Satellite remote sensing as a tool for spatial evapotranspiration estimation in vegetated areas

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The present paper outlines and tests a method for satellite mapping of evapotranspiration based on the canopy resistance theory. The dataset used for the analysis was obtained during a field campaign conducted in an agricultural region east of Viborg, Jutland, April to August 1990. Scale between low-resolution NOAA satellite images and ground truth values were tested with a single high-resolution Landsat satellite image.

The results are found to be in accordance with field observations. In accordance with canopy resistance theory, a simple empirical algorithm was found effective for evapotranspiration estimation using satellite data. This approach also produced better defined differences between fields than a model based on net radiation, air temperature, and satellite-derived surface temperature.

Keywords: *Remote sensing, evapotranspiration, NDVI.*

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The hydrological cycle is of indisputable importance to human life on earth. In vegetated regions water budget calculations are useful in determining growth potentials, irrigation needs, and potential wash out of sediments and pollutants to rivers, seas and groundwater. Evapotranspiration is a major factor in these water budget models. Until now, however, the spatial variation in evapotranspiration due to heterogenity of landscapes has been difficult to quantify.

Satellite remote sensing data offer a great potential for improving spatial estimates of phenomena like evapotranspiration (Seguin & Itier, 1983, Hope, 1988,

Nemani & Running, 1989, Lagouarde, 1991). The purpose of this study was to determine if sufficiently accurate estimates of evapotranspiration, and its variability over a significant area, could be derived in part from satellite data. In this study a combination of information from visual (VIS), near-infrared (NIR) and thermal infrared (TIR) channels were used to estimate and map evapotranspiration. Results were compared to ground reference evapotranspiration measurements. Evapotranspiration itself is not directly measurable by satellite techniques.

The ground measured evapotranspiration reference data were obtained from measurements in a springbarley field located east of Viborg in the vicinity of Research Center Foulum (Fig. 1). The field campaign was conducted in cooperation with Dept. of Agrometeorology, Research Center Foulum. Intensive data analysis was carried out (Højgaard et al., 1990, Søgaard, 1992, Hasager, 1992).

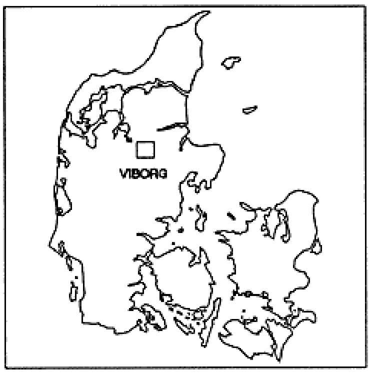

Fig. 1. Location of the 15 km by 15 km study area at Research Center Foulum.

SATELLITEE BASED ESTIMATION OF EVAPOTRANSPIRATION

Vegetation growth and transpiration is largely controlled by water and nutrient availability, photosynthetically active radiation (PAR) intensity, and temperature. Plant diseases and herbivores may retard or damage vegetation growth. In Danish agricultural crops adequate amounts of nutrients are supplied and pesticides and herbicides are used whenever necessary. The result is that micro-climatological parameters may be regarded as controlling factors.

Green leaves and stems contain chlorophyll, which absorbs part of the incoming PAR and converts it to biochemical energy used in photosynthesis. During photosynthesis plants capture CO_2 from the air through open stomata in leaves and stems. Whenever the stomata are open water vapor will diffuse out through the stomata and be lost as transpiration to the atmosphere. This means that the photosyntetic rate is in linkage with the amount of water loss. When the photosyntetic rate is low (near zero) due to lack of PAR, soil water, optimal growth temperature or nutrients the stomatal guard cells will close the stomata and thereby diminish the transpiration loss (Rosenberg et al., 1983).

Photosynthetic active green leaves absorb most of the PAR resulting in low reflectivity of visible light. Furthermore live vegetation reflects a high proportion of NIR radiation. Non-active leaves and soil have a much greater reflectivity in PAR and a lower reflectivity in NIR than live vegetation. Consequently the difference between reflection of PAR and NIR is widely used to discriminate vegetated from non-vegetated areas (Poulsen & Svendsen, 1992). In this study, though, the focus was on relative photosynthetic rates. According to two-way radiation transfer theory (Sellers 1989),the Normalized Difference Vegetation Index (NDVI) is positively and linearly correlated with photosyntetic rate. NDVI is defined as

$$NDVI = \frac{NIR - PAR}{NIR + PAR} \tag{1}$$

Remote sensing-derived NDVI of live vegetation is useful as a measure of canopy resistance in deterministic evaporation models (Hope et al., 1988, Hope, 1988, Nemani & Running, 1989). The higher the density of active leaves, the lower the canopy resistance will be. Well-watered vegetation is able to transpire a significant amount of water and thereby reduce the heating of the canopy. The surface temperature of such a canopy will be low relative to a dry, low-transpiring canopy. NDVI is within the range of such a temperature difference proportional to the number of open stomatas (Nemani & Running, 1989).

Inputs to a simple canopy resistance model are surface temperature, T_s, and NDVI. According to Nemani & Running (1989) T_s/NDVI can be used as a proxy for canopy resistance. And as canopy resistance in vegetated areas is a controlling factor of evapotranspiration, a simple regression model may be used as a first approximation

$$ET = a * \frac{T_s}{NDVI} + b \tag{2}$$

where
ET = evapotranspiration (mm/day)
T_s = surface temperature (°C).

A limitation of the model is that agricultural crops and forest may have different relations between NDVI and canopy resistance. Therefore evapotranspiration estimates within a region may need to be calculated individually for different vegetation types.

Spatial ET estimation from satellite data has previously been carried out in the Foulum area (Søgaard, 1992) using Landsat TM and NOAA AVHRR satellite data. A different approach was used namely the simplified relationship. This approach is based on the difference between evapotranspiration and net radiation (mm) and difference in surface and air temperature (Celsius) (Seguin & Itier, 1983).

GROUND OBSERVATIONS

The analysis is based on ground reference data measured on a 15 ha large springbarley field located at Research Center Foulum near Viborg. Micrometeorological data sampling from two masts as well as reflective radiometer measurements were carried out from April to August 1990 and were also used by Søgaard (1992). From Dept. of Agrometeorology, Research Center Foulum micrometeorological data of precipitation, soilwater content, reflective radiometer data, and Leaf Area Index data were obtained.

SATELLITE DATA

For the data analysis a number of NOAA-11 satellite images recorded with the radiometer AVHRR (Advanced Very High Resolution Radiometer) were used. Twentytwo images were obtained from Dundee, Scotland. The images were recorded between April 30 and August 3, 1990. All images were geometrically corrected to UTM coordinates. Information from channel 1 (0.58-0.68 μm, VIS), channel 2 (0.72-1.10 μm, NIR), channel 4 (10.3-11.3 μm, TIR) and channel 5 (11.5-12.5 μm, TIR) were used in the analysis. Pre-flight calibration data from Updates to Lauritson (1979/1990) and post-flight calibration data from Che & Price (1992) were used.

One Landsat-5 satellite image recorded with the radiometer TM (Thematic Mapper) on July, 15, 1990 was obtained from Kiruna, Sweden. Information from channel 3 (0.63-0.69 μm, VIS), channel 4 (0.76-0.90 μm, NIR) and channel 6 (10.4-12.5 μm, TIR) was calibrated (Markham & Barker, 1987, Wukelic et al., 1989) and analysed. The image was geometrically corrected to UTM coordinates.

METHODS USED TO DERIVE NDVI TEMPORALLY AND SPATIALLY

Ground-reference NDVI was calculated from measurements made with a Milton Multiband Radiometer (MMR) in the spring barleyfield and simoultaneously calibrated with Kodak Grey Cards. The observations were in close agreement with NDVI measured with a CROPSCAN radiometer in a nearby plot of spring barley by Dept. of Agrometeorology, Research Center Foulum. CROPSCAN was calibrated with hemispherical scans of incoming radiation (Thomsen, 1992). Evaluation of NDVI development during the growing season is shown (Fig. 2).

NDVI was also calculated from a Landsat TM satellite image using channels 3 and 4. The Landsat-derived NDVI in the Foulum region on July 15th., 1990, 10.30 local time, is shown (Fig. 3). The Landsat pixel size is 30 m by 30 m. The lakes of Viborg and Tjele Langsø are shown in black in the image. Research Center Foulum is visible as a dark semicircle north of "Foulum". The white area in the northern direction is a grass field, and, the springbar-

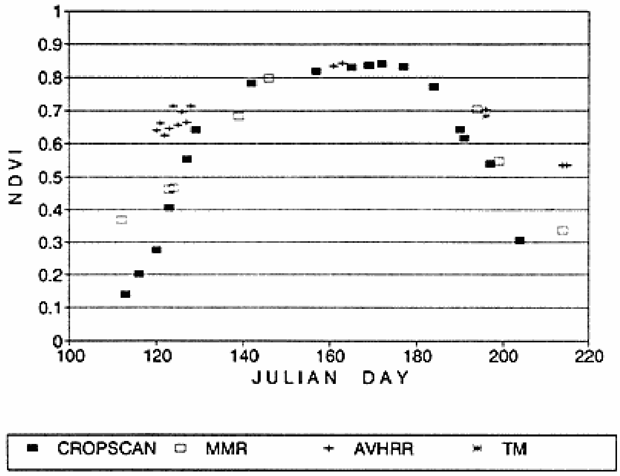

Fig. 2. Development in NDVI of spring barley during the growing season 1990 at Foulum. Spectral data obtained with ground radiometers (CROPSCAN, MMR) and satellite radiometers (NOAA AVHRR, Landsat TM).

ley field refered to in this experiment, is situated south of the buildings. The barley field covers 164 Landsat pixels with a NDVI mean value 0.684 and a 95% confidence interval of [0.682,0.686]. The field is very homogeneous and the NDVI values in the Landsat image are in very close agreement with ground radiometer observations (Fig. 2). The Foulum region is dominated by barley and wheat. Less frequently found are grass, rape, rye, beets, peas, and corn.

The Landsat NDVI of the agricultural crops clearly shows the field pattern (Fig. 3). Dark grey areas show low photosynthetic activity whereas light grey and white areas show higher photosynthetic activity. NDVI typically varies from 0.4-0.8. The Nørre Å Valley winding from West to East in the southern part of Fig. 3, and the valley southwest of Tjele Langsø are visible with relatively high values of NDVI. Forest is sparse and has slightly higher NDVI values than agricultural crops. Forests, like Sødal Skov south of Rødsø and Viskum Skov in the southeastern part of Fig. 3, are visible as large areas of high NDVI

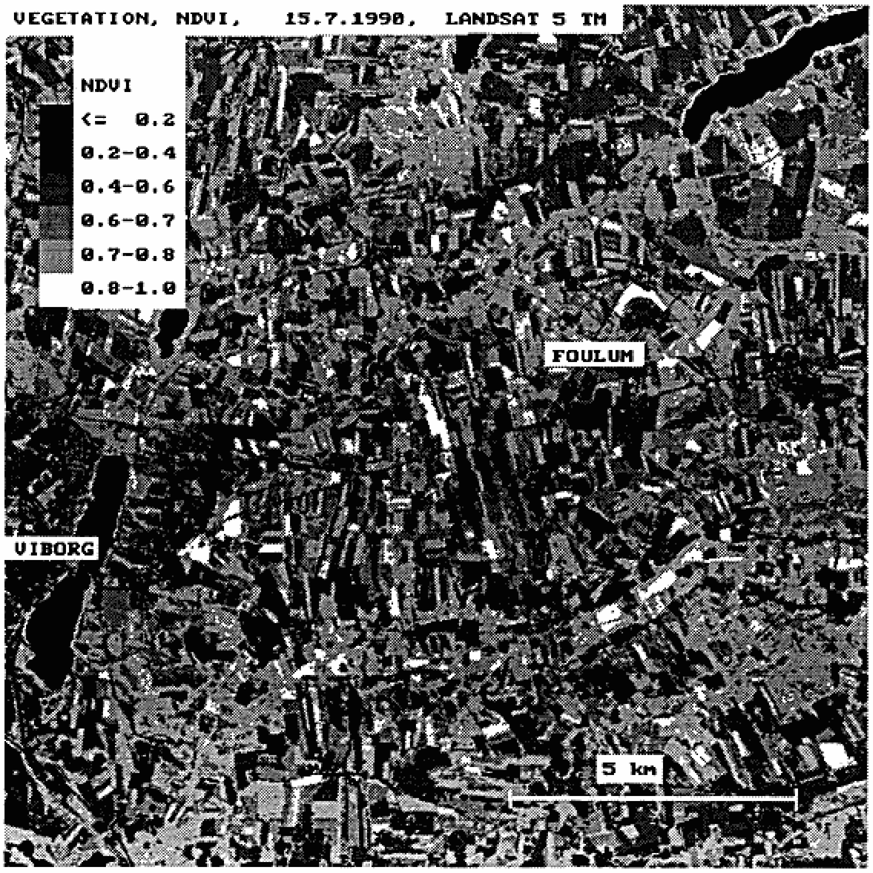

Fig. 3. Spatial distribution of vegetation in the Viborg region from Landsat 5 TM, July 15, 1990, at 10.30 local time.

without the typical field pattern mosaic. The urban environment of Viborg is characterised by areas of very low NDVIvalues.

Landsat high-resolution satellite images are, in a relative sense, expensive and only available every 16 days. Therefore, cheaper low-resolution NOAA satellite images available twice daily are preferred for multitemporal studies. NDVI was calculated from NOAA images using channels 1 and 2. NOAA-derived NDVI on July 15, 1990, 13.44 local time, in the Foulum region is shown (Fig. 4). The pixel size is 1 km by 1 km. The coarse resolution makes it possible to deduce only the more dominant features like low NDVI near Viborg and higher NDVI values in the agricultural areas. Visual comparision of Landsat TM and NOAA AVHRR satellite data from the same area (Fig. 3 and 4) clearly shows the difference between high and low spatial resolution images.

The barley field covers only a fourth of one NOAA pixel. NDVI values of the pixels that included the barleyfield was spatially registrered for all NOAA images (Fig. 2). It may be noted that the NOAA-derived NDVI is slightly higher than the ground radiometer observations. This may be due either to subpixel "noise" from the surroundings of the barleyfield (which are inevitably included in the registered pixel values) or to the type of atmospheric correction performed. To determine the actual mechanism, a test was carried out. NDVI from Landsat and NOAA images recorded on the same day were compared statistically. The result indicates that the atmospherical correction algorithms used (Goward et al., 1991, Justice et al., 1991) with input data of precipitabel water vapor content from radiosondes at Aalborg and Jægersborg, Danish Meteorological Institute, and aerosol loading at Karup, DMI, yielded correction values 0.09 NDVI-units too high in the NOAA image. In subsequent analysis this finding was taken into account.

The information content of NDVI in the NOAA scene relative to the Landsat scene was statistically evaluated. It was found that 72 % of the information content variation in NDVI in the Landsat scene was accounted for in the

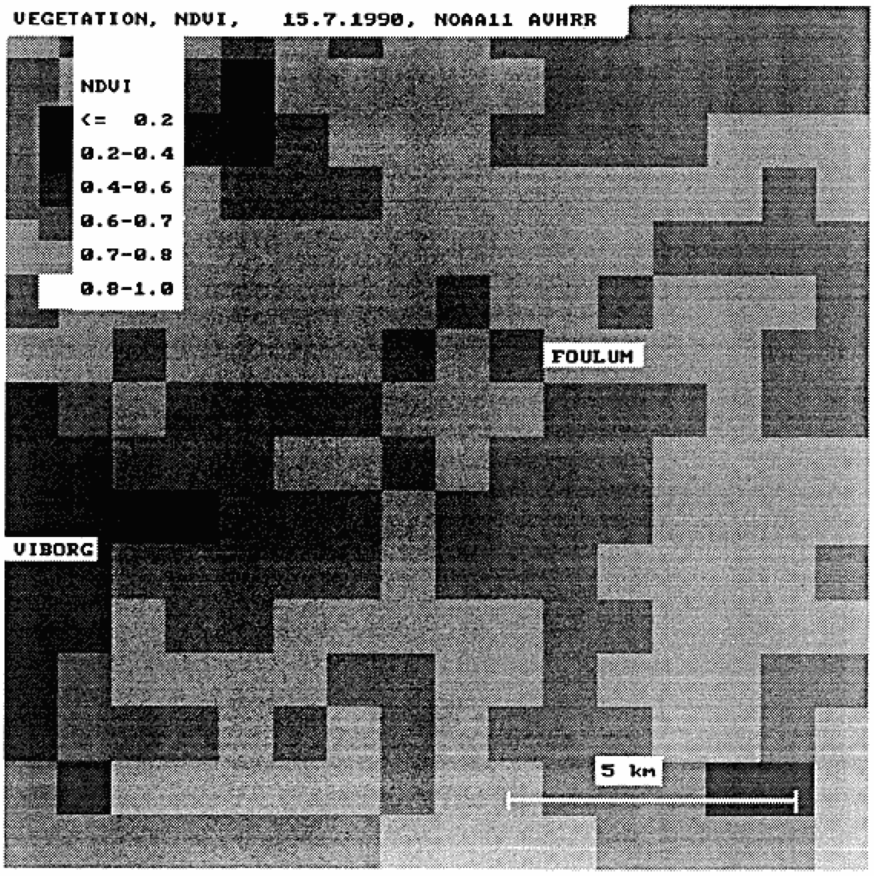

Fig. 4. Spatial distribution of vegetation in the Viborg region from NOAA 11 AVHRR, July 15, 1990, at 13.44 local time.

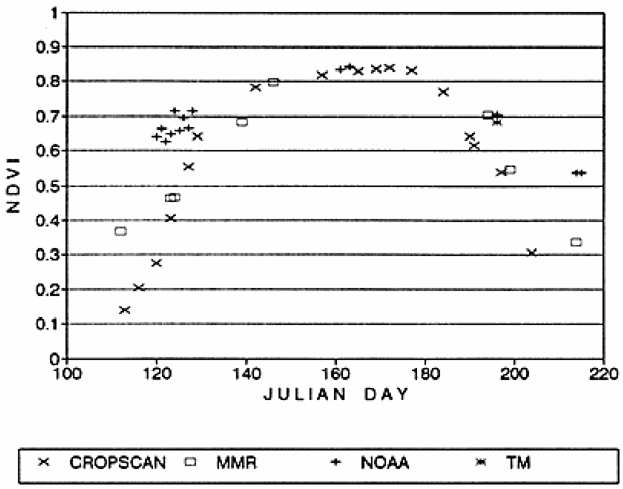

Fig. 5. Ground observations of ration of surface temperature/ NDVI versus evapotranspiration (ET) for spring barley, Foulum, July 9 to August 1, 1990, with linear regression line (R^2= 0.69).

NOAA scene. The indication is that NOAA AVHRR can be a reliable source of NDVI data when attention is focused on dominant features of the landscape.

SURFACE TEMPERATURE

Ground observations of surface temperature measured with a Heiman 17K infrared thermometer were found to be in agreement with surface temperature derived from Landsat and NOAA satellite images. Landsat TM data from channel 6 was calibrated and transformed to surface temperature (Søgaard, 1992, Wukelic et al., 1989) and NOAA AVHRR data from channel 4 and 5 were used with a split window technique (Price, 1983) to obtain surface temperature.

ESTIMATION OF SPATIAL EVAPOTRANSPIRATION

Ground observations of surface temperature, ground-derived NDVI, and calculated evapotranspiration from

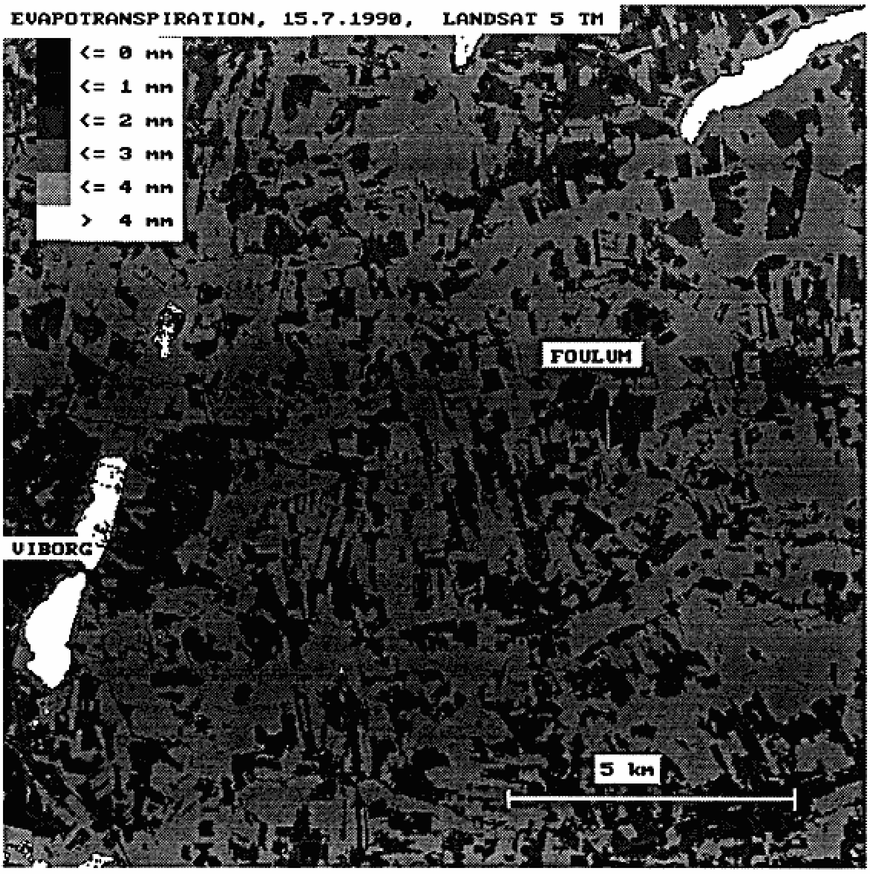

Fig. 6. Spatial distribution of evapotranspiration in the Viborg region from Landsat 5 TM, July 15, 1990.

ground observations of roughness, wind and temperature profiles obtained during July 1990 in the barley field in Foulum, were used to obtain regression values of a and b according to [2]. The following relation was found

$$ET = -0{,}06 * \frac{T_s}{NDVI} + 4.21 \tag{3}$$

The data and regression line are shown (Fig. 5) with R^2 value of 0.69 based on 22 observations

The regression result was applied to Landsat data to calculate evapotranspiration in the Landsat TM satellite image and the result is shown (Fig. 6).

Results of spatial evapotranspiration estimation

Actual evapotranspiration (ET) in the region of Foulum calculated from the Landsat satellite image ranges from (slightly) less than zero to more than 4 mm per day (Fig. 6). In the agricultural area, ET is mainly between 2 and 4 mm per day. In the springbarley field ET is around 3 mm. This is in accordance with ground measurement data. The field pattern is clearly visible. The phenomena may be assigned to crop specific relations of T_s/NDVI. This effect is not present in NOAA images where average ET of several crop types are mapped.

The forested areas of Sødal Skov and Viskum Skov show relatively high ET values on the Landsat image. Evapotranspiration in forest and non-vegetated areas may not be properly calculated as [3] is valid for the agricultural area. Areas with ET less than zero is obviously (slightly) too low. The lakes generally show high ET but some black spots (ET less than zero) is a non-correct classification of evapotranspiration rates. Low ET is encountered in the Viborg urban area.

Discussion of spatial evapotranspiration estimation

Comparision of the spatial variation on ET estimation between the results from canopy resistance theory [2] evaluated here and simplified relationship Søgaard's (1992) work shows close agreement for the agricultural area. For example the river course of Nørre Å with high ET can be seen to cross through Vejrum village with low ET (dark areas) in both cases. A difference between the results is that the field pattern is clearly distinguished by ET estimation from canopy resistance theory whereas this is not the case of ET estimation using the simplified relationship used by Søgaard.

The regression result on the simplified relationship yielded a R^2 value of 0.62 based on 23 observations (Søgaard, 1992) which is slightly lower than the canopy resistance method. Statistical testing including non-linear relations may improve ET estimation from canopy resistance theory.

Information on the spatial distribution of crop types, forest and non-vegetated areas may be obtained from Landsat satellite images or from a GIS (Geographical Information System) database. This information, in the author's opinion, would likely improve spatial estimation of evapotranspiration from canopy resistance theory because the relation T_s/NDVI may vary for different landcover classes.

The spatial distribution of ET calculated from satellite images using canopy resistance theory is encouraging. The results are in agreement with ground reference observations as well as with regional ET estimates from the simplified relation used by Søgaard (1992). Further development and evaluation of different approaches for satellite evapotranspiration estimation will require a dense net of regional ground observations of ET or model simulations.

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References

Che, N. & J.C. Price (1992): Survey of Radiometric Calibration Results and Methods for Visible and Near Infrared Channels of NOAA-7, -9, and -11 AVHRRs, Remote Sens. Environ, 1, pp 19-27.

Goward, S.N., B. Markham, D.G. Dye, W. Dulaney & J. Yang (1991): Normalized Difference Vegetation Index Measurements from the Advanced Very High Resolution Radiometer, Remote Sens Environ, 35, pp 257-277.

Hasager, C.B. (1992): Anvendelse af NOAA og Landsat satellitdata samt feltdata ved kortlægning af vegetation og overfladefluxe i Danmark, Speciale i naturgeografi, Geographical Institute, University of Copenhagen, Internal report.

Hope, A.S. (1988): Estimation of wheat canopy resistance using combined remotely sensed spectral reflectance and thermal observations, Remote Sens. Environ., 24, pp 369-383.

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vandsmagasin, NG4 projekt, Geographical Institute University of Copenhagen, Internal report.

Justice, C.O., T.F. Eck, D. Tanre & B.N. Holben (1991): The effect of water vapour on the normalized difference vegetation index derived for the Sahelian region from NOAA AVHRR data, Int. J. Remote Sensing,vol 12,no 6, pp 1165-1187.

Lagouarde, J-P. (1991): Use of NOAA AVHRR data combined with an agrometeorological model for evaporation mapping, Int. J. Remote Sensing, vol 12, no 9, pp 1853-1864.

Lauritson, L., A. Nelson & F.M. Porto (1979): Data extraction and calibration of Tiros N/NOAA radiometers. NOAA Technical Memorandum, NESS 107, Updates to Appendix B for NOAA-H/11, 13.7.1990.

Markham, B.L & J.L. Barker (1987): Thematic Mapper bandpass solar exoatmospheric irradiances, Int. J. Remote Sensing, vol 8, no 3, pp 517-523.

Nemani, R.R. & S.W. Running (1989): Estimation of Regional Surface Resistance to Evapotranspiration from NDVI and Thermal-IR AVHRR Data, Journal of Applied Meteorology,vol 28, pp 276-284.

Poulsen, J.N. & T.B. Svendsen (1992): Spectral signatures of Danish crops multitemporal signatures derived from high resolution satellites, Proceedings from the Workshop on Remote Sensing, Sostrup Castel, Grenå.(Eds) Thomsen,A. A.Jensen & H.E.Jensen, Landbrugsministeriet, Statens Planteavlsforsøg, Tidsskrift for Planteavls Specialserie, Beretning nr. S 2207-1992, pp 83-95.

Price, J.C. (1983): Estimating Surface Temperatures from Satellite Thermal Infrared Data - A Simple Formulation for the Atmospheric Effect, Remote Sens. Environ,13, pp 353-361.

Rosenberg, N.J, B.L. Blad & A.B. Verma (1983): Microclimate. The Biological Environment, John Wiley & Sons, New York.

Seguin, B. & B. Itier (1983): Using midday surface temperature to estimate daily evaporation from satellite thermal IR data, Int.J.Remote Sensing,vol 4, no 2, pp 371-383.

Sellers, P.J. (1989): Vegetation-canopy spectral reflectance and biophysical processses. pp297-335 in G.Asrar (ed):Theory and Applications of Optical Remote Sensing, John Wiley & Sons, New York.

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

Thomsen, A. (1992): Estimation of Leaf-Area-Index (LAI) from Radiation Measurements.In:Proceedings from the Workshop on Remote Sensing, Sostrup Castel, Grenå. (Eds.) Thomsen, A., A.Jensen & H.E.Jensen, Landbrugsministeriet, Statens Planteavlsforsøg, Tidsskrift for Planteavls Specialserie, Beretning nr. S 2207-1992, pp 29-36.

Wetzel, P.J. & R.H. Woodward (1987): Soil Moisture Estimation Using GOES-VISSR Infrared Data: A Case Study with a Simple Statistical Method, Journal of Climate and Applied Meteorology, vol 26, pp 107-117.

Wukelic, G.E., D.E. Gibbons, L.M. Martucci & H.P. Foote (1989): Radiometric Calibration of Landsat Thematic Mapper Thermal Band, Remote Sens.Environ, 28, pp 339-347.

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References

Che, N. & J.C. Price (1992): Survey of Radiometric Calibration Results and Methods for Visible and Near Infrared Channels of NOAA-7, -9, and -11 AVHRRs, Remote Sens. Environ, 1, pp 19-27.

Goward, S.N., B. Markham, D.G. Dye, W. Dulaney & J. Yang (1991): Normalized Difference Vegetation Index Measurements from the Advanced Very High Resolution Radiometer, Remote Sens Environ, 35, pp 257-277.

Hasager, C.B. (1992): Anvendelse af NOAA og Landsat satellitdata samt feltdata ved kortlægning af vegetation og overfladefluxe i Danmark, Speciale i naturgeografi, Geographical Institute, University of Copenhagen, Internal report.

Hope, A.S. (1988): Estimation of wheat canopy resistance using combined remotely sensed spectral reflectance and thermal observations, Remote Sens. Environ., 24, pp 369-383.

Hope, A.S., S.N. Goward & D.E. Petzold (1988): Tersail: A numerical model for combined analysis of vegetation canopy bidirectional reflectance and thermal emissions, Remote Sens. Environ,26, pp 287-300.

Højgaard, E., C.B. Jensen, T. Jensen & I. Sonne (1990): Bestemmelse af evapotranspiration ved 4 forskellige metoder: Aerodynamisk profilmetode, eddykorrelation, satellitbilleder og jord-