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Model estimates of local advection of sensible heat over a patchy snow cover

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Abstract In agricultural, grassland, tundra and mountainous areas, patchy snow cover may occur for periods of many months. Although much is known about surface energy exchanges during periods of continuous snow cover, there are major gaps in our understanding of fluxes during periods when the land surface has both snow and snow-free patches. A boundary layer model is used to document that the efficiency of sensible heat advection from snow-free to snow patches decreases with increasing snow free area, and for the same snow-free area, increases as individual snow patch size decreases. The average sensible heat flux to the snow patches increases significantly with increasing snow-free area and decreasing snow patch size. These variations in sensible heat flux have important hydrological implications and should be accounted for in simulations of energy fluxes over snow covered terrain.

INTRODUCTION

A common limitation of both climate and hydrological models is the inability to properly account for the sub-grid scale heterogeneity (Dickinson *et al.*, 1996) of variables such as surface fluxes of sensible and latent heat, and when snow is present, snowmelt. If the sub-grid land surface is composed of sufficiently large individual components, they may be considered to interact independently with the overlying homogeneous atmosphere (Koster & Suarez, 1992), and a tile-type approach may be used to estimate average fluxes over an entire grid from the weighted average of the fluxes for each landscape component (Dickinson *et al.*, 1996). Other landscapes are heterogeneous at much smaller scales, and although areal aggregation of surface characteristics such as albedo may be easily accomplished, others (e.g. roughness and energy exchange processes) are complicated by nonlinearities. At such scales, the average fluxes for each landscape component are affected by local scale advection and a simple tile model is not sufficient to estimate average fluxes for the composite landcover (Lhomme *et al.*, 1994).

Examples of landscapes that are heterogeneous at small scales are snow covered environments typical of prairie, arctic, and alpine regions where patches of snow and exposed ground are common. The impact of such landscape heterogeneities on energy fluxes is accentuated during periods of snowmelt, as the exposed ground surfaces absorb greater solar radiation and may warm to over 20°C (Liston, 1995) while the melting snow patches are limited to a maximum surface temperature of 0°C. Local or small-scale advection (Liston, 1995) has an impact on both the average energy fluxes for the snow patches, and average fluxes for the composite landscape. The role of patch size and geometry on the advection of sensible heat in naturally patchy snow covers has not been well explored to date. Liston (1995) provided some insight into the variability of advection with different patch distributions, but the scale used in the model runs does not allow easy comparison with many natural landscapes. Neumann & Marsh (1998) utilized field studies to consider changes in advection over a melt period.

This paper will consider factors affecting small scale advection of sensible heat during snowmelt for a tundra landscape in the Canadian Arctic with an emphasis on the role of patch size and spacing. This will be accomplished using a two-dimensional boundary layer model to simulate advective processes. This allows a better understanding of the influence of snow patch size on the local scale advection of sensible heat, and has future application for snowmelt estimates and flux aggregation over typical patchy snow covers in many prairie, arctic, and possibly alpine environments if appropriate irregular terrain wind flow models are available. This paper will present initial results for regular snow patches, while future work will consider natural snow patches.

METHODS

Local advective efficiency

Marsh & Pomeroy (1996) introduced a simple approach to characterize the efficiency of advection of sensible heat (F_S) from snow-free to snow patches during melt by

$$F_S = \left[\frac{Q_A P_S}{\overline{Q}_{H_V} P_V} \right] \qquad (1)$$

where the amount of energy advected to snow patches (Q_A) is given by $\left[\overline{Q}_{H_S} - \hat{Q}_{H_S}\right]$, the difference between the spatially averaged sensible heat flux over a snow patch ($\overline{Q}_{H_S}$) and the sensible heat flux at the downwind edge of a very large snow patch where local advection is negligible ($\hat{Q}_{H_S}$). The other terms are $\overline{Q}_{H_V}$, the average sensible heat flux over a snow-free surface, and P_V and P_S, the fractional snow-free and snow-covered areas, respectively. The resulting advective efficiency, F_S, will vary between 0 and 1, where a value of 1 implies that all of the sensible heat from the snow-free area is advected to nearby snow patches, and 0 implies that no energy is transferred. Neumann & Marsh (1998) provided estimates of F_S using field estimates of sensible heat flux and snow patterns from SPOT multispectral satellite images (20 m resolution) obtained on 23, 25 and 28 May and 1, 5 and 8 June 1996.

Boundary layer model

To determine the effect of changing snow cover patterns on local-scale horizontal transfers of sensible heat, a 2D boundary-layer model (BLM) was used. This model was originally developed to study roll vortices in neutral boundary layers (Mason & Sykes, 1980), but has since been used in several studies of flow over heterogeneous surfaces; Mason (1988) studied momentum fluxes over surfaces of heterogeneous roughness in neutral conditions; Wood & Mason (1991) extended this to consider heat transfer and the influence of thermal stratification; Blyth *et al.* (1993) added a surface moisture flux parameterization to study effective resistances to sensible and latent heat fluxes from heterogeneous vegetation, partitioning a fixed available energy; Essery (1997a,b, 1999) implemented a surface energy balance to allow simulation of fluxes over surfaces with large variations in albedo, typical of partial snow cover.

Separate values of albedo (0.15 and 0.5) and aerodynamic roughness length (0.001 and 0.015 m) were specified, respectively, for snow-covered and snow-free surface elements in the model domain; snow-free ground was assumed to be saturated with meltwater, so evaporation is not limited by moisture availability for either surface type. Thermal roughness lengths were taken to be one tenth of the momentum roughness length, as heat and moisture transfer by turbulence is less efficient than momentum exchange by turbulence and pressure forces. Incoming shortwave and longwave radiation fluxes (650 and 250 W m^{-2}, respectively) were assumed to be homogeneous across the surface, and the flow was driven by a constant horizontal pressure gradient giving a geostrophic wind of 10 m s^{-1}. Ground heat fluxes and heat storage are neglected in the surface energy balance, and a snowmelt term is calculated as the heat flux required to ensure that snow surface temperatures do not exceed 0°C. In all cases, negative fluxes are directed toward the surface.

In contrast with the model used by Liston (1995), for which vertical temperature and humidity profiles are specified as in-flow boundary conditions, the BLM imposes periodic boundary conditions in the horizontal direction. All model runs were bounded by an upwind 20-element snow-covered patch and a downwind 20-element snow-free patch to minimize any boundary influence at the horizontal extents of the model domain. Initial profiles of temperature and humidity were generated with a one-dimensional version of the BLM; in order to be comparable with previous studies, these initial conditions were chosen to be similar to those used by Liston (1995). The two-dimensional BLM was then run for a sufficient length of time to reach a near-steady state in each case. An initial run over 100% snow cover (Case A) provided $\hat{Q}_{H_S}$, which, following Neumann & Marsh (1998), was taken as the sensible heat flux at a point 1.8 km downwind of the leading edge and found to be equal to –5.6 W m^{-2}.

The BLM was run using two distinct snow and snow-free patch configurations. First, in order to consider the simplest case, single snow patches covering 94%, 88%, 50%, 12%, 6%, and 1% over a 10 km fetch (Case B to G) are used (Table 1). In these runs, each horizontal model element was 50 m in length. Second, in order to

Table 1 Comparison of F_S results from Cases B to G (BLM), and F_S values provided by Neumann & Marsh (1998) using data from Liston (1995), for similar conditions. Symbols used are as defined in the paper.

Case	Patch length (m)	P_V	$\overline{Q}_{H_s}$ (W m^{-2})	$\overline{Q}_{H_l}$ (W m^{-2})	$\hat{Q}_{H_s}$ (W m^{-2})	Q_A (W m^{-2})	$\frac{Q_A}{\hat{Q}_{H_s}}$ (%)	F_S	Liston F_S
B	7500	0.06	-6.1	124.5	-5.6	0.5	9	0.056	-
C	7000	0.12	-6.3	140.9	-5.6	0.6	11	0.031	0.088
D	4000	0.50	-9.5	151.2	-5.6	3.8	68	0.025	0.034
E	1000	0.88	-17.1	152.7	-5.6	11.5	205	0.011	0.012
F	500	0.94	-21.4	153.0	-5.6	15.8	282	0.007	0.007
G	100	0.99	-20.0	92.4	-5.6	14.4	257	0.002	0.003

Table 2 Results of decreasing patch size and horizontal domain extent. Symbols used are as defined in the paper.

Case	Patch size (m)	P_V	Domain extent (m)	$\overline{Q}_{H_s}$ (W m^{-2})	$\overline{Q}_{H_l}$ (W m^{-2})	$\hat{Q}_{H_s}$ (W m^{-2})	Q_A (W m^{-2})	$\frac{Q_A}{\hat{Q}_{H_s}}$ (%)	F_S
D	4000	0.5	10 000	-9.5	151.2	-5.6	3.8	68	0.025
H	1000	0.5	10 000	-14.6	147.4	-5.6	9.0	161	0.061
I	100	0.5	10 000	-20.0	143.7	-5.6	14.3	255	0.100
J	100	0.5	2 000	-22.0	147.5	-5.6	16.4	293	0.111
K	50	0.5	2 000	-23.4	141.0	-5.6	17.7	316	0.126
L	50	0.5	1 000	-23.4	140.7	-5.6	17.8	318	0.126
M	20	0.5	1 000	-24.5	135.7	-5.6	18.9	338	0.139

investigate the role of patch size, runs were made for a 50% snow cover with alternating patches of 1000, 100, 50, and 20 m length (Cases D and H to M) (Table 2). This extended the analysis of Liston (1995), where patch lengths varied from 4 km to 100 m. The large snow patches are typical of those found in the early part of the melt period, whereas smaller patches become more prevalent later (Shook *et al.*, 1993; Marsh & Pomeroy, 1996; Shook & Gray, 1997). In order to use the BLM for this range of patch sizes, the model had to be run with different element sizes and therefore model domains (Table 2). For runs D, H, and I each element was 50 m, for runs J and K each element was 10 m, and for runs L and M each element was 5 m.

RESULTS

Modelled advection of sensible heat

Single snow patches As shown in Fig. 1, the BLM predicts increased sensible heat flux at the upwind edge of a snow patch, with a rapid decline with distance from the leading edge. For the example shown in Fig. 1 (Case D), maximum sensible heat flux is –33.9 W m^{-2}, compared to only –4.5 W m^{-2} at the downwind edge of the patch, an increase of >750%. The rapid decline from the high sensible heat flux at the leading edge to a minimum value approximately 1 km downwind, with most of the decline

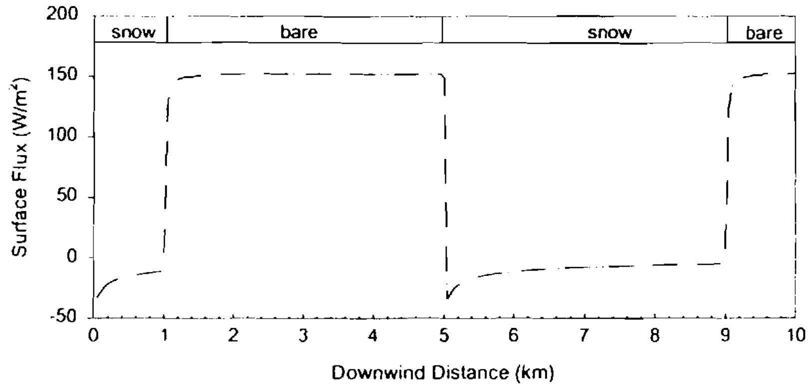

Fig. 1 Sensible heat flux from boundary layer model run Case D, 50% snow cover as a single large patch (4000 m in length). Note increased sensible heat flux on the upwind (*left-hand* side) edge of the snow patch.

occurring within the first few hundred metres, is similar to that shown by Neumann & Marsh (1998) for a variety of modelling and field observations provided by previous studies. This spatial variation in sensible heat flux results in increased melt at the upwind edge of snow patches, and illustrates the difficulty in estimating average snowmelt when the snow cover is patchy.

Model runs B to G show that advection greatly increases average sensible heat to the single snow patches, with Q_A up to 2.5 times $\hat{Q}_{H_S}$ as snow-free area increases (Table 1). During this same period, F_S decreases from a high of near 0.06 at the lowest snow-free fraction to 0.003 at the highest snow-free fraction (Fig. 2 and Table 1). These F_S values are slightly lower than, but similar to, those described by Neumann & Marsh (1998) using model data from Liston (1995), providing confidence that the BLM used in this study produces comparable results to that used by Liston (1995). The decline in F_S with increasing snow-free area, as shown in Table 1 and Fig. 2, is caused by the rise in total sensible heat from the snow-free fraction ($\overline{Q}_{H_V}\ P_V$) as P_V increases, while the total amount of energy which is advected to the snow patch ($Q_A\ P_S$) increases more slowly since the area of the small region at the upwind edge of the snow patch with enhanced sensible heat changes only slowly. As shown in Fig. 2, the total energy advected and the resulting F_S for these single snow patches is considerably smaller than that estimated by Neumann & Marsh (1998) for a natural snow cover with a wide variation in patch lengths. One possible reason for this difference, the effect of snow patch size, will be further explored in the following section.

Decreasing snow patch size The sensible heat advected to the snow patches (Q_A) increased from 3.8 W m^{-2} (Case D) for a single snow patch of 400 m covering 50% of the area, to 18.9 W m^{-2} (case M) for the same snow cover fraction but numerous snow patches of 20 m length (Table 2). Since total snow-free sensible heat ($\overline{Q}_{H_V}\ P_V$) is nearly constant (Table 2), while total advected energy ($Q_A\ P_S$) increases considerably, F_S increases with decreasing patch length (Fig. 3) (i.e. more sensible heat is advected to the snow patches). The approximately logarithmic decrease in F_S with increasing length of individual snow patches shows that for similar atmospheric conditions, more

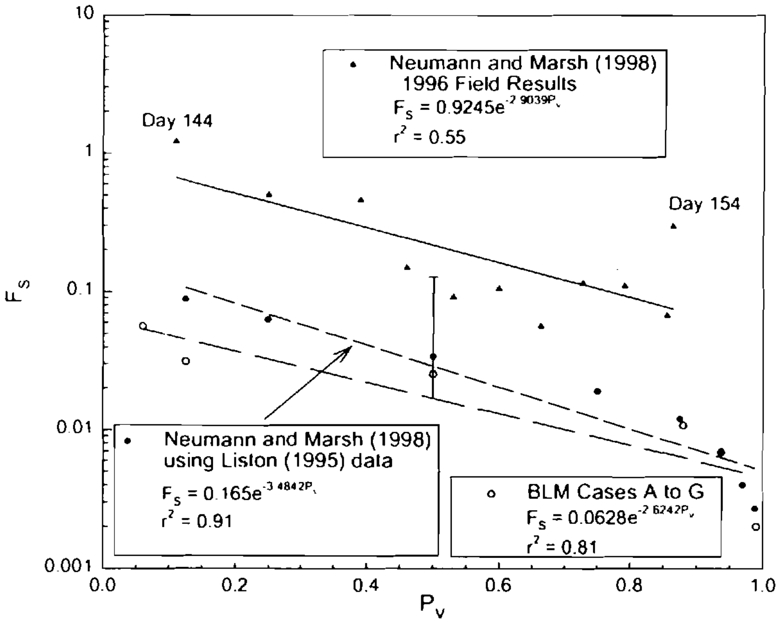

Fig. 2 F_S values derived from 1996 field data and Liston (1995) model results as presented by Neumann & Marsh (1998), and from Cases B to G from the boundary layer model (BLM). The vertical bar represents the range of F_S values from BLM runs D and H to M. In all cases the lines are the best fit lines through the respective data points.

energy is horizontally advected from snow-free to snow patches when a landscape is comprised of multiple small patches. For example, the magnitude of advected energy increases more than 300% as snow patch size decreases from 4000 to 20 m (Table 2), and F_S is 76% smaller for a single patch (Case D) than that calculated for an evenly distributed snowscape of 20 m patches (Case M). These results demonstrate that F_S is a function of both fractional snow cover and patch size. However, as shown by the vertical bar on Fig. 2, modelled F_S for multiple snow patches of decreasing length is still lower than those reported by Neumann & Marsh (1998) for natural snow patches under field conditions. It is unknown whether this difference is due to errors in the field data, the model used, or the distribution of patch sizes used.

CONCLUSIONS

A boundary layer model (BLM) demonstrated variability in the magnitude of the advection of sensible heat from snow-free to snow patches under a variety of snow patch conditions. This advection increased the sensible heat flux to the snow patches, with the increase being largest for smaller snow cover fractions and smaller snow patches. The value of a simple advection efficiency parameter (F_S) was found to decrease with increasing snow-free fractional area and snow patch size. Such a parameter may be used to estimate average sensible heat flux advected to snow patches using independent estimates of sensible heat over snow and snow-free areas.

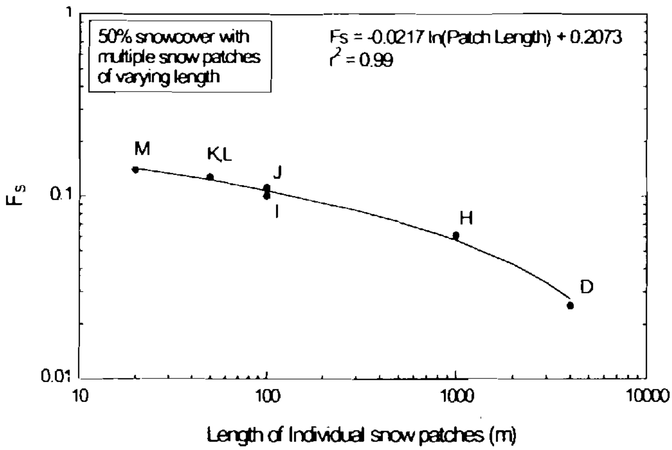

Fig. 3 F_S values resulting from decreasing snow patch size (BLM runs Cases D and H to M). This plot shows a relationship between mean patch length and advection; as snow patches decrease in size, advective processes have a larger influence on surface sensible heat fluxes.

The BLM estimates of advection for single snow patches were smaller than field estimates of advection. When multiple snow patches were used, advection increased but was still lower than field estimates. In addition, the results confirm previous studies that have demonstrated the large spatial variations in melt rate over individual snow patches, and illustrate the great difficulty in obtaining field estimates that provide reasonable estimates of average melt rates. Finally, the results demonstrate that these processes should be considered when attempting to aggregate sensible heat flux for a grid square composed of snow and snow-free patches. Ongoing studies will consider advection with natural snow patch conditions.

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