IMPACT OF SNOW AND MODEL STRUCTURE ON SOIL TEMPERATURES IN A LAND SURFACE MODEL

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1. Background, field sites and methodology

Field observations, satellite remote sensing data and models[1,2,3] suggest that climate warming can lead to densification or expansion of shrub patches at high latitudes. By trapping snow and thus preventing its loss in the winter through sublimation, this change in the vegetation structure can significantly affect the distribution and the physical characteristics of snow. An increase in exposed vegetation will also lower the albedo, and as a consequence affect the energy balance, of the region. Snow has a low thermal conductivity, insulating buried shrubs and underlying soil with important consequences for hydrological and biological processes. Here we introduce a new snow module in the JULES (Joint UK Land Environment Simulator) land surface model and use it to investigate the effects of changing air temperatures and snow depths on soil processes.

Meteorological measurements, snow depths and soil temperatures were obtained at two sites in the Wolf Creek Research Basin (60°36' N, 134°57' W), Yukon Territory, Canada[4]:

- Alpine tundra site: 1615 m.a.s.l., 0.01 – 0.3 m tall vegetation (willow, dwarf birch, grass and lichen) and bare rock, within the widespread discontinuous permafrost zone[5]. Soil temperatures were measured at 3 cm depth.
- Buck brush (shrub tundra) site: 1250 m.a.s.l., 0.4 – 3 m tall vegetation (willow, sparse white spruce, dwarf birch and grass), within a sporadic discontinuous permafrost zone. Soil temperatures were measured at 11 cm depth.

Data for the one-year period starting on 1 August 1998 are used here. Air temperatures at both sites were similar from November to February, but the alpine site was generally 2°C colder than the buck brush site for the rest of the year. Annual average wind speed at the alpine site was greater by 2.3 ms^{-1}. Increased wind ablation and reduced trapping by shrubs gives lower snow depths at the alpine site despite similar snowfall. The importance of snow insulation is reflected in differences in soil temperatures; the greatest differences occurred in March, for which average soil temperatures were -9°C at the alpine site but -4°C at the buck brush site. Summer differences were smaller, and down to 0.4°C in June and August (7°C at the alpine site and 6.6°C at the buck brush site).

2. Improved snow processes in the JULES land surface model

The old JULES snow model contains a composite snow / top soil layer that functions as a single thermal unit. The temperature of this layer is taken at a fixed depth beneath the surface whether snow is present or not, hence representing either the soil or snow temperature depending on snow depth. Snow density is fixed at 250 kg m^{-3} and surface melt water drains immediately from the snow pack.

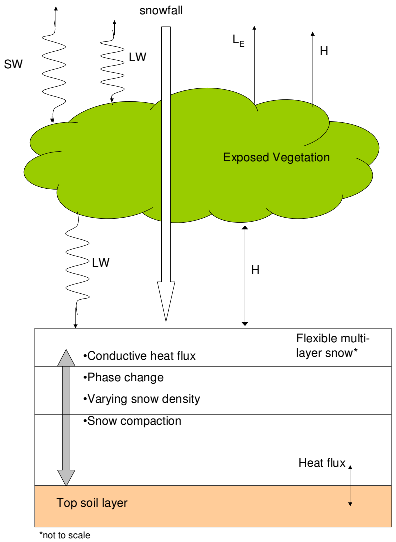

Figure 1: Schematic representation of new snow model in JULES

In the new version of JULES (Figure 1), a flexible multi-layer snow model structure has been introduced to distinguish the thermal regime of the snow from that of the soil. Separate temperatures, densities and liquid water contents are calculated for each layer. Snow layer depths and properties are updated at each timestep, allowing a density profile to develop with less-dense freshly fallen snow in the surface layer and mechanical compaction leading to higher snow densities in deeper layers. Upon growth of the snowpack, the first snow layer increases in depth until it reaches a prescribed depth, at which point the layer splits in two. This process is repeated as snow accumulates until a prescribed maximum number of snow layers is reached; subsequent increases in snow depth are accommodated by increasing the depth of the lowest layer. Melting of snow is diagnosed from the surface energy balance. A prescribed fraction of the mass in each snow layer can be stored as liquid water, delaying runoff from the base of the snowpack. Refreezing of liquid water in the snowpack releases latent heat. These model changes will impact on the calculations of snow depth and density and are expected to produce a more accurate physical representation of soil thermodynamics when snow is present.

The optional canopy model remains the same in both versions of JULES: Shrubs are progressively buried by increasing snow depths. The canopy is treated as opaque, so there is no penetration of shortwave radiation through the canopy to the ground. Long wave and sensible heat exchanges between the canopy and the ground are implemented[6]. We are currently developing the parameterization of shrub bending and a sparse canopy model.

3. Comparison of JULES 2.0 with JULES 2.1

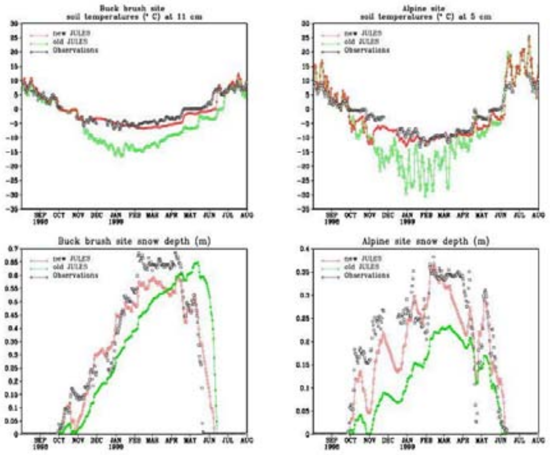

Figure 2: Comparison of JULES 2.0 and 2.1 results with observed soil temperatures and snow depth

In the absence of continuous snowfall measurements and a blowing snow model, snow accumulation at each site was estimated from continuous depth measurements for model driving. Snow depths and soil temperatures simulated by the new and old model versions are compared with observations in Figure 2. The old snow model underestimates winter soil temperatures because the surface soil temperatures lies within the snow / soil composite layer and the thermal conductivity is overestimated by the fixed snow density, whereas the insulation provided by the new multi-layer model considerably improves soil temperature simulations. The implementation of varying snow density also allows a more accurate representation of snow depth. Modelled snow densities (Figure 3) provide a good fit to monthly climatological densities calculated from 10 years of snow surveys. Colder than observed temperatures for October in the new model are due to the fact that the model reverts to the old snow model when the snow layer is shallower than a prescribed depth to avoid numerical instability.

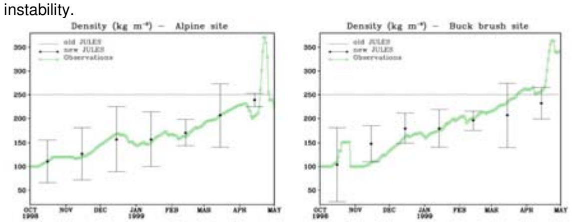

Figure 3: Modelled and climatological snow densities. Error bars show observed monthly standard deviation

4. Climate change scenarios and Discussion

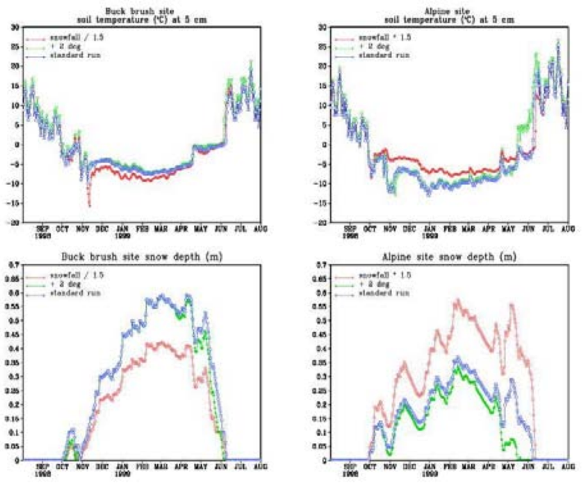

Figure 4: Soil temperature and snow depth for JULES runs with original driving data (OD), 2°C added to air temperatures (T2) and modified snowfall (S15)

The original driving data (OD) was modified to assess how much of the soil temperature variation between sites can be explained by air temperature or snow depth differences. One pair of runs with the new model was performed by increasing the snowfall amount at the alpine site by a factor of 1.5 and decreasing snowfall by the same amount at the buck brush site (S15). Another pair of runs was performed in which air temperatures were increased by 2°C (T2) at both sites. Results are shown in Figure 4.

At the alpine site, increasing snow depth affects winter soil temperatures more than increasing air temperature. The largest temperature difference between S15 and OD is 5.2°C in December, and the average temperature difference from 1 December to 1 May is 2.9°C. The average December to May temperature difference between T2 and OD is only 0.62°C for a 2°C increase in air temperature, but large differences occur in spring due to earlier melt of snow; most of the snow has melted by 25 April and completely disappears by 15 May in T2, compared with a snow-free date of 9 June in OD. The average temperature difference during this period is 7.6°C

At the buck brush site, reducing snowfall causes soil temperatures to be 1.3°C colder than OD on average from 1 December to 1 May, whereas there is a 0.4°C difference between OD and T2. Snowmelt occurs earlier in T2 than in OD and S15 (by 3 and 5 days respectively), but the difference is not large enough to significantly affect soil temperatures. There is little difference between T2 and OD snow depths because less snow is lost to sublimation during winter than at the alpine site and the dense canopy, as it is formulated in JULES, partially shelters the snow on the ground and prevents much melt enhancement.

These runs suggest that a snow depth increase at high latitude, which could occur in shrub-tundra landscapes with increased vegetation trapping more snow and reducing winter sublimation, is expected to have more significant effects on soil temperatures than a 2°C increase in air temperatures. This could have significant consequences on the carbon cycle, particularly in areas underlain by permafrost where deepening of the active layer causes the release of previously trapped methane to the atmosphere.

5. References

1. Sturm, M., et al. (2005). Winter biological processes could help convert arctic tundra to shrubland, *Bioscience*, **55**, 17-26.
2. Jia, G. J., Epstein H.E., Walker, D.A. (2006). Spatial heterogeneity of tundra vegetation response to recent temperature changes, *Global Change Biology*, **12**, 42-55.
3. Tape, K., et al. (2006). The evidence for shrub expansion in Northern Alaska and the Pan-Arctic, *Global Change Biology*, **12**, 686-702.
4. Pomeroy, J., Essery, R., Toth, B. (2003). Implications of spatial distributions of snow mass and melt rate on snowcover depletion: observations in a sub-arctic mountain catchment. *Annals of Glaciology*, **38** (1), 195-201.
5. Lewkowicz, A.G., Ednie, M. (2004). Probability mapping of mountain permafrost using the BTS method, Wolf Creek, Yukon Territory, Canada. *Permafrost Periglac.,* **15**, 67-80.
6. Essery, R., Pomeroy, J., Parvianen, J., Storck, P. (2003) .Sublimation of snow from coniferous forests in a climate model, *Journal of Climate*, **16**, 1855-1864

6. Acknowledgements

The authors would like to thank John Pomeroy and Rick Janowicz for data provision and the IP3 Network for travel support. Cécile Ménard is supported by a NERC studentship.