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Near-surface permafrost degradation: How severe during the 21st century?

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[1] A previously presented model on nearly complete near-surface permafrost degradation in the Arctic during the 21st century is critically reviewed. An alternative model with a more complete mathematical formulation of the physical processes acting in permafrost terrain is presented, which suggests that permafrost will mostly prevail in this century in areas north of 70°N. Furthermore, permafrost will survive at depth in most areas between 60° to 70°N. Based on paleoclimatic data and in consequence of this study, it is suggested that scenarios calling for massive release of methane in the near future from degrading permafrost are questionable. **Citation:** Delisle, G. (2007), Near-surface permafrost degradation: How severe during the 21st century?, *Geophys. Res. Lett.*, *34*, L09503, doi:10.1029/2007GL029323.

1. Introduction

[2] The Arctic regions have experienced considerable warming during the 20th century [*Lachenbruch and Marshall*, 1986], causing severe impacts on surface layers of permafrost and initiating thermokarst. The warming is likely to continue during the next decades with dire consequences for man-made infrastructures, especially in areas of discontinuous permafrost. A numerical simulation of impending permafrost degradation was presented by *Lawrence and Slater* [2005] based on a fully coupled atmosphere-ocean-land-sea ice model (CCSM3 by *Collins et al.* [2006]). However, their approach appears to be somewhat incomplete due to the application of several questionable boundary conditions.

[3] The limitation of the computational domain to the uppermost 3.43 m of the ground in their model excludes a proper inclusion of the cooling effect of colder and deeper levels acting on the active layer zone (a point actually touched upon in statement [15] of their paper), which (see below) leads to an improper estimate of the future fate of the active layer thickness (ALT).

[4] A second objection with the Lawrence and Slater model is in connection with the definition of an approximately 8°C difference (ΔT) between mean annual air temperatures (MAAT) versus mean annual ground surface temperatures (MAGT) during the 20th century (see top left of Figure 2 of *Lawrence and Slater* [2005]). ΔT is the key parameter to define the ground temperatures at depth below the zone of zero annual amplitude. The MAAT today is about −12°C along the northern coast of Alaska and about −7°C in the Interior along 66.5°N [*Lachenbruch and Marshall*, 1986]. Given a ΔT-value of +8°C, the MAGT below the zone of zero annual amplitude would be slightly warmer than −4°C along the Alaskan coast (a value typical of the widespread discontinuous permafrost zone) and slightly warmer than +1°C in the Alaskan Interior (no permafrost). This is in clear conflict with field evidence (see for comparison *Lawrence and Slater* [2005, Figure 1c]). Realistic ΔT-values are near +3.5°C [see e.g., *Brown and Péwé*, 1973]. A recent field study of *Chen et al.* [2003] in western Canada yielded again a ΔT-value of about +3.5°C. The ΔT-value is result of the insulating effects of the annual snow cover and the vegetation. Its value might slightly vary in time, if climate conditions and vegetation type change. Ground temperatures of −10°C to −12°C below the depth of zero annual amplitude were reported for Siberia by Baranov in 1959 [see e.g., *Washburn*, 1979, Figure 3.9]. MAAT's along the northern coast of Siberia between the Kara Sea and Bering Strait averaged at that time between −12°C to −14°C [*Joint Departments of the Army and Air Force, USA*, 1987]. Field relations here again suggest ΔT-values near 2°C to 4°C. For recent data on surface temperatures in the Arctic see e. g., *Comiso and Parkinson* [2004]. A MAAT minimum of −18°C (1987-data set) or surface temperature minimum of −15°C (2004-data set) occurs in Siberia near 135°E, 68°N. Notwithstanding projected climatic warming on the order of +8°C during the 21st century, this large region will continue to exhibit permafrost and an active layer in hundred years from now, not shown in Figure 2b of *Lawrence and Slater* [2005].

2. Model

[5] Here, a unidimensional long term permafrost temperature model of general application (for details see *Delisle* [1998]) is presented, which is capable to fully incorporate all relevant thermal processes within the active layer and the permafrost, and between the permafrost and the non frozen ground below. The model space is made up of 600 layers with a minimum spacing of 10 cm within the active layer and the uppermost "permafrost zone". The results of two model run versions are presented. Each model version considers four cases which feature different initial MAAT-values (−12.5°C, −9°C, −6°C and −4°C). Adopting a ΔT value of +3.5°C, MAGT-values are then −9°C, −5.5°C, −2.5°C and −0.5°C. Surface temperature will vary in a sinusoidal fashion with annual amplitude of ±15°C (see e. g., *Delisle and Allard* [2003] for field measurement of annual MAGT-amplitude in permafrost terrain). The surface temperatures will increase in model version 1 (MV1) at a constant rate of 0.8°C per decade for a time period of 100 years in close analogy to the SRES A2-scenario [*Intergovernmental Panel on Climate Change*, 2001].

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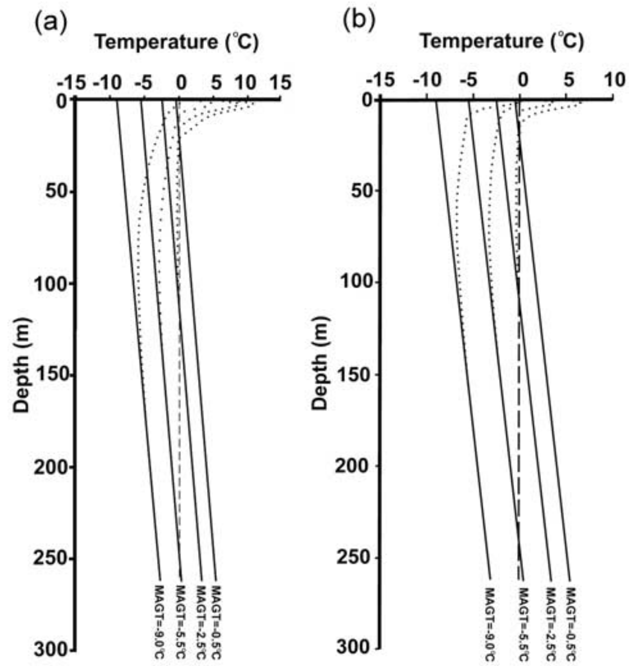

Figure 1. (a) Calculated temperature depth profiles for t = 0 (solid line) and t = 100.5 years (dotted line) for four model runs with different initial MAGT values and climatic warming by 8°C until the year 2100. Vertical broken line marks permafrost boundary. Model run with MAGT = −0.5°C today: permafrost completely degrades at a depth of 22.5 m in 100 years from now. (b) Same as in Figure 1a, but with assumed climatic warming by 4°C until the year 2100. Permafrost will survive in all four MAAT-scenarios.

Alternatively, a more modest surface temperature increase with a constant rate of 0.4°C per decade until 2100 (model version 2 – MV2) is considered (a reasonable assumption covering the possible scenario of effective measures to limit CO_2-emissions in the upcoming decades). For simplicity, a uniform thermal conductivity value of 1.8 W m^{-1} K^{-1}, a uniform heat capacity value of 2.2 10^6 W m^{-3} K^{-3}, a latent heat content of 0.9 10^8 Ws m^{-3} in permafrost (equivalent to 30% ice content) and a terrestrial heat flow of 40 mW m^{-2} (typical for continental shield terrain) was incorporated. A freezing point at 0°C is prescribed.

3. Principles of Permafrost Decay

[6] A region with permafrost degradation will pass through three successive stages. These are: (1) A permafrost layer exists with the presence of an annual active layer. (2) Progressive warming causes the top boundary of the permafrost to recede. An unfrozen zone between the base of the annually developing surficial freezing layer during winter and the main body of frozen ground at depth is maintained. (3) Permafrost at depth becomes isothermal and decays with time.

4. Discussion

[7] The calculated subsurface temperature depth profiles for t = 0 and after t = 100.5 years (time instant with temperature amplitude at maximum, i.e. end of summer for the active layer) are shown in Figure 1a for all MV1-versions and in Figure 1b for MV2-versions. Let us consider first the case of an 8°C-warming (MV1) until the year 2100: Areas with MAAT's below −9°C today will remain frozen within the next 100 years from the Earth's surface to the base of permafrost. However, their ALT will increase with time (solid line in Figure 2a). Areas with current MAAT's between −9°C to −6°C with keep their permafrost essentially intact as well, however with the exception that the top of the permafrost zone will drop by several m in comparison to the position of today (solid lines in Figure 2a). In the case of MAAT = −4°C (equivalent to MAGT = −0.5°C) will the permafrost body reach practically isothermal conditions within five years from now and will decay within the next 100 years (grey area in Figure 2a). The broken lines in Figure 2a indicate the maximum depth of the annual freezing top soil after it will no further reach the top of the permafrost main body (stage 2 - see above). The black arrows indicate the time instance of this disconnection. Afterwards, an ever widening unfrozen zone will develop between the annually freezing top soil and the top of the permafrost zone below (gap between broken to solid lines). From this time on a more rapid increase of permafrost degradation will ensue, since the physical connection from the permafrost zone to the annual cold wave (annual cooling event) from the soil surface is severely weakened. The MV1-runs with current MAGT's of −5.5°C (−2.5°C) suggest that the top of permafrost will be lowered from 1.6 m (2.1 m) to 6.9 m (15.9 m) within few decades beyond the break away points.

[8] In the case of a warming of +4°C until the year 2100 (MV2), permafrost will essentially remain intact for regions with current MAAT's between −12.5 to −6°C (MAGT between −9 to −2.5°C in Figure 2a). A disconnection of the base of the ALT with the top of the permafrost will occur in areas with MAGT > about −3°C (see broken lines in Figure 2b). In the case of current MAAT = −4°C (MAGT = −0.5°C), a remnant of isothermal permafrost is predicted to exist in the depth range between about 14 to 22 m depth in the year 2100 (grey area in Figure 2b).

[9] The presented numerical models include all relevant heat transfer processes and predict survival of continuous permafrost in Alaska and Siberia with current MAAT's below about −11.5°C within the next 100 years, even, if a significant climatic warming (such as predicted by SRES A2) takes place. Areas with current MAAT's below −6°C will essentially maintain their permafrost zone at depth, however with ground temperatures much nearer the melting point and with an upper permafrost boundary progressively receding from the Earth's surface.

[10] Disregarding Scandinavia, the discontinuous permafrost boundary coincides roughly with 60°N latitude. The most recent survey on Arctic surface temperatures [*Comiso and Parkinson*, 2004] indicates that vast areas of the Arctic bounded by 60°N are exposed to surface temperature values of less than −7°C. Based on this result and on the presented analysis, it appears that all areas north of 60°N will maintain permafrost at least at depth. North of 70°N, surface temperature values today are in general below −11°C. These areas should maintain their active layer. It appears unlikely that almost all areas with near-surface permafrost today will lose their active layer within the next 100 years (SRES A2-scenario) as concluded by *Lawrence and Slater* [2005].

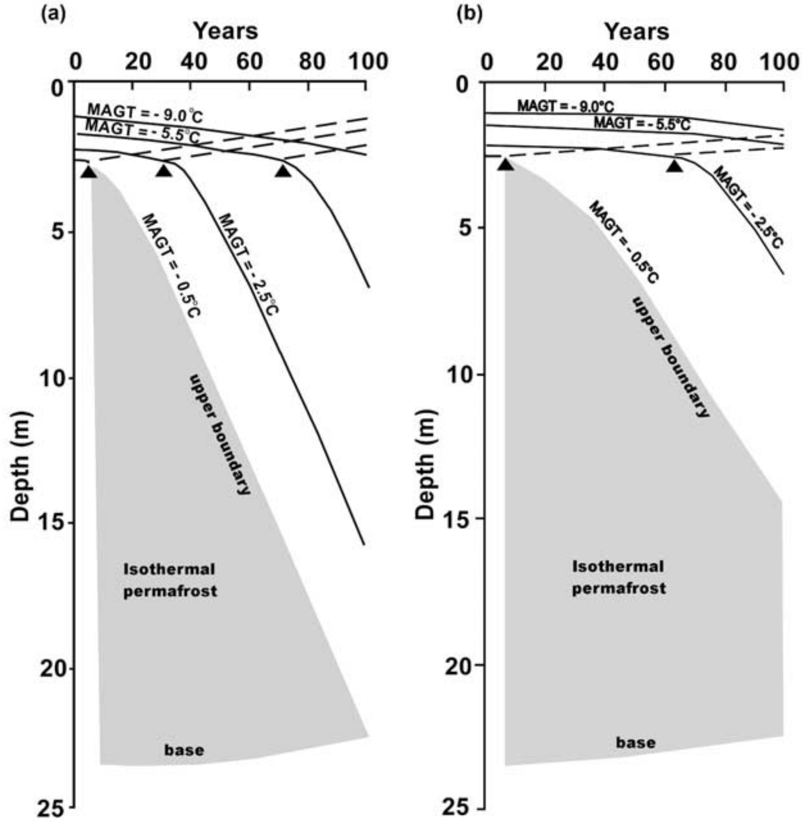

Figure 2. (a) Assumed climatic warming of 8°C until the year 2100: solid lines show base of ALT or, during stage 2 (for explanation see text), the upper limit of the permafrost zone. Broken lines show base of annual freezing zone, whenever the base of the annual freezing front no longer reaches the permafrost main body (stage 2). In the case of MAAT = −4°C (equivalent to MAGT = −0.5°C): permafrost soon reaches isothermal conditions. Final degradation occurs at a depth of 22.5 m. (b) Same as in Figure 2a, but with an assumed climatic warming rate of 4°C until the year 2100.

[11] The first key difference between the approach of this paper and *Lawrence and Slater* [2005] lies in the inclusion vs. omission of an energy flux component from the core body of permafrost toward the base of the active layer. This component cannot be disregarded. The negative energy flux from below (cooling) is on the order of several hundred mW m^{-2}. This flux - in comparison to the positive energy flux from the Earth's surface (typically 1–5 W m^{-2}, averaged over the course of one year) - is a non-negligible component. A second key difference between both approaches is the choice of the ΔT-value. The models presented here start with a more realistic estimate of temperature depth profiles in close agreement with field measurements.

5. Consequences

[12] Concern has been raised by *Lawrence and Slater* [2005] and others - e.g., *Zimov et al.* [2006] - over a much accelerated release of greenhouse gases following rapid degradation of permafrost. This study suggests that this concern should be limited largely to areas of discontinuous permafrost of today, where melting of permafrost is projected to be concentrated during the next 100 years. A second, rarely touched upon question is associated with the apparently limited amount of organic carbon that had been released from permafrost terrain in previous periods of climatic warming such as e.g. the Medieval Warm Period or during the Holocene Climatic Optimum. There appear to be no significant CH_4-excursions in ice core records of Antarctica or Greenland during these time periods [see e.g., *Chappellaz et al.*, 1997] which otherwise might serve as evidence for a massive release of methane into the atmosphere from degrading permafrost terrains. Pre-industrial methane concentrations in the atmosphere vary during the Holocene within a narrow bandwidth between 570 and 770 ppb.

[13] A drawback that afflicts the Lawrence and Slater- as well as the here presented model on permafrost degradation is the role of heat transfer by moving groundwater. Penetration of "warm" groundwater into unfrozen sections of permafrost has been observed to be a very effective agent to speed up permafrost melting [*Delisle et al.*, 2005]. This argument is a highly relevant factor in particular in areas with discontinuous permafrost. Future, more sophisticated models on permafrost degradation will have to include a mathematical formulation to include the magnitude of this thermal effect, whose magnitude, incidentally, depends strongly on local factors.

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