

Brief communication: Improved measurement of ice layer density in seasonal snowpacks

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Abstract. The microstructure and density of ice layers in snowpacks is poorly quantified. Here we present a new field method, for measuring the density of ice layers caused by melt or rain-on-snow events. The method was used on 87 ice layer samples in the Canadian Arctic and mid-latitudes; the mean measured ice layer density was $909 \pm 28 \text{ kg m}^{-3}$ with a standard deviation of 23 kg m^{-3} , significantly higher than values typically used in the literature.

1 Introduction

Ice structures form in snowpacks during melt or rain-on-snow events (Colbeck, 1991). Rain either freezes on contact with the surface of the snowpack, or water refreezes within the snowpack to form ice layers, lenses, crusts, columns, or basal ice layers (Gray and Male, 1981). Strong intercrystalline bonds created from refreezing of liquid water, lead to the formation of cohesive ice structures (Fierz et al., 2009). Permeability of ice layers to liquid water and gas is vastly reduced compared to snow (Albert and Perron Jr., 2000; Colbeck and Anderson, 1982). Impermeable layers are identifiable because pores do not connect within the ice formation, and the granular snowpack structure is missing (Fierz et al., 2009). Ice layers differ from ice crusts and ice lenses; ice crusts are always permeable and have a coarse grained granular snow-like structure (Colbeck and Anderson, 1982). Ice lenses can be impermeable, do not have a granular structure and are spatially discontinuous. Similarly to ice lenses, ice layers can be impermeable, and do not have a granular structure, however, ice layers are continuous (Fierz et al., 2009).

Ice layers introduce uncertainty into the performance of snow microwave emission models (Rees et al., 2010), which are an important component of satellite derived snow water equivalent (SWE) retrieval algorithms (Takala et al., 2011). The radiometric influence of even thin ice layers poses a significant challenge for physical and semi-empirical snow emission models, which can either treat ice layers as coarse grained snow (Mätzler and Wiesmann, 1999) or as planar (flat and smooth) ice layers (Lemmetyinen et al., 2010). Uncertainties attributed to not knowing the density of ice

25 layers are greater than any other parameter in snow emission models (Durand et al., 2008). Consequently, development and evaluation of snow emission models are hindered by poorly quantified field measurements of microstructure and properties of ice layers (Montpetit et al., 2012).

Pure ice density ranges from 916 kg m^{-3} at 0°C (Lonsdale, 1958), to 922 kg m^{-3} at -40°C (La Placa and Post, 1960). Only limited field measurements of ice layer densities have previously been
30 attempted. Ice layer density measurements taken in the Canadian Arctic by submerging pieces of ice crust into oil resulted in a range of densities from 630 to 950 kg m^{-3} (Marsh, 1984). Ice layer densities of 400 to 800 kg m^{-3} were measured using a snow fork, which measures the dielectric properties of snow around 1 GHz (Sihvola and Tiuri, 1986) in seasonal snow on the Greenland ice sheet (Pfeffer and Humphrey, 1996). The results from these studies vary drastically and a quantitative
35 assessment of the error in measurement techniques is absent. Consequently, the aim of this paper is to describe a newly developed field measurement technique for measuring ice layer density, and present density measurements made in Arctic and mid-latitude snowpacks.

2 Method

2.1 Development of ice density measurement method

40 A new laboratory and field-based method (Fig. 1) was developed to measure the density of ice layers found in seasonal snow, based on volumetric displacement. The basic principle is that when an ice layer sample is submerged in a vessel of liquid, calculating the volume displacement and sample mass will yield an estimate of density. The mass of a sealed 50 ml centrifuge tube with 2.5 ml graduations containing white spirit (sometimes termed “mineral spirits”), was measured with a precision
45 of $\pm 0.001 \text{ g}$ under laboratory conditions before entering the field. White spirit is immiscible with water and has a low freezing point (-70°C), eliminating potential sample melt. White spirit also has a low density (650 kg m^{-3}), making it likely that the ice sample would sink and be completely submerged. In the field the centrifuge tube was held by a fixed, levelled, mounting system within the macro setting range of a compact camera. Each camera image was centred on a visible datum on
50 the mounting system to ensure the camera was correctly focused, and that repeat images before and after each ice sample was submerged as shown in Fig. 1.

In each image three positions were identified during post processing: the liquid level, the graduation above the liquid level and the graduation below the liquid level. Pixel co-ordinates of these positions were recorded and the proportional height of the liquid level between the upper and lower
55 graduation was translated to a volume at a higher resolution than the centrifuge tube graduations alone would allow. The top of the liquid level was located rather than the meniscus for ease of identification; as relative volume change was used no error was introduced. After images were taken, the centrifuge tube containing the sample was sealed and the change in mass was measured on return to the laboratory. Only samples where the liquid in the tube was level in both images were considered.

60 2.2 Methodological error

Ice layers found in snowpacks are very difficult to accurately and consistently re-create under laboratory conditions. Therefore to assess the accuracy of the ice density measurement technique, ball bearings of known volume were measured. Stainless steel ball bearings were used (manufactured to a diameter of $1 \pm 2.5 \times 10^{-5}$ cm), resulting in a volume of 0.5236 ± 0.0004 cm³. The volume
65 of the ball bearings was calculated from before and after images of 10 ball bearings submerged in the centrifuge tube. The expected total volume of all ball bearings of approximately 5.236 cm³ is comparable to the mean volume of ice samples collected. Of 134 samples, each consisting of 10 ball bearings, the mean volume was 5.045 cm³. The volume measurements were normally distributed and an error value based on ± 1 standard deviations was calculated, resulting in a systematic volume
70 measurement error or bias of -0.19 cm³.

The largest source of error is in reading the height of the liquid in the centrifuge tube from the camera photos. Identifying the precise height of the surface of the liquid between the graduation markings on the cylinder is limited by the quality of the camera focus and resolution of the camera. If the camera focus is not perfect it is difficult to locate the height of the liquid, which result
75 in error and uncertainty. Based on carrying out 10 repeat measurements on 10 centrifuge tube photos the (mean) error was found to be ± 0.125 cm³ in each volume measurement photo, equating to a random root mean squared error in the measurement of the ice sample volume of ± 0.18 cm³ ($error = \sqrt{0.125^2 + 0.125^2}$), as each volume measurement involves reading the volume from two photos.

80 To calculate the optimum sample volume, the number of ball bearings used in each volume measurement was increased from 1 to 24, a volume range of 0.52 to 12.57 cm³. Correlation between standard deviation and sample volume was not statistically significant (confidence $> 99\%$), demonstrating that the error in volume measurement was independent of sample volume. Field trials suggested that 10 cm³ was the maximum sample volume routinely possible to use due to the diameter
85 of the centrifuge tube. Although no minimum sample volume was set, the largest possible sample was obtained.

To estimate the potential impact of the uncertainty in volume measurement on samples taken in the field, the random (± 0.18 cm³) volume measurement error from the ball bearing experiment was applied to a theoretical ice sample of volume 4.89 cm³ and mass 4.53 g (equating to a density
90 of 916 kg m⁻³). This volume error from the ball bearing experiment translated into an observed volume of 4.53–4.89 cm³ (i.e. 4.71 ± 0.18 cm³). Assuming no error in the mass balance (precision of ± 0.001 g), the upper density value (minimum volume) was 951 kg m⁻³ and the lower density value (maximum volume) was 881 kg m⁻³, representing an uncertainty in density of ± 35 kg m⁻³ or 4 %.

95 2.3 Field measurements

During the winter of 2013, ice layer density measurements were collected at three sites in Canada: North Bay, Ontario (46.33° N, 79.31° W) between 8–9 February, Canadian Centre for Atmospheric Research (CARE), Egbert, Ontario (44.23° N, 79.78° W) on 25 February, and Trail Valley Creek, Inuvik, North West Territories (68.72° N, 133.16° W) on 9 April. Ice layers were removed from the surrounding snow and broken to size using a scraper.

In North Bay, snow stratigraphy, density and the mean maximal extent of individual snow grains were measured in a woodland clearing. An artificial ice layer was created on the surface of the snowpack and compared with naturally formed ice layers. Artificial ice layers have been created in previous work (Montpetit et al., 2012) so it is important to know if their characteristics differ from naturally occurring ice layers. To create the ice layer a very thin top layer of undulating recent snow (less than 6 h old) was swept from the snowpack to expose a melt crust below, this was done to maintain an ice layer of even thickness across the site. After the removal of recent snow, water was sprayed onto the snowpack to create a surface ice layer. The ice layer was distinct to the melt-freeze crust and was removed from it when the layer was extracted. A natural ice layer covering the entire clearing was also present lower within the snowpack (formed by 2 mm of rain on 30 January). Density, bubble diameter, and thickness measurements of both natural and artificial ice layers were made; whenever bubbles were visible their diameters were measured using a field microscope and snow grain card, at a resolution of 0.1 mm. Very small bubbles, with a diameter of < 0.1 mm were recorded as being visible although a diameter could not be applied to them. Layer thickness was measured to a resolution of 1 mm for each sample. Density measurements were made of 15 natural and 15 artificial ice layer samples.

At CARE, measurements were conducted in an open, grass-covered field. A spatially continuous ice layer formed over an area of at least 200×100 m in the 10 cm deep snowpack as a result of above-freezing daytime temperatures for a period of 4 days prior to measurement. Ice layer thickness and densities were measured in the same manner as in North Bay, 29 measurements of ice density and thickness were made.

In Inuvik, water was sprayed onto a 30 cm tundra snowpack when air temperatures were approximately -25°C to form an artificial ice layer on the surface of the snowpack as no natural ice layer was present. Water was sprayed over an area of 1 m^2 , concentrating the spraying towards one edge, creating ice thicknesses between 1 to 6 mm which allowed 28 measurements of ice layer density across a range of ice layer thicknesses.

3 Results

3.1 Ice layer density

Mass, volume and density measurements were made of 86 samples of ice layers and are summarised in Table 1 and Fig. 2. After measurements were corrected for bias the mean sample volume was 6.4 cm^3 and when the random error of $\pm 0.18 \text{ cm}^3$ was applied to the volume measurements an uncertainty of $\pm 28 \text{ kg m}^{-3}$ was calculated. Ice layer densities varied between 841 and 980 kg m^{-3} , with an overall mean of 909 kg m^{-3} and standard deviation of 23 kg m^{-3} . Analysis using the Kolmogorov-Smirnov test showed all ice layers to be significantly different. Natural ice layers were on average less dense than artificial ones although the difference was within methodological error. The measurements in Inuvik were made outside, and whilst care was taken to ensure the balance was level and condensation was cleaned from the balance as it formed, these cannot be ruled out as sources of error and could be a reason why some of the high outlying measured densities (2) are physically unreasonable at the Inuvik site. The air temperature was so cold that the water source for creating the artificial layers was freezing up, therefore it is considered unlikely that the artificial ice layers were wet when measured.

3.2 Ice layer bubble size and thickness

Table 1 summarises the measurement of ice layer thickness and bubble size. In some cases bubbles were visible in the ice layer, but were not large enough to be measured using the field microscope. These were noted as $< 0.1 \text{ mm}$ in Table 1. For the purpose of calculating the mean and standard deviation of the bubble distribution a value of 0.05 mm was applied to these bubbles. There was no significant correlation between ice layer thickness and bubble diameter ($p < 0.01$).

3.3 Error analysis

Three sources of error were quantified in the measurement of ice layer density: (1) systematic error and (2) random error in the volumetric measurement of the ice samples, which would apply to any object measured using this method (both discussed in Sect. 2.2), as well as (3) error from sample porosity, which applies only to the measurement of ice layer density. The measured ice layers had a closed porosity, where layers contained bubbles they were not connected in a porous structure. However, due to the presence of bubbles in the ice layers some increase in porosity would occur as more bubbles are exposed when the ice layer was broken and placed in the centrifuge tube. The exposure of the bubbles causes effective porosity and is represented by a dimensionless fraction which represents the proportion of a volume which is available for liquid to flow through.

The influence of effective porosity on the ice layer density measurements was quantitatively evaluated by numerically modelling the bubbles within ice layers. Air bubbles within the ice layer were represented using spheres, scattered randomly, without any overlap within an ice sample of size

x, y, z and density d . The sizes of the spheres were determined by taking a random sample from a normal distribution of bubble sizes based on the mean and standard deviation of bubble diameter measurements. A sphere size was chosen randomly from the distribution and located randomly within the x, y, z axes. If the sphere overlapped another sphere then the location was changed until no overlap occurred. If after 1000 attempts a location for the sphere could not be found its radius was changed to another random sample from the normal distribution and the process repeated. After each sphere was placed, the total volume of all the spheres and the density of the ice sample was calculated. Spheres were added to the sample until the desired density was reached starting from an initial pure ice density of 916 kg m^{-3} . Examples of the ice layers with bubbles distributed in them are shown in Fig. 3.

Slices were taken through the modelled ice sample and the volume of the spheres that would be open to the surface and allow liquid to penetrate the ice surface was calculated. For example, if the slice went through a sphere at exactly the halfway point, half of the volume of that sphere would be added to the porosity value for that sample (Fig. 4). This method assumes that the ice layer is solid ice containing bubbles rather than a granular snow-like structure. For a theoretical ice sample of size $10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$ the sample density was increased in increments of 0.01 kg m^{-3} from 600 to 916 kg m^{-3} , and porosity was measured through the sample by taking slices at 0.1 cm intervals. The relationship between effective porosity and density (ρ) for this bubble and sample size is linear (Fig. 5), and the effective porosity (ϕ) is found using:

$$\phi = -0.00016\rho + 0.14 \quad (1)$$

assuming the same porosity on all edges of the ice sample (where the sample was broken). The mean bubble diameter and standard deviation were calculated from all samples. The root-mean-squared-error of Eq. (1) was 0.0007 with an r squared value of 0.998.

The impact of effective porosity on the samples was calculated by assuming a sample width of 2 cm (the width of the centrifuge tube). Sample thickness and volume were measured (with known methodological error) and used to estimate the maximum and minimum dimensions of each sample. The relationship in Eq. (1) was used to estimate the porosity of each sample based on the measured density. As the density of the sample decreased, volume error from porosity in the sample ranged from 6.5×10^{-5} to $1 \times 10^{-3} \text{ cm}^3$. The mean increase using either the maximum or minimum value for density in the porosity calculations was $1.42 \times 10^{-6} \text{ cm}^3$. The maximum random error ($\pm 0.18 \text{ cm}^3$), the volume measurement bias reflecting systematic error (-0.19 cm^3), and the porosity correction were applied to each volume measurement. The maximum range of density was calculated for each sample and the samples' porosity was negligible (less than 0.001 cm^3). Overall the measurements of ice layer density ($909 \pm 28 \text{ kg m}^{-3}$) were not significantly different to the actual density of pure ice $916 - 922 \pm 28 \text{ kg m}^{-3}$ between 0 to -40°C (Lonsdale, 1958; La Placa and Post, 1960).

4 Discussion and Conclusion

New laboratory and field protocols were used to produce direct measurements of ice layer density including a thorough assessment of measurement uncertainty. Measurements of natural and artificially made ice layers produced an average density of $909 \pm 28 \text{ kg m}^{-3}$, where uncertainty is a function of the random error in the method used to measure the volume of the ice samples. Effective porosity of ice layers was estimated using observations of bubble size and was deemed to be too low to impact the accuracy of the method. Our measured density values are higher than those previously measured by Marsh (1984) (mean 800 kg m^{-3}), and Pfeffer and Humphrey (1996) (400 to 800 kg m^{-3}). It is unclear whether previous studies measured the density of ice layers that were permeable and porous, including thin, non-continuous ice layers. Here only impermeable ice layers were measured and this may explain the density differences between studies. In addition, artificially created ice layers had a higher density than natural ice layers (Table 1). A possible reason for this is that the artificial ice layers were created on the surface of the snowpack, which is likely to experience lower air temperatures than naturally formed ice layers within the snowpack.

Densification and ice formation impacts passive microwave brightness temperatures at the satellite scale (Grody, 2008). Consequently, the evolution of ice structures is important in characterisation of snowpack microwave signatures, and may play an important role in ice layer detection algorithms. However, snow microwave emission models are currently unable to accurately model ice layers (Rees et al., 2010). Some snow emission models (e.g. Wiesmann and Mätzler (1999); Picard et al. (2013)) include a parameter for ice layer density, which has previously been very poorly constrained and is a large source of uncertainty in emission models (Durand et al., 2008) and remote sensing data assimilation applications (Langlois et al., 2012). Consequently, new ice layer density measurements presented here provide a means to reduce uncertainty in future snow radiative transfer modelling.

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Table 1. Measurements of ice layer density bubble size and thickness (all sizes in mm, all densities in kg m^{-3}). n is number of samples, $n < 0.1$ is the number of samples with a diameter of less than 0.1 mm. All ice layer density values have been corrected to account for the measured -0.19 cm^3 bias in volume.

		Bubble Diameter				Layer Thickness			Density		
	Type	n	n<0.1	Mean	SD	n	Mean	SD	n	Mean	SD
Care	Natural	0	-	-	-	29	8	0.6	29	906	17
North Bay	Natural	14	4	0.16	0.12	15	3	0.6	15	890	21
	Artificial	12	6	0.08	0.03	15	5	0.9	15	921	18
Inuvik	Artificial	0	0	-	-	28	2	0.5	18	915	26
Overall	-	26	10	0.12	0.1	86	5	2.7	86	909	23

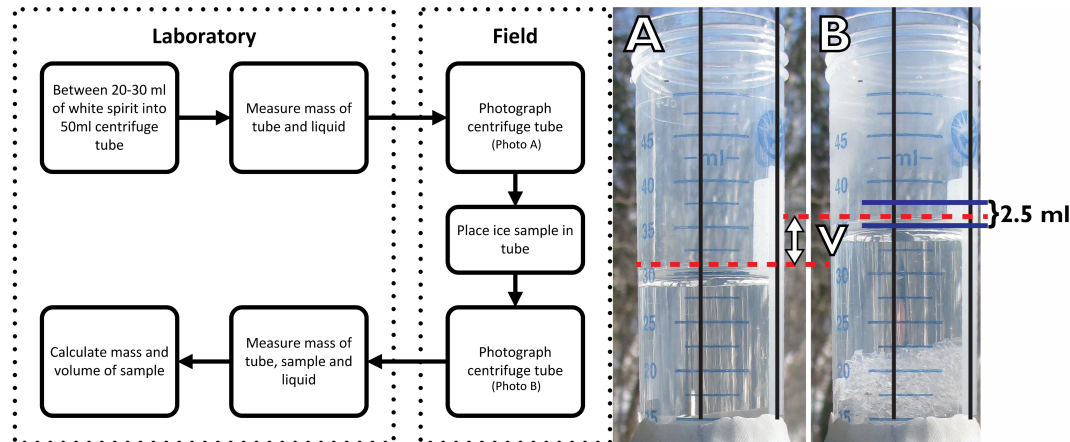


Figure 1. Flow chart describing the methodology to measure densities of ice layers from a snowpack. Photographs show an example pair of photos used in the calculation of ice sample volume. **A** taken before the sample was added and **B**, taken after. **V** is equal to the volume of the ice sample. Black lines are guides added to help assess the quality of the photos.

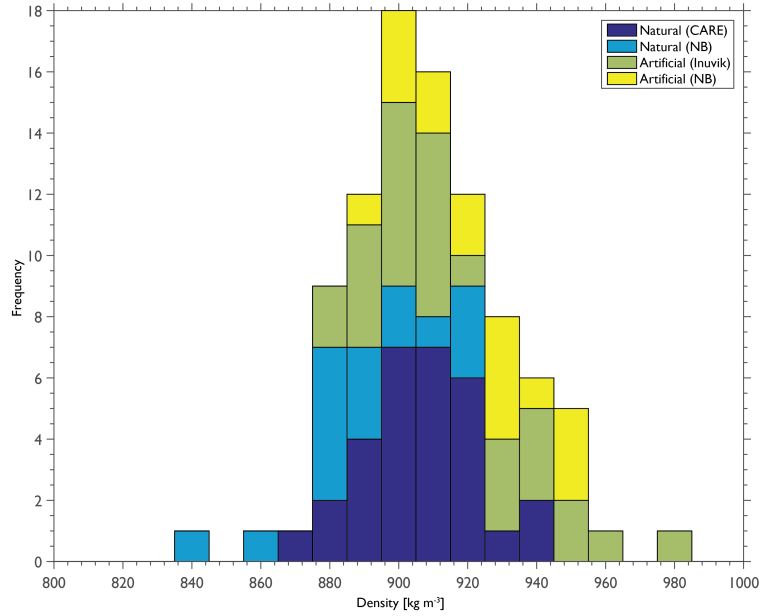


Figure 2. Summary of ice layer density measurements. Stacked histogram showing frequency of each density measurement, colours show distribution of artificial and natural ice layers across multiple sites.

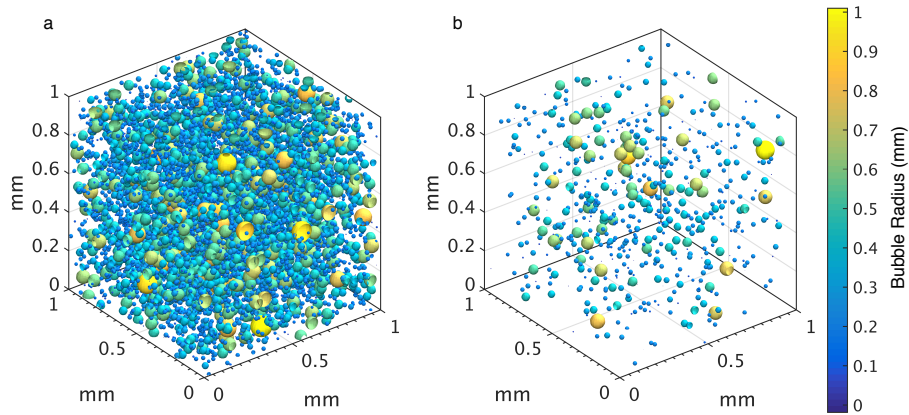


Figure 3. Examples of the numerical representation of ice layers used to investigate porosity, (a) shows a sample with simulated density of 800 kg m^{-3} and (b) shows a sample with density 909 kg m^{-3} .

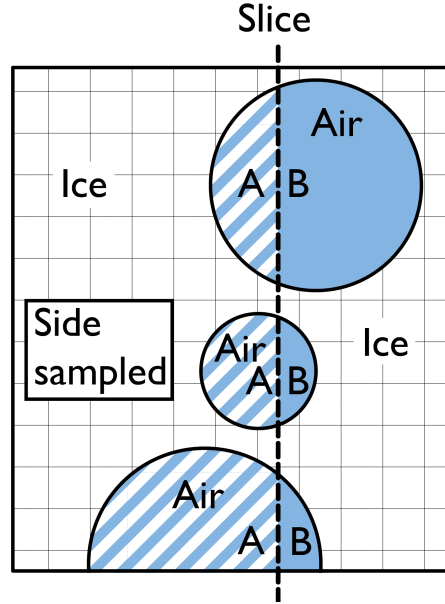


Figure 4. Schematic representation of slicing technique to measure porosity. Air bubbles (shaded in blue) are shown in an ice sample, the theoretical slice was made at the location of the dashed line. The left hand side was chosen as the side to be sampled, and so all of the diagonally striped areas marked “A” were calculated and summed to calculate the overall porosity of the sample.

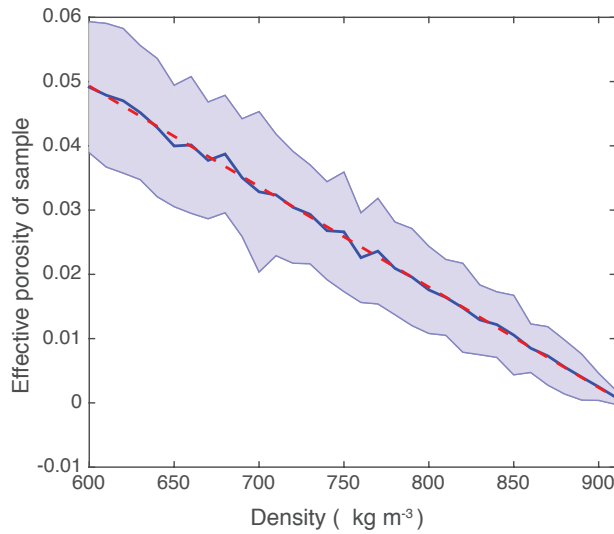


Figure 5. Sample density vs mean simulated sample porosity . Mean sample porosity (blue line) was calculated at 0.1 cm intervals throughout the sample, shaded area shows mean ± 1 standard deviation. Red dashed fitted linear trend line (Eq. 1) was calculated using a least squares regression.