A methodologically robust seasonal snow densification function from Soviet North Pole drifting station data

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INTRODUCTION

Snow on sea ice plays a critical role in the polar ocean's 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 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 kgm^{-3}, and t_m is the number of months since October. The equation has now been used in several publications (e.g. Chen and others, 2024; Shi and others, 2023; Jiang and others, 2023; Dong and others, 2023; Fredensborg Hansen and others, 2024; Sievers and others, 2023).

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). Values are sometimes negative 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 more desirable to compute the fits for density directly using the density measurements and their positions in the month concerned. Unfortunately the data to do this have not historically been easily accessible online.

Further drawbacks exist in the averaging and regression process underpinning Equation 1: the area over which M20 averaged the quadratic fits in each month goes beyond that covered by the source data: for example, it includes the Laptev Sea which NP drifting stations rarely visited. It was also only performed over the months of October - April, when the source data from NP stations potentially would allow a function to apply beyond those months. Finally, t 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 performing a direct linear regression on the mean densities measured by the original transects at the Soviet NP drifting stations. Each mean value can be associated with an integer day-of-year, rather than simply a month as in M20. After some data cleaning (see below), a regression of transect-mean density against day-of-year can then be performed, yielding:

$$\rho_s = 0.35t_d + 292.96 \tag{2}$$

Where t_d is the day of year (with a breakpoint on 1st August), and ρ_s remains the snow density in kgm^{-3} as in Equation 1. Five data points have been removed in the months of July and August, four of which are >500 kg^{-3} and one of which is 25 kgm^{-3} (this is likely a measurement error). These extreme values exist near the 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 use generate snow densities from Equation 2 in these months. Despite this, it is clear that Equation 2 can be used to produce values outside of the "cold season" considered by the M20 calculation, for instance in September, May and June.

Figure 1 also makes clear that the new regression slope is not very different from the M20 function in a quantitative sense. The publications cited above using M20 can therefore be trusted. So why make a new one? The first reason is that the simpler methodology can be better trusted in future to represent the underlying data. In addition, the new function also takes a continuous input of day-of-year rather than the month number, aiding its utility as discussed 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`.

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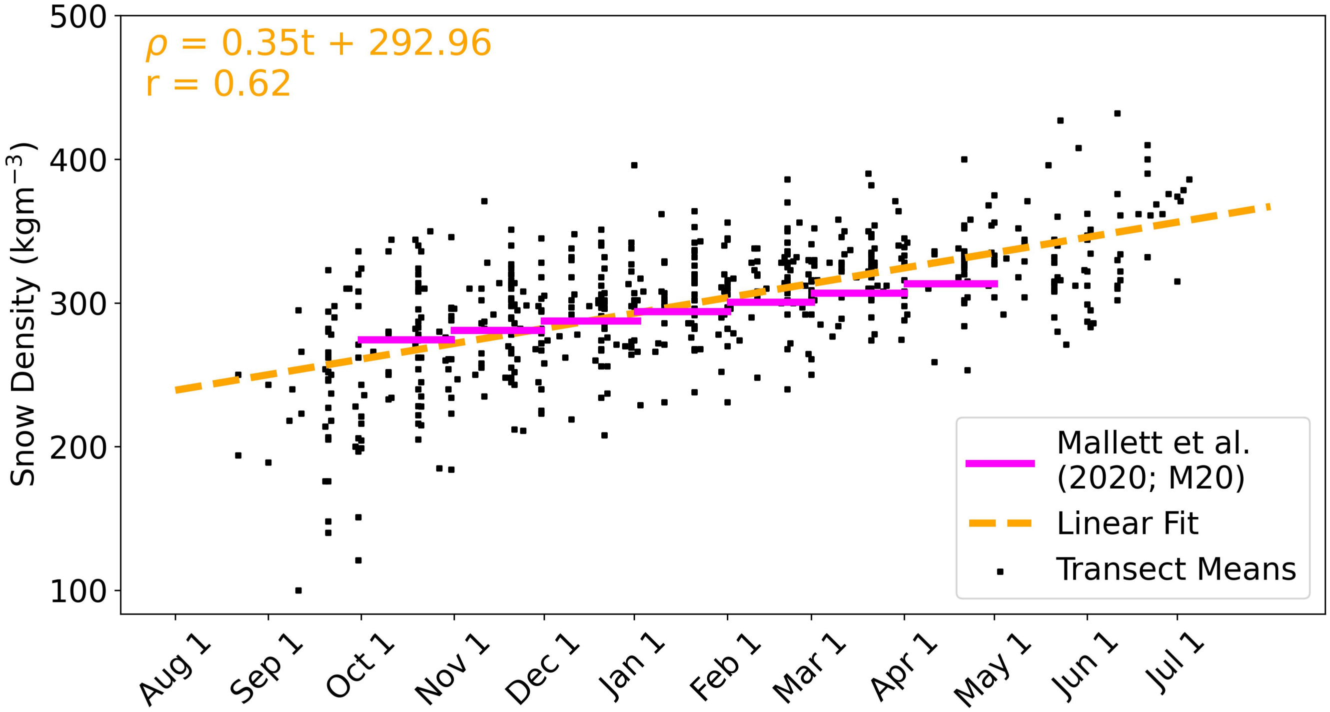

Fig. 1. Transect-mean snow densities (n=573; black scatter), with the M20 values shown as magenta lines. Linear regression through the scatter points shown in orange. Where possible, NP station transects were performed at ten day intervals on the 10th, 20th and 10th of each month, generating a periodic distribution of scatter along the time-axis.