THIS MANUSCRIPT HAS BEEN SUBMITTED TO THE JOURNAL OF GLACIOLOGY AND HAS NOT BEEN PEER-REVIEWED.

A methodologically robust densification function for snow on multiyear Arctic sea ice

Journal:	*Journal of Glaciology*
Manuscript ID	JOG-2024-0085.R1
Manuscript Type:	Communication
Date Submitted by the Author:	n/a
Complete List of Authors:	Mallett, Robbie; UiT The Arctic University of Norway, Physics and Technology
Keywords:	Snow, Sea ice, Snow physics, Ice thickness measurements
Abstract:	No abstract for communications

Journal of Glaciology, Vol. 12, No. 3, 2016

A methodologically robust densification function for snow on multiyear Arctic sea ice

Robbie D.C. MALLETT[1]

[1] *Earth Observation Group, Department of Physics and Technology, UiT the Arctic University of Norway, Norway <robbie.d.mallett@uit.no>*

Snow on sea ice plays a critical role in the polar oceans' energy balance, but also in satellite retrievals of sea ice thickness among other variables. The density of snow on sea ice evolves over the winter season, generally increasing as grains become rounder and the snowpack settles due to the effect of overburden. It is therefore desirable to form a simple equation for the snow density as a function of the time-of-year. In order to investigate the role of snow in radar-derived estimates of Arctic sea ice thickness, such an equation was put forward by Mallett and others (2020, henceforth M20):

$$\rho_s = 6.5t_m + 274.51 \tag{1}$$

Where ρ_s is the snow density in kg m^{-3}, and t_m is the number of months since October. The equation has now been used in several publications (e.g. Dong and others, 2022; Shi and others, 2023; Jiang and others, 2023; Dong and others, 2023; Sievers and others, 2023; Fredensborg Hansen and others, 2024; Chen and others, 2024).

Equation 1 was computed as follows: a large dataset of snow depth and snow water equivalent (SWE) was compiled from in-situ measurements at Soviet North Pole (NP) drifting stations by Warren and others (1999), and monthly quadratic fits were published for both variables. Following common practice in radar altimetry processing chains, M20 divided the quadratic fits for SWE by those for depth to produce spatial distributions for snow density. The spatial average of these density distributions in a subdomain of the Arctic Ocean was then computed, producing one mean snow density value for each winter month. These values were then regressed against the month number to generate Equation (1) of this manuscript. The above method has several drawbacks; their impact and remediation are the subject of this communication.

The first limitation of the method described above concerns the original quadratic fits for SWE and depth themselves, the parameters of which were published by Warren and others (1999). In some months the quadratic fits can produce negative values in the marginal seas of the Arctic, and are not inherently "snow conserving" (i.e. the mean value in the Arctic Ocean is not inherently the mean value of the underlying values, particularly since the spatial definition of the Arctic Ocean is not well defined). Furthermore, it is sub-optimal to compute monthly spatial distributions for density by dividing those for SWE by those for depth: it would be better to compute the density distributions directly from the density measurements and their positions in the month concerned.

Further drawbacks exist in the averaging and regression process underpinning Equation 1: the area over which M20 averaged the density distributions in each month goes beyond the area sampled by the NP station data. For example, the area considered by M20 includes the Laptev Sea, from which stations rarely collected data. It was also only performed in the months of October - April, when the source data from NP stations potentially would allow a function to apply beyond those months. Finally, t_m in Equation 1 represents the integer number of months since October, indicating that the formula is not weighted for the variable lengths of the winter months. In a sense, it is linear in month number, and thus not strictly linear in time.

All the methodological issues described above can be reduced (and some resolved), by directly regressing the mean densities calculated from the original transect data against the time-of-year at which they were generated. These data can be downloaded from the Joint US-Russian Sea Ice Atlas (Environmental Working Group, 2000). Measurements were taken in bulk, by weighing a cylinder of 50 cm^2 in cross section that had been pushed vertically down to the snow-ice interface (Colony and others, 1998). After some data cleaning (see below), this regression yields:

$$\rho_s = 0.35 t_{A_1} + 239.78 \tag{2}$$

Where t_{A_1} represents the number of days since August 1$^{\text{st}}$, and ρ_s remains the snow density in kg m^{-3} as in Equation 1. Five out of 578 data points have been removed for quality-control reasons. These were recorded in the months of July and August: four of them are >500 kg m^{-3} and one of them is 25 kg m^{-3} (this is likely a measurement error). These extreme values exist near the August 1$^{\text{st}}$ break-point of the analysis, and their inclusion makes the slope of the regression highly sensitive to the choice of this date. Because of their removal, it is inadvisable to generate snow densities from Equation 2 in July and August. Despite this, it is clear that Equation 2 can sensibly be used to produce values outside of the "cold season" considered by the M20 calculation, for instance in September, May and June. Individual transect

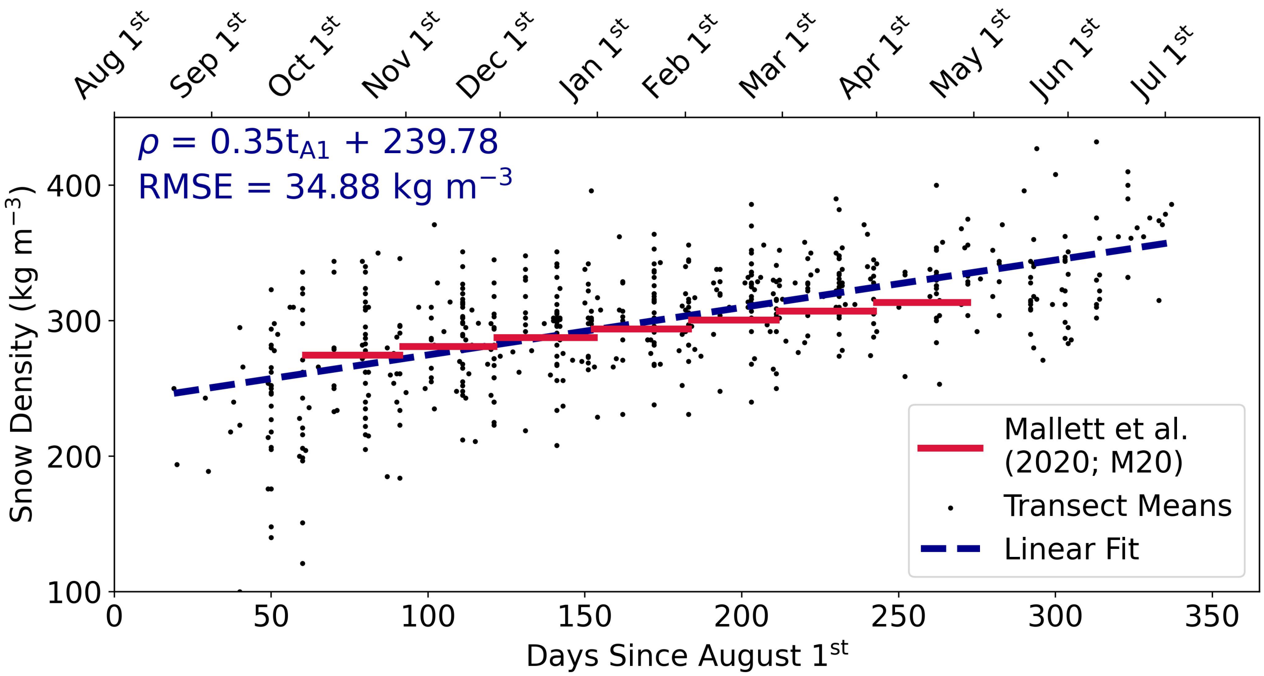

Fig. 1. Transect-mean snow densities (n=573; black scatter), with the M20 values shown as red lines. Linear regression through the scatter points shown in dark blue. Where possible, NP station transects were performed at ten day intervals on the 10th, 20th and 30th of each month, generating a periodic distribution of scatter along the time-axis. Dates are shown on upper x-axis for non-leap-years.

mean values in Figure 1 are scattered about the regression line (Equation 2) with a root mean squared error (RMSE) of 34.9 kg m^{-3}. This is the typical error that a user of the function should expect in an ice environment similar to that from which the NP data were collected.

Figure 1 also makes clear that the new regression slope is not very different from the M20 function in a quantitative sense. Density calculations in the publications cited above using M20 can therefore be trusted. So why make a new one? The first reason is that the new, simpler, more robust methodology can be better trusted in future to represent the underlying data, and in more months of the year. In addition, the new function also takes a more continuous input of *days since August 1st* rather than the month number, aiding its utility as described above.

This new densification function retains some key limitations. It still relies on data collected by Soviet NP drifting stations that operated on multiyear ice, and overwhelmingly in the Central Arctic, East Siberian and Chukchi seas (See Figure 2 of Mallett and others, 2021, for trajectories of stations contributing measurements to this analysis). Snow in the multiyear ice environment may well have a different densification rate to that in the first-year ice environment due to its relative lack of salinity and the rougher underlying ice. Relatedly, the high latitude of the measurements means that the densification rate in Equation 2 may not reflect that of lower latitudes where periods of diurnal cycling are more protracted and temperatures are often higher.

Code and Data Availability

All code and data required to reproduce this analysis can be downloaded from: `https://github.com/robbiemallett/densification`.

REFERENCES

Chen F, Wang D, Zhang Y, Zhou Y, Chen C, Ye Y, Chen F, Wang D, Zhang Y, Zhou Y and Chen C (2024) Intercomparisons and Evaluations of Satellite-Derived Arctic Sea Ice Thickness Products. *Remote Sensing 2024, Vol. 16, Page 508*, **16**(3), 508, ISSN 2072-4292 (doi: 10.3390/RS16030508)

Colony R, Radionov V and Tanis FJ (1998) Measurements of precipitation and snow pack at Russian North Pole drifting stations. *Polar Record*, **34**(188), 3–14, ISSN 1475-3057 (doi: 10.1017/S0032247400014923)

Dong Z, Shi L, Lin M and Zeng T (2022) A Suitable Retrieval Algorithm of Arctic Snow Depths with AMSR-2 and Its Application to Sea Ice Thicknesses of Cryosat-2 Data. *Remote Sensing 2022, Vol. 14, Page 1041*, **14**(4), 1041, ISSN 2072-4292 (doi: 10.3390/RS14041041)

Dong Z, Shi L, Lin M, Jia Y, Zeng T and Wu S (2023) Feasibility of retrieving Arctic sea ice thickness from the Chinese HY-2B Ku-band radar altimeter. *Cryosphere*, **17**(3), 1389–1410, ISSN 19940424 (doi: 10.5194/TC-17-1389-2023)

Environmental Working Group (2000) Joint U.S.-Russian Arctic Sea Ice Atlas. (G01962, Version 1). *Tanis, F. & Smolyanitsky, V. (Eds.) [Data Set]. Boulder, Colorado USA. National Snow and Ice Data Center.*

Fredensborg Hansen RM, Skourup H, Rinne E, Høyland KV, Landy JC, Merkouriadi I and Forsberg R (2024) Arctic Freeboard and Snow Depth From Near-Coincident CryoSat-2 and ICESat-2 (CRYO2ICE) Observations: A First Examination of Winter Sea Ice During 2020–2022. *Earth and Space Science*, **11**(4), e2023EA003313, ISSN 2333-5084 (doi: 10.1029/2023EA003313)

Jiang M, Zhong W, Xu K and Jia Y (2023) Estimation of Arctic Sea Ice Thickness from Chinese HY-2B Radar Altimetry Data. *Remote Sensing 2023, Vol. 15, Page 1180*, **15**(5), 1180, ISSN 2072-4292 (doi: 10.3390/RS15051180)

Mallett RDC, Lawrence IR, Stroeve JC, Landy JC and Tsamados M (2020) Brief communication: Conventional assumptions involving the speed of radar waves in snow introduce systematic underestimates to sea ice thickness and seasonal growth rate estimates. *Cryosphere*, **14**(1), 251–260, ISSN 19940424 (doi: 10.5194/tc-14-251-2020)

Mallett RDC, Stroeve JC, Tsamados M, Landy JC, Willatt R, Nandan V and Liston GE (2021) Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover. *The Cryosphere*, **15**(5), 2429–2450, ISSN 1994-0424 (doi: 10.5194/tc-15-2429-2021)

Shi H, Lee SM, Sohn BJ, Gasiewski AJ, Meier WN, Dybkjar G and Kim SW (2023) Estimation of Arctic Winter Snow Depth, Sea Ice Thickness and Bulk Density, and Ice Freeboard by Combining CryoSat-2, AVHRR, and AMSR Measurements. *IEEE Transactions on Geoscience and Remote Sensing*, **61**, ISSN 15580644 (doi: 10.1109/TGRS.2023.3265274)

Sievers I, Rasmussen TA and Stenseng L (2023) Assimilating CryoSat-2 freeboard to improve Arctic sea ice thickness estimates. *Cryosphere*, **17**(9), 3721–3738, ISSN 19940424 (doi: 10.5194/TC-17-3721-2023)

Warren SG, Rigor IG, Untersteiner N, Radionov VF, Bryazgin NN, Aleksandrov YI and Colony R (1999) Snow depth on Arctic sea ice. *Journal of Climate*, **12**(6), 1814–1829, ISSN 08948755 (doi: 10.1175/1520-0442(1999)012<1814:SDOASI>2.0.CO;2)