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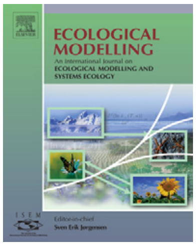

Hourly and daily models of active layer evolution in arctic soils

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ABSTRACT

For models to predict arctic ecosystems' responses to climate change, it is important to first predict soil thermal responses. However, soil heat-budget models are generally too finely scaled and detailed to couple with large-scale biogeochemical models. Appropriate data sets to derive simple models capable of predicting active soil layer behavior on a time scale appropriate to biogeochemical models do not exist. One solution is to scale a highly detailed, physical heat model. The fine-scale predictions of this model can be aggregated to generate coarse-scale data, which can be used to derive an appropriately scaled model. We develop an hourly, spatially detailed model of soil temperature based on well-understood physical and biological processes and driven by detailed data. Under a range of environmental conditions, the hourly model predicts active layer behavior. From these predictions we construct a daily model that requires far fewer data about the climatic, environmental, and physical conditions to predict the volume of thawed soil over longer time scales.

1. Introduction

Rising global air temperatures (Lachenbruch and Marshall, 1986; King, 2004) are predicted to have a large effect on polar regions (Serreze et al., 2000), whose large store of soil organic carbon (Schlesinger, 1977; Hinzman et al., 1996) makes them critical to climate change (Shaver et al., 1992; Goulden et al., 1998; Chapin et al., 2000; Clein et al., 2000; Oechel et al., 2000). Atmospheric warming will potentially lead to increased soil temperature and respiration, soil organic carbon release to the atmosphere, and a positive feedback on global warming. Melting of permafrost and the consequent increase in soil drainage might lead to a significant increase in decomposition and the loss of carbon from tundra soils (Schlesinger and Andrews, 2000). Higher soil temperatures should also result in faster nutrient release, stimulating plant production, which could increase terrestrial carbon stores, causing a negative feedback on global warming (Shaver et al., 1992; Clein et al., 2000; McGuire et al., 2000). The flow of carbon from or to the arctic depends strongly upon the effects of increased temperature on soil processes.

In the arctic, most biological and chemical activity occurs in the seasonally thawed active soil layer overlaying the permafrost (Goulden et al., 1998), however, the importance of winter mineralization and soil respiration is beginning to be recognized. Winter microbial community studies suggest that some microbes that persist are active, but only under a narrow range of conditions (Wallenstein et al., 2007). Kielland et al. (2006) and Schimel et al. (2006) suggest that activity occurs as winter begins, but Schimel et al. (2006) find that most activity occurs before soils completely freeze. The soil can remain thawed for several weeks beneath the snowpack. To model the seasonal and long-term response of arctic ecosystems to climate change, it is important to predict the appearance and

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Nomenclature

b_1	canopy conductance sensitivity to vapor pressure (MPa^{-1})
b_{H1}, b_{H2}	cloud cover parameters
$c(z, t)$	volumetric heat capacity of soil (J m^{-3} °C^{-1})
c_{ice}	volumetric heat capacity of ice (J m^{-3} °C^{-1})
c_p	specific heat of air at constant pressure (J kg^{-1} °C^{-1})
c_{snow}	volumetric heat capacity of snow (J m^{-3} °C^{-1})
$c_{soil}(z)$	volumetric heat capacity of dry soil (J m^{-3} °C^{-1})
$c_{soil,mnrl}$	volumetric heat capacity of dry mineral soil (J m^{-3} °C^{-1})
$c_{soil,org}$	volumetric heat capacity of dry organic soil (J m^{-3} °C^{-1})
c_{water}	volumetric heat capacity of water (J m^{-3} °C^{-1})
C_d	drag coefficient for heat convection
d	index of Julian day of the year
$d_d(z, t)$	soil drainage rate downwards ($\mathrm{m_{water}\,h^{-1}}$)
$d_s(z, t)$	soil drainage rate sideways ($\mathrm{m_{water}\,h^{-1}}$)
DD_n	cumulative negative degree days after 15 August (°C)
DD_p	cumulative positive degree days after snow-off (°C)
$e_s(T)$	saturation vapor pressure of temperature T (MPa)
$E_T(t)$	evapotranspiration rate (m h^{-1})
$f_1(t)$	canopy conductance: radiation and vapor pressure deficit
$f_2(t)$	canopy conductance: leaf area index
$f_3(t)$	canopy conductance: water stress
$F_{ice}(z, t)$	fraction of frozen water in a layer
$F_{snow}(t)$	fraction of snow in the top layer
$F_{soil}(t)$	fraction of soil/plant in the top layer
g_A	boundary layer conductance ($\mathrm{m_{water}\,h^{-1}}$)
$g_c(t)$	canopy conductance ($\mathrm{m_{water}\,h^{-1}}$)
$g_{c_{max}}$	maximum canopy conductance ($\mathrm{m_{water}\,h^{-1}}$)
$h_a(t)$	hour angle: angular distance from the meridian of the observer (rad)
$h_d(t)$	hour of the day
$H_I(t)$	one minus the fractional cloud cover
$I_I(t)$	solar radiation, a driver (J m^{-2} h^{-1} or J m^{-2} day^{-1})
$I_{I,daily}(d)$	measured daily solar radiation (J m^{-2} day^{-1})
$I^{sim}_{I,hourly}(h, d)$	simulated hourly solar radiation (J m^{-2} h^{-1})
$I_0(t)$	radiation at the top of the atmosphere (J m^{-2} h^{-1})
$j_d(t)$	Julian day of the year
$k(z, t)$	thermal conductivity of an entire soil layer (J m^{-1} h^{-1} °C^{-1})
k_{ice}	thermal conductivity of ice (J m^{-1} h^{-1} °C^{-1})
k_{snow}	thermal conductivity of snow (J m^{-1} h^{-1} °C^{-1})
$k_{soil}(z)$	thermal conductivity of dry soil (J m^{-1} h^{-1} °C^{-1})
$k_{soil,mnrl}$	thermal conductivity of dry mineral soil (J m^{-1} h^{-1} °C^{-1})
$k_{soil,org}$	thermal conductivity of dry organic soil (J m^{-1} h^{-1} °C^{-1})
k_{water}	thermal conductivity of water (J m^{-1} h^{-1} °C^{-1})
$k_0(d)$	extraterrestrial radiation (J m^{-2} h^{-1})
lai	leaf area index, this can be allowed to vary with season or year but we hold it constant ($\mathrm{m^2_{leaf}\,m^{-2}_{ground}}$)
$\mathrm{lai_{max}}$	canopy conductance parameter: upper sensitivity limit to lai ($\mathrm{m^2_{leaf}\,m^{-2}_{ground}}$)
L_f	latent heat of fusion for water (J m^{-3})
$L^*_f(z, t)$	latent heat of fusion for water added to the soil heat capacity of layers undergoing a state change and zero otherwise (J m^{-3})
$L_v(t)$	latent heat of vaporization (J m^{-3})
$m(h, d)$	optical thickness of the atmosphere
m_W	snow melt parameter: radiation ($\mathrm{m^3_{water}\,J^{-1}}$)
$M_{initial}$	average moisture of top 1 m of soil on 1 January ($\mathrm{m_{water}\,m^{-1}_{pore\ space}}$)
p_1–p_4	canopy conductance parameters: sensitivity to water stress
$P(t)$	frozen and unfrozen precipitation, a driver ($\mathrm{m_{water}\,h^{-1}}$ or $\mathrm{m_{water}\,day^{-1}}$)
$P^{sim}_{daily}(d)$	simulated daily precipitation ($\mathrm{m_{water}\,day^{-1}}$)
P_{pw}	probability of precipitation during the winter
$Q_C(t)$	surface heat flux: convection (J m^{-2} h^{-1})
$Q_{ET}(t)$	surface heat flux: evapotranspiration (J m^{-2} h^{-1})
$Q_{In}(t)$	surface heat flux: radiation (J m^{-2} h^{-1} or J m^{-2} day^{-1})
$Q_R(t)$	surface heat flux: rain (J m^{-2} h^{-1})
R_0	canopy conductance: sensitivity to radiation (J m^{-2} h^{-1})
$s(d)$	day length (h)
$s'(d)$	half day length hour angle (rad)
S_0	solar radiation constant (J m^{-2} h^{-1} or J m^{-2} day^{-1})
t	index of time
Δt	length of time step (h or days)
$T(z, t)$	temperature of soil layer z at time t (°C)
$T_a(t)$	air temperature, a driver (°C)
$T^{sim}_{ave}(d)$	simulated daily average air temperature (°C)
$T_{dma}(t)$	daily minimum air temperature (°C)
$T^{sim}_{hourly}(d)$	simulated hourly air temperature (°C)
$T_{initial}$	average temperature of top 1 m of soil on 1 January (°C)
$T_{Ka}(t)$	temperature of air (K)
$T_{Ks}(t)$	temperature of ground surface (K)
T_{liquid}	soil temperature above which all soil water is unfrozen (°C)
$T^{sim}_{max}(d)$	simulated daily maximum air temperature (°C)
$T^{sim}_{min}(d)$	simulated daily minimum air temperature (°C)
$T^{sim}_{range}(d)$	simulated daily range in air temperature (°C)
T_{snow}	air temperature below which precipitation is snow (°C)
T_{solid}	soil temperature below which all soil water is frozen (°C)
$V_d(d)$	daily average thaw volume ($\mathrm{m_{ground}}$)
V_{pw}	average volume of daily precipitation during winter (m)
$w_a(t)$	fraction of soil water available to plants
$w_c(z, t)$	soil water content ($\mathrm{m_{water}}$ per soil layer)