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Permafrost response to climate change: Linking field observation with numerical simulation

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The Scotty Creek basin (152 km²) is located in the Northwest Territories, Canada, within the peat-covered discontinuous permafrost zone with a high density of wetlands. The extensive peat layer (up to 3-4 m thick) is underlain by generally clay-rich glacial sediments. The landcover consists of peat plateaus underlain by permafrost, permafrost-free channel fens, and connected and isolated permafrost-free ombrotrophic flat bogs, occurring as a complex mosaic of patches. The runoff from peat plateaus drains into isolated bogs and a network of connected bogs and fens.

During the course of field studies since 1999, stark changes have been observed on the permafrost plateaus, including a deepening of active layer, soil settlement and depression formation, and changes in the lateral and vertical extent of the unsaturated zone. In general, the area of permafrost plateaus is decreasing, and the areas of fens and bog areas are increasing. These changes affect water flow and induce changes in heat transport, which in turn affect the aforementioned changes in permafrost plateaus (i.e. feedback processes). The goal of this study is to understand the feedbacks and their effects on permafrost degradation by using field observations and numerical simulations.

We use a modified version of the three-dimensional SUTRA model that can simulate groundwater flow and heat transport, including freeze-thaw processes. Numerical simulation of heat transport accounts for the effects of latent heat associated with freezing and thawing, and variable heat capacity, thermal conductivity, and permeability as a function of ice content. The model is used to simulate the plateau-fen-bog complex, where intensive field studies have generated a large amount of data. The SUTRA model does not simulate complex surface processes such as radiative and turbulent heat exchange, snow accumulation and melt, and canopy effects. We use an energy and water transfer model, Northern Ecosystem Soil Temperature (NEST) to calculate the surface conditions and provide the surface boundary conditions for SUTRA. The SUTRA results are then compared to the long-term field and remote sensing data of permafrost degradation.

Various hypotheses regarding permafrost degradation are tested: a) tree canopy density, water saturation, soil settlement, and snow cover impact the surface energy budget, b) warmer water flow in fens and connected bogs influences the relative roles of conductive and advective heat transfer, c) the type of mineral soil located below the peat (e.g. silty sand, clay) influences heat transport, water storage and possibly sub-permafrost flow and d) the isolated bogs become connected with each other to form the drainage network. In addition, model simulations are conducted for a small section (3 km²) of the Scotty Creek basin to understand the current permafrost state and predict the degradation in the next twenty years using scenarios generated by a regional climate model.

```
lam_s = pow(K_Organic*100,Organic[L]* Fsoil[L]/Solid) *
        pow(K_Minerals[L]*100, (Mineral[L]* Fsoil[L] + Soil_Fstone[L])/Solid);
```

```
void Temp_ThermalP(int Material_ID, double *C, double *K, double K_Minerals,
                  double Snow_Density, double Mineral, double Organic, double
Soil_Water)
{
//define the relationship table between T~Hc and T~K (corresponding to TMPB)
int i;
double F, Kf, Kt, Cf, Ct, Air;

//      TMPB[NTAB] = {-200, -100, -0.1, 0, 0.1, 100};

switch(Material_ID) {
case 1:      //snow
//      K0=0.000358+0.0264*Snow_Density*Snow_Density; //Yin and Arp
//      Kf = (0.00074 +0.02576*Snow_Density*Snow_Density)*100; //Mellor, 1976, in
W/m/k
Cf= HCw_Ice*Snow_Density;

for(i=1; i<NTAB; i++) { // [0] not used
K[i] = Kf;
C[i] = Cf;
}
for(i=3; i<NTAB; i++) C[i] = Cf + Water_Ice_w*Snow_Density/0.1;

break;
case 2:      //soil
F = 100 * pow(K_Organic,Organic) * pow(K_Minerals,Mineral);
//frozen
Air = 1.0 - Organic-Mineral-Soil_Water;
Kf = F * pow(K_Ice,Soil_Water)*pow(K_Air,Air);
Cf = HCw_Organic*Organic+HCw_Minerals*Mineral + HCw_Ice*Soil_Water;
//thaw
Air = 1.0 - Organic-Mineral-Soil_Water;
Kt = F * pow(K_Water,Soil_Water) * pow(K_Air,Air);
Ct = HCw_Organic*Organic+HCw_Minerals*Mineral + HCw_Water*Soil_Water;

K[1] = Kf; C[1] = Cf; // -100C
K[2] = Kf; C[2] = Cf; // -0.1
K[3] = Kt; C[3] = Ct + Water_Ice_w*Soil_Water/0.1; // 0.0
for(i=4; i<NTAB; i++) { // 0.1, 100
K[i] = Kt;
C[i] = Ct;
}

break;
case 3:      //peat
F = 100 * pow(K_Organic,Organic) * pow(K_Minerals,Mineral);
//frozen
Air = 1.0 - Organic-Mineral-Soil_Water;
Kf = F * pow(K_Ice,Soil_Water)*pow(K_Air*5,Air);
Cf = HCw_Organic*Organic+HCw_Minerals*Mineral + HCw_Ice*Soil_Water;
//thaw
Air = 1.0 - Organic-Mineral-Soil_Water;
Kt = F * pow(K_Water,Soil_Water) * pow(K_Air*5,Air);
Ct = HCw_Organic*Organic+HCw_Minerals*Mineral + HCw_Water*Soil_Water;

K[1] = Kf; C[1] = Cf; // -100C
K[2] = Kf; C[2] = Cf; // -0.1
```

```
    K[3] = Kt; C[3] = Ct + Water_Ice_w*Soil_Water/0.1; //0.0
    for(i=4; i<NTAB; i++) { //0.1, 100
        K[i] = Kt;
        C[i] = Ct;
    }
break;
break;
case 4: //bedrock
    Kf = 100 * K_Minerals;
    Cf = HCw_Minerals;

    for(i=1; i<NTAB; i++) {
        K[i] = Kf;
        C[i] = Cf;
    }
}
}
```