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## PERSPECTIVE

# Non-climatic factors and long-term, continental-scale changes in seasonally frozen ground

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Numerous studies indicate that the northern high latitudes are experiencing an unprecedented rate of environmental change, including an increase in air temperatures (e.g. Serreze and Francis 2006), reduction of snow cover (e.g. Brown and Robinson 2011), ecosystem transformations and land cover changes (e.g. Callaghan *et al* 2011). Many of the potential environmental impacts of global warming in the high latitudes are associated with frozen ground, which occupies about 55% of the unglaciated land area in the northern hemisphere and consists of both permafrost and seasonally frozen ground. Frozen soils have a tremendous impact on hydrologic, climatic and biologic systems. Periodic freezing and thawing promote changes in soil structure, affect the surface and subsurface water cycle, and regulate the availability of nutrients in the soil for plants and biota that depend upon them. Freezing and thawing cycles can affect the decomposition of organic substances in the soil and greenhouse gas exchange between the atmosphere and land surface.

Significant efforts have been devoted to permafrost-related studies, including the establishment of standardized observations (e.g. Romanovsky *et al* 2010, Shiklomanov *et al* 2008), modeling (e.g. Riseborough *et al* 2008), and climate-related feedback processes (e.g. Schuur *et al* 2008). Despite its vast extent and importance, seasonally frozen ground has received much less attention. One of the major obstacles in assessing changes in seasonally frozen ground is the lack of long-term data. In general, observations on soil temperature and freeze propagation are available for a limited area and involve a relatively short time period, precluding assessment of long-term, climate-driven change. A few known exceptions include shallow soil temperature and freeze/thaw depth observations conducted as part of the standard hydrometeorological monitoring system in China (e.g. Zhao *et al* 2004) and the Soviet Union/Russia (e.g. Gilichinsky *et al* 2000).

In their recent paper entitled 'An observational 71-year history of seasonally frozen ground changes in Eurasian high latitudes', Frauenfeld and Zhang (2011) provided detailed analysis of soil temperature data to assess 1930–2000 trends in seasonal freezing depth. The data were obtained from 387 Soviet non-permafrost meteorological stations. The authors performed systematic, quality-controlled, integrative analysis over the entire former Soviet Union domain. The long-term changes in depth of seasonal freezing were discussed in relation to such forcing variables as air temperature, degree days of freezing/thawing, snow depth and summer precipitation as well as modes of the North Atlantic Oscillation. The spatially average approach adopted for the study provides a generalized continental-scale trend. The study greatly improves, expands and extends previous 1956–90 analysis of the ground thermal regime over the Eurasian high latitudes (Frauenfeld *et al* 2004).

Although the work of Frauenfeld and Zhang (2011) is the most comprehensive assessment of the continental-scale long-term trends in seasonal freezing

available to date, more detailed analysis is needed to determine the effect of climate change on seasonally frozen ground. It should be noted that, in addition to the variables considered for analysis, other non-climatic factors affect the depth of freezing propagation. Unlike the surface, which is influenced by the climate directly, the ground even at shallow depth receives a climatic signal that is substantially modified by edaphic processes, contributing to highly localized thermal sensitivities of the ground to climatic forcing. Subsurface properties, soil moisture, and snow and vegetation covers influence the depth of freezing. Topography also plays an important role in establishing the ground thermal regime. It is an important determinant of the amount of heat received by the ground surface, affects the distribution of snow and vegetation, and influences the surface and subsurface moisture regimes. As a result, the ground temperature and the related depth of freezing propagation are characterized by very high variability over short lateral distances.

The data used for analysis by Frauenfeld and Zhang are single-point measurements obtained from a network of stations sparsely distributed over a very large spatial domain. Since no variability in edaphic conditions was considered, the presented results should be interpreted with some degree of caution. In addition, long-term soil observations at a single point using unautomated techniques unavoidably cause site disturbance, which may significantly modify the ground thermal regime over time.

I would like to emphasize that the generalized continental trend in the depth of seasonal freezing presented by Frauenfeld and Zhang is very likely associated with changes in atmospheric forcing. However, any long-term continental trends of such a spatially heterogeneous and sensitive parameter as shallow soil temperature potentially include a significant non-climatic component. Although the single-point temperature data used by Frauenfeld and Zhang might not be sufficient to fully evaluate the localized effects on the overall trend, they are a terrific asset for further studies on climate and ground thermal regime. Detailed spatial assessment of the available ground temperature records over relatively homogeneous regions is a necessary next step in the assessment of climate-induced changes in seasonally frozen ground. Such an analysis is likely to show significant regional differences in long-term freeze propagation trends over Northern Eurasia and reveal region-specific sensitivities of the ground thermal regime to climatic forcing.

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