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Surface Atmosphere Exchange During and After Snow Melt for Different Arctic Environments During MAGS

CONSTANCE M. BROWN-MITIC, IAN J. MACPHERSON,
PETER H. SCHUEPP, AND ROGER BALES

ABSTRACT

The arctic environment and in particular the Mackenzie Basin displays a very dynamic interrelationship between the atmosphere and the surface for the different ecosystems represented. The Canadian Twin Otter research aircraft flew a total of 24 grid and long regional transects, over tundra, forest and delta ecosystems, during the period of snow melt (late May - early June) and early summer (early July) as part of the 1999 Mackenzie Area GEWEX Study (MAGS) field campaign. Observations over tundra showed a sharp rise in the sensible heat flux at the onset of melt, reaching a maximum plateau at the end of the melting period and into early summer. The latent heat flux showed a more gradual rise with a Bowen ratio of two during melt, and continuing to rise through to early summer. The forested system demonstrated similar gradual rise in the latent heat flux, while the sensible heat flux was already high with Bowen ratios reaching three at the start of the observation period in late May. For both systems, the Bowen ratio stabilizes at approximately 1 by early summer. The gradual rise in latent heat flux can be tied to gradual thawing of the root zone and the significance of transpiration. This is corroborated with a similar gradual trend in the carbon dioxide flux. The relatively low solar elevation angle and earlier start of snowmelt along the regional transect, may account for the much larger sensible heat flux. The closure of the energy balance and the portion of the flux attributed to non-turbulent fluxes and energy consumption is further refined by including flux contributions from low frequency events. Analysis of the distribution of the turbulent coherent structures along the flight transect and over the grid area has the potential of identifying the particular source areas for the different turbulent fluxes. The coincidence of the fluxes within these structures, may also indicate co-location of sources. The findings from this study fill gaps in our knowledge about energy partitioning during snow melt, and broadens our contemporary view of evapotranspiration dynamics of wet surfaces.

Keywords: sensible heat flux, latent heat flux, energy balance, surface-atmosphere exchange, snow melt, arctic ecosystems

INTRODUCTION

The Canadian National Council Twin Otter research aircraft participated in the Mackenzie Area GEWEX Study (MAGS) 1999 intensive field campaign. MAGS is a series of larger scale hydrological and related atmospheric and land surface studies conducted within the Mackenzie Basin in Canada, aimed at providing improved understanding of cold region high latitude hydrological and atmospheric processes and their role in the global climate system. The overall objectives and scope of MAGS is detailed in Stewart et al. (1998). Twenty-five project flights were flown in 1999 from Inuvik NWT (68 N, 133 W) over tundra, forest and the Mackenzie Delta, during two periods covering the spring snow melt and early summer (May 21 to June 15 and July 5 to July 14, respectively). The project provided the only measurements in MAGS of radiometric surface properties and surface-atmosphere exchange of sensible and latent heat at temporal and spatial scales suitable for testing models based on remote sensing and numerical simulation. Of particular interest are surface radiation balances, surface-atmosphere fluxes and energy partitioning (between sensible and latent heat flux) during and after snowmelt, and potential regional effects of surface features that cannot be adequately resolved by remote sensing observations from satellites, such as small lakes. This objective was based on the fact that due to the sparseness of direct observations over the Mackenzie Basin, the surface-atmosphere exchange over the basin will be estimated primarily from coupled atmospheric-hydrological-land surface models and algorithms based on remote sensing observations of surface characteristics, supplemented by standard meteorological data. The validity of such estimates needs to be assessed, and flux measurements from low-flying aircraft are the only available means for measuring surface-atmosphere energy exchange at regional scales.

The Twin Otter flux research aircraft has participated in many previous international land surface climatology projects, including the First International Satellite Land Surface Climatological Project Field Experiment (FIFE) Sellers et al., (1988), Northern Wetlands Study (NOWES) Glooshchenko et al., (1994), California Ozone Deposition Experiment (CODE) Pederson et al., (1995), Boreal Ecosystem-Atmosphere Study (BOREAS) Sellers et al., (1995, 1997), Southern Great Plains 1997 (SGP-97). Over the past fifteen years the research teams have developed particular expertise in relating flux and radiometric observations to land surface characteristics (Mitic et al., 1995 and 1996; Schuepp et al., 1996; Ogunjemiyo et al., 1997 and 1999; MacPherson et al., 1999).

STUDY SITES

Twenty-five project flights (each generally covering more than one target area) were operated from Inuvik, North West Territories (NWT) (68 N, 133W) between May 21 and June 8, 1999 (calendar days 141-159) and between July 5 and July 14 (days 186-195). The first ‘window’ covered the critical snowmelt period and the latter was representative of early summer conditions. Flights were generally executed within three hours of solar noon. For details on flight operations, instrumentation and logistics please see MacPherson (2000). Repeated flux runs were flown over several tracks representative of the different ecosystems (tundra, forest and delta) in the northern Mackenzie Basin. The main emphasis in data collection was on a 16 km x 16 km grid pattern over tundra 50 km north of Inuvik, a 100 km transect over forested areas with varying degrees of small-lake density in a direction S from Inuvik, and a 20-km run over the Delta.

A total of nine repeated and one single grids were flown. Grid patterns consisted of a series of nine lines 16-km in length, separated by approximately 2 km, flown twice in opposite directions in a time-centered fashion to minimize temporal effects. The average flight altitude was 60 m. The southern part of the grid contained a few lakes 1-2 km in size and a few scattered stands of very small trees. The northern part of the grid consisted of typical tundra shrubs and included Trail Valley, the site of a surface tower observations of fluxes and radiometric properties, operated by National Hydrology Research Center (NHRC) of Environment Canada. The Flux tower was located at the eastern end of Line 8 of the grid. An additional six runs were made of grid line 8. Grid averages of fluxes represent 288 km of airborne sampling, which is expected to give convergent flux estimates within < 5 % error. They are taken as representative area averages for tundra surfaces

Two regional transects, were flown over very sparse black spruce forested area, scattered with small lakes, of which one was selected for repeated runs. The selected 100 km transect was flown in both directions at an altitude of approximately 60 m. The transect was divided into five sections approximately 20 km in length. Average estimates over each section represents 40 km sampling with an expected repeatability for the sections within 10 to 15 %, and 5% for the averaged entire run.

A series of flights were made over the sparse black spruce forest in Havikpak Creek Valley, where the NHRC operated a second flux tower. This area has a denser canopy and is at a higher latitude and altitude than the site of the forested regional run. The transect was 2 km in length over consistent forest. A total of 66 runs were made and a minimum of six runs were used to calculate flux estimates, in an effort to reduce sampling errors. Both forested sites represent the northern limits of the Canadian boreal forest, which extends into the Mackenzie basin.

A 20 km track was selected within the Mackenzie Delta, over a representative section that is not influenced by the hills on either shore. The Delta track was flown a total of 51 times. The Mackenzie Delta covers a significant part of the northern Mackenzie Basin and is expected to make a substantial contribution to the surface-atmosphere exchange process.

Supplementary data were also collected over Noell Lake (approx. 20 km N of Inuvik), to examine typical lake effects in the Basin. Figure 1 gives the locations of the various study sites within the Lower Mackenzie Basin. Transect A-C represents the 100 km forested run, and E-D represents the Delta run.

More than 50 parameters relating to aircraft attitude and motion, air motion, temperature, gas concentrations (moisture and CO_2), surface characteristics such as terrain roughness, surface temperature, vegetation index, and incoming and reflected short- and long-wave radiation were recorded by the Twin Otter at flight altitudes generally between 45 and 60 m a.g.l. Some complementary runs were also done at higher altitudes up to the top of the convective boundary layer, for inter-comparison with boundary layer models. Flux estimates were made by the eddy-covariance technique by statistically correlating 32-Hz fluctuations of the vertical turbulent air motion with those of potential temperature, moisture and CO_2.

The Grid and Delta had the highest amount of snow cover at the start of the project in late May. Approximately 10% of the Grid was bare ground on May 27 when the first full grid was flown. The regional forested run, been further south and at a lower elevation had most of the snow melted by the first flight on May 23. The delta was completely frozen at the beginning. Observations covered the periods of thaw, flooding and dry out.

Boundary layer (BL) heights over the Grid during the first week of June ranged from approximately 280 m. to 510 m. and reached 1110 m. in early July. The forested area (A-C) had BL heights of 420 m on May 24, 1500 m. on May 28, and 990 m. on July 10.

On May 27 the Grid surface and air temperatures were averaging 4-5^{o}C, while lake-free sections of the forested AC site had averaged air temperatures of 14^{o}C and surface temperatures of 22^{o}C on May 28. On June 8 Grid surface temperature averaged 13^{o}C and the air temperature had dropped to freezing. Grid temperatures for July 8 averaged 10^{o}C for the air and 17^{o}C for the surface, and the forested site had air and surface temperatures of 16^{o}C and 21^{o}C respectively.

OBSERVATIONS AND RESULTS

Tundra Grid

During the period of *rapid snow melt*, when the Grid surface is closely coupled to the atmosphere, the spatial distribution patterns of sensible heat flux strongly reflects the distribution patterns of surface temperature excess. The areas of the grid where the surface is colder than the air has a strong negative sensible heat flux. This represents turbulent energy contribution to the warming of the surface and melting of the snow pack. The distribution pattern of latent heat flux corresponds well with the areas of positive sensible heat flux and is directly correlated to the warmer surfaces of the grid. These areas are also indicative of where the root zone has sufficiently thawed to facilitate the uptake of CO_2. The areas where CO_2 flux is positive, indicating either degassing from the snow pack or soil respiration, corresponds well with the colder surfaces. The distribution pattern of CO_2 and surface temperature excess may be used as an indication of the general distribution pattern of the melting snow.

During the *transition period* the surface warmed significantly, averaging around 14 ^{o}C on June 8, while the air temperature remained cool, below 2 ^{o}C over the grid. The surface is predominantly snow free, and almost the entire grid is taking up CO_2 from the atmosphere. The distribution patterns of CO_2, and surface temperature excess are reflected in the sensible and latent heat flux distribution. However the emerging distribution patterns of CO_2 uptake by the vegetation is now exerting a stronger influence on the patterns of the energy fluxes. The spatial pattern of latent heat flux more closely resembles that of CO_2, and the sensible heat flux pattern reflects the distribution pattern of CO_2 flux superimposed on the pattern of surface temperature excess.

By *early summer*, the surface temperature seems to have reached a level of equilibrium with the atmosphere. There is very little variation in the surface temperature excess across the grid. The distribution patterns for sensible and latent heat flux is now a reflection of the vegetation at the surface indicated by the distribution patterns of CO_2 uptake.

Figure 1 shows the aircraft-measured averages of sensible heat flux (H), latent heat flux (LE), and the CO_2 flux, averaged over the grid (18 runs) and for repeated passes over Line 8 of the grid, where the NHRC tower was located. The H and LE plots are restricted to clear or almost clear conditions, whereas the CO_2 flux includes overcast or broken cloud conditions. Corrections for variations in incident solar radiation were made but did not significantly affect the findings. The data for Line 8 where the tower was located did not systematically differ in flux characteristics from the overall grid. A dramatic increase in sensible heat flux occurred during the rapid snowmelt period (May 21 to June 3). Latent heat flux over the grid exhibits a much more gradual approach to summertime values. It appears that, even though the surfaces are wet during snow melt, there is sufficient aerodynamic resistance to convective moisture loss from the vegetation to suppress latent heat flux in favor of sensible heat flux until the root-zone is thawed sufficiently for transpiration to become significant. This is documented by the CO_2 flux, which initially shows a small upward (positive) flux indicating respiration from the newly exposed surface, followed by negative values as the vegetation greens and photosynthesis increases, in conjunction with the increase in latent heat flux associated with increased transpiration. Bowen Ratios (H/LE) were of the order of two during snowmelt, reducing to about one in early summer.

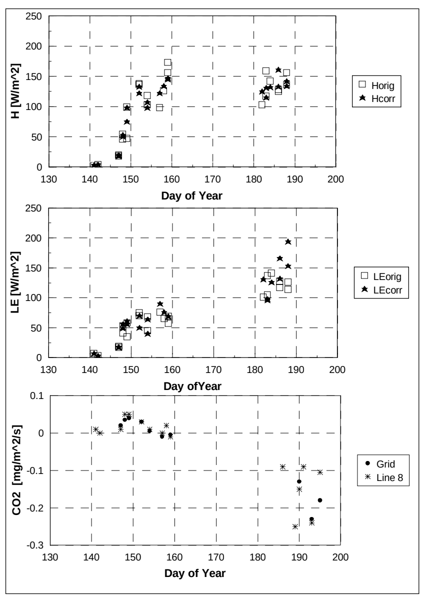

Figure 1: Time series of averaged fluxes of sensible and latent heat and CO_2 fluxes observed over the Tundra Grid and line 8 of the Grid: From snowmelt to early summer

Regional Forest Transects

During the first observation period (late May–early June), sensible and latent heat fluxes are considerably higher with sensible heat flux dominating at ~ 200 W m^{-2} (much higher for some individual sections). This is partially due to the earlier timing of snow melt along this transect to the south, partly due to the low albedo of coniferous trees at the relatively shallow solar elevation angles, the warmth of the snow-free hummocks and lichen patches, and possibly also due to differences in aerodynamic surface-atmosphere coupling. This finding is also consistent with similar studies in the boreal forest where large dominant sensible heat fluxes was attributed to the snow free canopy (Nakai et al., 1999, Harding and Pomeroy, 1996), as well as the decoupling of the underlying wet surface with the atmosphere (Ogunjemiyo et al., 1997). Bowen Ratios are of the same order of magnitude as those observed over the (tundra) grid, two to three during the first observation period, reducing to values slightly exceeding one during the early summer period. The flux estimates over the forested regional transect gradually converge towards those observed over tundra during the early summer, with values of sensible and latent heat flux typically between 100 and 200 W m^{-2}. Figure 2 gives the average fluxes for the AC regional transect.

Keeping in mind the high variability of airborne estimates expected over a short sampling track, the comparison between the (3 km) Havikpak forested run, the area where the NHRC tower is located, and the AC regional forest run, showed that the Havikpak site can be considered to be broadly representative, in terms of energy exchange and partitioning, of the sparse forests in that region of the northern Mackenzie basin (Figure 3).

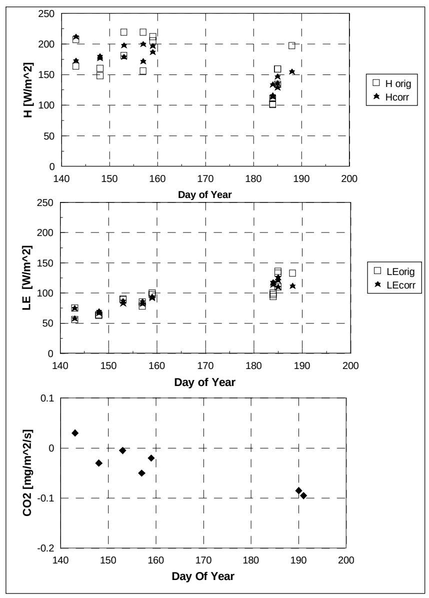

Figure 2: Time series of averaged fluxes of sensible, latent and CO_2 fluxes observed along the forested AC regional transect: from snow melt to early summer

Delta vs. Forest

Flux data for the 20 km track in the Mackenzie Delta and the 3 km Havikpak forested track are shown in Figure 3. The strong temporal variations in fluxes observed over the Delta reflect the physical changes of snowmelt, flooding and gradual drying out. The largest sensible heat fluxes were measured over the forested site, for reasons stated in the preceding section. As was the case for the tundra (grid), sensible heat flux (H) reached summertime levels over both the Delta and forest by the end of the first observation period (June 8). Latent heat flux (LE) remained low, with only a very small increase during the snowmelt and flooding stages of the Delta, reaching higher values during the drying out early summer season. During snow melt and flooding, the sensible heat flux decreased, while the CO_2 flux remained positive, with a slight increase. The Delta uptake of CO_2 is comparable to the tundra grid area and is higher than the forested areas for early summer. A detailed interpretation of these results will have to consider the different status of vegetation between delta and regional forest, as well as the dynamics of flooding in the delta.

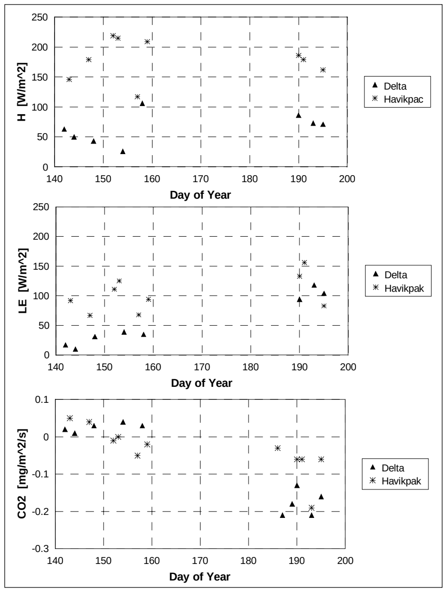

Figure 3: Time series of averaged fluxes of sensible, latent and CO_2 fluxes observed over the over the Delta and along the Havikpak forested run: from snow melt to early summer

STRUCTURAL ANALYSIS OF TURBULENT TRANSPORT

Structural analysis of the airborne data was performed (a) to define the size distribution of ‘coherent’ turbulent structures that are primarily responsible for the turbulent exchange of energy and gases between the surface and the atmosphere and (b) to determine the composition of such structures in terms of constituent scalars (heat, moisture and/or CO_2). Structures transporting individual fluxes represent a low level of convective mixing and suggest different time scales for the build-up of heat, moisture and CO_2 within the surface layer. Structures transporting multiple fluxes reflect a high degree of thermal mixing and coupled sources and sinks at the surface. Such information is useful when the sampling criteria for flux estimates, such as the length of a sampling run required for a convergent estimate, and the links between surface-atmosphere exchange and the characteristics of the underlying surface are to be better defined. They are also expected to serve as a base of reference for detailed surface-atmosphere modelling with explicit surface description.

The procedure used on MAGS data follow similar previous analyses of Twin Otter data (Mitic et al., 1995 and 1997), by defining from the raw data the spatially contiguous sequences of flux events in an upward or downward motion. Flux contributions are then defined in one of four modes: excess up/down and deficit up/down (where excess and deficit is in reference to the mean), with the aircraft seeing a one-dimensional slice through the three-dimensional coherent structures. Several points are illustrated by this analysis for the MAGS airborne data. The density of structures for both latent heat and sensible heat increases strongly with season, from snow melt into the early summer conditions. This has implications for sampling issues and optimum averaging period and suggests that longer averaging times (run lengths) are advisable for flux observations over areas with snow cover. The structures with the highest degree of mixing have the largest spatial scales while the unmixed shear driven structures are much smaller. In terms of composition, the flux associations for the grid and forest show a gradual progression from predominantly single component structures, through combined structures of heat and moisture in late May, to well mixed multiple compositions of heat, moisture and CO_2 during early summer as the vegetation becomes the dominant (and co-located) source/sink for surface-atmosphere exchange. This is evident for both the tundra grid and the forested sites, and is illustrated in Figure

4. The composition analysis may be a more sensitive indicator of the role of vegetation in surface-atmosphere exchange than the greenness index in these areas of relatively sparse foliage.

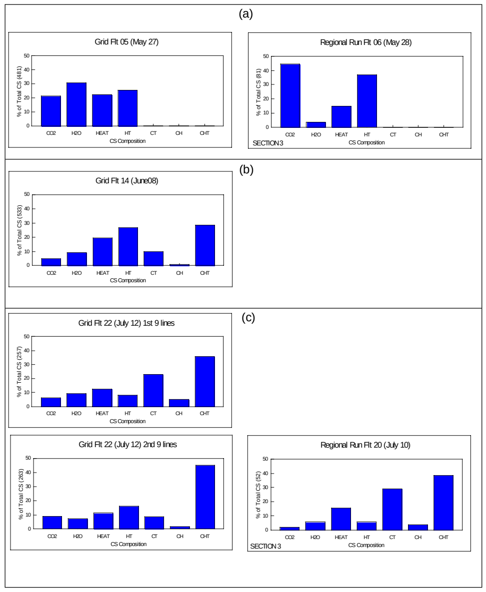

Figure 4: Composition characteristics and distribution of the turbulent coherent structures over the tundra grid and along section 3 (low lake density) of the forested regional transects, for periods during snow melt, transition and early summer

ENERGY CLOSURE AND NON-TURBULENT FLUXES

Airborne eddy correlation flux estimates have traditionally been plagued by non-closure, i.e., by the fact that sensible and latent heat fluxes (the turbulent fluxes between surface and atmosphere), when added to measured or estimated ground fluxes, do not add up to measured or estimated net radiation. A ‘residual’ of the order of 10 to 20% of net radiation has been hypothetically attributed to factors such as insufficient sampling of low-frequency contributions, regional advection or large scale transport associated with non-zero vertical velocity. Figure 5 shows the residual energy flux R in terms of available net radiation:

$$R = [Rn - (H + L E)]/Rn$$

There are distinct differences in energy partitioning between the various arctic ecosystems represented, and the controls on the energy and water balance are related (among other things) to the nature of the soil, the numerous shallow lakes, synoptic weather systems and the ice rich permafrost (Rouse, 2000). At the beginning of the observation period, almost all the net radiation over the delta and tundra regions is utilized in non-turbulent form, while the forested areas use less than 50% of the available energy for non-turbulent purposes. The non-turbulent component of the available energy over the forested areas remain relatively constant from snow melt to early summer at 20 - 30 %, while, in sharp contrast, the tundra grid area does a completely reversal in its energy partitioning between turbulent and non-turbulent components. At the beginning of snow melt the non-turbulent component of the available energy over the tundra site is greater than 80%, which is sharply reduces to about 40% by the end of snow melt, and then gradually to 20% by early summer. For the Delta, non-turbulent energy use is almost always greater that 50%.

$$T_s(t) = \langle T \rangle + T_o \sin(Tt)$$

The MAGS data differed from those obtained by the Twin Otter over any previously investigated ecosystem (e.g., grasslands, agricultural lands, temperate forests and Hudson Bay lowlands under summer conditions) (a) by the unusually large part of available energy that is dissipated by non-turbulent fluxes, primarily snow/permafrost melting and heat storage in gradually warming soil and water bodies, and (b) by a high degree of variability, including some runs where H+LE nearly equaled or even exceeded Rn. The latter conditions were associated with clear sky followed by overcast conditions. In such cases, the waterlogged surface systems exhibited a thermal inertia (or possibly a sign change in the ground flux G) which appeared to delay the expected drop in energy fluxes, particularly that of sensible heat. Baldocchi et al. (2000) and Eugster et al. (2000) provide detail reviews of energy balance studies at high latitudes and their interactions with the landscape.

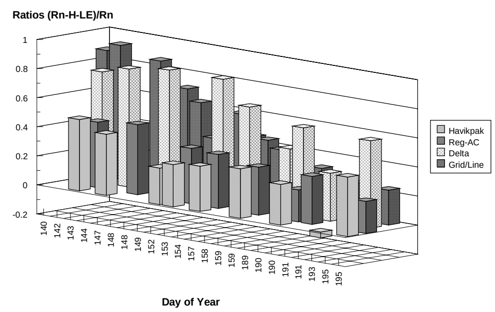

Figure 5: Time series of the residual energy flux for the four Mackenzie Basin ecosystems studied: Havikpak (a northern limit forest), Boreal forest regional transect, Mackenzie Delta, and the Grid over Tundra: From snow melt to early summer

DISCUSSION

Successful scaling up on the basis of soil-vegetation-atmosphere-transfer (SVAT) schemes in this landscape requires a good understanding of the interaction between: 1) surface/subsurface moisture status, including the melting of permafrost; 2) the physiological response of vegetation, 3) the thermal properties of this structurally complex, highly porous and often waterlogged surface and its response to changing radiation conditions. The dynamics of these interactions must be expected to be highly variable temporally and spatially, leading to potentially high errors, possibly exceeding 100 W m^{-2}, and highly variable non-turbulent energy fluxes which is usually taken as the ‘residual’ of the traditional energy balance. This short-term variability depends very strongly on the physical soil conditions (wet or dry), the surface temperature regime, not just in terms of the amplitude of its cycle but also its ‘position’ on the temperature scale which is highly variable from day to day, and on the level of permafrost in the ground. Consequently, detailed modeling of the energy balance of this region, with high time resolution will be quite difficult and it might be advisable to limit such efforts initially to consideration of the dominant seasonal trends.

The dominant seasonal trends in energy exchange (particularly sensible heat flux) however, differ very significantly between forested and non-forested areas at the time of full and partial snow cover, due to the low albedo of coniferous trees for shallow sun angles and the presence of snow-free hummocks in forested areas as snow melt approaches. The correct delineation between tundra and ‘forest’ in land cover classification schemes based on remote sensing, which is not easy in this transition landscape, is important for extrapolation of findings to the larger scale.

Given the paucity of direct observations of energy fluxes in northern ecosystems, due to the low population density and accessibility of the terrain, the data obtained in this project are expected to be in demand for partial validation of models on radiation and flux balances. This paper only touches on directions in which they may be used. For example, a systematic comparison between structural analysis of turbulent fluxes and structural characteristics of surface dynamics, both physical and physiological, might be very helpful when extrapolating expected surface fluxes to wider terrain and add physical realism to surface-atmosphere exchange models with increasingly sophisticated spatial and temporal resolution. It also shows that sampling requirements (run lengths) increase when surfaces are partially or completely snow covered, not so much because of low values of flux contribution but because of the low density of structures that transport significant flux.

CONCLUSIONS

Absolute energy exchange (particularly sensible heat flux) differed very significantly between forested and non-forested areas at the time of full and partial snow cover. Observations permitted the assessment of the spatial relevance of the two surface flux stations operating in the Inuvik area. The study also illustrated the dynamic changes in energy partitioning between sensible and latent heat fluxes during snow melt and - subsequently - the important role of vegetation status on energy partitioning. Of particular importance for accurate modeling of this ecosystem are the very significant and highly variable non-turbulent fluxes associated with melting processes and surface heating. It is expected that the unique database accumulated by the aircraft will find further use by other research groups concerned with regional radiation-, energy- or moisture balances and boundary layer structure.

Future analysis will also have to focus on the comparison of fluxes measured by the aircraft and the two flux towers. The generally good agreement between the grid averages and Line-8 (where one of the flux towers was located) is a promising start to scaling up the tower data to regional scales. The preliminary MC2 model inter-comparison with regional airborne observations on the effects of small lake distributions, which seem to be in broad agreement on magnitudes of increase in latent heat flux due to the presence of small lakes, but in qualitative and quantitative disagreement on sensible heat flux and Bowen Ratio, call for a re-examination of the physical model assumptions before extrapolation to larger areas can be made with any reasonable degree of accuracy.

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