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Modeling thermokarst lake expansion on the Qinghai-Tibetan Plateau and its thermal effects by the moving mesh method

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ABSTRACT

The increasing number of engineering activities on the Qinghai-Tibetan Plateau, along with a warming climate, tend to induce significant thermokarst processes. However, thermokarst lake development on the plateau and the long-term influence of thermokarst dynamics on the surrounding permafrost have not been fully understood. Based on the moving mesh method, we developed a dynamic model of lake growth with phase change to investigate the morphologic processes of a thermokarst lake and its long-term influence on the local permafrost thermal regime. Our numerical results indicated that lake expansion due to thermokarst development was fairly rapid, and it depended on many factors including lake-bottom temperature and permafrost temperature. The depth and radius of the simulated lake increased gradually from the end of May to the end of the following January, and remained stable from February to May due to the lower lake-bottom temperature. Our results also showed that lake expansion was not very sensitive to climate warming in the first 50 years after the formation of a thermokarst lake, but the lake expansion was clearly affected by a warming climate in the long run (200 years). The development of a thermokarst lake is shown to significantly enhance the thermal effects on the surrounding permafrost. Compared with a fixed-boundary thermokarst lake, an active (moving-boundary) thermokarst lake caused greater thermal disturbance to the permafrost around and beneath it.

1. Introduction

Thermokarst lakes are topographic depressions which develop as a result of thawing of ice-rich permafrost or melting of massive ground ice. Thermokarst lakes area major component of ice-rich permafrost landscapes and are widespread on the Qinghai-Tibetan Plateau, and are seen as sensitive indicators of environmental change (Niu et al., 2011). Thermokarst lakes have a significant influence on surrounding permafrost environments (Osterkamp et al., 2000), mainly on changes in thermal regimes and permafrost degradation (Zhou and Huang, 2004). These cause a series of environmental problems, such as water table depression, vegetation degradation, land desertification, and infrastructure instability (Burn, 2005; Lin, 2011; Lunardini, 1996; Osterkamp et al., 2009). In recent years, human activities and changed climate along the Qinghai-Tibet engineering corridor have initiated significant thermokarst processes (Niu et al., 2011; Wang and Mi, 1993) and have resulted in extensive and serious disturbances in sensitive permafrost environments on the Qinghai-Tibetan Plateau. These disturbances have seriously affected the stability of nearby infrastructure and the performance of built structures in that vicinity (Lin et al., 2012).

Thermokarst processes usually develop rapidly after the formation of thaw ponds. Both the rates of thermokarst lake development and changes in the dimensions of thermokarst lakes play an important role in the local permafrost thermal regime and permafrost degradation. For example, the thermal impacts of thermokarst lakes on nearby engineering works can show a visible difference due to the changes in the lake expansion rate and a decreasing distance between an engineered structure and a thermokarst lake (Lin et al., 2012). Thermokarst expansion may accelerate the release of greenhouse gases sequestered in permafrost and can disperse a significant amount of methane into the atmosphere (Zimov et al., 1997). To predict the future environmental effects of thermokarst dynamics, it is necessary to understand the processes involved in thermokarst lake development and their thermal effects.

Several models have already been developed to study thermokarst lakes and their effects on ground temperatures. Lin et al. (2012) employed a heat transfer model with phase change to predict the thermal regime changes beneath a frozen ground roadbed, and possible subgrade defects. Their results showed that a thermokarst lake caused thermal erosion of permafrost under the roadbed and the amount of thermal erosion depended mainly on the annual average lake-bottom temperature and the distance from the roadbed to the lake edge. Ling and Zhang (2003) simulated the long-term influence of shallow thermokarst lakes on the thermal regime of permafrost and talik development on the Alaskan Arctic Coastal Plain, by an unsteady finite-element heat transfer model with phase change. Zhou and Huang (2004) developed a transient heat transfer model to simulate a

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multimedia system including snow cover, thermokarst lake, and frozen soil, which revealed the impacts of thermokarst lakes on the thermal regime and the formation of talik and lake ice. However, most thermokarst lake models ignore thermokarst lake dynamics and treat the lake morphology as unchanging.

Similar to other thermokarst processes, the evolution of a thermokarst lake is a sediment redistribution process initiated by thawing of ice-rich permafrost (Sun et al., 2012). As a heat source, thermokarst lakes provide continuous heat flow to surrounding permafrost and result in the increase in thawing depth and ground temperature (Lin et al., 2010). Consequently, thermokarst lakes increase in area and depth over time due to long-term slumping and collapse. Increased engineering disturbance in recent years has induced the formation of many thermokarst ponds or lakes on the Qinghai-Tibetan Plateau, which in turn has caused serious thermal erosion and thaw settlement, resulting in decreased bearing capacity of permafrost under engineered embankments (Niu et al., 2011).

Past investigations also indicated that climate warming has resulted in increased numbers of thermokarst lakes in the continuous permafrost region along the Qinghai-Tibet Railway (Wang and Mi, 1993). Thermokarst lakes have been increasingly studied in recent years, but the future thermokarst development on the Qinghai-Tibetan Plateau is not yet fully understood. The morphology of thermokarst lakes in permafrost regions is in a dynamic change. The depth, radius, and area of such lakes vary significantly over time. Lakes on the Qinghai-Tibetan Plateau have been found to be mostly enlarging (Niu et al., 2008).

To understand the evolution of thermokarst lakes on the Qinghai-Tibetan Plateau, we employed moving mesh technology to assess the dynamic morphology during thermokarst lake evolution. We developed a coupled numerical model for heat transfer with phase change and thaw subsidence to simulate thermokarst lake expansion and the effects of thermokarst dynamics on local permafrost temperature. To simulate the impact of lake expansion on the thermal regime of permafrost under and surrounding the lake, we compared the thermal effects of a dynamic morphology (moving-boundary) thermokarst lake with those of a fixed morphology (fixed-boundary) thermokarst lake. We conducted a series of simulation cases and investigated the influence of lake-bottom temperature, permafrost temperature, and rates of climate warming on thermokarst dynamics.

2. Model description and numerical methods

2.1. Moving mesh method

Dynamic fluid grids are commonly used for the solution of flow problems with moving boundaries, including blood flow circulation, parachute dynamics, airfoil oscillations, flutter prediction, and a large class of free-surface flow problems (Batina, 1990). When the fluid mesh undergoes large displacements and/or deformations, the existing grids are allowed to deform to follow the computational domain geometries. We used the spring analogy approach (Bohn and Moritz, 2005) to serve for the mesh deformation in the thermokarst lake moving-boundary problem. The spring analogy approach differs from the grid re-meshing method in that it does not generate the mesh automatically at each step on the time-dependent domain, and a dynamically deforming computational domain is established by moving internal modes or mesh deformation in response to redefined boundary geometry. The lateral thermal erosion of a thermokarst lake results in permafrost thawing, bank collapse, and mass redistribution. The depth, radius, and area of a thermokarst lake vary significantly over time; thus, the evolution of thermokarst lakes in ice-rich permafrost regions is a typical moving-boundary problem.

2.2. Computation model

The ice-rich permafrost on the Qinghai-Tibetan Plateau is generally underlain by low-permeability, intensely weathered mudstone, so most of the thermokarst lakes on the plateau are unlikely to drain, even if the underlying permafrost thaws entirely. If the water remains on the surface, it acts as a heat source and tends to thaw more ground ice. Thus, the lakes will increase in size.

To investigate typical thermokarst lake expansion on the Qinghai-Tibetan Plateau and its thermal impacts on permafrost, we developed an axis-symmetrical heat transfer model with phase change. The depth of the analysis domain was 100 m and the radius was 300 m. To simulate the evolution of a thermokarst lake, the initial depth of the lake was assumed as 0.3 m and its radius was 6.4 m. Based on common features of permafrost on the Qinghai-Tibetan Plateau, the model assumed that the lake shores were underlain by ice-rich permafrost and the permafrost table was at a depth of 2 m. To calculate the potential thaw settlement, the model assumed a layer of ice-rich permafrost with a thickness of 2 m located below the permafrost table, the water content of which was about 50%. To simulate the thaw subsidence, the temperature distribution was first calculated, and then the thawed zone was distinguished by the information of the thermal regime. The thaw settlement coefficient of ice-rich permafrost was assumed as 60%. The thaw subsidence was determined by the depth of the thawed zone and the thaw settlement coefficient. It was also assumed that the thawing of ice-poor permafrost below the ice-rich permafrost did not lead to thaw settlement.

In the moving-boundary model, the lake bottom was defined as the dynamic boundary, and mesh updating in response to redefined boundary geometry was accomplished by mesh deformation. The moving speed of the grids depended on the increase of the thaw depth and the thaw settlement coefficient. The model ignored the delay of thaw consolidation. The moving speed of the lake-bottom boundary was equal to the thaw subsidence speed of the ice-rich permafrost. The displacement that resulted from thaw settlement was evenly distributed at the depths of 2 m to 4 m. The occurrence of thaw subsidence stopped until the underlying ice-rich permafrost thawed entirely. Due to permafrost thawing and thawing subsidence, the ground surface boundary was transformed into the lake-bottom boundary, and the lake expansion for the next 200 years was simulated.

To compare with this moving-boundary model, a fixed-boundary thermokarst lake model with a depth of 1.2 m and a radius of 40 m was established, in which the lake-bottom boundary did not change with time. The parameters, including stratum, thermal, and boundary conditions, were similar to the moving-boundary model (Fig. 1).

2.3. Mathematical description

Taking the phase change into consideration, and ignoring water movement in the cylindrical coordinate system, the governing equation for heat conduction in a lake-permafrost system can be described as follows (Ling and Zhang, 2003):

$$\rho C\frac{\partial T}{\partial t}=\frac{\partial}{\partial r}\left(\lambda\frac{\partial T}{\partial t}\right)+\frac{\lambda}{r}\frac{\partial T}{\partial r}+\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)\qquad(1)$$
$$(0<t<D, 0<x<X, 0<r<R)$$

$$C=\begin{cases}C_u & (T<T_m-\delta T)\\ C_f+\dfrac{C_u-C_f}{\delta T}(T-(T_m-\delta T))+\dfrac{L}{(1+W)}\dfrac{\partial W_i}{\partial T} & (T_m-\delta T<T<T_m)\\ C_f & (T>T_m)\end{cases}\qquad(2)$$

$$\lambda=\begin{cases}\lambda_u & (T<T_m-\delta T)\\ \lambda_f+\dfrac{\lambda_u-\lambda_f}{\delta T}(T-(T_m-\delta T)) & (T_m-\delta T<T<T_m)\\ \lambda_f & (T>T_m)\end{cases}\qquad(3)$$

where ρ is the soil density (kg/m^3), C is specific the heat capacity of soil (J kg^{-1} °C^{-1}), λ is the coefficient of heat conductivity (J m^{-1} °C^{-1} s^{-1}),