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The use of HIRLAM climate predictions and AVHRR data for the calculation of evapotranspiration rates in Denmark

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ABSTRACT *In order to calculate the spatial distribution of evapotranspiration rates in Denmark, grid-based predictions of weather conditions are combined with remote sensing based estimates of surface temperature, global albedo and vegetation index. The climate predictions were calculated by the high-resolution limited area resolution model, HIRLAM, at 5 km grid resolution to represent the atmospheric conditions in Denmark. The predictions were used both for atmospheric correction of satellite imagery and as inputs for the calculation of evapotranspiration rates. The evapotranspiration rates were calculated at the 1 km^2 resolution of the AVHRR data and validated using landscape scale atmospheric fluxes of sensible and latent heat recorded for an agricultural region, a beech forest and a conifer forest.*

1 INTRODUCTION

Evapotranspiration rates constitute a sensitive linkage of atmospheric and hydrological processes. While the land surface feedback of heat and water vapour is important for an accurate prediction of atmospheric circulations, the net input of precipitation (precipitation minus evapotranspiration) is important for the evaluation of water resources on Earth. Since an increase in the global temperature of several degrees is anticipated in the present century, accurate methods for evaluating the interactions between the atmosphere and the land surface have become acutely important. Because Earth observations can be used to quantify the spatial distribution of evapotranspiration rates, they constitute an important extrapolation tool in support of field measurement based studies and modelling activities within the fields of meteorology and hydrology.

One constraint for remote sensing based flux estimation at the larger scale is the spatial representativity of the applied meteorological data. Field measurements of global radiation, air temperature and air humidity, which are needed for calculating the evapotranspiration rates, may vary significantly within the area monitored by satellites. Because of the difficult and expensive access to spatial representative meteorological field data, in this study, a high-resolution regional weather forecasting model, HIRLAM, is used to provide spatially distributed inputs of weather conditions to facilitate the atmospheric correction of satellite imagery and the subsequent calculation of evapotranspiration rates.

2 METHODS

2.1 Climate predictions

The HIgh Resolution limited Area Model (HIRLAM) is a routine weather forecast model used in Denmark, Sweden, Finland, Iceland, Ireland, the Netherlands and Spain. The model system consists of three nested models operating at different horizontal resolutions (50 km, 15 km and 5 km). The 50 km resolution model receives lateral boundary conditions from the European Centre for Medium-Range Weather Forecast (ECMWF) every 6 hours. The 15 km resolution model then receives the predictions from the low resolution model, and it provides the 5 km resolution HIRLAM model version with hourly predictions. Predictions are given 4 times a day by the high resolution HIRLAM model (at 0.00 GMT, 6.00 GMT, 12.00 GMT and 18.00 GMT). The 5 km resolution predictions of air temperature and air humidity at 12.00 GMT were extracted for use in the present study.

2.2 Satellite processing

All midday/afternoon NOAA satellite passages in the year 1998 and in the period 15th April-15th May 2000 were downloaded from the NOAA HRPT receiving station facilities at the Institute of Geography, Copenhagen. The data set was cloud screened and images with extreme off-nadir view-angles were detached. The image processing was conducted using the software WinCHIPS (www.geogr.ku.dk/chips) which includes a NOAA module for unpacking, geo-registration, calibration and calculation of the spectral surface albedo and the surface temperature.

While the estimation of the surface temperature (T_s) uses the split-window technique, the calculation of the spectral surface albedoes includes HIRLAM predictions of integrated atmospheric water vapour content to facilitate the atmospheric correction of the satellite data. Atmospheric correction of the data recorded by the AVHRR sensors onboard the NOAA satellites was conducted using the 5S-SMAC radiative transfer model (Rahman and Dedieu, 1994). The optical depth (τ) was estimated using visibility observations and the Dark Dense Vegetation (DDV) approach (ie Kaufmann and Sendra, 1988). Details on the processing is described in Boegh et al. (2002a).

2.3 Global albedo and net radiation

Calculation of the global albedo (α) is based on a conversion of the narrow-band red (0.57-0.7 μm) and near-infrared (0.72-0.99 μm) albedoes computed from the NOAA-AVHRR channels into a broad-band (0.3-2.5 μm) albedo (Valiente et al., 1995). The net radiation (R_n) is then calculated

$$R_n=R_s(1-\alpha)+R_l(1-\varepsilon_s)-\varepsilon_s\sigma T_b^4 \qquad (1)$$

Where R_s is global radiation, R_l is incoming longwave radiation which is calculated (Idso et al., 1981) using the HIRLAM predictions of air temperature and air humidity, ε_s is the surface emissivity, σ is the Stefan-Boltzman coefficient and T_b is the brightness temperature recorded by the satellite.

2.4 Soil heat flux

The soil heat flux (G) is estimated using an empirical linear relationship between G/R_n and NDVI (Kustas and Daughtry, 1990) where the coefficients were obtained by stretching the full range of observed NDVI'es towards a full range of G/R_n fractions. It is assumed that G/R_n is 0.4 for bare soil and 0.05 for dense vegetation.

2.5 Evapotranspiraton rate

The evapotranspiration rate (E) is calculated by

$$\lambda E= (\rho c_p/\gamma)(e_s^*-e_a)/(r_{ae}+r_s) \qquad (2)$$

where λ is the latent heat of vapourization, ρc_p is the volumetric heat capacity, γ is the psychrometric constant, e_s^* is the saturated vapour pressure at the evaporating front which is evaluated at the temperature of the saturated evaporation front (T_s^*), e_a is the air humidity at the atmospheric reference level (the lower boundary level in HIRLAM), r_{ae} is the atmospheric resistance beween the surface and the atmospheric reference level and r_s is the surface resistance. For a wet or densely vegetated soil, $T_s^*=T_s$, but for a dry soil, the effective source of water vapour is below the surface so that $T_s^*<T_s$. In this case (Boegh and Soegaard, 2002),

$$(T_s-T_s^*)=B(T_s-T_a) \qquad (3)$$

where $B=\rho c_p z_d(G/H)/(r_{ae}k_s)$ with H being the sensible heat flux, z_d is the thickness of the upper dry soil layer and k_s is the thermal conductivity of dry soil. Assuming G/H to be constant (ie. Berkowicz and Prahm, 1982), the factor B remains dependent on variations in z_d and r_{ae}. Because the transition from energy-limited to soil-limited evaporation is usually abrupt and accompanied by an increase in T_s (Amano and Salvucci, 1999), literature values of the maximum thickness of the upper dry soil layer (Yamanaka and Yonetani, 1999) is used to assess the factor B. For a sandy loam (80 % sand, 10 % silt, 10 % clay), B= 1.2 can be used as a proxy in Equation 3 for estimating T_s^* when (T_s-T_a) > 5 K (Boegh and Soegaard, 2002). For (T_s-T_a) <= 5 K, T_s and T_s^* are assumed to be equal.

The r_{ae} is calculated by

$$r_{ae}=\rho c_p[(T_s-T_a)+(e_s-e_a)/\gamma]/(R_n-G) \qquad (4)$$

and r_s is calculated as

$$r_s=r_{ae}(e_s^*-e_s)/(e_s-e_a) \qquad (5)$$

The vapour pressure at the surface (e_s) is estimated using an empirical expression (Boegh et al., 2002b),

$$e_s= A\Omega e_s^*+(1-\Omega)e_a \qquad (6)$$

where A=0.9 and $\Omega=(\Delta/\gamma+1)/(\Delta/\gamma+1+r_s/r_{ae})$ is the decoupling coefficient (Jarvis and McNaughton, 1986) (Δ is the slope of the temperature-saturation vapour pressure curve). High atmospheric turbulence facilitates a close coupling between the surface and the air (Ω→0) in which case $e_s \rightarrow e_a$ (Equation 6). In contrast, when Ω→1, there is a poor atmosphere-surface coupling which causes water vapour to accumulate at the surface, thus approaching Ae_s*. Equations 4, 5 and 6 are solved using Newton-Raphson iteration.

3 FIELD DATA

Atmospheric fluxes of latent and sensible heat were available for 3 experimental sites; ie. an agricultural region located in affinity to the Institute of Agricultural Sciences in Foulum, a beech forest (EUROFLUX site) located near Soroe which is close to the centre of the major island (Zealand) in Denmark, and a conifer forest which is located at an extensive sandy outwash plain close to the Western shoreline (Ulborg site). All flux measurements were recorded using the eddy covariance technique. Field measurements of global radiation, air temperature and air humidity were also made available for the study. Further description of field data is given by Boegh et al. (2002a).

4 RESULTS

4.1 Weather predictions

The predicted weather conditions at 12 GMT were used as proxies for the air temperature and air humidity at the time of satellite passage (12.30 – 15.00 GMT). The root mean square error (rmse) of the assessed (proxy) air temperature was 1.9 °C (Boegh et al., 2002a) which is lower than the rmse of 3-5 °C which have been reported for remote sensing based estimates of in situ air temperature (ie. Prince et al., 1998). Generally, the temperature predictions tended to be lower than the field measurements. This may well be explained by the difference between prediction level (approximately at 30 m height) and measurement level (a few meters above the canopy).
For the air humidity, the rmse is 204 Pa. This is comparative to the accuracy with which air humidity can be assessed using microwave remote sensing observations above the ocean (Schüssel et al., 1995). Remote sensing based estimation of air humidity in heterogeneous landscapes is not yet feasible (Czajkowski et al., 2002). Except for the Ulborg site in West Jylland, the HIRLAM predicted (proxy) air humidity tended to be underestimated.

4.2 Evapotranspiration rates

An example on the HIRLAM and satellite inputs for calculating the evapotranspiration rates is shown in Figures 1 and 2. Figure 1 shows the HIRLAM predicted air temperatures (degrees Celsius) and air humidities (g m^{-3}) for Denmark on 29th April 2000 at 12.00 GMT. Due to the encirclement by sea shorelines, there is a significant spatial variation in the weather conditions in Denmark. In particular, the effect of the sea breeze circulation system is responsible for the intrusion of cooler air temperatures along the shorelines. This effect is stronger on the shorelines located in the upwind direction (Eastern winds prevail on 29th April 2000). Inland, the air temperature is up to 3 degrees higher (Fig. 1). With respect to the air humidity, the larger values in the Southern part of the country agree with the presence of clouds in the satellite data (Fig. 2).
Figure 2 shows the surface temperature (degrees Celsius) and the net radiation (W m^{-2}) which are calculated on the basis of the satellite data. The surface temperature is generally highest in West Denmark because of the location of an extensive sandy outwashed plain in this part of the country. Because of a low surface albedo, the net radiation is also relatively high for this geomorphological unit.

Combining the weather predictions and the satellite data, it appears that the intrusion of cooler air temperature by the sea breeze circulation system increases the sensible heat flux and suppresses the evapotranspiration rates (Boegh et al., 2002a). The effect of cooler air temperature on the evapotranspiration rate is most pronounced in the Northern and Eastern parts of Denmark in Fig. 3 while, in South Denmark, the high atmospheric humidity also works to suppress the evapotranspiration rate. Because of the high surface temperatures of the drier sandy outwashed plain in West Jylland, the evapotranspiration rates are also lower in this part of the country. The spatial pattern of the calculated evapotranspiration rates at sea are governed mainly by the HIRLAM predicted air temperature.
The comparison between calculated and measured atmospheric heat fluxes in Foulum (agriculture), Sorø (beech forest) and Ulborg (conifer) disclosed a linear relationship with a rather large degree of scattering. The root mean square errors were found to be 67 W/m^2 and 80 W/m^2 for the latent and sensible heat fluxes, respectively (Boegh et al., 2002a). Improved accuracies in both the weather (proxied) predictions and the processed satellite image quality are warranted to advance the presented approach for calculating evapotranspiration rates at larger scale. In order to improve satellite data quality, spatially distributed information on atmospheric conditions should be allowed as inputs for the atmospheric correction of satellite (instead of single values representing all Denmark).

5 SUMMARY

The importance of using spatially distributed weather conditions for remote sensing based calculation of evapotranspiration rates at larger scale were testified,

and the benefits of using meteorological predictions by a regional weather forecast model for 1) atmospheric correction of satellite imagery and 2) calculation of evapotranspiration rates were highligthed.
The weather predictions at 12 GMT were found to be reasonable proxies for the atmospheric conditions at the time of satellite passage, and the feasibility of using HIRLAM predictions for the atmospheric correction of satellite imagery was encouraging. Therefore, the combination of the weather predictions and timeseries of atmospheric corrected satellite observations were useful for the calculation of evapotranspiration rates in Denmark. In Denmark, the sea breeze effect and the distinct (observed) surface properties of the sandy outwash plain in West Jutland had significant impact on the spatial distribution of evapotranspiration rates in Denmark. The scatter between predicted and measured evapotranspiration rates is expected to reduce with increased accuracies in both the weather predictions and the satellite observations.

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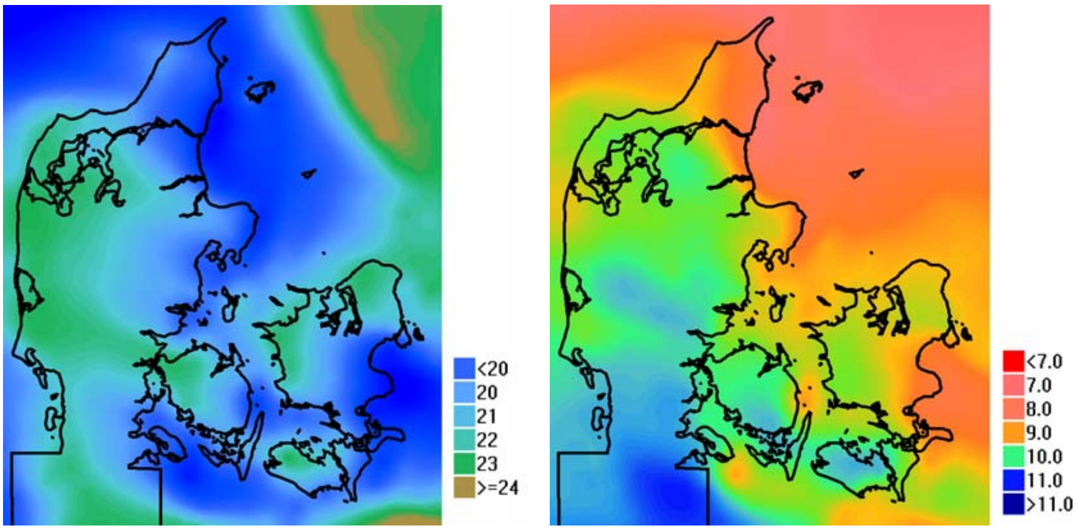

Fig. 1. HIRLAM predicted air temperature in degrees Celsius (left) and air humidity in g m^{-3} (right). Denmark, 29th April 2000 at 12.00 GMT.

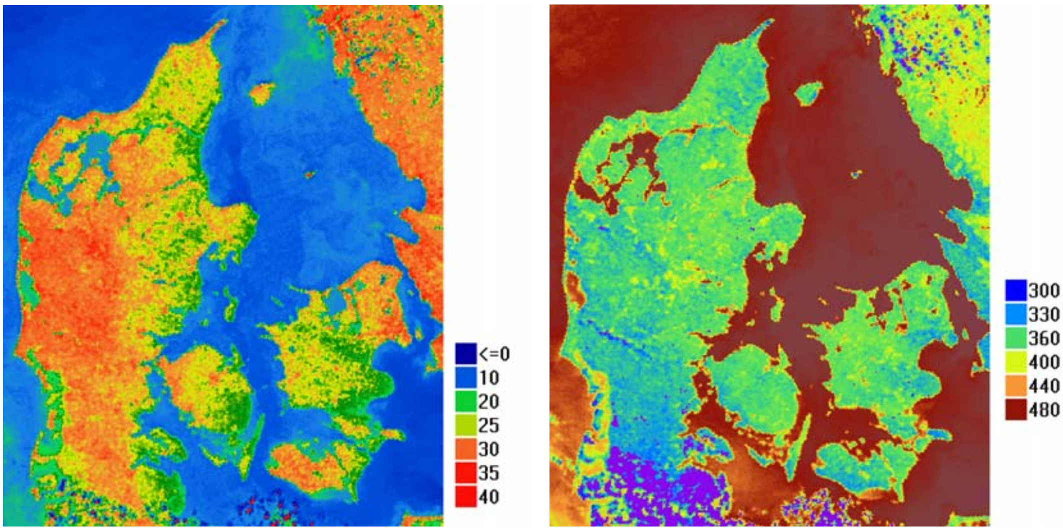

Fig. 2. Surface temperature in degrees Celsius (left) and net radiation in W m^{-2} (right) calculated from NOAA-AVHRR. Denmark, 29th April 2000 at 14.00 GMT. The dark blue dots in the lower part of the surface temperature image (left) illustrates very low temperatures due to cloud coverage.

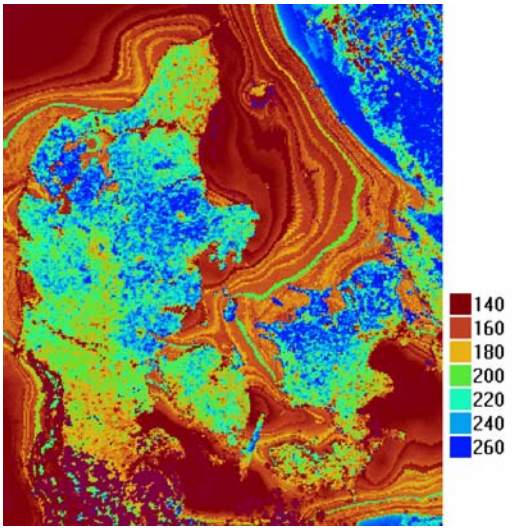

Fig. 3. Evapotranspiration rates in W m^{-2} calculated using HIRLAM weather predictions and NOAA-AVHRR observations. Denmark, 29th April 2000 at 14.00 GMT.