LOCAL ADVECTION OF SENSIBLE HEAT DURING SNOWMELT

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ABSTRACT

Heterogeneous land surface characteristics during the spring melt of an Arctic snowpack produce a horizontal transfer of energy at a small scale, a process termed local advection. Techniques were developed and applied to determine the importance of this local scale advection to both the magnitude of snowmelt and the average flux from a composite snow and snow-free surface. A tile-model approach was evaluated in estimating the spatial sensible heat flux over a patchy snow cover by comparison to eddy correlation measurements. These results suggest that a simple tile model is sufficient in determining the sensible heat flux over a heterogeneous surface, agreeing with other studies. An advection efficiency term, calculated from both field data and published model results (Liston, 1995), was used to determine the effect of advection on local snowmelt patterns. These calculations resulted in different patterns of influence, probably due to differences between the ideal modelled and natural surface conditions.

INTRODUCTION

Natural surfaces are generally heterogeneous in their characteristics, and the melt landscape of the Arctic tundra is an excellent example of this. Temperature, wetness, surface resistance, albedo and roughness all vary spatially as well as temporally during the snowmelt period. This surface heterogeneity affects the vertical transfers of radiation and sensible and latent heat, and it also generates horizontal gradients for sensible and latent heat transfer. Philip (1959) defined local advection as this horizontal exchange of energy, moisture or momentum due to small scale heterogeneity.

Surface heterogeneity exists at many different scales, and each patchwork pattern regulates and partitions energy differently (Oke, 1978; Guo and Schuepp, 1994). Many field studies in the past have looked at the role of surface heterogeneity at large scales with effectively single step changes in landcover. For example, Dyer and Crawford (1965) and Mahrt *et al.* (1994) studied agricultural landscapes, which have discontinuities with large fetches and well-defined surface conditions. These scales of study support a tile-type approach and consider the landscape as a "mixture of independent, homogeneous elementary surfaces" (Brunet *et al.*, 1994). The overall effect of multiple discontinuities or perturbations at the local scale of heterogeneity, however, may be more complex than the linear sum of individual discontinuities (Arya, 1988), indicating that the results from single step studies cannot simply be superimposed (Smits and Wood, 1985; Boudreau and Rouse, 1995). Any studies of local scale heterogeneity must be structured to look at the "forest," in addition to the individual "trees" (Schmid and Bunzli, 1995).

The study of local advection has potential importance to snow and ice hydrology (Claussen, 1991; Shook, 1995), especially to snowmelt energy balance studies in open terrain and atmospheric studies concerned with fluxes of energy and water from heterogeneous, patchy snowcovered surfaces. Early in the spring, snow melt is generally driven by the radiant energy (Male and Granger, 1981), but as the season progresses the contribution by sensible heat increases (Marsh and Pomeroy, 1996). This increase is due both to large scale air mass advection and the energy available locally from bare ground patches. Liston (1995) suggested that such local advection is a function of windspeed, surface roughness, albedo, cloud cover, vapour pressure and other surface characteristics, and that it has the greatest effect immediately downwind of the snowpatch edge. Since snowcovers are not uniform in depth or density, shallow areas soon melt away to expose the ground, with the magnitude of local advection increasing average melt rates by up to 30% (Liston, 1995). However, when considering grid-average fluxes from a combined snow and snow-free surface, Liston's (1995) modelling study suggested that advection was of secondary importance and could be ignored. In this case the average flux could be calculated from an areally weighted average of the sensible heat for surfaces that are 100% and 0% snowcovered.

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Although modelling studies have considered the role of local advection for snowcovered areas, there are few field studies documenting its magnitude. In light of this deficiency, the purpose of this paper is twofold: first to document the increase in sensible heat flux, and therefore snowmelt, due to local advection, and second to compare a simple tile model estimate of areally averaged sensible heat flux to measured values as the land surface changes from 100% snowcover to 0% snowcover. This paper reports results from an ongoing study of the suite of processes controlling the hydrologic cycle at the northern treeline, with the long term goal to develop physically based models for predicting environmental change.

STUDY AREA AND MEASUREMENT SITES

Field research was conducted between April 13 and June 6, 1996 at Trail Valley Creek (TVC) (68° 45'N, 133° 30'W), approximately 55 km Northeast of Inuvik, N.W.T., at the northern extent of the boreal forest-tundra ecotone in a region of rolling tundra terrain (for site description and map, see Marsh and Pomeroy, 1996).

Meteorological measurements were obtained in an open tundra domain with a fetch length of approximately 1 km. Data were collected at temporary stations over a persistent snow patch and over an early-emergent bare ground patch, and from a permanent site representative of the heterogeneous combination of snow and snow-free patches. These three stations were located within 400 metres of each other. Instruments at the two temporary stations collected standard micrometeorological measurements at half hour intervals. These two sites were selected to be representative of snow and bare patches across the domain. Initial snow depth at the snow site prior to the onset of the main melt period was 1.7 metres. The bare ground site was one of the first to become snow-free within the study domain. This occurred on May 11, 1996, while the persistent snow site retained snow for the duration of the study.

An eddy correlation system (Kaimal and Finnigan, 1994) was installed at the permanent site at a height of 2.4 metres above the ground, to measure directly the areal sensible heat flux $\overline{Q_H}$ as the site changed from completely snowcovered to snow free. The landscape snowcover changes were monitored using SPOT satellite images (20 metre resolution) and daily snow surveys over the melt period.

METHODOLOGY

Surface energy balance

The surface energy balance is described by:

$$Q_N - Q_H - Q_E - Q_G - Q_M = 0 \qquad (1)$$

where Q_N is net radiation, Q_H is sensible heat flux, Q_E is latent heat term, and Q_G is ground heat flux. For snow covered surfaces Q_M is melt, otherwise it is zero. For the snowcover there may be an additional term, the energy provided by precipitation (Q_P); however, since it is of minor importance in this study it will not be discussed. In addition, since the surface layers of the melting snowpack are isothermal at 0°C, no heat conduction occurs and therefore heat flux from the ground and energy stored in the pack are ignored. To avoid confusion between snowcovered and vegetated snow-free surfaces the subscripts S and V will be used respectively. In addition an overbar (‾) will be used to denote an average flux and a hat (^) will be used to denote the flux over a landcover which is continuous (i.e. either 100% snowcover or 0% snowcover). In all cases a single convention is adopted for the flux sign. Following Oke (1978), non-radiative fluxes directed away from the surface are positive in sign, while radiative fluxes toward the surface are positive. This convention differs from that normally adopted in snowpack energy studies, but follows the convention typically used by atmospheric models and by those studying the fluxes of snow-free surfaces.

Local scale advection of sensible heat

During much of the snowmelt period, the TVC landscape is characterised by a complex assemblage of snow and snow-free patches (see Marsh and Pomeroy, 1996 for photograph; Pomeroy *et al.*, 1993). The size and shape of these patches is related to the original snow accumulation pattern and the spatial variations in melt, and is constantly evolving as melt progresses (Shook, 1995). The influence of local scale horizontal advection changes over time. Early in the melt period, small bare patches would be expected to transfer all of their sensible heat to the adjacent snowcover, yet would have minimum impact on the average melt as the total transferred energy is small. As the patches increase in size, the total sensible heat from the surface increases and has a considerably larger impact on the areal melt rate. However, it may be expected that a smaller portion of the sensible heat from the bare patches goes to increasing snowmelt, and therefore the efficiency of transfer to the snow patches decreases (Marsh and Pomeroy, 1996). It is expected that the local advection will also vary with windspeed, landscape roughness, upwind distance of bare ground, and the perimeter to area ratio of the snowpatches.

The surface characteristics and energy fluxes from the snow and snow free surfaces are very different, resulting in large spatial variations in the sensible heat over the snow patches (Figure 1). Weisman (1977) concluded that the influence of advection decreases exponentially with distance from the leading edge, but was unable to quantify this relationship. Liston (1995) used an atmospheric boundary layer model for a simple case with one snow patch covering 50% of the area, to show that sensible heat flux was highest at the leading edge of the snowpatch, decaying to a steady state value after approximately 500 m. However, the actual distance required to decay to such a value is a function of patch size and geometry, wind speed, and surface roughness. A practical implication of the poor understanding of this distance decay relationship is that it is difficult to locate instruments which will represent the average advective influence. Given that local scale advection is potentially large, this problem of instrument location has important implications for both hydrological studies where there is a need to estimate the average basin snow melt, and atmospheric studies where there is a need to determine the average surface flux to the atmosphere from a highly heterogeneous land surface. In both cases the problem is further complicated as the location of the station relative to the snow patches changes as the snow cover evolves and with changes in wind direction. As a result, flux estimates will vary from low when a station is located at the downwind edge of a snow patch to high if it is at the upwind edge, or representative of bare ground when the snow is removed from the station site, although snow patches may still exist. Even relatively small remnant snow patches can have a large impact on streamflow (Marsh and Woo, 1981).

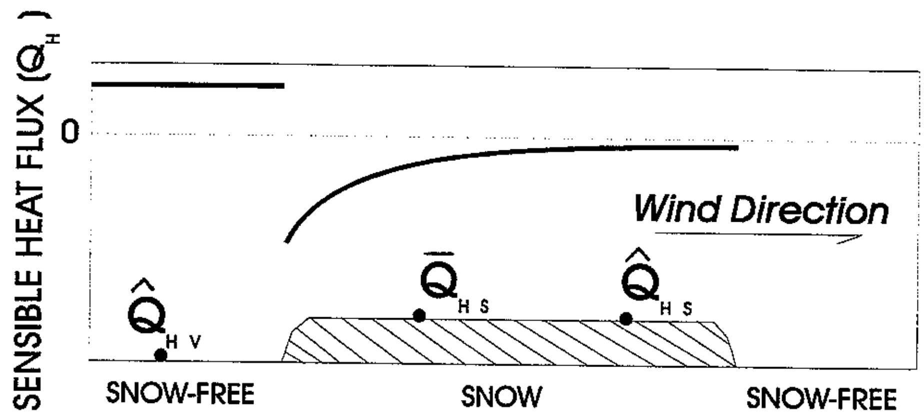

Figure 1: Schematic diagram illustrating the changes in sensible heat flux for a snow-free and snow patch during melt. Also shown are various sensible heat flux (Q_H) terms, where subscripts V and S refer to vegetated snow-free and snow patches respectively. The ¯ and ^ symbols refer to mean values, and $\overline{Q_H}$ is the flux averaged over the entire domain (spatial average).

Marsh and Pomeroy (1996) described a method for estimating the average advection of sensible heat (Q_A) to snow patches as:

$$Q_A = \left[\frac{\hat{Q}_{H_V} P_V}{P_S}\right] F_S \qquad (2)$$

where $\hat{Q}_{H_V}$ is sensible heat to vegetated snow free area (i.e. 0% snowcover), P_V and P_S are the fraction of the basin snow free and snow covered respectively, with the snow area for TVC determined from SPOT images. F_S is a function expressing the portion of the bare area sensible heat which is advected to the snow patches. F_S would have a value between 0 and 1 depending on the relative portion of the bare versus snow covered area, wind speed, terrain roughness, upwind bare fetch length and the perimeter to area ratio of snow patches. F_S may be calculated by rearranging equation 2, and estimating Q_A independently from:

$$Q_A = \overline{Q}_{H_S} - \hat{Q}_{H_S} \tag{3}$$

where $\overline{Q_{HS}}$ is the average sensible heat flux to the snow patches and $\hat{Q}_{HS}$ is the sensible heat flux to a surface with 100% snowcover (but with the same atmospheric conditions).

Sensible heat fluxes

To investigate the role of local advection following equations 2 and 3 requires estimates of (see Figure 1):

(a) sensible heat flux for a vegetated, 0% snowcovered location ($\hat{Q}_{H_V}$)

(b) the average sensible heat flux for the snow patches ($\overline{Q}_{H_S}$)

(c) the sensible heat flux over a surface which is 100% snowcovered ($\hat{Q}_{H_S}$). This would also be the minimum sensible heat occurring at the downwind edge of a large snow patch, a site unaffected by local advection and invariable with further downwind distance.

(d) the average sensible heat flux for the entire domain with a mixture of snow and snow-free surfaces ($\overline{Q}_H$).

Details on the methodology used to estimate each of these fluxes are provided in the following sections.

Sensible heat flux for a vegetated, 0% snowcovered surface **($\hat{Q}_{H_V}$):** For the snowfree surfaces Q_{G_V} and Q_{N_V} were measured. Aerodynamic or eddy correlation methods would be preferable for calculating the latent (Q_{E_V}) and sensible (Q_{H_V}) heat fluxes; however, the small size of the patches during the early stages of melt requires measurements at very close proximity to the surface, in order to be within the internal boundary layer of the vegetated surface. This would require very accurate profile methods due to the shallow depth of the boundary layer, and/or extremely fast eddy correlation equipment in order to monitor the properties of the very small eddies typical of this height. Such methods were not used in this experiment because of difficulties in working at a remote site, as well as the concern that such measurements would be very prone to large "errors" induced by the relative location within the snow-free patch. Instead, the relatively simple and robust Priestley-Taylor method (Shuttleworth, 1993) was used to estimate Q_{E_V}. The evaporation coefficient (α) in the Priestley-Taylor equation was evaluated from four evaporation lysimeters, similar in design to those used by Marsh *et al.* (1981), located around the study domain. These lysimeters showed an average α value of 0.69. Marsh *et al.* (1994) found a similar value for α for Trail Valley Creek. The Priestley-Taylor method has been shown to apply to northern environments (Rouse *et al.*, 1977), and Marsh *et al.* (1994) used water balance information to confirm that it is applicable to the Trail Valley Creek site. Q_{H_V} was then estimated from the residual of equation 1. Such a residual term will of course also include errors associated with the calculation of any of the other terms. Previous studies suggest that the maximum error would be $< \pm 15\%$.

Average sensible heat flux for a snow patch **($\overline{Q}_{H_S}$):** For a snow patch Q_{N_S} was measured directly. As in the case for snow-free patches, there are concerns over detailed profile or eddy correlation systems for estimating sensible and latent fluxes over small snow patches. As a result, standard, robust bulk transfer methods (Dunne *et al.*, 1976; Moore, 1983) were used to estimate Q_{H_S} and Q_{E_S}. For these calculations, air temperature, surface temperature and humidity were measured, and the momentum roughness height of the snowcover (0.0018 m) was estimated from wind profile data. Since wind data was unavailable at the site due to instrument failure, data from the nearby permanent meteorological station was used. Errors in Q_{H_S} and Q_{E_S} terms would be expected to be $<\pm$ 10%. From equation 1, the melt term was calculated as the residual of the energy balance.

Since the objective was to measure the average sensible heat flux for a snow patch ($\overline{Q_{H_S}}$), not to document the spatial variations in Q_{H_S}, and since previous modelling work (i.e. Liston, 1995) suggested large spatial variations in sensible heat flux occur, the exact location of sensors is critical. It was felt that a large, persistent snow patch would provide the most consistent estimate of $\overline{Q_{H_S}}$. Using snow survey results, such a site was selected and instruments were positioned near its centre. The necessary data to clearly demonstrate that measurements from this site are representative of average values would be very difficult to obtain. However, since the instruments were not located near the edges of the patch, and the patch size was typical of patches within the study area, the data from this location are likely to be representative of average values.

Sensible heat flux for 100% snow cover without the influence of advection **($\hat{Q}_{H_S}$):** A relationship between 850 millibar air temperature and sensible heat flux to a continuous snow cover was used to estimate $\hat{Q}_{H_S}$, a method suggested by Male and Granger (1981) and utilised by Marsh *et al.* (1997). Male and Granger (1981) demonstrated that at Bad Lake, Saskatchewan, the surface sensible heat flux of a continuous, melting snowcover could be estimated using the 850 millibar level temperature. Inuvik 850 mb temperature measurements collected by the Atmospheric Environment Service were related to measured $\hat{Q}_{H_S}$ during periods when the snow cover was melting but continuous (Marsh *et al.*, 1997). This relationship was then used to determine daily values of $\hat{Q}_{H_S}$ during periods of patchy snowcover. This technique assumes that for similar atmospheric conditions, $\hat{Q}_{H_S}$ for a patchy snowcover is equal to $\hat{Q}_{H_S}$ for a continuous snow cover. It is hoped that ongoing work using an atmospheric boundary layer model (Essery, 1997) will provide validation of this concept.

Average sensible heat flux for a heterogeneous surface **($\overline{Q_H}$):** The patchwork or tile-type approach used by Dyer and Crawford (1965) and Mahrt *et al.* (1994), for example, may be used to estimate sensible heat flux over a patchy surface ($\overline{Q_H}$). This involves the linear sum of the sensible heat fluxes of the component landcovers weighted by their area:

$$\overline{Q_H} = (\hat{Q}_{H_S} P_S) + (\hat{Q}_{H_V} P_V) \qquad (4)$$

where $P_V = 1 - P_S$, and the overbar here indicates a spatial mean. $\hat{Q}_{H_S}$ and $\hat{Q}_{H_V}$ are used in equation 4 as they are the values typically calculated in atmospheric models, where fluxes are calculated independently for each landcover type. Estimated sensible heat flux from equation 4 can then be compared to measured values from the eddy correlation system.

Snowmelt

The derivation of Q_{M_S} from field measurements typically provides a point estimate of surface melt, and as Liston (1995) suggested, such point estimates could be very different from the average melt. Such spatial variation could explain the relatively large errors that often occur when energy balance methods are used to calculate melt rates. Over a period of a few days such estimates may be close to the average, but for shorter time periods they would be expected to have large deviations from the mean, depending on relative location of snow patch and instrumentation. Another approach is to estimate the mean melt from:

$$\overline{Q_{M_S}} = Q_{N_S} + Q_{E_S} + (\hat{Q}_{H_S} + Q_A) \qquad (5)$$

where Q_A is found from equation 2, and using an appropriate F_S.

RESULTS AND DISCUSSION

Surface energy balance

The main period of continuous, uninterrupted melt began on May 21. The areal snow depletion curve (Figure 2) shows that snowcover quickly became patchy following this day. As the season progressed and the cover became increasingly patchy, local scale advection presumably increased and the contribution to melt from sensible heat increased (Figure 3). Results from the snow-free site indicate that a significant amount of the available energy was converted to sensible and latent heat which was lost from the surface to the atmosphere (Figure 3). During the study period, the peak sensible heat flux from the snow-free surface was approximately 250 W/m^2, which was energy transferred to the overlying air. This energy was potentially available by horizontal advection to snow patches downwind of the bare ground, and was greater in magnitude than the net radiation value over snow for that day. This suggests that the amount of energy which is locally advected from bare ground patches to adjacent snow may be significant.

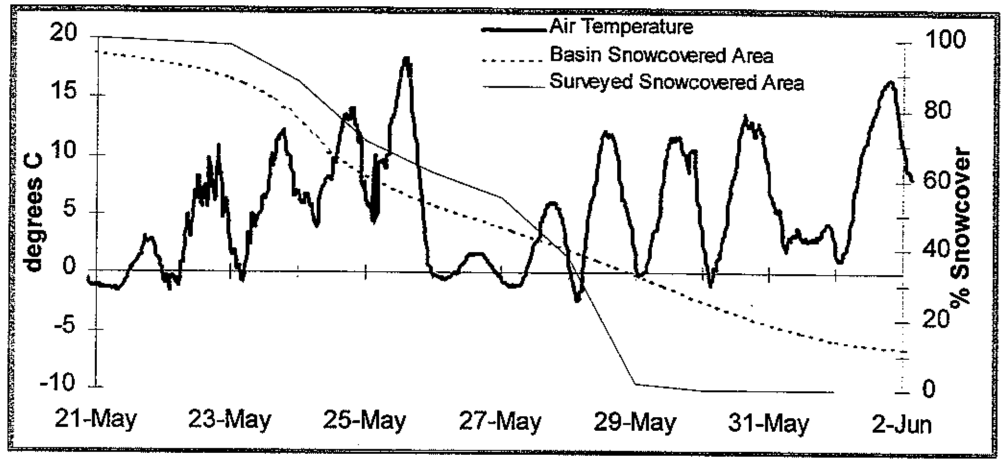

Figure 2: Air temperature time series during the melt period. Also plotted are snowcovered area data, extracted from SPOT satellite images for the basin, and derived from snow survey data for the area surrounding the micrometeorological stations.

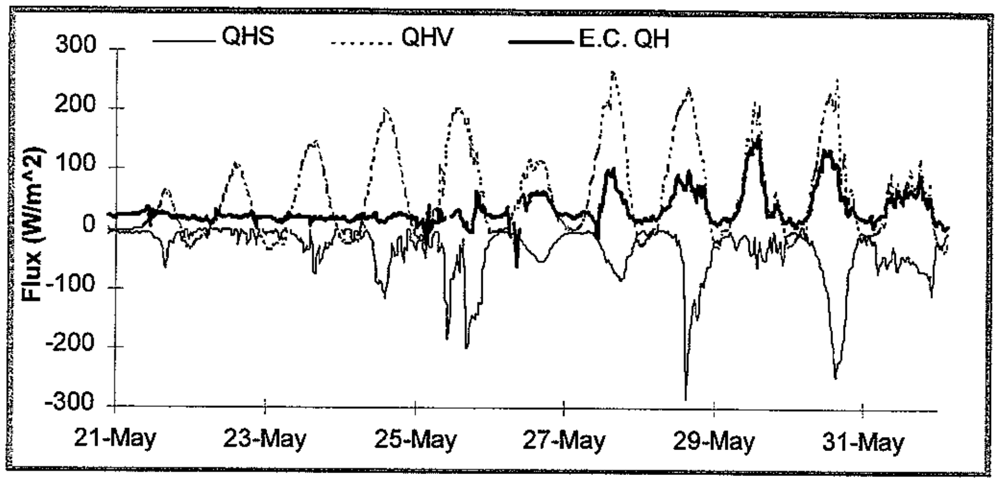

Figure 3: Half-hourly sensible heat flux for the snow site (Q_{HS}), the vegetated snow-free site (Q_{HV}), and for the entire domain with patchy snow conditions as measured by the eddy correlation system (E.C. Q_H).

Advection efficiency (F_S)

Liston (1995, Figure 6a) used model results to show the increase in melt due to advection of sensible heat for various snowcover conditions. These data were used to calculate values for Fs (assuming % melt increase is completely due to advection of sensible heat). Figure 4 shows that F_S had a maximum value of near 0.1, and decreased to approximately 0.01 as snowcover depleted. Figure 4 also shows that F_S rises as wind speed increases from 1 to 8 m/s. Field estimates of F_S for 1993 (Marsh *et al.*, 1997) and 1996 show some scatter when compared to P_V (Figure 4), but the relationship shows F_S near 0.5 with snow covered areas > 0.5, and decreasing to < 0.01 with Pb = 0.9. The model results and the field results differ considerably, only intersecting when the bare fraction reaches 0.95 (5% snowcover). At high snow cover values, the field estimates show Fs much higher than suggested by the model results of Liston (1995). This indicates that advection is more efficient at TVC, with a larger percent of the Q_{H_V} being used to enhance snow melt. The reason for the differences between the field and model results are unclear, but are probably related to the fact that the TVC area is undulating with local topographic differences of up to 30 m, while the Liston (1995) simulations are over flat terrain. Another difference is the snowcover. Liston (1995) used a single snow patch of various sizes, while the field conditions are for a large number of small patches with fractal dimensions and distributions (Shook, 1995).

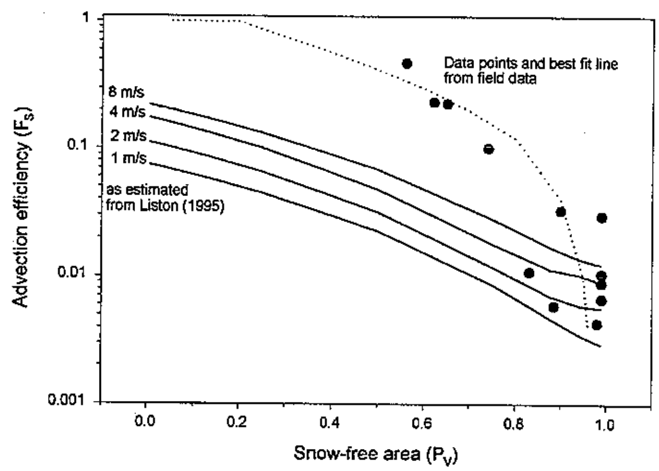

Figure 4: Fs vs. Snow-free area for various windspeeds (derived using model results from Liston, 1995) and for TVC field data.

Increases in sensible heat and snow melt due to advection

The effect of the relationships between Fs and the fraction of bare ground (P_V) shown in Figure 4 are compared in Figure 5 by setting typical values for Q_{H_S} (-100 W/m2) and Q_{H_V} (40 W/m2) and calculating Q_A from equation 2 for a decreasing snowcover. The resulting increase in Q_{H_S} are presented for Liston's model simulations in Figure 5. This shows that the largest increase in Q_{H_S} is for a higher windspeed and decreasing snowcover area. For the example shown, the maximum increase in average Q_{H_S} is 12% as the snowcover approaches 5%. F_S values calculated using field data are also plotted in Figure 5. These results suggest a differently shaped curve with the maximum increase in Q_{H_S} due to advection occurring when P_V is around 0.7. At this point, average sensible heat flux and melt would increase by approximately 30% and 25% respectively. The different shape of the increase in Q_{H_S} curves is due to differences in the Fs vs P_V relationships, with the Liston model suggesting a near linear decline in Fs (on a log scale) while the field data suggest than Fs remains high and then very rapidly decreases in value.

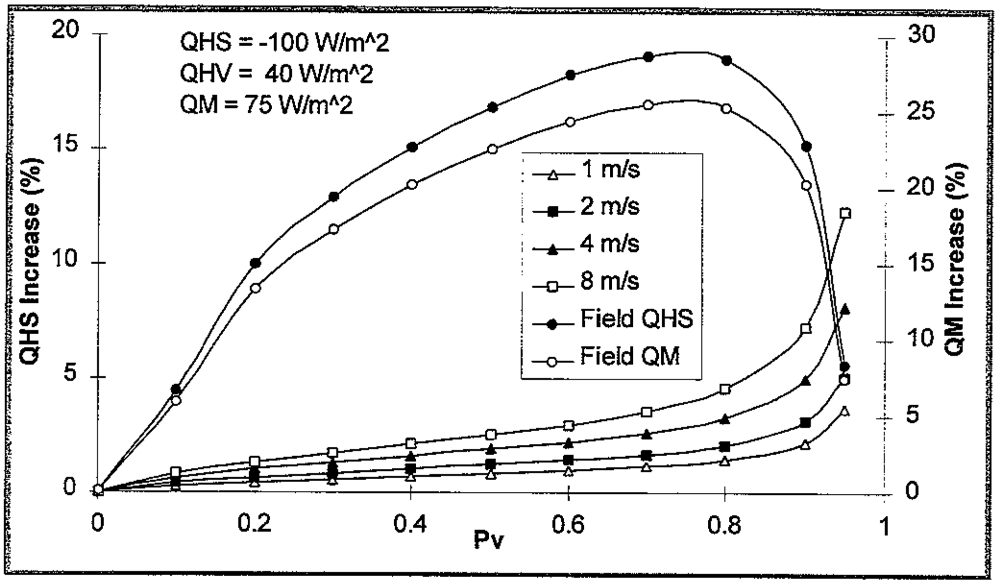

Figure 5: Percent increase in Q_{HS} were calculated using the F_S vs P_V relationships from Figure 4. The shape of these curves differ significantly, although the differences in Figure 4 are less dramatic, apparently only differing in magnitude. Note that Q_M is plotted on the second y-axis.

The differences in the increase in Q_{HS} using the modelled and the field data *Fs* values are quite dramatic. It is not likely that the errors in the field data are sufficiently large to explain the dissimilarities, but more likely that the model, which didn't include small "naturally-spaced" snow patches or uneven terrain, did not closely mimic reality. These suggest areas for future research in both field studies and modelling efforts.

<u>Sensible heat flux over a composite snow and snow-free surface</u>

Measured: The eddy correlation system measurements show that the sensible heat flux remained low between May 21 and May 25, after which a slight diurnal cycle became evident (Figure 3). By May 25, the basin snowcover was approximately 55% (Figure 2), and the influence of the bare ground patches became more important. The diurnal cycle strengthened by May 27, and was generally positive in sign (energy directed away from the surface) and coincided with a basin snowcover of 45% (Figure 2).

Tile model: Figure 6 plots the daily average sensible heat flux for 100% snowcover and 0% snowcover, as well as the results from tile model (equation 4) and measured values from the eddy correlation instruments. The plot shows an under-prediction of the patchy $\overline{Q_H}$ compared to the eddy correlation measurements early in the melt period with the tile model showing a negative sensible flux, while the eddy correlation showed a positive flux. Given the large snowcovered area and negative Q_{HS} during this period, it is hard to understand the positive $\overline{Q_H}$ from the eddy correlation, and may in fact suggest a small positive bias of the eddy correlation system. Later in the melt period the tile model tends to slightly overestimate sensible heat flux when compared to the eddy correlation measurements. These consistent differences are also illustrated in Figure 6 inset. What is clear from Figure 6 is that the tile model provides a reasonable estimate of $\overline{Q_H}$, and as suggested by Liston (1995) estimates of average sensible heat flux from a patchy snow surface can be estimated from a simple tile model which neglects local scale advection. Further work is required to determine if the small discrepancies are due to advective influence.

One possible approach to improve the tile model results is to use spatial analysis of the source area surface, instead of using only the basin areal depletion curve. Figure 2 shows that the basin snowcover area and the snowcover area derived from daily snow surveys in the region surrounding the instrument towers are quite dissimilar over the melt period. Source area analysis of the eddy correlation station would lead to a better understanding of the surface area influencing the flux measurements, while the use of a spatial statistic may help describe the potential interaction between patches. This approach will be taken in future work.

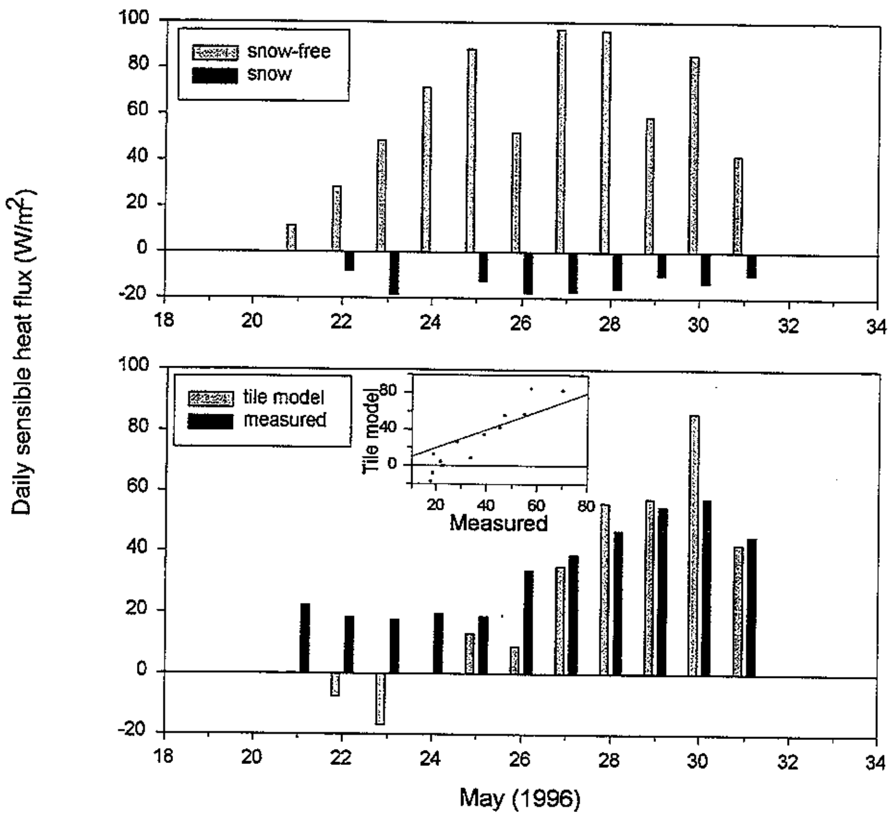

Figure 6: Daily average sensible heat fluxes compared. Inset graph is a comparison of measured and predicted Q_H from a simple tile model.

CONCLUSIONS

As expected, the surface energy balances are significantly different between the two landcover types, bare ground and snow. The resulting horizontal heterogeneities of temperature and water vapour drive the process of local advection, and the amount of energy which is potentially available from the bare ground is often greater in magnitude than the net radiation energy over the snow. Some of this energy is advected to adjacent snow patches. Preliminary comparisons of an advection effectiveness function determined by field measurements and published model results (Liston, 1995) suggest that the method has potential for estimating the increase in sensible heat and therefore melt due to local advection. Such conditions can increase average melt by up to 30%. However, there were differences between the two estimates of Fs that require further field and model studies. Although advection is important at this scale, when considering the average sensible heat flux from a domain with a mixture of snow and snow-free areas, it appears that a simple tile model is sufficient and that local advection does not need to be considered. This preliminary result is in agreement with the model results of Liston (1995).

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