Comparison of sensible heat flux estimates using AVHRR with scintilllometer measurements over semi-arid grassland in northwest Mexico

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Abstract

The problems associated with the validation of satellite-derived estimates of the surface fluxes are discussed and the possibility of using the large aperture scintillometer is investigated. Simple models are described to derive surface temperature and sensible heat flux from the Advanced Very High Resolution Radiometer (AVHRR). Data were collected over an extensive site of semi-arid grassland in Northwest Mexico during the summer of 1997 as part of the Semi-Arid Land-Surface-Atmosphere (SALSA) Program. Comparison of surface temperature derived from AVHRR with that derived from a ground-based infrared thermometer showed an RMSE of around 2°C while estimates of sensible heat flux derived from AVHRR compared well with measurements using either eddy correlation or a large aperture scintillometer.

Keywords: Sensible heat flux, surface temperature, satellite, AVHRR, scintillometer

1. Introduction

The measurement of surface fluxes of radiation, heat and water vapor requires sophisticated instrumentation so that these measurements have been mainly confined to intensive field experiments. In recent years, efforts have begun to establish quasi-operational networks in Europe, North America and elsewhere. Nevertheless, the cost and expertise involved make it impossible to set up a dense network of stations in remote areas in the foreseeable future. Thus, the use of spaceborne sensors to estimate these fluxes over large areas remains the only feasible technique. Since these fluxes have a large diurnal variation and are subject to significant change from one day to another, a high-frequency repeat rate is required and this is only available on geostationary satellites or from wide-swath sensors on low earth orbiting satellites. The sensor which has received the most attention for estimating the sensible heat flux is the Advanced Very High Resolution Radiometer (AVHRR) which is carried on board the NOAA series of (near) polar orbiters whose repeat rate is 12 hours. Two satellites are operational at any time so that the same area on the surface can be observed approximately every 6 hours. [It cannot be overstressed that this frequency is only possible *in the absence of clouds* and that observations are usually much less frequent.] The AVHRR sensor has 5 channels, each one having the same spatial resolution (with pixels of 1.1 km at nadir) of which two of these are in the thermal region and may used to estimate ground surface temperature and sensible heat flux. Since the sensor views each pixel during only a fraction of a second, these estimates are essentially instantaneous. Furthermore, the images show considerable distortion (and larger pixels) at the edges because of the wide swath and the earth's curvature, so that the heat flux estimated for one pixel can represent an area between 1.2 km^2 at nadir and 20 km^2 or more at the edges. Thus the satellite estimates offer instantaneous values which are spatially averaged over several km^2, while ground data (e.g. from eddy correlation) usually provide local spatial values which are temporally averaged over several minutes (usually 30 - 60). This mismatch in both temporal and spatial sampling makes it very difficult to perform a convincing validation of the satellite estimates, so that a ground based sensor capable of measuring fluxes over large areas with shorter averaging times would be very useful. It should be noted that these long averaging times are inherent in all eddy correlation systems and would not be substantially improved by new technology.

The technology for scintillometry has been developed over the last 25 years, mainly at NOAAs Wave Propagation Laboratory (now Environmental Research Laboratory) in Boulder, CO (Clifford et al., 1974; Hill, 1992). The technique consists of transmitting a beam of electromagnetic radiation and measuring the intensity variations of the received signal. These variations are related to the movement of heat and moisture in the path between transmitter and receiver and the relative contributions from heat and moisture depend on the wavelength. In the visible and near infrared, the signal is much more sensitive to heat movement while in the microwave region it is more sensitive to moisture movement. Prototypes have been built and tested for different regions of the electromagnetic spectrum and methods have been developed to derive the surface fluxes for heat, humidity and momentum (Kohsiek, 1982; Hill, 1997). The Large Aperture Scintillometer (LAS), which uses an incoherent beam in the near infrared region (Ochs and Wilson, 1993) is becoming popular in hydrometeorological studies (de Bruin et al., 1995; McAneney et al., 1995; Lagouarde et al., 1996, Chehbouni et al., 1999a) because it is a relatively cheap, robust instrument which can be used to estimate sensible heat fluxes over distances of several kilometers. Furthermore, since it measures a line average over the path between transmitter and receiver, stable averages for the flux can be obtained over much shorter times, typically 10 minutes. Indeed, as the path length increases the averaging period required should decrease. These features make the LAS a very attractive choice for the validation of satellite estimates of sensible heat flux.

The objective of this study is to determine he feasibility of using LAS measurements of the sensible heat flux from a semiarid grassland area in northeast Sonora, Mexico to validate estimates obtained using surface temperature obtained from AVHRR. The data was obtained during 1997 field campaign in Mexico. The paper is organized as follows: in section (2), the basic methodology is discussed for deriving sensible heat flux estimates from the satellite and the scintillometer; in section (3), the experimental setup is presented; in section (4) results are presented, with comparisons between ground-based surface temperatures and heat fluxes and those derived from AVHRR. Finally, in section (5) the conclusions are presented and the need for future studies is discussed.

2. Materials and Methods

2.1 Scintillometer

The LAS used in this study was manufactured at Wageningen University in the Netherlands. The design is based on that of Ochs and Wilson (1993) but with improved electronics.

The detailed methodology for deriving the sensible heat flux from the scintillometer measurements is described elsewhere (e.g. Chehbouni et al., this issue) so only an outline will be presented here. The output voltage from the scintillometer (V) is related directly to the refractive index structure parameter C_n^2 by

$$V = 12 + \log_{10} C_n^2 \qquad (1)$$

Which, for moderately dry surfaces, can be written as a function of the structure parameter for temperature C_T^2

$$C_T^2 = C_n^2 \left(\frac{T_a^2 10^6}{0.78\, P} \right)^2 \qquad (2)$$

where T_a is the air temperature at a reference height above the surface (K) and P is the atmospheric pressure (Pa). Monin-Obukhov similarity theory is then invoked to obtain

$$\frac{C_T^2 (z - d)^{2/3}}{\theta_*^2} = f(V) \qquad (3)$$

where z is the measurement height (m), d is the displacement height of the surface (m), θ_* is the temperature scale (K) and the right hand side is a dimensionless, empirical function of the stability parameter $\varsigma = (z - d)/L$, where L is the Obukhov length. The sensible heat flux is then obtained using

$$H = \rho\, C_P\, u_* \theta_* \qquad (4)$$

where ρ is the air density (kg m^{-2}), C_p is the specific heat of air at constant pressure (J kg^{-1} K^{-1}) and u_* is the friction velocity (m s^{-1}). The latter may be obtained in various ways, including the use of 2 LAS deployed at different heights (see Lagouarde et al., this issue). The simplest method is to use measurements of wind speed and roughness length in the classical flux-profile relationship. Then an iterative procedure combining all these equations is used to generate the sensible heat flux (Lagouarde et al., 1996). This approach has been used successfully over homogeneous and flat terrain and the case of more complex surfaces is currently an important research area (Lagouarde et al., 1996; Chehbouni et al, this issue). In this study, the values for the displacement height (d) and roughness length (z_0) were estimated using the usual rule of thumb relationship with the vegetation height (h): d = 0.67 h and z_0 = 0.1 h, where all units are meters. It should be noted from the above equations that the sensible heat flux depends roughly on $(z-d)^{1/3}$ and so is not particularly sensitive to slight errors in the estimation of these parameters. Nonetheless, for LAS measurements over terrain which is not flat, it is very important to make good estimates of z and d over the whole path and calculate an appropriate average.

2.2 Estimation of surface temperature using AVHRR

The retrieval of accurate surface temperatures from one band of a thermal sensor requires knowledge of surface emissivity and atmospheric effects. If these are not taken into account properly, errors of more than 10K may occur (Cooper and Asrar, 1989). The "split window” technique, which uses two adjacent bands in an atmospheric window of variable transparency, has proved very successful for dealing with atmospheric effects. Over the oceans, where the emissivity is constant and close to one, this technique gives sea surface temperatures within 1K of those observed (McLain et al., 1985). Over land, however, emissivity is highly variable and needs to be included in the methodology. Unfortunately, information about surface emissivity is not generally available so that methods which require values for local surface emissivity cannot be applied. Kerr et al. (1992) proposed an improved split-window method whereby each pixel is regarded as a mixture of two components: vegetation and bare soil. The temperature for each component is calculated separately, according to the equations:

$$T_v = -2.4 + 3.6\,T_4 - 2.6\,T_5$$
$$T_s = 3.1 + 3.1\,T_4 - 2.1\,T_5 \qquad (5)$$

where T_v and T_s are the temperatures of the soil and vegetation respectively and T_4 and T_5 are the brightness temperatures from the thermal bands (4 and 5) of the AVHRR. The constants in these equations include the effects of the *average* difference in emissivity between bare soil and vegetation. Finally, the surface temperature is obtained using

$$T_r = C_v T_v + (1 - C_v) T_s \qquad (6)$$

where C_v is the fractional ground cover, which may be obtained from ground measurements or by using vegetation indices constructed using bands 1 and 2 of the AVHRR. The method is quite robust and these coefficients have proven adequate for a wide variety of conditions. In a recent study using data from diverse surface types in different parts of the world (Kerr et al., 1997), it was found that the method described here *with these same coefficients* generally gave similar results to more complicated methods which require explicit knowledge of surface emissivities.

2.3 Model for sensible heat flux

The sensible heat flux emanating from the ground surface may be expressed

$$H = \rho C_p \frac{(T_0 - T_a)}{r_a} \tag{7}$$

where T_o is the *aerodynamic* surface temperature (K), and r_a is the aerodynamic resistance which may be written (Choudhury et al., 1986):

$$r_a = \frac{r_{a0}}{(1+\eta)^p}, \text{ and } \quad r_{a0} = \frac{[\ln(z-d)/z_0]^2}{k^2 u} \tag{8}$$

where p=.75 in unstable conditions and 2 in stable conditions and

$$\eta = \frac{5(z-d)g(T_0 - T_a)}{T_a u^2} \tag{9}$$

where g is the gravitational acceleration (9.81 m s^{-2}) and u is the wind speed (m s^{-1}) at the reference height. This formulation is a close fit to the classical flux-profile equations and is more convenient to use since no iteration is required using the formulation for T_0 which is described next.

In sparsely vegetated, semi-arid land, T_o is very much smaller than the observed *radiometric* surface temperature, T_r, as measured by an infrared thermometer. In order to account for this, multi-layer models have been proposed (Shuttleworth and Wallace, 1985; Lhomme et al., 1994) to estimate T_o. However, these models require soil and canopy temperatures which are not routinely available from remote sensing. Therefore, we seek a simpler, empirical approach. One common method to account for the difference between aerodynamic and radiative surface temperature is to introduce an excess resistance (Kustas et al., 1989; Hall et al., 1992; Moran et al., 1994; Stewart et al., 1994). Alternatively, Chehbouni et al. (1996, 1997) have shown that T_o-T_a and T_r-T_a are usually highly correlated so that we can write

$$T_o - T_a = b\ (T_r - T_a) \qquad (10)$$

where β is an empirical function of the leaf area index (LAI). This expression may be used to replace the aerodynamic temperature in equations 7 and 9. It is easy to show that this method is functionally equivalent to the excess resistance method (Chehbouni et al., this issue). The above formulation is convenient and it will be used in this study. However, we make no claim here that this method is better than the alternative one of using an excess resistance. It should also be mentioned that the empirical parameterization of β as a function of LAI has been calibrated for a grassland site similar to the one studied here (Chehbouni et al., 1996). Since this parameter contains implicitly other structural properties, it is likely that the parameterization depends on vegetation type.

3. Experimental design

3.1 Site description

The study site is located near Zapata village in the upper Sap Pedro basin (110º 09´ W; 31º 01´ N; elevation 1460 m) which was the focus for SALSA activities in Mexico during the 1997 and 1998 field campaigns. The natural vegetation is composed mainly of perennial grasses, the dominant species being *Bouteloua*, and the vegetation cover was estimated as 15%. The average vegetation height was 0.12 m and the average LAI was about 0.15. The climate is semi-arid with hot summers and cold winters and the mean annual rainfall is 440 mm.

3.2 Date description

A 6 m meteorological tower was set up in July 1997 as part of the measurement campaign for the Semi-Arid Land-Surface-Atmosphere (SALSA) program (Goodrich et al., 1998). The measurements included surface fluxes at 6.8 m from an Edisol eddy correlation system (Moncrieff et al., 1997), air temperature at 6.8 m using a 25 μm fine-wire thermocouple and wind speed at 6.8 m (Gill Instruments, UK). One infrared thermometer (Everest International, Model 4000 with 60º field of view) was installed at 2.5m over the grass. The scintillometer was deployed over a 300 m path (from DOY 205 – 219), over a 600 m path (from DOY 233-252), and over 850 m path (from DOY 254-262) pointing SW-NE with the tower near the middle.

AVHRR data from satellites NOAA12 and NOAA14 were captured at the HRPT (High Resolution Picture Transmission) receiving station (Bradford University Remote Sensing, UK) located at the office of IMADES in Hermosillo, Sonora throughout the study period. Images were selected for further processing for those days when the scintillometer was operating at the site. Data from channels 1 and 2 were processed to produce reflectances while those from channels 4 and 5 were converted to brightness temperatures. These images were then re-projected to latitude-longitude coordinates and a sub-image extracted corresponding to 28º - 29ºN and 110.5º - 112ºW with a pixel size of .01° x .01°. Images with cloud cover over the sites were eliminated by visual inspection of the reflected channels. Finally, nine pixels centered on the site were examined and the median of these was taken as the brightness temperature for the site. This procedure was chosen to minimize the effect of inaccuracies in the projection process and problems due to partial cloud cover. The brightness temperatures for the thermal channels 4 and 5 were then used in the modified split-window method to obtain an estimate for the average surface temperature as described in section 3.2.

Data from the ground observations (scintillometer, 3D sonic anemometer and fine wire thermocouple) were extracted to coincide as closely as possible with the satellite overpass (nearest 10 minutes average for the scintillometer data and nearest 30 minutes average for the other parameters). Thus the data set used in the subsequent analysis consisted of "simultaneous" values for sensible heat flux (from scintillometer and 3D sonic anemometer), surface temperature (from AVHRR and the ground based infrared thermoneter), air temperature and wind speed. The procedure described in section 3.3 was used to derive estimates of sensible heat flux using both the satellite and ground surface temperatures.

4. Results and discussion

The sensible heat flux obtained from the LAS and the sonic anemometer are compared in Figure 1. There is good agreement, with an RMSE of 38 W m^{-2} and a slope of 1.02. This indicates that the iterative procedure used in processing the LAS data is adequate and that the site is relatively homogeneous at the scale of these measurements. A comparison between surface temperature derived from AVHRR satellites with that from ground-based infrared thermometers (Figure 2) shows an RMSE of about 2°C. This confirms previous results using the improved split-window method and suggests that the coefficients in equation 1 (which were originally obtained using data from African locations) are applicable to the Mexican site. We should remember that the infrared thermometer measurements cover only a few square meters so that we cannot regard these as “true” values for the average over one or more square kilometers which is observed by the satellite sensor. Thus, the close agreement between ground and satellite derived surface temperature indicates that the site is relatively homogeneous. In Figure 3, the estimates of sensible heat flux obtained using satellite and ground based surface temperature are compared to the measurements from the sonic anemometer. Both estimates are in good agreement, with an RMSE of 33 W m^{-2} from the satellite and 30 W m^{-2} from the ground-based infrared thermometers. Finally, the satellite estimates of sensible heat flux are compared to those from the LAS (Figure 4) and the statistics in Table 1. The LAS data has been divided into three groups, corresponding to the different path lengths used (Section 3.2) of 300m, 600m and 850m. Unfortunately, there is only one data point at 850m and no statistics could be calculated. The results show a marked improvement as the path length increases. Nevertheless, the results at 600m are still slightly worse than those derived from the 3D sonic anemometer and three reasons may be suggested:

- The area sampled by the sonic anemometer (at 6.8m elevation) is representative of the whole homogeneous area
- The path length for the LAS should be longer. Indeed, since the LAS is rather insensitive to the surface near the receiver and emitter, a path greater than 1.1 km should be used.
- The LAS is expected to perform better than the sonic anemometer when the sensible heat flux is changing rapidly. This is most likely under broken cloud conditions but data for these cases are usually removed in the screening process to avoid cloud contamination in the estimates of surface temperature.

Further work is needed to provide firm conclusions to these issues.

These results indicate that the LAS can be successfully used to validate satellite-based estimates of large-scale sensible heat flux. However, this study has been performed over sparsely vegetated surface with a single biome where the problem associated with the geometrical geo-location of satellite images is not an issue. A problem arises when the surface is made up of different patches. In this case, the images need to be precisely co-registered to ensure that the ground-based measurements and the satellite estimates refer to the same surface. Unfortunately, the best geo-location algorithms which are currently available for AVHRR images do not provide an accuracy of better than one pixel. This makes it difficult to use the LAS for validating AVHRR-based flux over patchy surfaces, especially in the case where the size of surface patches are of the same order as the satellite pixels (1km).

5. Conclusions

The estimates of sensible heat flux derived from AVHRR and ground based temperatures are in close agreement with those obtained from the LAS and the sonic anemometer. We conclude that the LAS provides a viable alternative to more traditional micrometeorological techniques for measuring the sensible heat flux and validating satellite-derived estimates. In addition to the problem associated with the geo-location issue, another limitation to the methodology described here for using AVHRR to derive flux estimates is the presence of clouds. During the measurement period (monsoon season), only about 25% of the images were free of clouds over the study site. The use of geostationary satellites would greatly increase the probability of obtaining cloud-free views of a site. The current generation of GOES satellites (and the next generation of METEOSAT) includes thermal sensors in the same bands as the AVHRR, albeit with a reduced spatial resolution of 4 km. The LAS would appear to be the only available instrument capable of providing long-term data to validate estimates derived from these sensors, assuming improved geo-location algorithms.

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References

Chehbouni, A, Lo Seen, D, Njoku, EG and Monteny, BA, 1996.Examination of the differences between radiative and aerodynamic surface temperatures over sparsely vegetated surfaces, Rem. Sens. Environ., 58:177-186.

Chehbouni, A, Lo Seen, D, Njoku, EG, Lhomme, J-P, Monteny, B and Kerr, YH, 1997. Estimation of sensible heat flux over sparsely vegetated surfaces, *J of Hydrology*,188-189: 855-868.

Chehbouni A., Kerr, Y.H., Watts, C., Hartogensis, O., Goodrich, D., Scott, R., Schieldge, J., Lee , K., Shuttleworth, W.G., Dedieu, G. and De Bruin, H.A.R., 1999a. Estimation of area- average sensible heat flux using a large aperture scintillometer, Water Resour. Res., 35 (8): 2505-2512.
in press.

Chehbouni, A, Watts, C, Lagouarde, J-P, Kerr, YH, Rodriguez, J-C, Bonnefond, J-M, Santiago, F, Dedieu, G, Goodrich, D and Unkrich, C, 1999b. Estimation of heat and momentum fluxes over complex terrain using a large aperture scintillometer, this issue.

Chehbouni A., Watts, C., Kerr, Y.H., Dedieu, G., Rodriguez, J-C, Santiago, F., Cayrol, P., Boulet, G. and Goodrich, D., 1999c. Methods to aggregate turbulent fluxes over heterogeneous surfaces: Application to SALSA data set in Mexico, this issue.

Choudhury, BJ, Reginato, RJ and Idso, SB, 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux", *Agric. For. Meteorol.*, **37:** 75-88.

Clifford, SF, Ochs, GR and Lawrence, RS, 1974. Saturation of optical scintillation of strong turbulence, J. Opt. Soc. Am., 64:148-154.

Cooper, D and Asrar, G, 1989. Evaluating atmospheric correction models for retrieving surface temperature from the AVHRR over a full grass prairie, Rem. Sens. Environ., 27:93-102.

De Bruin, HAR, van den Hurk, BJJM and Kohsiek, W, 1996. The scintillation method tested over a dry vineyard area, *Boundary-Layer Meteorol*., 76:25-40.

Goodrich, DC, Chehbouni, A and 29 Co-authors, 1998. An overview of the 1997 activities of the Semi-Arid Land-Surface Atmosphere (SALSA) Program, in Proceedings of the 1998 Am. Met. Soc. Meeting, January 1998, Phoenix, AZ.

Hall, GH, Huemmrich, KF, Goetz, SJ, Sellers, PJ and Nickerson, JE, 1992. Satellite remote sensing of surface energy balance: success, failure and unresolved issues in FIFE, J. Geophys. Res., 97:19061-19089.

Hill, RJ, 1992. Review of optical scintillation methods of measuring the refractive index spectrum, inner scale and surface fluxes, Waves in Random Media, 2:179-201.

Hill, RJ, 1997. Algorithms for obtaining atmospheric surface layer fluxes from scintillation measurements, J. Atmos. Oceanic Tech., 14:456-467.

Kerr, YH, Lagouarde, J-P and Imbernon, J, 1992. Accurate land surface temperature retrieval from AVHRR data with the use of an improved Split Window algorithm, *Rem. Sens. Environ.*, 41:197 -209.

Kerr, YH, Guillou, C, Lagouarde, J-P, Nerry, F, Ottlé, C, 1997. Land Surface Temperature Processor. Final Report, ESA.

Kohsiek, W, 1982. Measuring C_T^2, C_Q^2 and C_{TQ} in the unstable surface layer and relations to the vertical fluxes of heat and moisture", *Boundary-Layer Meteorol.*, 24:89 - 107.

Kustas, W.P., Choudhury, B.J., Moran, M.S., Reginato, R.J., Jackson, R.D., Gay, L.W., and Weaver, H.L., 1989. Determination of sensible heat flux over sparse canopy using thermal infrared data, *Agric. For. Meteorol*. 44:197-216.

Lagouarde, J-P, McAneney, KJ and Green, EF, 1996. Scintillometer measurements of sensible heat flux over heterogeneous surfaces, in Scaling up in hydrology using remote sensing, JB Stewart, ET Engman, RA Feddes and YH Kerr (eds.) 147 – 160, John Wiley and sons, Chichester.

Lhomme, J.P., Monteny, B., Chehbouni, A. and Trouffleau, D., 1994. Determination of sensible heat flux over Sahelian fallow savannah using infrared thermometry, *Agric. For. Meteorol.* 68:93-105.

McAneney, KJ, Green, AE and Astill, MS, 1995. Large aperture scintillometry: the homogeneous case", *Agric. For. Meteorol.*, **76:**149 – 162.

McLain, EP, Pichel, WP and Walton, CC, 1985. Comparative performance of AVHRR-based multichannel sea surface temperatures, J. Geophys. Res., 90C6:11587-11601.

Moncrieff, JB, Massheder, JM, de Bruin, HAR, Elbers, J, Friborg, T, Heusingveld, B, Kabat, P, Scott, S, Soegaard, H and Verhoef, A, 1997. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide, J. Hydrology, 188-189:589-611.

Moran, M.S., Kustas, W.P., Vidal, A., Stannard, D. I., Blanford, J. H., Nichols, W.D., 1994. Use of ground-based remotely sensed data for surface energy balance evaluation of a semi-arid rangeland, *Water Resour. Res.* 30:1339-1349.

Ochs, GR and Wilson, JJ, 1993. A second-generation large-aperture scintillometer, NOAA Tech. Memo, ERL WPL-232, NOAA Environmental Research Lab., Boulder, Co.

Stewart, JB, Kustas, WP, Humes, KS, Nichols, WD, Moran, MS and de Bruin, HAR, 1994. Sensible heat flux - radiometric surface temperature relationship for 8 semi-arid areas", *J. Appl. Meteorol.*, **33**, 1110-1117.

Table1. Comparison of AVHRR-based estimates of sensible heat flux with eddy flux and LAS measurements

Measurement	RMSE (W m^{-2})	Slope	R squared
Eddy flux	32	1.00	0.90
LAS (at 300m)	31	0.61	0.69
LAS (at 600m)	43	1.02	0.84

Figure captions

Figure 1: Comparison between sensible heat flux values obtained from the 3D sonic and those obtained from the scintillometer (LAS). Units are in W m^{-2}

Figure 2: Comparison of ground-based and AVHRR-based estimates of surface temperature. Units are in ^{o}C

Figure 3. Cross-plot of 3D Sonic-based estimates of sensible heat flux and those simulated using ground-based and AVHRR-based surface temperature). Units are in W m^{-2}

Figure 4: Comparison of scintillometer and AVHRR-based estimates of sensible heat flux values. Units are in W m^{-2}

Figure 1. Comparison between sensible heat flux values obtained from the 3D sonic and those obtained from scintillometer (LAS).

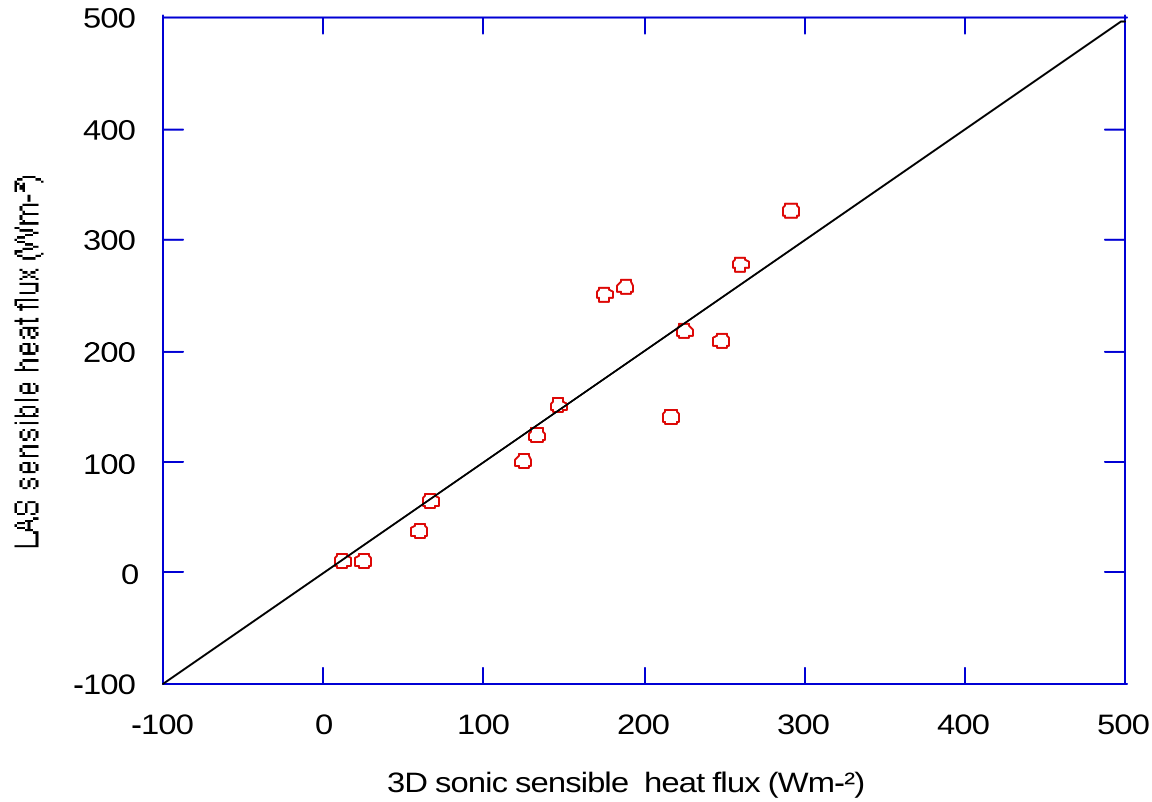

Figure 2. Comparison of ground -based and AVHRR- based estimates of surface temperature.

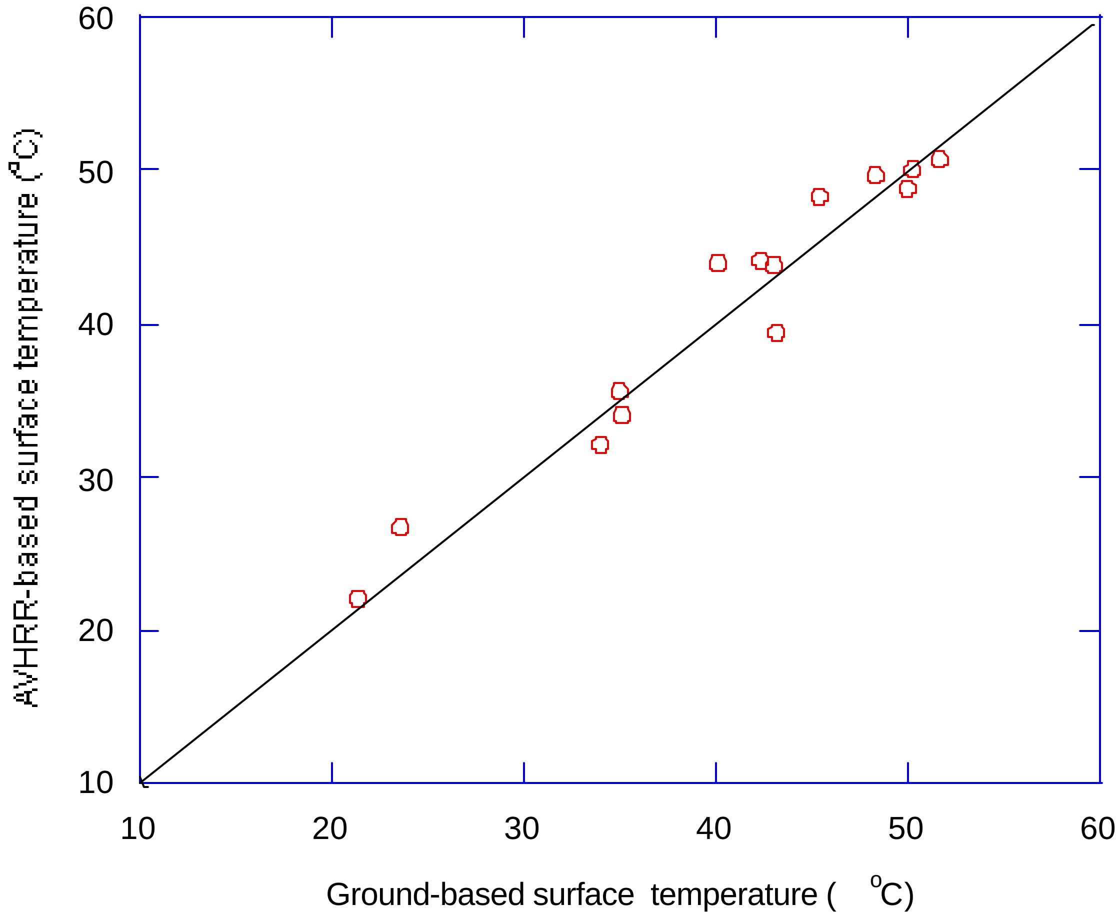

Figure 3. Cross-plot of 3D sonic-based estimates of sensible heat flux and those simulated using ground-based and AVHRR-based surface temperature.

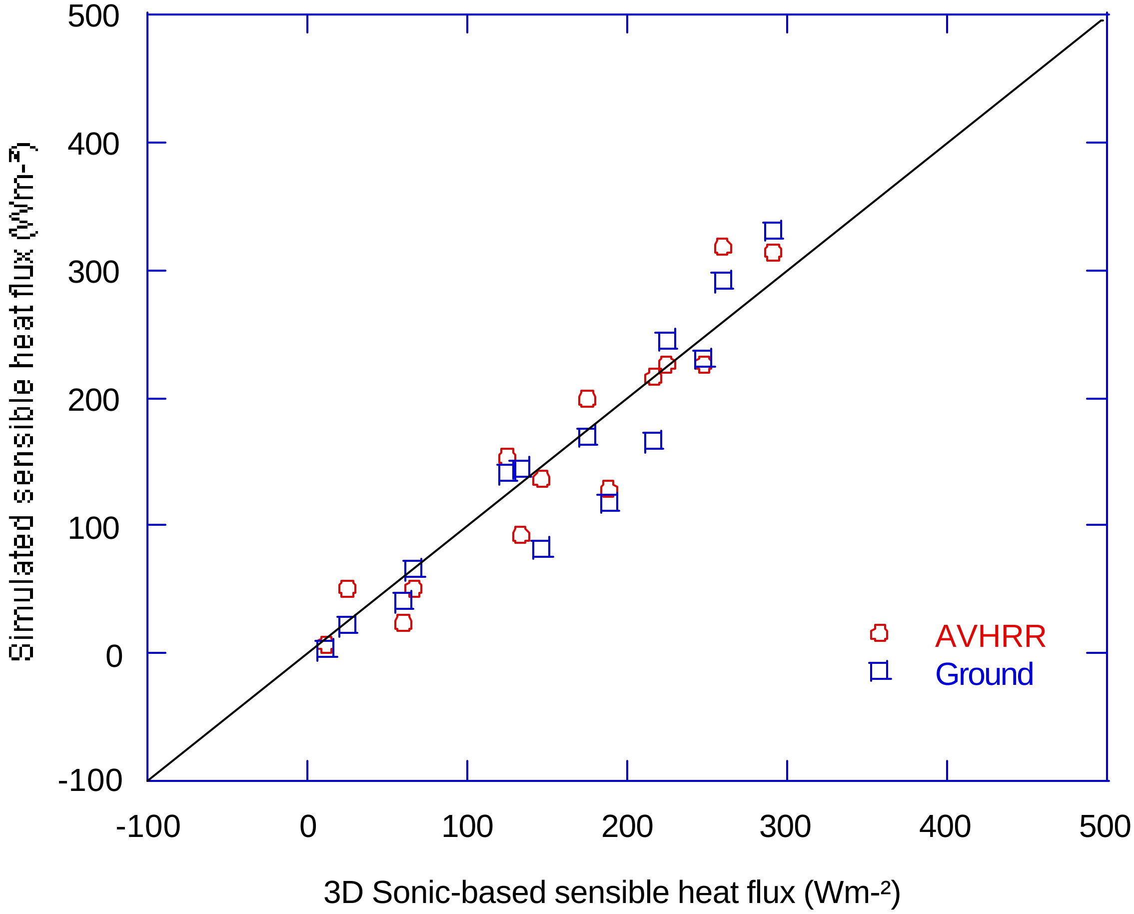

Figure 4. Comparison of scintilometer and AVHRR-based estimates of sensible heat flux.