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Short Communication
Discussion on 'Active Layer Thickness Prediction on the Western Antarctic Peninsula' by Wilhelm *et al.* (2015)

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ABSTRACT

Wilhelm *et al.* (2015) employed the widely used Stefan and Kudryavtsev equations to predict the maximum active-layer thickness (ALT) on Amsler Island, Western Antarctic Peninsula. Their predictions far exceed the observations of ALT reported from other parts of the region. Here, I demonstrate that the values of ALT are significantly overestimated by the predictive equations because the authors incorrectly assumed that little or no latent heat of phase change is absorbed during thawing. Although the area is the warmest in the Antarctic Peninsula region, with a rapid increase in air temperature and permafrost temperatures close to 0 °C, the active layer is likely to be substantially thinner than values predicted by Wilhelm *et al.* (2015). Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: active-layer thickness; permafrost; Stefan equation; Kudryavtsev equation; thermal modelling; Antarctic Peninsula

INTRODUCTION

Wilhelm *et al.* (2015) examined the ability of the Stefan and Kudryavtsev equations and the HYDRUS thermal model to predict maximum active-layer thickness (ALT) and active-layer temperature dynamics at three sites located on Amsler Island (Palmer Archipelago), in the Western Antarctic Peninsula region. The ALT was predicted to be 4.7–8.7 m in soils and unconsolidated materials, and 11.9–18.6 m in bedrock. These values of ALT are exceedingly large compared to others reported from the region (usually up to 1–2 m in unconsolidated materials and up to 2–6 m in bedrock; Vieira *et al.*, 2010; Bockheim *et al.*, 2013) and were attributed to regional climate warming.

I consider this explanation to be oversimplified for the following reasons: (i) the values of ALT predicted by the Stefan and Kudryavtsev equations represent upper limits that assume negligible or no latent heat of phase change is absorbed during thawing; (ii) the ALTs were not validated against any reference ground temperature records from depths exceeding the predicted ALTs (except at the bedrock summit site); and (iii) the predicted ALTs far exceed the ALT ranges reported elsewhere in the Antarctic Peninsula region. Hence, the values of ALT predicted by Wilhelm *et al.* (2015) are thought to be of doubtful validity.

Here, I address these issues by recalculating the original values of ALT predicted by Wilhelm *et al.* (2015) using the Stefan and Kudryavtsev equations and I briefly discuss the ALT in the context of active-layer dynamics in the Antarctic Peninsula region.

ALT PREDICTIONS

The Stefan and Kudryavtsev equations are simplified analytical solutions that have been extensively used for predicting depths of thawing and freezing in unconsolidated sediments/soils (e.g. Romanovsky and Osterkamp, 1997; Klene *et al.*, 2001; Heggem *et al.*, 2006) and rock materials (e.g. Matsuoka, 2008). Both equations incorporate the volumetric latent heat of phase change of water Q_L (J.m^{-3}):

$$Q_L = \rho L(\omega - \omega_u) \quad (1)$$

where ρ is the dry bulk density of the ground (kg.m^{-3}), L is the latent heat of phase change of water (J.kg^{-1}), ω is the total gravimetric water content expressed as a proportion of the mass of total water to the mass of dry ground and ω_u is the unfrozen gravimetric water content (i.e. water not involved in the phase change) expressed as a proportion

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of the mass of unfrozen water to the mass of dry ground. Note that Wilhelm *et al*. (2015) incorrectly used the expression ρL for the volumetric latent heat of phase change in their Equations 1 and 2 (i.e. excluding the water content members). This would imply very high values of volumetric latent heat of phase change and thus a thin active layer.

In order to review the values of ALT predicted by Wilhelm *et al*. (2015), I recalculated the ALT using the Stefan and Kudryavtsev equations with ground temperature data and ground material properties reported in their paper (Table 1). Several scenarios of unfrozen water content (which controls the amount of latent heat of phase change) were entered into the equations in order to obtain ALT limits at the solifluction lobe and climate station sites. Only one scenario was considered for the bedrock summit site, where a total water content of zero was observed. The minimum difference between the total and unfrozen water contents was set to 0.1 % in the Stefan equation to avoid division by zero.

The ALT recalculations most closely match the original ALTs predicted by Wilhelm *et al*. (2015) when the unfrozen water contents are set close to or equal to total water contents. Under these conditions, the recalculated values of ALT average 4.6–8.9 m at the solifluction lobe and climate station sites, and 10.1–16.5 m at the bedrock summit site (Figure 1; Table 2). The relatively small difference between the original and recalculated ALTs likely results from the fact that statistical characteristics (averages and standard deviations) of ground temperature data for the whole observation period entered the calculations instead of real annual ground temperature data. Secondly, the fixed 0.1 % minimum difference between the total and unfrozen water contents (to avoid division by zero in the Stefan equation) likely results in different amounts of latent heat of phase change entering the calculations than in the original paper by Wilhelm *et al*. (2015), which may lead to significant differences in the predicted ALTs due to the exponential nature of the equation. In fact, changes in the unfrozen water content in the order of tenths of a per cent may produce decimetre- to metre-scale differences in the predicted ALTs in cases when little water is involved in the phase change.

Nevertheless, the above predictions represent upper ALT limits by assuming unrealistically high unfrozen water contents. The equations significantly overestimate ALTs in this situation (particularly the Stefan equation), because negligible or no latent heat of phase change enters the calculations. However, the Stefan equation was derived with the assumption that the latent heat of phase change in the active layer is much larger than the sensible heat. If the latent heat approaches zero, then the equation gives invalid results (Romanovsky and Osterkamp, 1997). On the other hand, the Kudryavtsev equation builds on Fourier temperature wave propagation theory and therefore, substituting the latent heat for zero, predicts the maximum depth of the 0 °C isotherm without phase change (Romanovsky and Osterkamp, 1997). Since the soils and unconsolidated

Table 1 Ground temperature data and ground material properties used as input data in the active-layer thickness predictions (averages and standard deviations).

Site	FDD_s	TDD_s	MAGST	A_s	T_z	K_t	C_t	ρ	ω
Solifluction lobe	888 ± 164	307 ± 91	−1.6 ± 0.2	14.0 ± 2.1	−0.7 ± 0.3	0.84	1.45	1700	5.7
Climate station	966 ± 140	175 ± 39	−2.2 ± 0.3	10.4 ± 3.4	−1.9 ± 0.5	1.34	1.83	1520	8.4
Bedrock summit	980 ± 110	219 ± 52	−2.1 ± 0.2	14.8 ± 1.8	−1.3 ± 0.6	3.57	0.78	4000	0.0

FDD_s = surface freezing degree-days (°C.days); TDD_s = surface thawing degree-days (°C.days); MAGST = mean annual ground surface temperature (°C); A_s = annual ground surface temperature amplitude (°C); T_z = mean annual temperature at the top of permafrost (°C); K_t = thermal conductivity of the ground in the thawed state ($W.m^{-1}.°C^{-1}$); C_t = volumetric heat capacity of the ground in the thawed state ($J.m^{-3}.°C^{-1} \times 10^6$); ρ = dry bulk density of the ground ($kg.m^{-3}$) calculated as weighted average of horizon thicknesses; ω = total gravimetric water content (%).

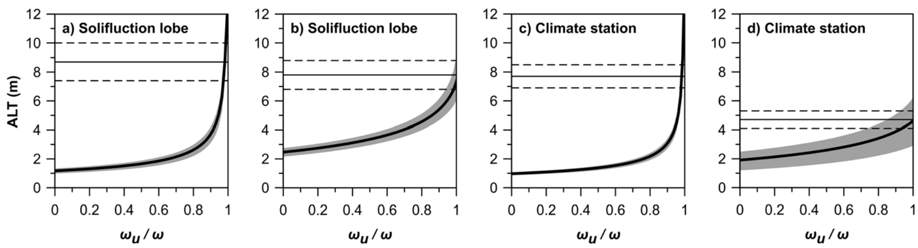

Figure 1 Active-layer thicknesses (ALTs) at the solifluction lobe (a, b) and climate station (c, d) sites as a function of the unfrozen to total water content ratios (ω_u/ω) predicted by the Stefan (a, c) and Kudryavtsev (b, d) equations. Thick black lines show the average ALTs derived on the basis of the average ground temperature data. Grey zones outline the upper and lower ALT thresholds derived on the basis of the standard deviations of ground temperature data. Black solid and dashed horizontal lines represent the original average ALTs and their standard deviations reported by Wilhelm *et al*. (2015).

Table 2 Comparison of the original (Wilhelm *et al.*, 2015) and recalculated active-layer thickness (ALT) predictions (averages and standard deviations).

Site	ALTs (m)		
	Solifluction lobe	Climate station	Bedrock summit
Observed ALT by Wilhelm *et al.* (2015)	—	—	12.5–14.5
Stefan equation			
Original ALT predicted by Wilhelm *et al.* (2015)	8.7 ± 1.3	7.7 ± 0.8	11.9 ± 1.4
Recalculated ALT for $\omega_u \rightarrow \omega$	8.9 ± 1.3	8.9 ± 1.0	10.1 ± 1.2
Recalculated ALT for ω_u = 2 %	1.5 ± 0.2	1.1 ± 0.1	—
Recalculated ALT for ω_u = 0 %	1.2 ± 0.2	1.0 ± 0.1	—
Kudryavtsev equation			
Original ALT predicted by Wilhelm *et al.* (2015)	7.8 ± 1.0	4.7 ± 0.6	18.6 ± 4.9
Recalculated ALT for $\omega_u = \omega$	7.2 ± 1.5	4.6 ± 1.7	16.5 ± 4.2
Recalculated ALT for ω_u = 2 %	3.0 ± 0.3	2.2 ± 0.7	—
Recalculated ALT for ω_u = 0 %	2.5 ± 0.3	1.9 ± 0.6	—
HYDRUS-predicted ALT by Wilhelm *et al.* (2015)	6–8	4–6	8–10

Note: The minimum difference between the total and unfrozen water contents was set to 0.1 % in the Stefan equation to avoid division by zero. ω_u = unfrozen gravimetric water content; ω = total gravimetric water content.

materials at the solifluction lobe and climate station sites have a sand or silty sand texture and winter ground temperatures are well below 0 °C (Wilhelm *et al.*, 2015), the unfrozen water contents are likely very low (Andersland and Ladanyi, 2004). This means that most of the water is involved in the phase change and absorbs the latent heat during thawing, which decelerates active-layer thickening. This is confirmed by Figures 3, 4 and 6 in Wilhelm *et al.* (2015), which clearly show the zero-curtain periods during freezing and thawing at the solifluction lobe and climate station sites. Accordingly, at the bedrock summit site, where the total water content was zero, no zero curtain was observed (see Figures 5 and 8 in Wilhelm *et al.*, 2015). I therefore conclude that the values of ALT at the solifluction lobe and climate station sites should be substantially smaller than those predicted by Wilhelm *et al.* (2015).

Because maximum annual ground temperatures measured at the solifluction lobe and climate station sites in the shallow boreholes at 2 m depths did not fall below 0 °C during the observation period and no ice was present in the excavations (Wilhelm *et al.*, 2015), the ALTs should range between 2 m and the upper ALT limits shown in the previous paragraphs (Figure 1; Table 2). There is a little change in ALTs predicted by the Stefan equation within a wide range of unfrozen water contents until a certain threshold is reached (Figure 1). The unfrozen water contents necessary to exceed the ALT of 2 m are approximately 3.7 % and 6.4 % at the solifluction lobe and climate station sites, respectively (i.e. 65 % and 76 % of the total water content, respectively). However, these unfrozen water contents are too high for sand or silty sand materials (Andersland and Ladanyi, 2004). On the other hand, the Kudryavtsev equation predicts an active layer thicker than 2 m for unfrozen water contents equal to 0 % and 0.7 % at the solifluction lobe and climate station sites, respectively (i.e. 0 % and 8 % of the total water content, respectively), which is much closer to the real situation. Since part of the water always remains unfrozen in the form of thin layers on particle surfaces (Andersland and Ladanyi, 2004), the unfrozen water contents are likely a little higher at these sites (up to 1–2 %). It should generate slightly thicker active layers, on average 2.2–3 m for unfrozen water contents of 2 % (Figure 1; Table 2). In this context, the Kudryavtsev equation seems to provide more accurate ALT predictions than the Stefan equation.

Because the Stefan and Kudryavtsev equations, in their simplest forms, assume homogeneous and temporally invariant ground material properties within the profile (e.g. Kurylyk, 2015), special attention must be paid to the careful collection of representative input data. Although the Palmer Archipelago has one of the largest precipitation rates in the Antarctic Peninsula region (Bockheim *et al.*, 2013) and winter snow cover thickness can exceed 1 m (Wilhelm *et al.*, 2015), the total water contents reported at the solifluction lobe and climate station sites (Table 1) are smaller than elsewhere in the region (e.g. Cannone *et al.*, 2006; Michel *et al.*, 2012). The reason may be that the samples used for determining ground material properties were collected only from near-surface horizons at the end of the thawing season (in April). In summer, however, water migrates downwards under a negative temperature gradient and the total water content at the bottom of the active layer and the upper part of permafrost increases, while it decreases near the ground surface (French, 2007). It is therefore possible that the total water contents reported by Wilhelm *et al.* (2015) are close to their seasonal minima. This is particularly important because the water content and its distribution within the active layer define the amount of latent heat and the rate of thawing, but also the thermal properties, as these parameters are interdependent (Shur *et al.*, 2005). Additionally, the bulk density, also determining the amount of latent heat, was estimated from sand and organic matter contents using pedotransfer functions given in Minasny and Hartemink (2011). These equations can be particularly useful in cases when input data are lacking or cannot be obtained directly, but they generally show a considerable scatter. More importantly, they were calibrated for predicting bulk densities in the tropics and their accuracy in polar soils has not yet been tested, which may further complicate ALT predictions.

ALT VALIDATION

Wilhelm *et al.* (2015) measured ground temperatures using iButton® DS1922L loggers (Maxim Integrated Inc.) with a resolution of ±0.0625 °C and an accuracy of ±0.5 °C, which have also been used elsewhere in the Antarctic Peninsula region (e.g. Ramos *et al.*, 2009; De Pablo *et al.*, 2014). Although Gubler *et al.* (2011) stated that the accuracy of these devices can be as good as ±0.125 °C, it should be emphasised that they can show a significant offset (Schoeneich, 2011), occasionally even beyond the manufacturer-specified limits (personal observations of Tomáš Uxa and Peter Mida). Hence, the loggers should be calibrated at 0 °C in an ice-water bath or using the zero curtain to obtain more accurate ground temperature data (Schoeneich, 2011). If not calibrated, the data should be treated with caution. Because Wilhelm *et al.* (2015) did not calibrate the loggers, their ground temperature data may significantly deviate from real conditions. This is important, especially with respect to ground temperatures in the deep borehole at the bedrock summit site, where minimum and maximum annual ground temperatures at a depth of 8 to 14.5 m are between −0.5 and 0.5 °C (see Figure 7 in Wilhelm *et al.*, 2015). Given the accuracy of the loggers, the active layer at this site may be much thinner than the values of 12.5 to 14.5 m reported by Wilhelm *et al.* (2015). Further, the temperature of the deep borehole should be considered carefully because it was drilled using a water-cooled system that generally causes great thermal disturbance (e.g. Ramos *et al.*, 2009) and the time required to re-establish thermal equilibrium can take up to several weeks or even months (Andersland and Ladanyi, 2004; Miller, 2004).

One of the major problems of the paper by Wilhelm *et al.* (2015) is the absence of any reference ground temperature records below 2 m depth at the solifluction lobe and climate station sites, which would allow the authors to directly validate the accuracy of the predicted ALTs. Instead, it relies on tests of accuracy carried out in previous studies (e.g. Romanovsky and Osterkamp, 1997; Klene *et al.*, 2001; Heggem *et al.*, 2006) and on the ALTs predicted by the HYDRUS thermal model. The HYDRUS-predicted ALTs were generally smaller than those obtained by the Stefan and Kudryavtsev equations, which exceeded or ranged around the upper HYDRUS-predicted ALT limits (Table 2). However, HYDRUS is unable to accurately model isothermal conditions associated with the latent heat release and absorption during freezing and thawing (the zero-curtain effect) in the soils and unconsolidated materials (see Figures 4 and 6 in Wilhelm *et al.*, 2015). This causes, on the one hand, temperature overestimation during the thawing periods and, on the other, temperature underestimation during the freezing periods. Although the authors state that the difference between the observed and HYDRUS-modelled temperatures became negligible after a few weeks of thawing or freezing, even this relatively small difference may result in modelled active layers that are substantially thicker than the real ones. Further, the comparison of the observed and HYDRUS-modelled temperatures was done for relatively shallow depths (60 and 80 cm). But temperatures at these depths are strongly controlled by the upper boundary conditions, and the model may perform much worse at greater depths. Therefore, with respect to ALT predictions, model validation against the deepest temperature sensors located at 2 m depth would be more appropriate.

Another important source of error in the HYDRUS-modelled temperature is setting the initial ground temperatures at −1 °C at all the modelling depths without model equilibration prior to the start of the modelling period. Consequently, the model deviates from the actual conditions at the beginning of the modelling period (see Figures 4 and 6 in Wilhelm *et al.*, 2015). However, much more importantly, the 3-year model run is too short to equilibrate temperatures, particularly at greater depths, which may significantly affect the HYDRUS-predicted ALTs. In order to eliminate this problem, the initial conditions should be created (e.g. using one season as spin-up until steady-state conditions are reached) (e.g. Hipp *et al.*, 2014), at least in the uppermost part of the modelling domain, where maximum ALT is expected.

CLIMATE WARMING EXPLANATION?

Palmer Archipelago is the warmest in the Antarctic Peninsula region (Morris and Vaughan, 2003), with a rapid warming trend (e.g. Turner *et al.*, 2005) and permafrost temperatures close to 0 °C (Bockheim *et al.*, 2013; Wilhelm *et al.*, 2015). Because climate is a first-order control on ALT (Bonnaventure and Lamoureux, 2013), thicker active layers on Amsler Island are expected. However, their exceptional thickness in comparison to other ALTs reported from the region is hard to explain by regional climate warming alone. Positive temperature trends have been detected throughout the whole Antarctic Peninsula over the past few decades, with the lowest spatial variability during the summer months (e.g. Turner *et al.*, 2005). This climate signal would undoubtedly thicken active layers in a similar magnitude at other locations affected by climate warming, even though the importance of mean annual ground surface temperatures, ground temperatures during the freezing season and/or precipitation rates for active-layer dynamics has also been highlighted recently (Bonnaventure and Lamoureux, 2013). Nevertheless, such thick active layers as those inferred by Wilhelm *et al.* (2015) have not been observed elsewhere in the region, even in a similar climate and geological setting (see Vieira *et al*., 2010; Bockheim *et al*., 2013).

Reports prior to 1980 mention ALTs of 0.25–0.35 m below moss beds in the Palmer Station area, located approximately 1 km from Amsler Island (Everett, 1976, and Smith, 1982, cited in Bockheim *et al*., 2013). Observations from maritime Antarctica show that moss-covered sites have active layers approximately two to four times thinner than bare ground locations (Cannone *et al*., 2006; Guglielmin *et al*., 2012). Accordingly, it can be estimated that over 35 years ago, the approximate ALT at bare ground sites ranged between 0.5–0.7 and 1–1.4 m in the Palmer Station area. Unfortunately, because permafrost temperature and ALT monitoring started no earlier than in 2000 throughout most of the Antarctic Peninsula, with most monitoring starting during the International Polar Year 2007–2009 (Vieira *et al*., 2010), it is difficult to quantify reliably the climate change impact on ALT at most of the monitoring sites. The rare long-term ALT observations on Signy Island, in the South Orkney Islands, however, show that active-layer thickening rates are slow, averaging 1 cm.yr^{-1} (Cannone *et al*., 2006). The same or even slower rates were reported from Victoria Land, in continental Antarctica (Guglielmin and Cannone, 2012; Guglielmin *et al*., 2014a). In this context, the extremely thick active layers predicted by Wilhelm *et al*. (2015) appear to be unlikely.

Further, the Western Antarctic Peninsula area has smaller ranges of temperature than other parts of the Peninsula, owing to its more maritime climate. This should generate smaller ALTs, assuming that the mean annual ground surface temperatures and ground material properties are equal. However, the ALTs predicted by Wilhelm *et al*. (2015) show the opposite tendency when compared to those of other locations with larger temperature amplitudes and similar mean annual ground surface temperatures (e.g. Guglielmin *et al*., 2012, 2014b), which is hard to explain by differences in ground material properties. In fact, the surface thawing degree-days are substantially lower on Amsler Island than at other sites within the Antarctic Peninsula (e.g. Guglielmin *et al*., 2012, 2014b; Hrbáček *et al*., 2015) or the northern hemisphere (e.g. Christiansen *et al*., 2010), where thinner active layers have been reported.

CONCLUSIONS

Palmer Archipelago is the warmest area in the Antarctic Peninsula region, with permafrost temperatures close to 0 °C. In this context, the ground temperature data presented by Wilhelm *et al*. (2015) are of great interest, particularly with respect to ongoing climate change in the region.

Nevertheless, extremely thick active layers predicted by the Stefan and Kudryavtsev equations represent the upper limits of ALT and assume that little or no latent heat of phase change is absorbed during thawing. The predictive equations overestimate ALTs in this situation and therefore, the ALTs predicted by Wilhelm *et al*. (2015) are significantly overestimated and misleading. This is all the more serious as the region is an important climate change hotspot and the ALT predictions presented by Wilhelm *et al*. (2015) bring noise into the debate on climate change and its quantification.

Unfortunately, the Wilhelm *et al*. (2015) study lacks any reference ground temperature records from depths exceeding the predicted ALTs (except at the bedrock summit site) and so cannot validate the predicted values of ALT. As a result the study is unable to properly answer the main research question, which was to examine the ability of the Stefan and Kudryavtsev equations and the HYDRUS model to predict ALTs on Amsler Island.

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