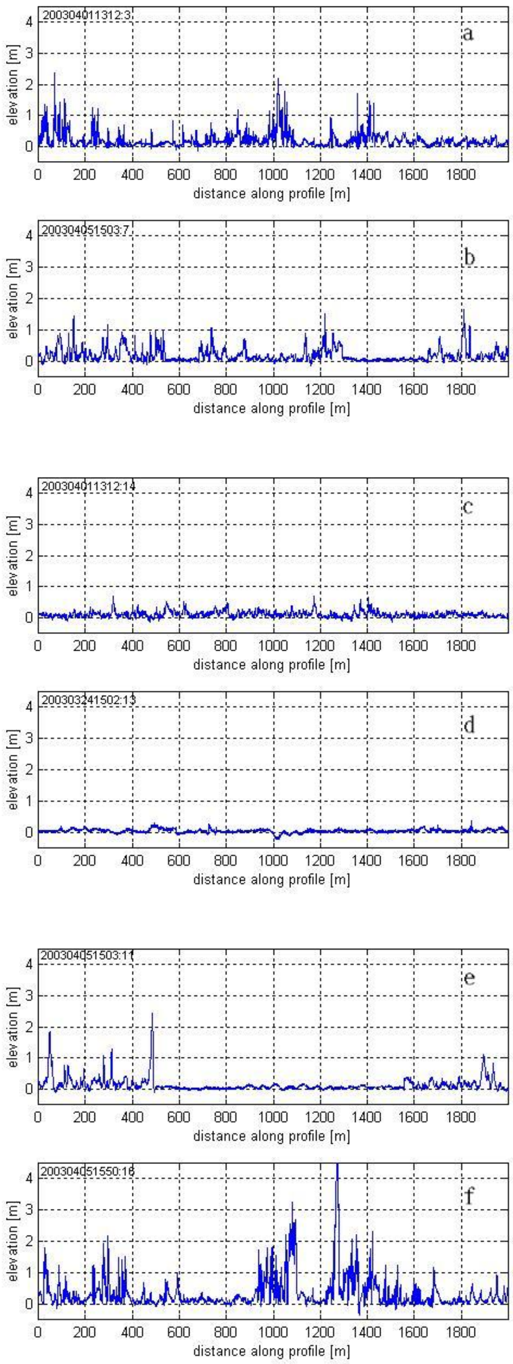

Fig. 2. Typical surface profiles from cluster 1 (a), 2 (b), 3 (c), 4 (d), 5 (e) and 6 (f)

Cluster 2 forms the largest group and is thus representative for the prevailing ice type for the profiles in the sample. The mean elevation of 0.15 m is lower than for group 1, while the values of skewness and kurtosis of 2.71 and 10.98 are slightly higher than those of group 1. These values indicate that there are slightly more ridges than in cluster 1. Taking into account the lower mean elevation suggests the interpretation that the ice between the ridges is smoother. The value of 0.2 m for the RMS height is lower than for cluster 1, also indicating that the ice is more level than in cluster 1. This supports the interpretation that the pressure ridges are separated by areas of smooth level ice. A typical section from cluster 5 is shown in Fig. 4 b.

Cluster 3 consists of ice with a mean elevation 0.08 m. The values for skewness and kurtosis are 1.39 and 6.49, indicating the presence of only very few ridges. The RMS height is 0.08 m. This leads to the interpretation that the profiles consist mainly of level ice. Fig. 4 c displays a typical profile section from this group.

Cluster 4 contains only one element. The mean elevation is 0.04 m, and the values for skewness and kurtosis are -0.16 and 3.57, respectively. The RMS height is 0.05 m, which is the lowest value of all clusters. Cluster 4 also has the lowest values for skewness and kurtosis, and the only one with a negative skewness. The profile in this group is the one that most strongly resembles a normally-distributed profile. A large proportion of the profile thus appears to consist of very level, ice, with even smaller variation than cluster 3. The profile section from this group is illustrated in Fig. 4 d.

Cluster 5 consists of ice with a low mean elevation of 0.1 m. The values of 4.84 for skewness and 35.36 for kurtosis are the highest of all groups. The RMS height is 0.18 m. This leads to the interpretation that the profiles contain many high surface features i.e. pressure ridges. The low values for the mean elevation and the RMS height suggest that the ridges are separated by stretches of level ice. Fig. 4 e displays a typical profile section from this cluster.

Cluster 6 has the largest values for mean elevation and RMS height, with 0.26 m and 0.43 m, respectively. The values for skewness and kurtosis are 3.69 and 20, respectively. As for cluster 5, the profiles contain many ridges. However, the overall elevation is higher and the ice between the ridges is more deformed than for cluster 5. A profile section from this cluster is shown in Fig. 4 f.

The statistical parameters suggest that most of the profile samples consist of multi-year ice (clusters 1, 2, 5 and 6), whereas clusters 3 and 4 contain younger ice.

4.2 Ice thickness

The mean ice thickness for the thickness profiles corresponding to the surface profiles for each cluster has been calculated and is displayed in Fig. 5. Clusters 1 and 2 contain profiles of similar ice thickness, ranging from 1.56 to 1.81 m for cluster 1 and from 1.62 to 2.15 m for cluster 2. The ice is of moderate thickness. Clusters 3 and 4 contain thinner ice, with profile thickness between 0.30 and 0.87 m for cluster 3 and 0.09 for cluster 4. Clusters 5 and 6 display the largest variation in thickness, where values range from 1.19 to 2.56 m for cluster 5 and from 1.8 to 3.17 m for cluster 6. Clusters 1 and 3 can be distinguished best. Cluster 2 is similar to cluster 1, with slightly thicker ice.

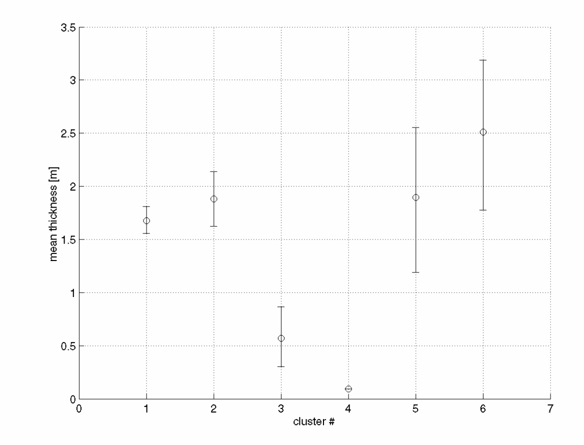

Fig. 5. Mean ice thickness for all clusters. Error bars indicate 95%-confidence intervals

However, the mean surface elevation for cluster 2 is less than for cluster 1, which appears to contradict the values for the ice thickness. This illustrates the fact that the surface profiles are not freeboard measurements, but relative to level ice. Cluster 2 contains ice which is less rough than in cluster 1, thus leading to a lower value for the mean elevation and the RMS height. Clusters 5 and 6 contain thick ice, with cluster 6 containing the thickest ice of the sample. This is in agreement with the roughness parameters. Clusters 2 and 5 contain profiles of similar thickness, even though the roughness parameters indicate that cluster 5 contains more pressure ridges than cluster 2. However, cluster 5 also has a lower mean elevation relative to the level ice than cluster 2.

A comparison of the results from the roughness analysis with the ice thickness data shows a good qualitative agreement. Clusters 1 and 2 contain ice of moderate thickness. Clusters 3 and 4 contain thin ice, while clusters 5 and 6 contain thick ice. From the roughness analysis, more detail concerning the deformation of the ice can be derived, which is less apparent in the thickness data (e.g. compare clusters 2 and 5).

4.3 Radar backscatter

For a selected surface profile from April 11, 2003, coincident Radarsat-1 C-band data were analysed. The images were obtained from standard beam mode with a swath width of 100 km and incidence angle between

35.63 and 41.72 degrees. The effective resolution after geo-coding of the image was 30 m. In order to allow a comparison with the 2 km surface sections, the backscatter coefficients were averaged over all pixels relevant for each section. The total length of the surface profile was 27 km, and it was divided into 13 approximately 2 km long sections.

A separate cluster analysis using the same parameters as in section 4.1 was run for the surface parameters of the profile from April 11. The resulting clusters contained 1 (cluster 1), 3 (cluster 2), 2 (cluster 3), 2 (cluster 4), 1 (cluster 5) and 2 (cluster 6) profile sections.

Cluster 1 has a moderate mean elevation, but very low values of RMS height, skewness and kurtosis, which indicates that the ice is relatively level, with very few pressure ridges.

Cluster 2 has a high mean elevation, and moderate values of RMS height, skewness and kurtosis. This suggests that the ice is less level and contains more ridges than for cluster 1.

Cluster 3 has a very low mean elevation and RMS height, but moderate values for skewness and kurtosis. The profile contains several pressure ridges, which are separated by longer stretches of level ice.

Cluster 4 has the lowest mean elevation and RMS height, again suggesting that the ice is very smooth. However, the values for the skewness and kurtosis indicate that cluster 4 contains more ridges than cluster 3.

Cluster 5 has moderate values for all parameters. This indicates that there are several pressure ridges, between which the ice is characterized by a relatively large small scale roughness.

Cluster 6 has a high mean elevation, and the largest values for RMS height, skewness and kurtosis. This suggests that the ice is very rough and contains many pressure ridges.

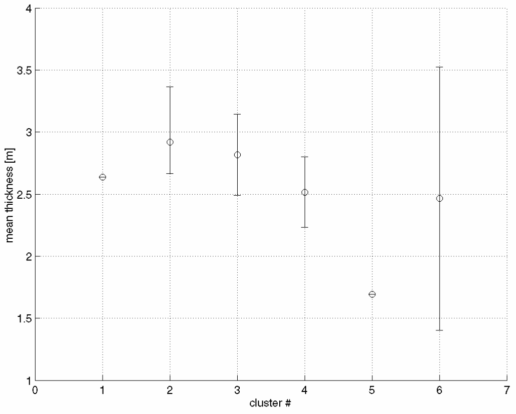

Fig. 6. Thickness variation in the surface profile from April 11, 2003. Error bars indicate 95%-confidence intervals

Fig. 6 displays the thickness variation contained within the profile. Apart from cluster 5, the ice consisted mainly of thick second-year or multiyear ice. Cluster 6 contains the largest thickness variation.

Figs. 7 and 8 display the mean and standard deviation of the averaged backscatter coefficients for all sections. The clusters obtained from the surface roughness are indicated. Cluster 1, which contains level ice with only few ridges, has rather high values for both mean and RMS backscatter. This illustrates the fact that for multiyear ice, volume scattering increases the backscattering coefficient even if the surface is smooth. The two profile sections in cluster 6, which are very rough, display very different backscatter values. On the other hand, the profile sections from cluster 3, which contains areas of smooth level ice between pressure ridges, appear to have similar mean and RMS backscatter. The largest values of both mean and RMS backscatter are found for sections belonging to cluster 2, which also contains the thickest ice.

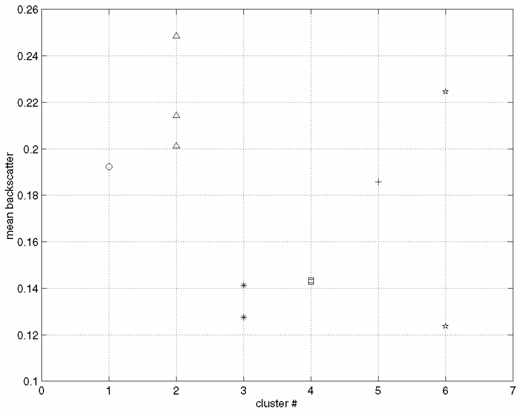

Fig. 7. Mean backscatter coefficients for April 11, 2003. Sections belonging to the same cluster have the same symbol

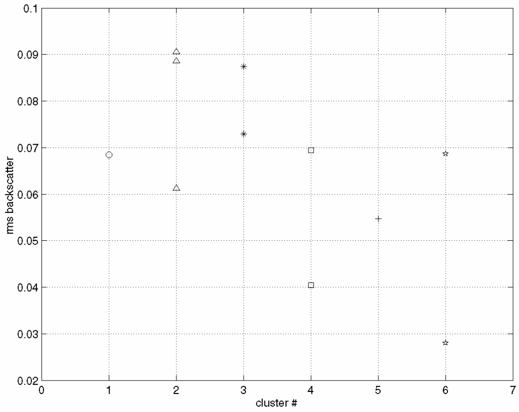

Fig. 8. RMS backscatter coefficients for April 11, 2003. Sections belonging to the same cluster have the same symbol

5. CONCLUSION

The statistical properties of sea ice surface profiles have been analysed with regards to roughness. Meaningful information could be derived from the parameters mean elevation, RMS height, skewness and kurtosis. A comparison with the ice thickness yielded good qualitative results, suggesting that information about ice thickness can be obtained from surface roughness. A preliminary comparison with radar mean and RMS backscatter has been presented. Here, further analysis is required, particularly taking also into account speckle and volume scattering. An extended analysis is intended with Envisat data.

6. REFERENCES

1. Schauer U. and Kattner G., *Reports on Polar and Marine Research*, Vol. 481, Alfred Wegener Institute for Polar and Marine Research, 2004

2. Hibler W.D.III, Removal of Aircraft Altitude Variation from Laser Profiles of the Arctic ice pack, *J.Geophys. Res.* Vol. 77, No. 36, 7190-7195, 1972

3. Goff J.A. et al. Quantitative Analysis of Sea Ice Draft 1: Methods for Stochastic Modeling, *J. Geophys. Res.*, Vol. 100, No. C4, 6993-7004, 1995

4. Goff J.A. et al. Quantitative Analysis of Sea Ice Draft 2: Application of Stochastic Modeling to Intersecting Topographic Profiles, *J. Geophys. Res.*, Vol. 100, No. C4, 7005-7017, 1995

5. Key J. and McLaren A.S. Fractal Nature of Sea Ice Draft Profile, *Geophys. Res. Lett.*, Vol. 18, No. 8, 1437-1440, 1991

6. Bishop G.C. and Chellis S.E. Fractal Dimension: A Descriptor of Ice Keel Surface Roughness, *Geophys. Res. Lett.*, Vol. 16, No. 9, 1007-1010, 1989

7. Lewis J.E. et al. Statistical Properties of Sea Ice Surface Topography in the Baltic Sea, *Tellus*, Vol. 45A, 127-142, 1993

8. Hibler W.D.III Power Spectrum Analysis of Undersea and Surface Sea-Ice Profiles, *J. Glaciology*, Vol 11, No. 3, 345-356, 1972

9. Rothrock D.A. and Thorndike A.S. Geometric Properties of the Underside of Sea Ice, *J. Geophys. Res.*, Vol. 85, No. C7, 3955-3963, 1980

10. Adolphs U. Roughness Variablility of Sea Ice and Snow Cover Thickness Profiles in the Ross, Amundsen, and Bellingshausen Seas, *J. Geophys. Res.*, Vol. 104, No. C6, 13577-13591, 1999

11. Sachs L. *Angewandte Statistik*, Springer Berlin 2002

12. Steinhausen D. *Clusteranalyse* , de Gruyter 1977