Estimation of the Spatial Variation in Evapotranspiration based on Landsat TM and NOAA Satellite Imagery

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Søgaard, Henrik: Estimation of the Spatial Variation in Evapotranspiration based on Landsat TM and NOAA Satellite Imagery. Geografisk Tidsskrift 92: 80-85. Copenhagen 1992.

During the last decade, the use of satellite imagery for monitoring water and energy budgets has gained increasing interest. Based on ground reference data collected above a barley field located near Viborg in Jutland, the so-called simplified relationship between net radiation, temperature, and evapotranspiration was examined. It was found that the difference between evapotranspiration and net radiation depends on both the temperature difference between the surface and the air, and the surface roughness. The derived relationship was applied for monitoring evapotranspiration on the basis of surface temperature measured by the NOAA-satellites. This paper will present this study and examine the resolution problem caused by the field size being less in area than the 1 km by 1 km covered by a single NOAA picture element. For a selected day in July, this was done by comparing the NOAA data with Landsat TM-data which has a 120 m resolution in the thermal band.

Keywords: *Evapotranspiration, Landsat TM, NOAA.*

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In relation to the study of the changing global climate, it has long been agreed that it is necessary to improve our knowledge on surface energy and water budgets. The overall aim of the present study may be regarded as a contribution to the elaboration of a methodology for mapping actual evapotranspiration which is a parameter essential to both energy and water budgets. Several methods for the point estimation of evapotranspiration, such as those based on the 3-D-eddy correlation technique, are presently being developed and tested. Future evapotranspiration monitoring cannot depend only on these kinds of sophisticated instruments but will have to be modelled to be used in conjunction with more easily derived parameters. For this purpose, data from operational satellites like NOAA, Meteosat and Landsat would be able to play an important role. Most of the current activities now developing this methodology have adopted the early models proposed by Jackson et al. (1977) and Seguin & Itier (1983). Several studies have confirmed that the difference between evapotranspiration and net radiation may be expressed as a function of the difference between the surface and the air temperature in the early afternoon (Riou, Itier & Seguin, 1988; Søgaard, 1989; Lagouarde & MacAnney, 1991). In these cases, the relationships within the formula given below have proved to be useful although the coefficients have differed slightly from study to study:

$$ET\text{-}Rn = b \cdot (T_{s14}\text{-}T_{a14}) + a \qquad [1]$$

where:
- ET is the daily evapotranspiration (mm d^{-1})
- Rn is the daily net radiation (mm d^{-1})
- T_{s14} is the surface temperature at 14 h
- T_{a14} is the air temperature at 14 h
- b is the slope coefficient (mm d^{-1} °C^{-1})
- a is the intercept.

The unit for daily values of net radiation, here and in the following equations, is mm d^{-1}, the measured radiation (MJ m^{-2} d^{-1}) is converted into mm d^{-1} by dividing by the latent heat of vaporization of water (2.47 MJ kg^{-1}).

The application of the outlined methodology under Nordic climatic conditions had only been examined in a few cases (e.g. Svendsen et al., 1989), and due to the lack of daily ET values, equation [1] had not be examined directly. To overcome this limitation, a field experiment was designed by a research group, from the University of Copenhagen (Højgård et al., 1990) in cooperation with Agro-meteorological Survey, Foulum, and was based on barley fields belonging to a farm next to the latter institution (cfr. figs. 1, 6 and 8). The measuring equipment was mounted in mid-April and the recording continued until the barley was ready to be harvested at the beginning of August.

EXPERIMENTAL PROCEDURE FOR COLLECTING GROUND REFERENCE DATA

The methodology used to derive daily values of evapotranspiration (ET) was based on the surface energy budget:

$$Rn = Q_h + ET + Q_g \qquad [2]$$

where:
- Rn is the net radiation
- Q_h is the sensible heat transfer (to or from the atmosphere)
- ET is the latent heat of evaporation/condensation
- Q_g is the soil heat flux.

For daily values, the unit equivalent to evaporating 1 mm of water was used, while hourly values were expressed by W m^{-2}. The net radiation term, Rn, was measured using a pyrradiometer, while the soil heat flux was measured by 2

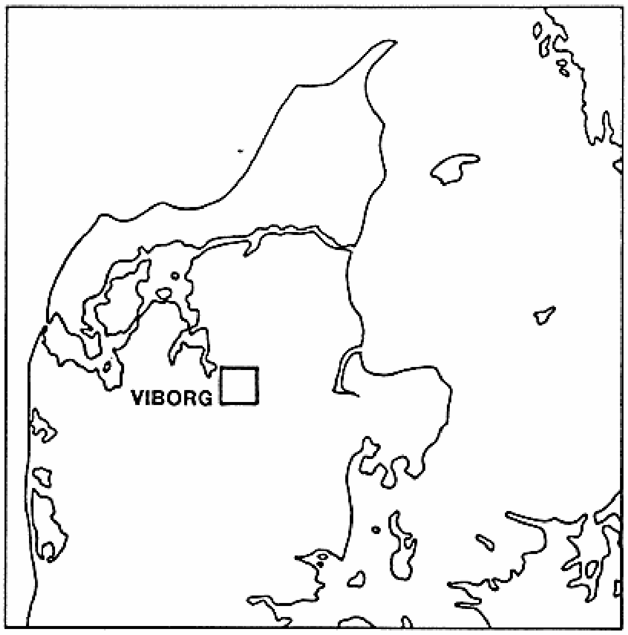

Fig. 1. The location of the 15 km by 15 km study area.

heat flux plates mounted at a depth of 5 cm. The estimation of Q_h was based on two different methods:

1) the flux profile relationship (which will be discussed below),
2) the eddy correlation technique.

For the collection of ground reference data, a 4 meter tall mast for measuring temperature at two levels and wind speed at three levels was deployed throughout the period. From the middle of June onwards, this was supplemented by a taller mast for measuring at three levels reaching as high as 9 meters above ground surface. For measuring temperature gradients artificially, ventilated thermocouples were used. All sensors were scanned every 5 seconds, and integrated by the logger to show 15 minute mean values. For the final flux calculations, the data were averaged over 1 hour-intervals.

The calculation of the sensible heat flux from vertical wind speed and air temperature gradients was based on the Monin-Obukhov similarity and mixing length theory. The total set of algorithms for the calculation of Q_h has been reported in earlier, recent studies (e.g. Søgaard, 1988; Vogt & Jaeger, 1990). As the flux profile calculation is found to be sensitive to changes in surface roughness (roughness length and displacement height), it was necessary to calibrate the algorithms to the actual conditions. For the calibration of sensible heat flux and latent heat flux, an eddy correlation device was deployed on selected days.

The eddy correlation system consists of two sensor units:

1) a one-dimensional sonic anemometer, CA27, equipped with fine-wire thermocouple.
2) a krypton hygrometer.

Both units produce analog signals which are collected and processed on-line by a 21X datalogger using covariance software at a sampling rate of 10 Hz. Supplementary measurements were made of the air temperature, rainfall and surface radiation temperature. The latter being measured by use of a Heiman K17.

ANALYSIS OF NOAA-AVHRR AND LANDSAT TM- SATELLITE DATA

A total of 20 NOAA-11 satellite images were selected to cover the growing season from April to August 1990. The satellite images were processed by applying the CHIPS-software (Rasmussen, 1988). The processing consisted of the following steps:

1) geometrical registration based on a UTM-grid (zone 32) with a spatial resolution of 1 km by 1 km.
2) radiometric calibration of raw count to albedo or surface temperature neglecting the least significant bit of the NOAA 10-bit-words. The temperature was thus calculated with a resolution of 0.2 °C.

The NOAA data were corrected for atmospheric attenuation using the atmospheric transfer model developed by Price (1983. To study the small-scale spatial variability within each of the 1 km by 1 km NOAA picture elements, a Landsat TM image from 15 July, 1990 was purchased as well.

Like the NOAA, the Landsat image was geometrically corrected to the same UTM coordinate system as was applied for use with the NOAA-data. In the final product, the spatial resolution was 30 m. The thermal band 6 with 120 m resolution was also resampled to fit this grid size. The Landsat TM-data was radiometrically calibrated by applying the method prescribed by Wukelic et al. (1989). To make the atmospheric correction, the same method was used as described for the NOAA data, only the coefficients were adjusted to the Landsat TM5 radiometer.

RESULTS

Calibration of the ET-Rn Model

For the calibration of the ET-Rn algorithm [1], the measurements of hourly fluxes were supplemented by measurements of the surface temperature above the barley field and the air temperature during the campaign. The hourly values cover the whole period from 11 April

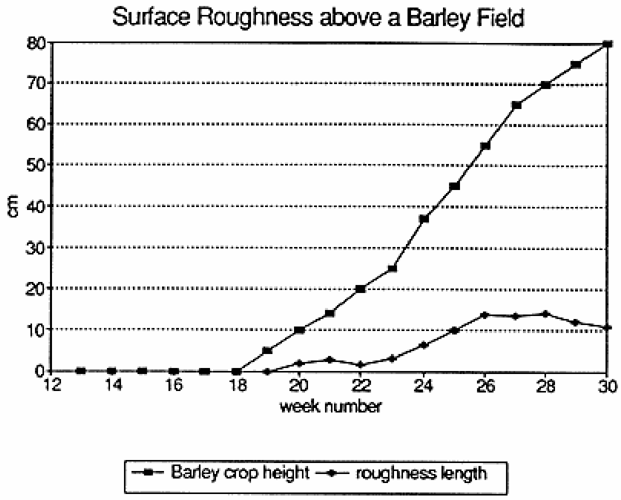

Fig. 2. Variation in surface roughness estimated by wind speed measurements at three levels.

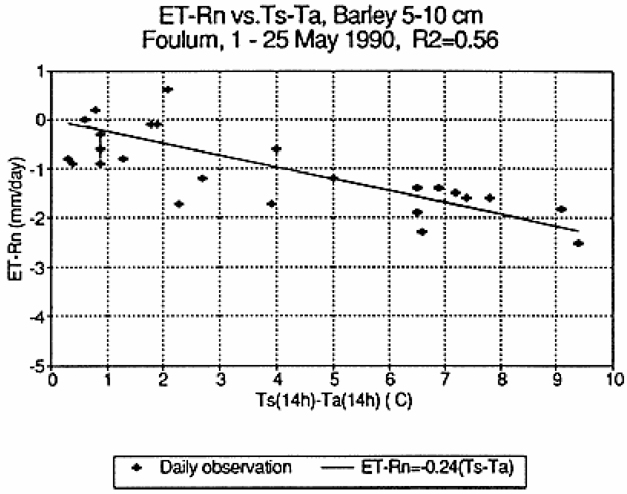

Fig. 3. The relationship between ET-Rn, and the difference in temperature between the surface and the air at 14 h during the period 1-25 May.

(Julian day 101) to 2 August (Julian day 214). In practice, however, the data set was reduced, mostly due to instrumental problems with the infrared thermometer. However, the final data set consists of more than 90 daily records with measurements of all parameters.

In the calibration of the simplified relationship [1], it is evident that the slope coefficient, b, cannot be assumed constant for the whole period. Several recent studies (Lagouarde, 1991; Lagouarde & MacAnney, 1991) have shown that the numerical value of b will increase with increasing surface roughness. For the barley field studied, it is evident that the aerodynamic roughness increases with the height and density of the barley. The technique applied for estimating the roughness length (z_0) from profiles with 3-6 wind speed levels has been discussed by Jacobs & Van Boxel (1988). In fig. 2, the weekly variation in z_0 is shown, assuming the displacement height to be zero. The roughness length increases from 0.01 m to roughly 0.13 m which is found to accord quite well with the following rule of thumb (Brutsaert, 1984) that $h/z_0 = 7$, where h is the vegetation height.

Due to these changes, the calibration procedure has been concentrated on periods with only slowly changing surface roughness, i.e. the first part of May (1 to 25 May) and July (9 July - 1 August). For the May period, the daily ET-Rn values were plotted as shown in fig. 3 related to the difference between surface and air temperatures at 14 h, corresponding roughly with the time of maximum temperature difference and the overpass of the NOAA-satellite. Despite the scatter, the data set confirms the strong linkage between ET-Rn and the temperature difference between the surface and the air. On some days, especially those with daytime rainfall, the 14 h-observation is not representative of the diurnal temperature variation, and this will cause some of the scatter in the diagram.

In the analysis of exchange coefficients, it was further assumed that Equation [1] could be simplified by setting the intercept to zero. From a physical point of view, this seems reasonable as the soil heat flux on a daily basis is normally close to zero and can thus be neglected. In this case, referring to [2], the sensible heat flux (Q_h) is thus equal to -(ET-Rn). On days with no midday excess surface-heating as compared to the air, i.e. $T_{s14} - T_{a14} = 0$, it is also a reasonable assumption that $Q_h = 0$ and the intercept, a, in [1] should then be equal to zero. This leads to the following equation:

$$\text{ET-Rn} = c \cdot (T_{s14} - T_{a14}) \text{ (mm/day)} \qquad [3]$$

where:
c is the surface specific exchange coefficient (mm $d^{-1}{}^{\circ}C^{-1}$)

For the May period the following relation was found:

$$\text{ET-Rn} = -0.24 \cdot (T_{s14} - T_{a14}) \text{ (mm/day)} \qquad [4]$$

The Inter-dependence of Surface Roughness and the Exchange Coefficient

In fig. 4, the result of running the calibration procedure based on the data from the last part of the experiment (July) is shown. The formula for the last 22 days at the end of July is:

$$\text{ET-Rn} = -0.62 \cdot (T_{s14} - T_{a14}) \text{ (mm/day)} \qquad [5]$$

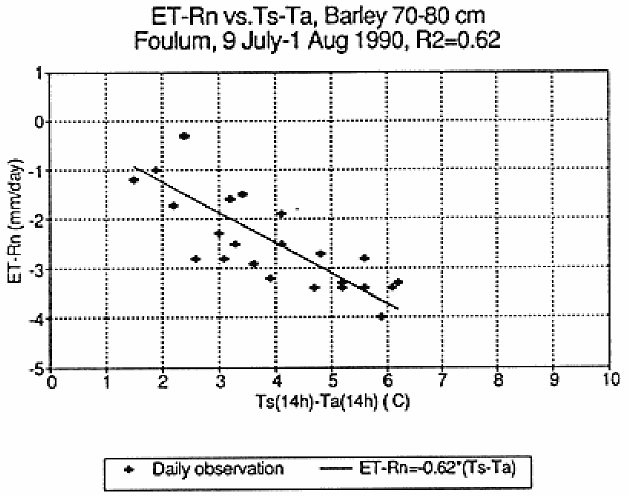

Fig. 4. The relationship between ET-Rn, and the difference in temperature between the surface and the air at 14 h during the period 9 July - 1 August.

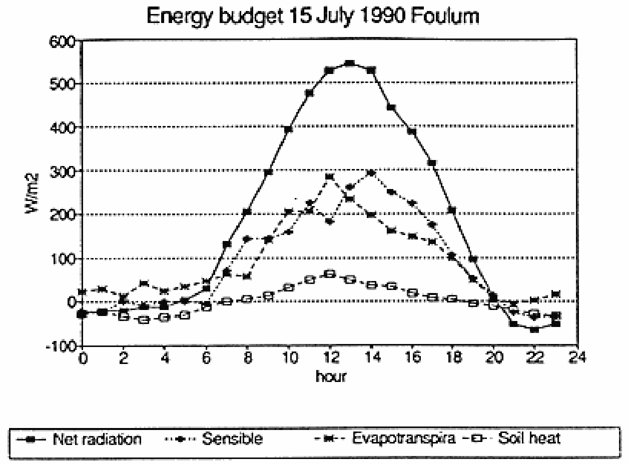

Fig. 5. Diurnal variation in energy balance components on 15 July 1990.

Here the model explains an even greater part of the variation, namely 62%, although some scatter still occurs. In this data set, one daily observation (27 July) was excluded due to an error in the sensible flux estimation. The big difference between fig. 3 and fig. 4 is to be found in the exchange coefficient as expressed by means of the shape of the curve on the graph. If we assume that the increase in slope is due to increasing surface roughness, the values can be compared to the model used by Lagouarde (1991). For z_0=1 cm the Lagouarde- model gives a slope coefficient b =- 0.244 (mm day^{-1} $°C^{-1}$) compared to -0.24 here. The Lagouarde-model only reaches to z_0 = 10 cm with b= -0.498 while the slope here (-0.62) corresponds to z_0=12 cm. Thus, the results seems to confirm the model proposed by Lagouarde (1991). It should be mentioned, however, that the Lagouarde model is based on both slope and intercept. Here it was found, however, that the model can be more easily explained physically when neglecting the intercept.

Evapotranspiration based on Satellite and Ground Data

In accordance with [1], the first step in the satellite data analysis is to calculate the net radiation at ground surface. In the second step, atmospherically-corrected surface temperatures are calculated from the satellite data, while the third step is to combine these data with traditional air temperature measurements using an appropriate exchange coefficient.

This approach was demonstrated by Søgaard (1990), showing each single step in calculating the surface evapotranspiration. In the present study, which aims at comparing ET-estimates at different scales, some simplification has had to be introduced. Only one day has been considered, namely 15 July 1990, for which both NOAA, Landsat and ground-reference data were available. Only the region around Viborg and the Foulum Research Station has been used (fig. 1) and, finally, the ground-based measurements of net radiation and air temperature at Foulum have been applied for all three data sources.

The ground-based estimation of evapotranspiration is found in fig 5, showing an energy balance diagram for the

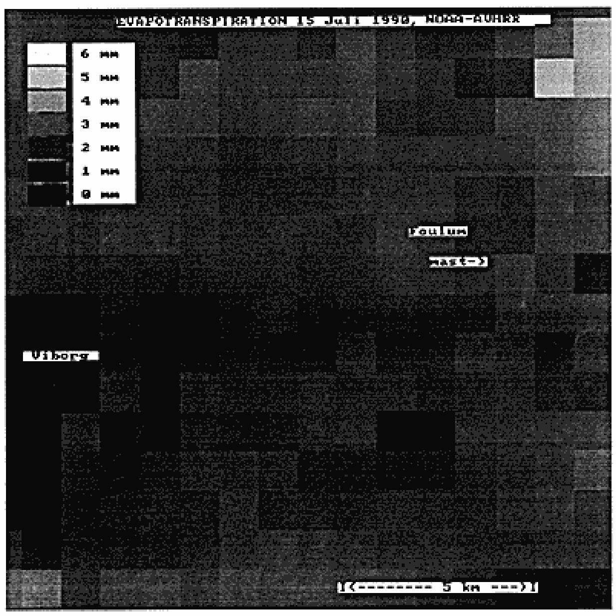

Fig. 6. Spatial distribution of ET on 15 July 1990, based on NOAA-AVHRR. The image covers 15 km by 15 km.

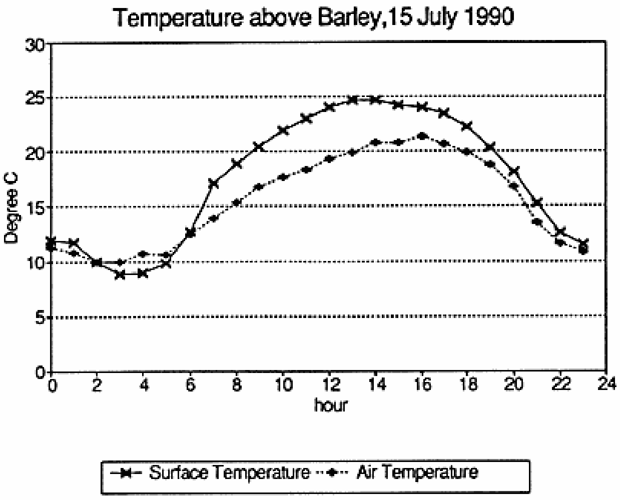

Fig. 7. Diurnal temperature variation on 15 July 1990.

actual day. The evapotranspiration and the sensible heat flux consume a nearly equal amount of energy only at the end of the afternoon. The dense barley canopy restricts the soil flux to roughly 10% of the net radiation. The total amount of energy during the 24 hours is Rn = 6.3 mm, Q_h = 3.0 mm, ET = 3.1 mm, and Q_g = 0.2 mm.

Evapotranspiration based on NOAA-AVHRR and Landsat TM Data

In the NOAA-AVHRR case, the calculation of ET is relatively straightforward using [4]:

$$ET_{NOAA} - 6.3 = -0.62\ (T_{NOAA} - 20.4)\ (mm/day) \qquad [6]$$

T_{NOAA} is the temperature calculated from NOAA channel 4 corrected for atmospheric attenuation (+ 3.37 °C). The exchange coefficient 0.62 is used for the whole image as barley is considered the predominant crop in this region. The geographical distribution shown in fig. 6 will be discussed below.

The Landsat TM-data differs from the NOAA-data in two ways:

1) the spatial resolution
2) the time of the satellite overpass is different from the time of the thermal maximum signal.

While the difference in spatial resolution is obvious when comparing the images, the second point is more problematic as the basic algorithms for deriving evapotranspiration are based on midday temperatures, while the Landsat flies over nearly 3 hours earlier. Examples of the use of Landsat for evapotranspiration mapping may be found in Stewart & Holwill (1989).

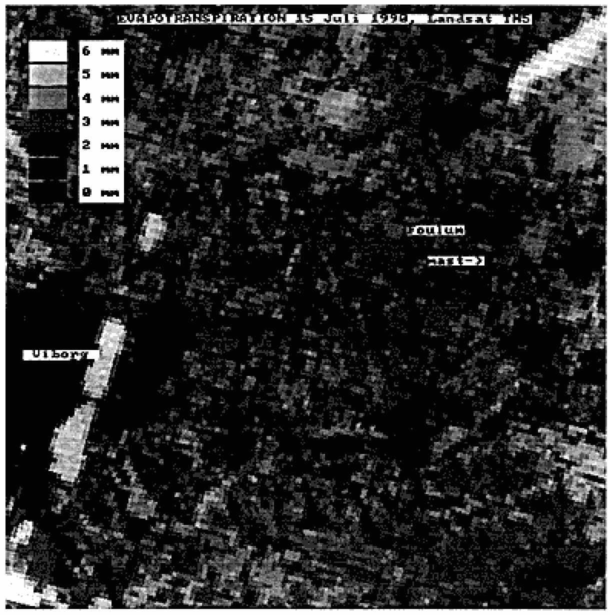

Fig. 8. Spatial distribution of ET on 15 July 1990, based on Landsat TM. The image covers 15 km by 15 km.

The diurnal temperature variation on 15 July was examined in order to evaluate whether [3] could be applied in the present case. Looking at fig. 7, it is seen that the temperature difference between the surface and the air obviously changes during the course of the day, but in the period between 10 h and 14 h it is nearly constant on the actual day observed. Similar studies made in tropical areas with only around 12 hours of daylight show that, at the time of Landsat overpass, the temperature difference is only two-thirds the value found at 14 h.

In this case, it is assumed that [5] may be applied directly, using, of course, the 10 30 h value for the air temperature:

$$ET_{Landsat} - 6.3 = -0.62\ (T_{Landsat} - 18.0)\ (mm/day) \qquad [7]$$

$ET_{Landsat}$ is the temperature calculated from the Landsat TM band 6, corrected for atmospheric attenuation (+3.71 °C). The difference in the correction value compared to that of NOAA is due to different radiometric sensitivity. The resulting ET distribution is found in fig 8. When looking at the image, the scanner geometry, with its original 120 m spatial resolution appears as small squares. The scan lines are turned approximately 13° as part of the UTM-registration. Despite some slightly disturbing scanner errors, the distribution shows a distinct pattern, namely low values in urban areas, reaching as low as (0.5 mm/day in central Viborg. In fact, most of the villages in the area are low-evaporation areas. High ET-values are recorded for the major lakes (5 mm/day) and river courses such as the river Nørre Å, which is distinguishable as it crosses from east to west through the black spot of Vejrum village, east of Viborg. The agricultural areas produce values around 3 mm/day. In the Foulum area, the main agricultural research station can easily be identified by its low evaporation rate, while in the neighbourhood of the mast, the mean value is close to 3 mm/day, as is also found in ground reference observations. Returning to fig. 6, the same pattern can be distinguished despite the crude picture elements.

DISCUSSION

The results of the present study confirm that ET-Rn, with reasonable accuracy, may be expressed as a function of the temperature difference between the surface and the air at the time of the NOAA-satellite overpass in the early afternoon. Without any loss of accuracy, the traditional ET-Rn model has been simplified by a physical interpretation of the exchange coefficient. It has been found that the numerical value of this coefficient depends on the surface roughness. The rougher the surface, the higher the exchange coefficient. The results contradict the conclusion by Svendsen et al. (1989) that this methodology would only be of restricted use under Danish conditions. It has been proved that the results confirm the model proposed by Lagouarde (1991).

For the selected case study it has also been proved that both Landsat and NOAA-AVHRR give results which are similar to the ground ET-estimations, presenting a regional distribution in accordance with what might be assumed. It is obvious that problems still occur and some of these are related to:

1) The inaccuracy in the ET-estimation,
2) The problem of parametrizing the surface roughness.

With respect to instrumentation, these ground observations could be improved by adopting the eddy correlation technique in the operational measuring program. The problem of surface roughness might be tackled using the visible and near-infrared Landsat bands for high-resolution vegetation mapping.

ACKNOWLEDGEMENTS

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