2.3 Parameterization of Evapotranspiration Using Remotely-Sensed Data

Raoul Granger[1](presenter)**, John Pomeroy [1,2], Normand Bussières[3], Ric Janowicz[4]**
[1]National Water Research Institute, National Hydrology Research Centre, Saskatoon, SK
[2]Centre for Glaciology, Inst. of Geography & Earth Sciences, University of Wales, Aberystwyth, UK
[3]Climate Research Branch, Atmospheric Environment Service, Downsview, ON
[4]Indian and Northern Affairs Canada, Whitehorse, YK

Introduction

At the onset of the project, the following objectives were defined:

1) To develop and evaluate parameterizations for the application of remotely-sensed data within operational evapotranspiration models.
2) To develop a framework for assessing GCM evapotranspiration algorithms using remotely-sensed regional data in conjunction with operational evapotranspiration models (this remained as a long-term goal).
3) To parameterize the effects of the soil heat storage term in the regional energy balance.

The following additional objectives were introduced as a result of initial findings:

4) To develop new parameterizations for the estimate of lake evaporation using remotely-sensed data.
5) To develop and evaluate techniques for using remote sensing for the scaling of evapotranspiration from point to basin and regional scales.
6) To develop scientifically correct approaches for the estimate of evapotranspiration on sloped surfaces.

Methodology

Field sites were set up within two main research areas, The Prince Albert Model Forest region, in Saskatchewan, and the Wolf Creek research watershed, near Whitehorse, Yukon. The two areas are on the fringe of the Mackenzie Basin, and represent the southern and northern boreal forest regions. The Prince Albert sites included a variety of stand types, including recent clearcut and a regenerating stand. The Wolf Creek Basin includes the three major eco-types: boreal forest, high bush taiga, and tundra.

At the Prince Albert sites, four instrument towers are maintained (at Jackpine, mixed wood, a recent clearcut and a regenerating cut site).

At the Wolf Creek watershed, three instrument towers are maintained (at jackpine forest, highbush taiga and alpine sites). These were the main data sites used for the study. NOAA AVHRR images were obtained as required for comparison with ground-based observations. As well, within the Wolf Creek watershed, a smaller basin (Granger sub-basin) was instrumented with three towers (valley bottom, north and south-facing slopes) for the purpose of exploring appropriate parameterizations for the evapotranspiration on sloped surfaces.

For lake evaporation, data obtained from the 1993 HEATMEX study of Quill Lake, Saskatchewan, along with data from a concurrent energy balance study adjacent to Quill Lake, were used.

Results

Parameterizations for the Application of Remotely-Sensed Data within Operational Evapotranspiration Models

The data collected at the field sites were used to verify:

(a) the ability of the split-window technique applied to a NOAA AVHRR image to approximate the surface temperature:

AVHRR channels 4 (10.3-11.3 µm) and 5 (11.5-12.5 µm) can be used to provide an estimate of the land surface temperature. A split-window technique, similar to that used by Prata and Platt (1991) and Vidal (1991) was chosen for the analysis. This split-window relationship for surface temperature is given as:

$$T_s = 2.09 + 2.84 T_4 / \varepsilon_4 - 2.03\, T_5 / \varepsilon_5 \tag{1}$$

where T_4 and T_5 are the brightness temperatures for AVHRR channels 4 and 5, respectively, and ε_4 and ε_5 are the respective surface emissivities. The surface emissivity varies with the satellite viewing angle; approximate relationships were developed using the emissivity data presented by Prata and Platt (1991).

Figure 1 shows a comparison of the observed surface temperature with those estimated using Eq. 1. The observed surface temperature is that measured at the time of the satellite pass; the four land cover types are represented in the figure. A very good agreement is shown between the observed and satellite-derived land surface temperatures; the standard deviation of the difference is 1.18°C, and the mean difference is 0.42°C. Although, one would ideally like the standard error to be less than 1°C for surface temperature estimates, the agreement shown may be as good as can be expected for forested surfaces. The results presented in Figure 1 do show that for conditions where atmospheric corrections using standard atmospheric models are not feasible because of a lack of data (i.e., from atmospheric soundings), the split-window technique can provide useful and reliable results.

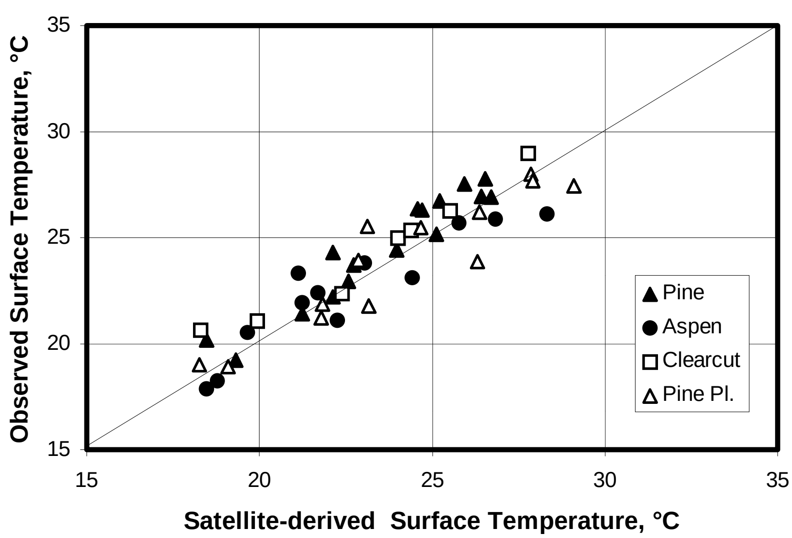

Figure 1 Comparison of observed surface temperature with AVHRR-derived land surface temperatures. Data include four forest cover types, and include data from July and September observation periods.

(b) the reliability of the feed-back relationship to predict the vapour pressure deficit of the air:

Using field data collected over a variety of land surfaces (bare ground, growing wheat, grass, southern boreal forest), where the surface temperature was measured using a mast-mounted infrared temperature sensor, the author had derived the following relationship between the mean daily vapour pressure deficit of the air, VP_{def}, and the saturation vapour pressure, VP^{*}_{Ts}, at the mean daily surface temperature:

$$VP_{def} = -0.278 - 0.015\,T_{ltm} + 0.668\,VP^{*}_{Ts} \qquad (2)$$

in which T_{ltm}, the long-term mean air temperature for the site, is used to account for seasonal effects in the relationship.

Further testing of this approach using ground data has been carried out. The data from the Wolf Creek Basin were used to verify the applicability of the relationship for a variety of northern surface covers. Figure 2 shows the comparison between observed vapour pressure deficits and those calculated using Eq. 2. The standard error of the estimates for the comparison shown in Figure 2 is 0.141 kPa. Similar results were obtained at the Taiga and forest sites, where the respective standard errors of the estimates are 0.130 kPa and 0.140 kPa.

The results do suggest that Eq. 2 can be applied over a very broad range of surfaces within the climatic zones represented between the western prairies and the northern boreal forest regions. This method of obtaining the vapour pressure deficit of the air from remotely-sensed surface temperatures provides a means of using a conventional model in conjunction with satellite data in the estimate of daily regional evapotranspiration rates.

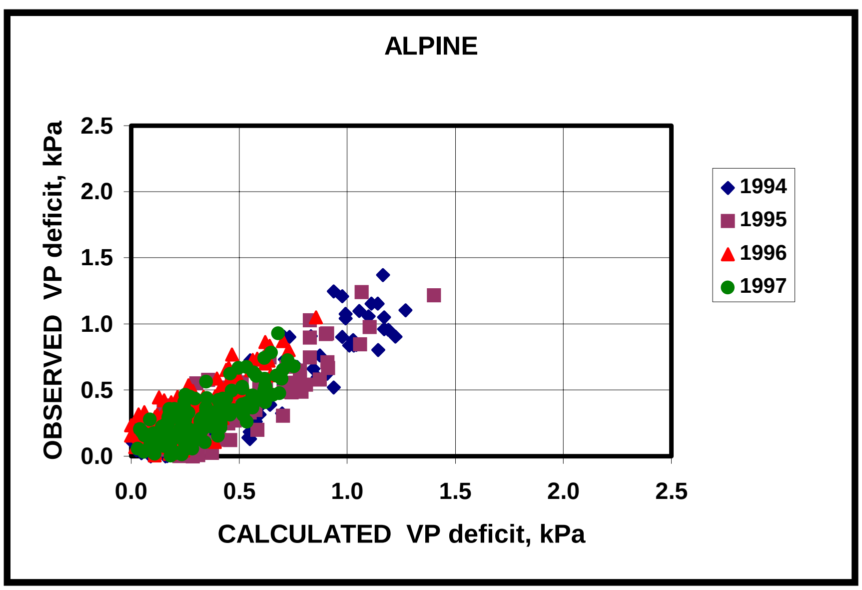

Figure 2 Comparison of calculated and observed vapour pressure deficits at the Alpine tundra site, Wolf Creek, Yukon, 1994 -1997.

(c) the reliability of the evapotranspiration estimates obtained from NOAA-AVHRR imagery:

Figure 3 presents a comparison of the ground-based estimates of daily evapotranspiration with the satellite-derived estimates. The agreement between the two approaches is very good; the standard deviation of the difference is 0.31 mm/d, and the mean difference between ground-based and satellite-derived estimates is -0.05 mm/d.

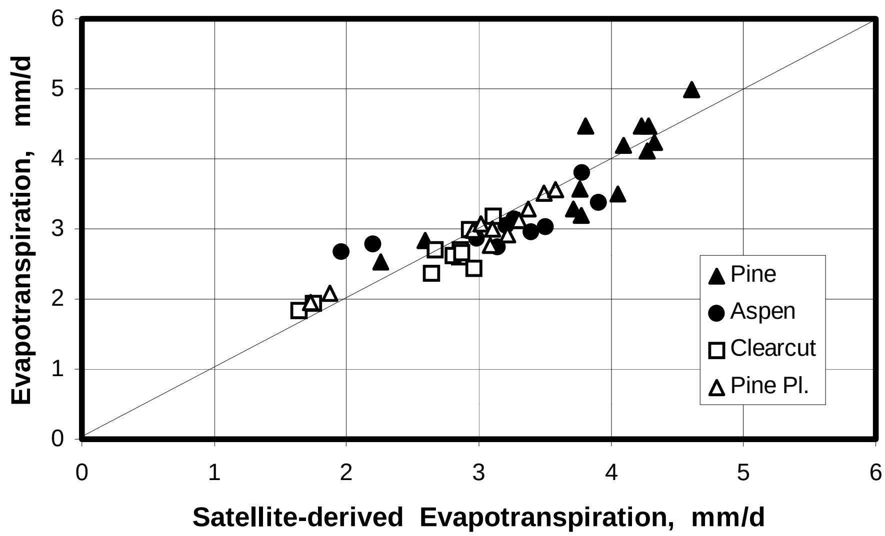

Figure 3 Comparison of daily evapotranspiration values obtained using a conventional model in conjunction with ground-based data with those obtained using satellite-derived data.

Parameterization of the Soil Heat Storage Term in the Regional Energy Balance

Soil heat flux was routinely measured at all sites. Its relative importance within the regional energy balance was determined. During the snow-free season, in all cases, the soil heat flux term is small compared to the net radiation term. The largest fluxes, in the order of 10% of the net radiation term, occur at sites with the least vegetation, while in the mature forest sites, the soil heat flux is of the order of 2 to 6% of the net radiation. The north slope site is the only site known to be underlain with permafrost.

Table 1 presents a summary of these findings; results are presented as the fraction of net radiation being diverted to soil heat flux. These are presented graphically in Figure 4 as a plot of the soil heat flux ratio against the Leaf Area Index at each site. The only outlying point represents the north slope site with permafrost. For the permafrost-free sites, this relationship can be given as:

$$Q_G / R_N = .103 + .005LAI - .01LAI^2 \tag{3}$$

It should be cautioned that Eq. 3 should not be used as is to parameterized the soil heat flux. Its intent is mainly to demonstrate the effect of the vegetation cover on the partitioning of energy. Figure 4 does not yet take into account the seasonal trend which, for most points, is a significant effect.

Table 1 Ratio of Soil heat flux to Net radiation, with vegetation characteristics, for sites at Prince Albert (PA) and Wolf Creek (WC).

Site		Height of Vegetation	LAI	Ratio: Qg/Rn
Clearcut	PA	0.60 m	0.06	0.107
Aspen Forest	PA	25 m	2.36	0.111
Mature Pine	PA	25 m	2.2	0.066
Young Pine	PA	4-5 m	1.4	0.086
Alpine Tundra	WC	0.02 m	.08	0.102
Taiga (1)	WC	2.0 m	1.91	0.077
Taiga (2)	WC	2.5 m	1.37	0.089
Spruce Forest	WC	20 m	2.63	0.022
South slope	WC	0.02 m	1.07	0.089
North slope	WC	0.20 m	1.03	0.027

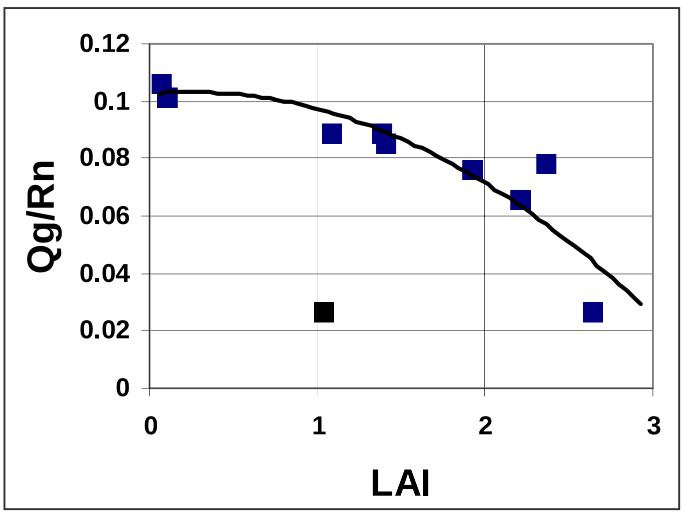

Figure 4 Ratio of soil heat flux to net radiation plotted against leaf area index for sites at Prince Albert and Wolf Creek.

Parameterizations for the Estimate of Lake Evaporation Using Remotely-Sensed Data

Evaporation from open water bodies is an important component of the hydrologic cycle for many watersheds; yet it remains a difficult one to measure or estimate. The major source of difficulty is the fact that the required meteorological parameters are rarely measured over the water surfaces, and the thermal lag between the water and land surfaces renders the land-based measurements ineffective in the parameterization of open water evaporation. The use of remotely-sensed data provides a means of obtaining useful information about the evaporating water surface; however, an appropriate formulation of the transfer processes occurring in the advective boundary layer are required.

The numerical study of evaporation from a relatively warm lake (Weisman and Brutsaert 1973) is used as the basis for the development of a new approach for the use of remote sensing in the estimate of lake evaporation. The method relates the mean lake evaporation to the upwind evapotranspiration and to the discontinuity in surface values of specific humidity. From the point of view of developing a remote sensing application, this approach is interesting in that most of the terms can be obtained with the use of remotely-sensed data (upwind ET, water surface temperature and vapour pressure).

The method was tested using data obtained during an extensive lake evaporation study (HEATMEX) in 1993. Big Quill Lake is a shallow (2 m depth) prairie lake in central Saskatchewan, Canada; it has a somewhat "teardrop" shaped outline and is approximately 8 km wide and 12 km long. It is completely surrounded by a very flat, slightly saline, short grass prairie border from 0.5 to 2 km in width. The surrounding agricultural land is for the most part treeless and has very little relief. During the HEATMEX study, six micrometeorological platforms were installed on the lake, one platform at the approximate geographical centre of the lake and the others set out approximately mid-way to shore around this point. Each platform was equipped with a 20 m tower on which were deployed eight levels of wind speed, air temperature and humidity sensors. Water temperature and sediment temperature profiles were also monitored. Other parameters measured at each platform were: wind direction, net all wave radiation, rainfall and water level; solar radiation was measured at the centre platform. The observation platforms were operating without interruption from mid-July to mid-October.

During the same period, a micrometeorological tower (6 m) was installed on the western shore of Big Quill Lake. The site was located on the short grass prairie, mid-way between the agricultural lands and the lakeshore; at this point the prairie border is approximately 1 km wide. The tower was equipped with four levels of wind speed sensors, and three levels of air temperature and humidity sensors. Wind direction, net all wave radiation, solar radiation, infrared surface temperature, soil heat flux, soil temperatures, rainfall and soil moisture were also monitored. The tower was operating without interruption from late May to late October.

The results of these calculations using the Weisman and Brutsaert approach are shown in Figure 5; also shown, for the sake of comparison, are the lake evaporation, from the tower estimates, and land surface evapotranspiration for the same three day period in August 1993.

Immediately obvious from Figure 5, is the fact that the Weisman and Brutsaert approach does not estimate the lake evaporation during the daytime periods. This is not unexpected, since the analysis from which it was developed included only the unstable conditions, that is, where the water temperature is greater than that of the overlying air.

During the daytime, with solar heating of the surrounding land surface, the air passing over the lake is warmer than the water surface and the boundary layer stratification is a stable one. In this case, the Weisman and Brutsaert formulation is dominated by the land processes and the calculated evaporation follows the land surface evapotranspiration.

For the night time periods, when an unstable boundary layer is present above the lake (conditions for which the method was developed) the Weisman and Brutsaert estimate follows the observed lake evaporation closely. This does indicate that the combined approach of using remotely-sensed data with a model of the advective boundary layer can be used to estimate lake evaporation. The advective boundary layer needs to be analysed and described for the stable case.

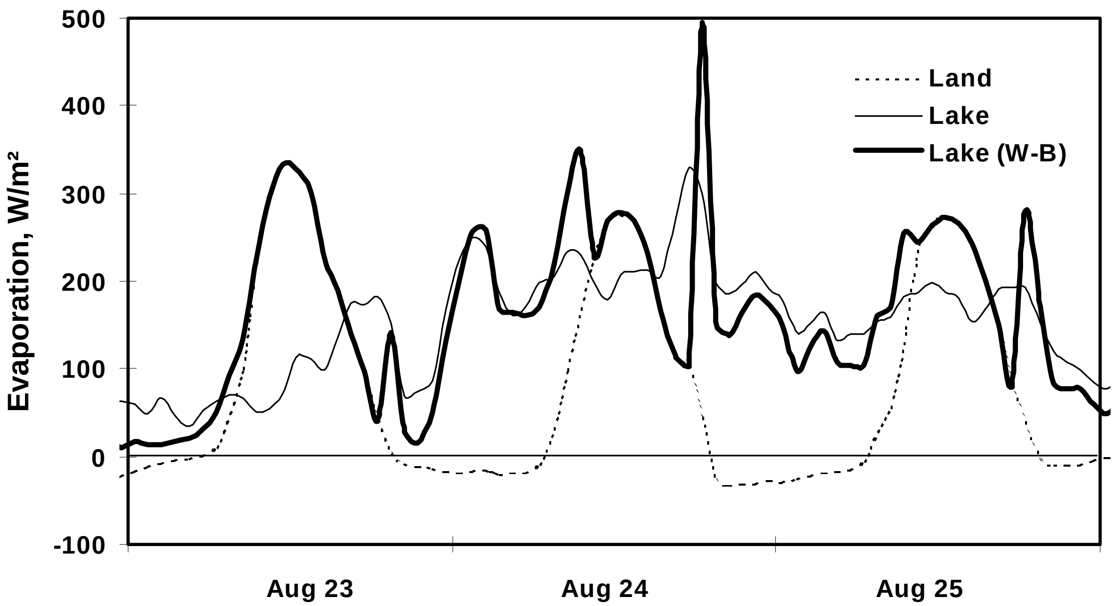

Figure 5 Lake evaporation rates estimated using the Weisman and Brutsaert (W-B) approach, compared with observed lake evaporation and land surface evapotranspiration rates for the period August 23-25, 1993 at Big Quill Lake.

Estimate of Evapotranspiration on Sloped Surfaces

The turbulent fluxes of latent and sensible heat are important components of the surface energy balance and the evapotranspiration can represent a critical portion of the water balance. Since the headwaters of many significant watersheds lie in mountainous regions, the correct determination of the surface energy and water balances in these areas is a key element of hydrological modelling.

The great majority of calculation schemes used to estimate turbulent fluxes from meteorological measurements were derived from boundary layer theory as it relates to horizontal, semi-infinite, flat planes. When these calculation schemes find their way into hydrological models, they are generally applied indiscriminately in a variety of situations for which they were not designed, and as such can be subjected to significant error. The applicability of current turbulent flux calculation schemes to sloped surfaces using field data was tested on two sloped surfaces: one north-facing and the other with a southern exposure. The instrumentation deployed allowed for the direct determination of all the components of the energy balance, and included the profile measurements required for the application of the turbulent transfer equations. Data were collected during the snow-free seasons in 1998 and 1999. The results show that the traditional "horizontal surface" algorithms result in significant errors for the sensible and latent heat fluxes on sloped surfaces. As an example, Figures 6a and 6b show a comparison of calculated and measured latent and sensible heat fluxes on north- and south-facing sloped surfaces at Wolf Creek. Similar results are obtained for flows up and down the slopes.

The results point to the need to develop appropriate techniques for estimating turbulent fluxes on sloped surfaces. This will require a significant advancement of our understanding of the turbulent flow regime over non-uniform terrain.

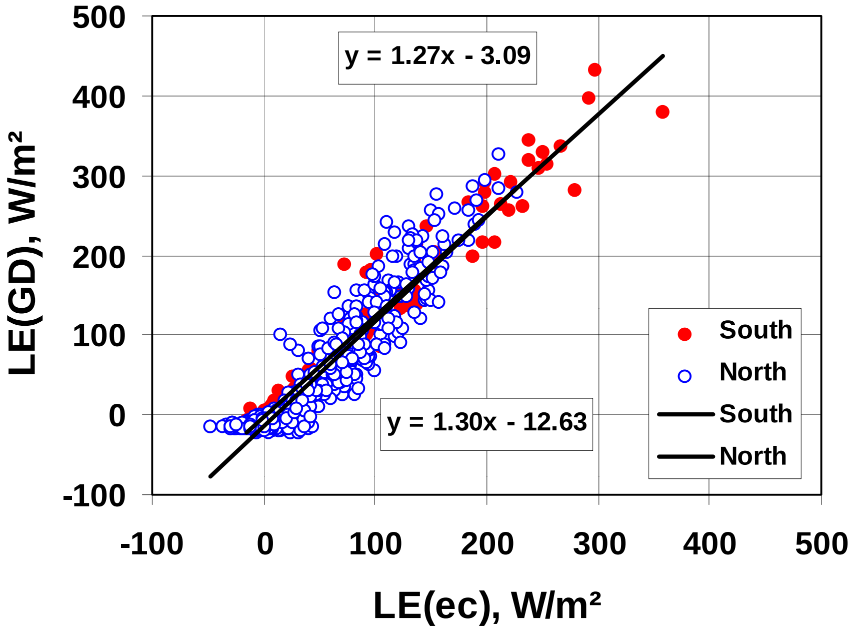

Figure 6a **Comparison of Latent heat flux calculated using the G-D model with measurements obtained using the Eddy-correlation instrumentation over sloped surfaces at Wolf Creek. The data are for periods with flow along the slope.**

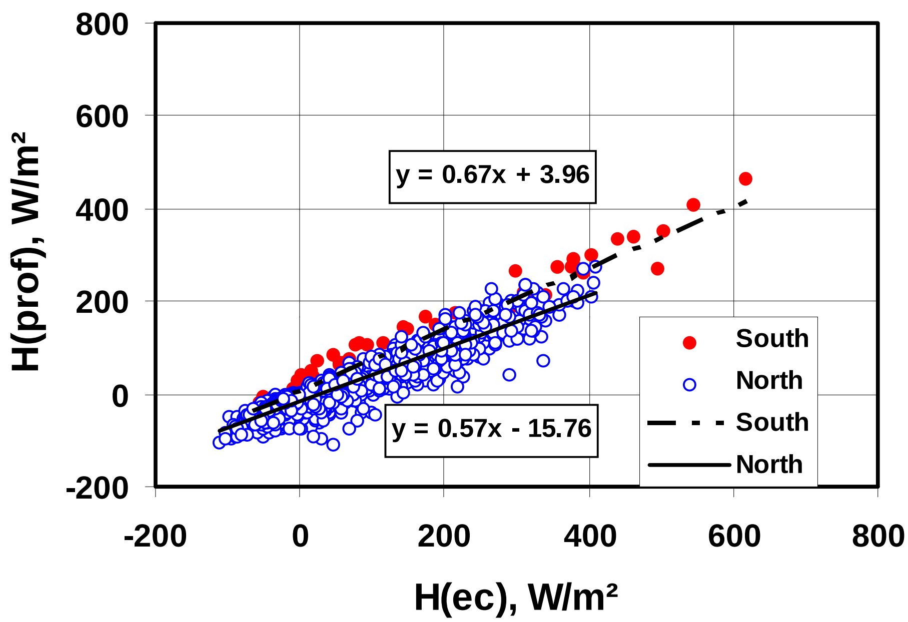

Figure 6b **Comparison of Sensible heat flux calculated using the flux-profile method with measurements obtained using the Eddy-correlation instrumentation over sloped surfaces at Wolf Creek. The data are for periods with flow along the slope.**

Discussion, Conclusions, Recommendations

Parameterizations were developed for the estimate of evapotranspiration using remotely-sensed data. The applicability of the split-window technique for estimating surface temperature using AVHRR data was demonstrated. The reliability of the feed-back relationship to predict the vapour pressure deficit of the air using observed surface temperatures was also shown.

A relationship between the soil heat flux ratio (Qg/Rn) and the LAI was developed and presented. The approach allows for a simple, reliable method of parameterizing the soil heat flux term within the regional energy balance for permafrost-free areas. The relationship for permafrost regions has yet to be developed.

A new approach was developed and presented for the estimate of lake evaporation using remotely-sensed data. The method works well for advective situations were unstable conditions exist within the boundary layer. Successful application of the method requires that the numerical analysis of Weisman and Brutsaert must be repeated for stable conditions.

The magnitude of the errors resulting from the application of traditional “flat-earth” approaches to the calculation of turbulent fluxes on slopes was demonstrated. The results strongly indicate that new approaches, based on a better understanding of turbulent flow on slopes, be developed in order to ensure confidence in our calculation of the regional energy balance in mountainous areas.

Acknowledgements

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Scientific Training under MAGS

Technical, Technical and term staff involved in the studies and receiving training in field operations and remote sensing: Randy Schmidt, Brenda Toth, Dell Bayne.

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