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Brief communication: An empirical relation between center frequency and measured thickness for radar sounding of temperate glaciers

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Abstract. Radar sounding of the thickness of temperate glaciers is more challenging than for polar ice sheets, due to the former's greater volume scattering (englacial water), surface scattering (crevasses and debris) and dielectric attenuation rate (warmer ice). Lower frequency (~1–100 MHz) radar sounders are commonly deployed to mitigate these effects, but the lack of a synthesis of existing radar-sounding surveys of temperate glaciers limits progress in system and survey design. Here we use a recent global synthesis of measured glacier thickness to evaluate the relation between the radar center frequency and maximum thickness. From a maximum reported thickness of ~1500 m near 1 MHz, the maximum thickness sounded decreases with increasing frequency by ~500 m per frequency decade. Newer airborne radar sounders generally outperform older, ground-based ones at comparable frequencies, so radar-sounder success is also influenced by system design and processing methods. Based on globally modeled glacier thicknesses, we conclude that a multi-element airborne radar sounder with a center frequency of ≤ 30 MHz could survey most temperate glaciers more efficiently than presently available systems.

1 Introduction

Measuring the thickness of Earth's mountain glaciers is essential for advancing understanding of their volume, flow and future amid ongoing anthropogenic warming, consequent mass loss and contribution to sea-level rise (Farinotti et al., 2019; Zemp et al., 2019). Radar sounding is unambiguously the method of choice for most surveys of glacier thickness, due to its logistical efficiency relative to other methods while achieving satisfactory precision and accuracy (Welty et al., 2020). However, most mountain glaciers outside the polar regions are either observed or assumed to be temperate (at or near the pressure-melting point throughout), and radar sounding of such ice is substantially more challenging than for polar ice sheets (most of ice column well below the pressure-melting point) or polythermal glaciers (e.g., Pritchard et al., 2020). Three main factors conspire to cause this challenge: 1. Englacial water in pore spaces or fractures, increasing volume scattering (e.g., Fountain et al., 2005); 2. More common crevassing and supraglacial debris, increasing surface scattering (e.g., Herreid and Pellicciotti, 2020); and 3. Warmer ice, increasing the englacial dielectric attenuation rate (e.g., Stillman et al., 2013).

Watts and England (1976) described what may be the primary challenge in radar sounding of temperate ice: meter-scale, water-filled englacial cavities that efficiently scatter incident radio waves when the ratio of those cavities' radius to the radar's englacial wavelength exceeds ~0.1. This analysis favors center frequencies ≤ ~10 MHz to keep the signal-to-noise ratio high between the ice–bed reflection (signal) and the volume scattering arising from the cavities (noise). Their lucid description of this challenge motivated the development of numerous "low-frequency" radar sounders (e.g., Watts and Wright, 1981; Fountain and Jacobel, 1997; Conway et al., 2009; Mingo and Flowers, 2010; Rignot et al., 2013; Arnold et al., 2018; Björnsson and Pálsson, 2020). However, subsequent advances in available hardware, system design and processing demonstrated that higher-frequency (> 10 MHz) radar sounders can also sound hundreds of meters of temperate ice (e.g., Rutishauser et al., 2016; Pritchard et al., 2020). No synthesis yet exists of the success of these radar sounders as a function of center frequency, limiting our ability to identify outstanding opportunities in system design for more efficient sounding of temperate glaciers. Here we evaluate past and potential radar-sounder performance by examining recent global syntheses of both observed and modeled glacier thickness.

2 Data and methods

We primarily use three data sources in this study: 1. The maximum reported ice thickness for individual surveys compiled in the Glacier Thickness Database (GlaThiDa) version 3.1.0 (Welty et al., 2020); 2. The consensus modeled thickness estimates for all glaciers on Earth (Farinotti et al., 2019); 3. The regions, glacier locations, areas and identification numbers of the Randolph Glacier Inventory (RGI) version 6 (RGI Consortium, 2017).

We extend GlaThiDa with one additional field: the center frequency of the deployed radar sounder for surveys that used this method (Supplementary Information). In most cases, we could determine the value of this field directly from other metadata provided by GlaThiDa. In dozens of cases, we reviewed the primary source for the survey cited by GlaThiDa to determine the center frequency, assuming that the radar sounder with the lowest center frequency reported was that which detected the maximum ice thickness reported by GlaThiDa, if that was not stated explicitly. In 210 cases (4% of radar surveys in GlaThiDa), we were unable to determine the center frequency of the deployed radar sounder. For all GlaThiDa entries that reported a maximum thickness for a presumed temperate glacier at the upper end of the range reported for that frequency, we reviewed the original study to validate the value reported in GlaThiDa. For all glaciers with reported raw glacier-thickness data in GlaThiDa but no reported maximum value, which are mostly attributed to Rignot et al. (2013) and Rutishauser et al. (2016), we calculate the maximum thickness directly from those raw data. Finally, we adjust GlaThiDa's survey method field to further distinguish airborne radar-sounding surveys between helicopter and fixed-wing surveys.

We distinguish between regions that are most likely to contain temperate glaciers versus those that mostly contain polythermal or polar glaciers, while recognizing that substantial uncertainty remains in the thermal structure of many mountain glaciers (e.g., Wilson and Flowers, 2013). We assume that temperate glaciers are predominant within all RGI regions except Arctic Canada (03 and 04), Greenland (05), Svalbard (07), the Russian Arctic (09), and the Antarctic and sub-Antarctic (19). Glaciers situated at ≥ 67° latitude (e.g., McCall Glacier, Alaska, and Storglaciären, Sweden), along with known polythermal glaciers in presumably otherwise temperate regions, are excluded from the remaining set: 1. Hazard, Rusty and Trapridge glaciers, Canada (Narod and Clarke, 1980); 2. Gornergletscher, Switzerland (Rutishauser et al., 2016); and 3. Khukh Nuru Uul, Mongolia (Herren et al., 2013). In addition to the resulting 324 frequency–thickness pairs for glaciers in temperate regions from GlaThiDa, we also show values from ground-based surveys recently completed for the Himalaya (440 m at 3.5 MHz; Pritchard et al., 2020) western Canada (318 m at 10 MHz; Pelto et al., 2020) and the Bagley Icefield, Alaska (1460 m at 1.875 MHz; M. Truffer and J. W. Holt, pers. comm., 2020).

3 Results

Fig. 1a shows the relation between reported maximum ice thickness and the center frequency of the deployed radar sounder, further differentiated by survey year (if known or reported) and platform type (for presumed temperate glaciers: 155 ground-based, 102 helicopter and 67 fixed-wing). While qualitatively recognized by many practitioners and sometimes investigated directly for the purposes of system design (e.g., Watts and Wright, 1981; Rutishauser et al., 2016; Pritchard et al., 2020), this relation has not been quantified previously across the full spectrum of frequencies used to sound terrestrial ice masses (~1–1000 MHz).

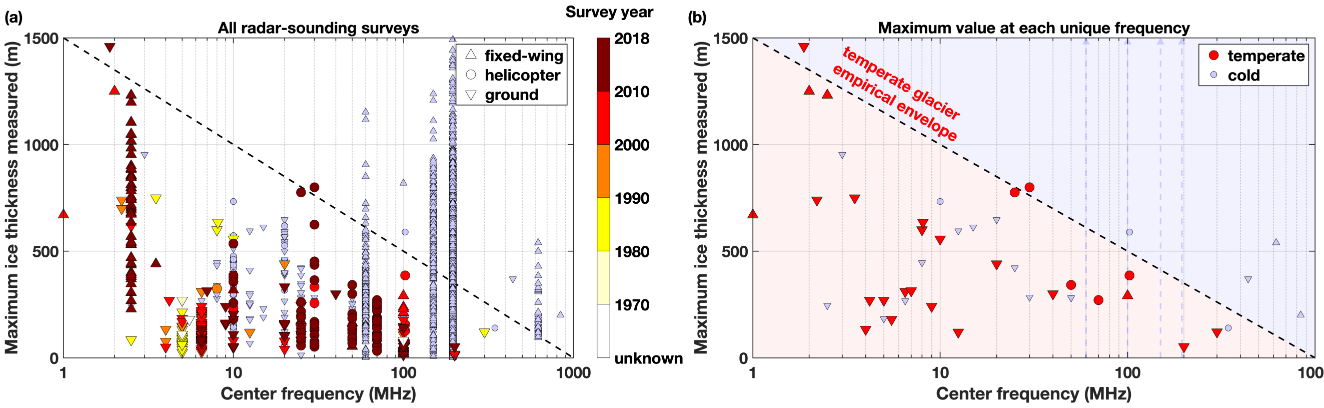

Figure 1: (a) Synthesis of all GlaThiDa v3.1.0 reported maximum ice thickness measured versus the center frequency of the deployed radar sounder, and (b) subset showing only maximum value for each unique frequency (temperate or "cold"). "Cold" glaciers are either those from the polar regions or in temperate regions that are known to be polythermal. Symbol shape indicates platform type. Black dashed line represents the empirical envelope of apparent best sounding performance for temperate glaciers. In panel (a), for presumed temperate

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glaciers, color indicates survey period (if reported). In panel (b), the maximum measured ice thickness for “cold” glaciers at four frequencies (60, 100, 150 and 195 MHz) exceeds the maximum value on the vertical axis (1500 m), represented by vertical blue arrows.

Especially at higher frequencies (≥ 20 MHz), newer radar sounders (2000–onward) outperform older ones, which favored lower frequencies (≤ 10 MHz). Newer airborne systems tend to outperform ground-based systems, and helicopter-borne systems tend to outperform fixed-wing systems at comparable frequencies (e.g., 100 MHz) – presumably due to the former’s slower platform speed and potentially lower altitude above ground level (Fig. 1b). Higher frequencies (≥ 60 MHz) can sound much thicker polythermal or polar ice that has been achieved for temperate glaciers, but this relative performance advantage over temperate ice is reduced significantly at lower frequencies (≤ 20 MHz).

This synthesis contains multiple sampling biases: 1. A radar sounder can only sound temperate ice as thick as the glaciers it surveys, so reported thicknesses are potentially underestimates relative to an individual system’s true capability; 2. While the situation is changing with the advent of globally modeled glacier thicknesses (e.g., Farinotti et al., 2019), radar-sounding surveys have historically not always known beforehand where ice thickness is predicted to be greatest, nor its expected value; 3. Ground-based surveys can only occur where it is safe to do so; and 4. Some surveys were performed during the summer, when englacial water is likely more abundant and hinders radar performance; 5. Some glaciers we assume are temperate – due to their regional setting and the lack of contraindicating observations – are not. The first four biases are likely negative, i.e., they induce an underestimate of the maximum ice thickness that could be sounded at a given frequency, while the fifth bias is positive with the opposite effect. Separately, off-nadir clutter is a well-known source of ambiguity in identification of the ice–bed reflection within valley glaciers (e.g., Holt et al., 2006), and most surveys had no direct method for clutter discrimination (e.g., Conway et al., 2009; Rignot et al., 2013), but its bias can be positive or negative depending on glacier geometry.

Based on this synthesis, we identify a simple envelope of maximum ice thickness sounded for temperate glaciers across more than two decades of frequency range spanned by deployed radar sounders (Fig. 1b). Within this frequency range, the maximum possible ice thickness that can be sounded decreases at a rate of ~500 m per frequency decade, descending from ~1500 m at 1 MHz. This empirical envelope has several limitations: 1. It is simply a linear relation between ice thickness and logarithmic frequency, which was selected because it captures the predominant trend and does not overfit thickness maxima with as-of-yet unjustified complexity; 2. No meaningful uncertainty bounds can be specified presently; and 3. Two surveys report sounding temperate ice slightly thicker than this envelope suggests. The envelope’s value lies in its indirect synthesis of the previously mentioned factors that challenge sounding of temperate ice, its identification of frequencies for radar sounders that may be performing near a natural or present technical limit (e.g., ~2–3, ~25–30 and 100 MHz), and others where radar sounders have either underperformed or may be unusually challenged by temperate ice (~5–20 MHz).

We next calculate the maximum modeled thickness for all larger glaciers (RGI-reported area ≥ 5 km^2) in the RGI inventory within regions where temperate glaciers are assumed to be predominant (Fig. 2). The maximum thickness distribution for each region can be related crudely to a maximum plausible radar-sounder frequency using the empirical envelope from Fig. 1. This comparison highlights the range of frequencies that could plausibly sound most glaciers in these regions, which is larger than assumed previously (Watts and England, 1976). For most temperate regions (10/13), a modern ≤ 100-MHz radar sounder could plausibly sound the maximum ice thicknesses of 95% of their glaciers (< 500 m; Fig. 2). For Alaska, Iceland and the Southern Andes, a lower-frequency (≤ 30 MHz) radar sounder remains necessary, as is observed in practice (e.g., Conway et al., 2009; Björnsson and Pálsson, 2020).

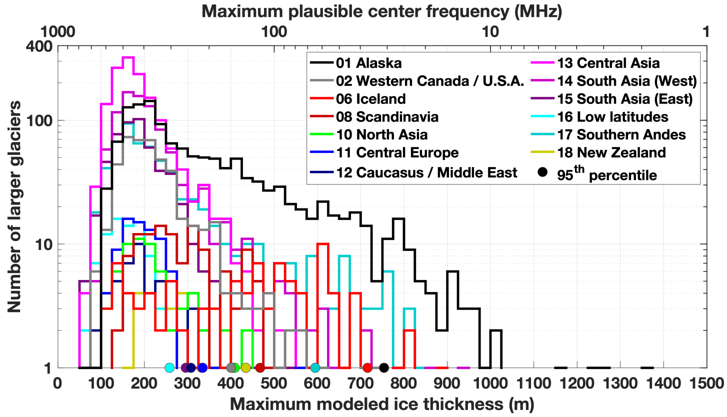

Figure 2: Distribution (line) and 95th percentile (circle) of maximum modeled ice thickness for all larger (≥ 5 km^2) glaciers in RGI regions assumed to contain mostly temperate glaciers. Bin interval is 25 m. Upper horizontal axis is equivalent to the empirical envelope in Fig. 1, e.g., for a glacier whose maximum ice thickness is ~500 m, the maximum center frequency of a radar sounder that could plausibly sound that glacier is ~100 MHz.

We note two contrasting caveats to this analysis: 1. While the modeled maximum thicknesses do not appear to be biased significantly relative to measured values (+62 ± 197 m for the 36% of GlaThiDa surveys we could confidently match using glacier names to a modeled glacier in the RGI inventory), it is not uncommon for radar-sounding surveys of ice masses to report ice thicknesses greater than predicted beforehand, so any survey design based on Fig. 2 should assume a negative model bias and err on the side of a lower frequency; and 2. The maximum modeled thickness is generally only reached at a single point on a glacier, so surveys aiming to measure glacier volume must also consider the ability to resolve smaller thicknesses at a satisfactory resolution. This trade-off could favor a higher center frequency, for which a larger bandwidth is easier to achieve, potentially resulting in a finer range resolution.

4 Discussion and conclusions

Our evaluation of GlaThiDa-compiled thicknesses challenges the conventional wisdom that only low-frequency (≤ 10 MHz) radar sounders are suitable for sounding temperate glaciers that are hundreds of meters thick. An empirical envelope derived from this synthesis suggests that – for many larger temperate glaciers on Earth – higher frequencies are indeed appropriate for radar sounding thereof, assuming suitable system design. While a full accounting of the physical underpinnings of the simple empirical envelope we identified was beyond the scope of this study, the envelope cannot be explained by the relatively weak dispersion of the radio-frequency dielectric attenuation rate (MacGregor et al., 2015), so volume and surface scattering are the more likely controls. Not all glaciers are created equal, and in some cases abundant englacial water, thicker supraglacial debris, an exceptionally crevassed or rough surface, or simply exceptionally thick ice will continue to necessitate the use of lower frequencies to ensure successful sounding.

Models of glacier thickness are increasingly incorporating mass conservation and global satellite remote-sensing datasets, but there remains an outstanding need for additional thickness measurements to both validate and refine those models' underlying assumptions (e.g., Farinotti et al., 2019; Pelto et al., 2020). Our synthesis suggests a higher upper limit (~30 MHz) on potentially suitable radar sounders for sounding temperate ice up to ~700 m thick. Recent advances in hardware and system design could further increase that range, e.g., solid-state transmit/receive switches, higher peak-transmit powers and platform-aware numerical optimization of antenna configurations (Arnold et al., 2020).

The spatial coverage of even the most extensive ground-based radar-sounding survey of a glacierized region can be easily dwarfed by a single airborne survey – assuming that survey's radar sounder can match the performance of the ground-based system (e.g., Pritchard et al., 2020). A higher frequency (e.g., 30 MHz) translates to a dipole antenna that is ≤ 5 m long, a dimension that is sufficiently small that several such elements could potentially be mounted on a fixed-wing aircraft (e.g., Arnold et al., 2018). Multiple (≥ 3) antenna elements in a plane perpendicular to the platform's direction of travel are essential to resolving cross-track ambiguity in the direction of arrival of coherently recorded reflections, i.e., "swath mapping" (e.g., Holschuh et al., 2020). Such a capability could be quite useful for sounding mountain glaciers, as it could transform some of what is presently discarded as noise (discontinuous near-bed subsurface reflections not attributable to surface clutter) into useful signal (geolocated, off-nadir ice–bed reflections) and substantially expand our ability to measure glacier thickness efficiently.

Author contribution. JAM initiated this study, led the analysis and drafted the manuscript. MS aided in the study design, analysis and manuscript preparation. EA, CJL and FRM aided in interpretation of the analysis.

Data and code availability. The Supplementary Information associated with this article contains the new metadata generated for this study, which is in a format similar to GlaThiDa v3.1.0. The analysis was performed using MATLAB R2020b and both its Mapping and Statistics & Machine Learning toolboxes. The script used to perform the analysis and generate the figures is available at: https://github.com/joemacgregor/misc/blob/main/temperate_sounding.m.

Competing interests. JAM is a member of the editorial board of this journal.

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