

Modelling the hydrological cycle of river basins using high resolution satellite information

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Abstract The results of modelling the hydrological cycle (HC) for river basins using satellite-based land surface temperature (*LST*) fields are presented. The HC model describes vertical moisture and heat transfer in the soil-plant-atmosphere system, as well as overland flow formation and flow in river networks, and allows one to estimate the effect of large- and small-scale land surface heterogeneities. It is applied to the Seim River basin with a watershed area of 7460 km² situated in the forest-steppe zone of Central Russia (Kursk Region). The satellite *LST* estimates were used to validate the model and to specify the initial conditions. The retrieval of *LST* fields from cloud-free NOAA-AVHRR data is performed using a technique which is based on the split-window method. It is shown that using satellite *LST* retrievals provides improved model results.

Key words hydrological cycle model; evapotranspiration; land surface temperature; AVHRR data; split-window algorithm; emissivity; vegetation index

INTRODUCTION

To estimate vertical water and heat fluxes adequately from large areas using the hydrological cycle (HC) model, it is necessary to couple various meteorological, soil, and vegetation data at appropriate spatial and temporal scales for modelling. In particular, uncertainties due to aggregation can be revealed using satellite estimates of land surface characteristics. Therefore, accurate knowledge of the land surface temperature, *LST*, and emissivity, *E*, as well as specification of other relevant parameters (such as leaf area index, *LAI*, albedo, and normalized difference vegetation index, *NDVI*) are of significant importance for the development and adjustment the HC models. One of the main objectives of this study was to develop the methodology for *LST* retrieval from National Oceanic and Atmospheric Administration Advance Very High Resolution Radiometer (NOAA-AVHRR) data and then use satellite-derived products either for validation or for updating the model (by tuning some relevant parameters) accounting for land surface heterogeneities.

HYDROLOGICAL MODEL AND *LST* RETRIEVAL SCHEME

The HC model (Kuchment *et al.*, 1996) consists of several blocks: a soil–vegetation–atmosphere transfer (SVAT) model, a runoff formation model and a procedure for averaging the HC components over the whole river basin area. The SVAT model includes the Richards equation with account for water movement in the root zone and the bulk mass transfer relationships (computing evaporation from soil surface and transpiration), as well as the heat transfer equation (determining soil surface temperature), and the heat balance equation (estimating foliage temperature and air humidity within the canopy). Standard daily meteorological measurements of air temperature, humidity and pressure, precipitation, wind speed and cloudiness are used in the model as input data. The *LST* is one of the model output products and is derived from the expression for the long-wave part of the radiation heat balance (Taconet *et al.*, 1986).

The runoff formation model contains a description of overland, subsurface, and river channel flow. It was used to estimate the water balance for the entire watershed as well as to calibrate and to verify the SVAT model.

To account for large-scale (mosaic) spatial land surface heterogeneities in the HC model the catchment area was divided into elementary plots with uniform soils, land use and vegetation. Four soil types and 10 land-use and vegetation species were identified in the catchment. Each soil is characterized by bulk density, porosity, maximum hygroscopicity, field capacity and saturated hydraulic conductivity. Vegetation heterogeneity is described by minimum stomatal resistance, *LAI* and roughness coefficient depending on plant height. The effect of small-scale (sub-grid) land surface heterogeneities was studied assuming the knowledge of statistical distributions for land surface characteristics within each elementary plot. The model was calibrated and verified using measurements of agrometeorological stations of the Kursk region and results of the international atmospheric–hydrological field experiments KUREX-88, KUREX-91 which were carried out in the Seim River basin (Kozodorov & Deering, 1998).

To summarize the problems of the *LST* derivation from NOAA-AVHRR measurements, the following factors should be taken into account: (a) atmospheric radiance attenuation effects caused by the absorption of the water vapour, aerosol and other gas components; (b) non-blackness of the land surface, i.e. the emissivity may be substantially lower than unity and may be imperfectly known for many generic surfaces; and (c) the difference between the *LST* and air temperature T_a near the surface may be significant.

In order to account for all of the above factors, we propose to apply the “local” version of the well-known split-window method (SWM) (e.g. Uspensky & Scherbina, 1998). This method allows one to retrieve *LST* from cloud-free AVHRR radiance measurements in split-window channels 4,5; moreover a reasonable accuracy level is achieved if the values of emissivities E_4 , E_5 for these channels are known. The problem of E_4 , E_5 specification is solved using the empirical relationship between emissivity and vegetation cover (Van de Griend & Owe, 1993).

Furthermore, it is very important to specify the effective surface temperature, $T_{s,eff}$ that accounts for the difference between the temperatures of the bare soil and the vegetation. According to Romanov & Gutman (1997), it may be defined as follows:

$$T_{s,\text{eff}} = B \cdot T_{\text{veg}} + (1 - B) \cdot T_g \approx B \cdot T_a + (1 - B) \cdot T_s \quad (1)$$

where T_{veg} and T_g are temperatures of vegetation and ground, respectively, and T_a and T_s are ground-based observations. The vegetation cover fraction B can be estimated using the vegetation index, $NDVI = (A2 - A1)/(A1 + A2)$ and the empirical relationship $B = 2(NDVI - 0.1)$, where $A1$ and $A2$ are reflectances measured in AVHRR channels 1 and 2.

RESULTS

Calculations of evapotranspiration, EV , infiltration, soil water content, and fluxes from the 1-m soil layer into deeper layers were carried out for each elementary plot and for the whole Seim River basin for 10 vegetation seasons with noticeable rainfall floods extracted from the 1974–1999 period. As an example, the values of EV for the period between the beginning of vegetation and rainfall flood (for 1997) are presented in Table 1. Mosaic spatial heterogeneity of the catchment characteristics appears to be highly noticeable, in particular values of EV for the same soils and various vegetation types differ by a factor of about 1.3–1.5. The dependence on the soil type is not so strong. The influence of soil and vegetation characteristics on infiltration and vertical soil moisture distribution is rather significant. These results were obtained by calcula-

Table 1 Calculated averaged evapotranspiration values (mm) for various soil types and vegetation for 18 April–27 June 1997.

Soil type/ Vegetation	Flood plains and meadow soil	Grey forest soil	Leached and podzolized chernozem	Ordinary and thick chernozem	Average
Winter wheat	-	140.6	163.4	167.4	162.9
Spring wheat	-	128.3	144.4	145.6	143.2
Buckwheat	-	131.5	146.2	149.9	146.6
White beet and potatoes	-	141.7	154.8	157.5	155.0
Maize	-	137.3	151.2	154.4	151.2
Grass	163.5	139.1	155.6	160.3	157.7
Pasture	188.3	163.8	178.8	181.1	179.7
Wood	173.6	156.7	169.1	169.1	168.7
Fallow	-	44.8	60.4	61.7	59.2
Urbanized area	-	128.9	147.5	149.2	145.7
Average	172.9	134.8	149.8	153.3	150.3

Table 2 Calculated vertical water fluxes averaged over the Seim River basin area for three consecutive periods in 1997.

Calculation period	Precipitation (mm)	EV (mm)	Infiltration (mm)	Water flux into deeper layer (mm)	Soil moisture content variations (mm)
18 April–27 June	178.3	150.3	138.3	109.2	-73.4
28 June–8 July	82.1	43.3	74.3	14.4	22.9
9–31 July	93.5	59.1	83.0	42.7	-9.3

27 June and 8 July are the beginning and the end of the summer rainfall flood, respectively; 31 July corresponds to corn cutting.

tion of the water balance components for the whole river basin and for all seasons under consideration. Vertical water fluxes calculated for the 1997 vegetation season are presented in Table 2.

The model sensitivity studies demonstrate that values of the HC components averaged over the entire river basin area are significantly affected by the saturated hydraulic conductivity K_o and the minimum stomatal resistance r_o . The effect of small-scale variations of K_o and r_o on the HC components was assessed assuming the gamma distribution for these parameters within each elementary plot. The coefficient of variation was assigned to be constant for the whole river basin area. It equals 1.3 for K_o and 1.0 for r_o . The values of the HC components were calculated and compared for a

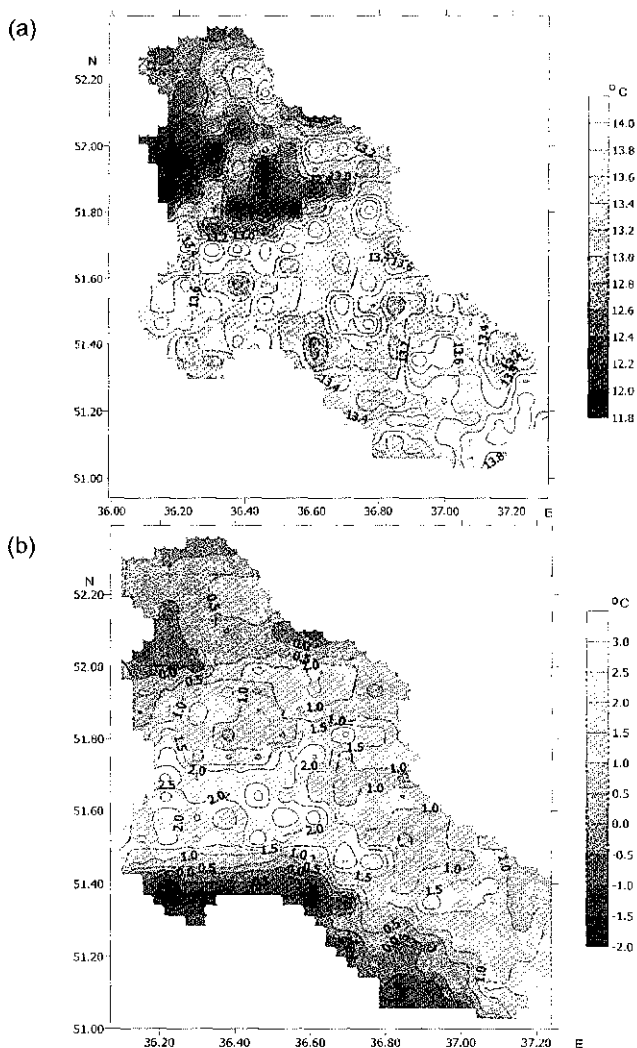


Fig. 1 (a) Effective land surface temperature map derived from NOAA-AVHRR-14 data and (b) LST difference map ($dT = T_{\text{eff}}(\text{sat}) - T_{\text{eff}}(\text{model})$) for the Seim River basin with spacing of ~ 10 km, 28 April 1997.

constant value of K_o within the elementary plot, and for the gamma distributed one, and averaged over the whole river basin area for the period from the beginning of vegetation until the corresponding rainfall flood. Variations were insignificant for EV (~1%) and considerable for soil moisture content (5–15% for different seasons) and infiltration (~10–15%). The random variation of r_o within the elementary plot provided considerable variation for EV (~15–20%) and for soil moisture content (~20–30%).

The LST retrieval algorithm development and testing has been accomplished using the ensemble of the NOAA-AVHRR-14 measurements and ground-based observations (20–40 daily fixed-term reports) that were collected over the Seim River basin area during the vegetation periods 1997–1999. Along with this, the standard hydrometeorological observations (including daily means T_s and T_a , as well as 10 days soil moisture measurements) were compiled during the same period and area from five agrometeorological stations.

As retrieved quantity the effective temperature $T_{s,eff}$ from equation (1) is used. Figure 1(a) shows an example of a satellite-derived LST map for one spring day in 1997. The error statistics analysis that was carried out for several days in April–July 1997 demonstrates acceptable agreement of satellite-derived T_s with observed $T_{s,eff}$. The cited standard error of T_s retrievals is in the range 1.5–2.5°C. According to the state of the art these results seem satisfactory.

Results of the comparison of remotely sensed and modelled LST are shown in Figs 1(b) and 2. As can be seen, the agreement is quite acceptable. The difference between the modelled and satellite-derived values of LST lies in the range of 1.5–2.5°C, which does not exceed the standard error of the AVHRR-based LST retrieval.

To study the model sensitivity with respect to vegetation and soil parameter variations (LAI , soil and vegetation albedos, A_s and A_v , and emissivities, E_s and E_v) the EV values relating to the LST variations were derived and analysed. The modelled EV values were compared with the results of evaporation soil tank measurements, and the LST values were verified using remotely sensed data. Both the LST and EV are very sensitive to variations of LAI , especially at the beginning of the vegetation period and for the moments of significant phytomass changes. In particular, the variation in the

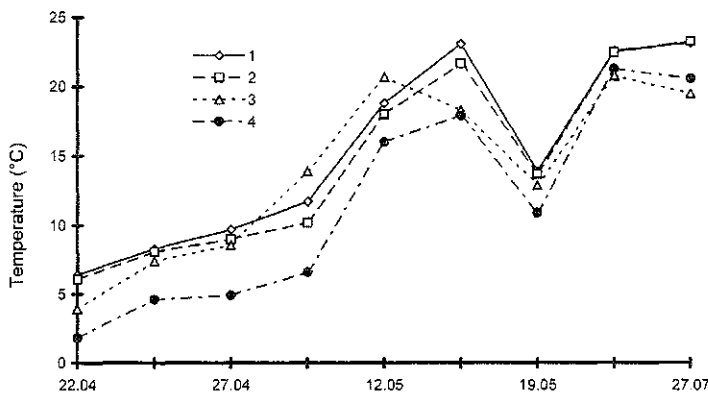


Fig. 2 Comparison of the LST : modelled for winter wheat (1), grass (2), and remotely sensed (3) at different dates 1997 for Petrinka agrometeorostation. (4: air temperature.)

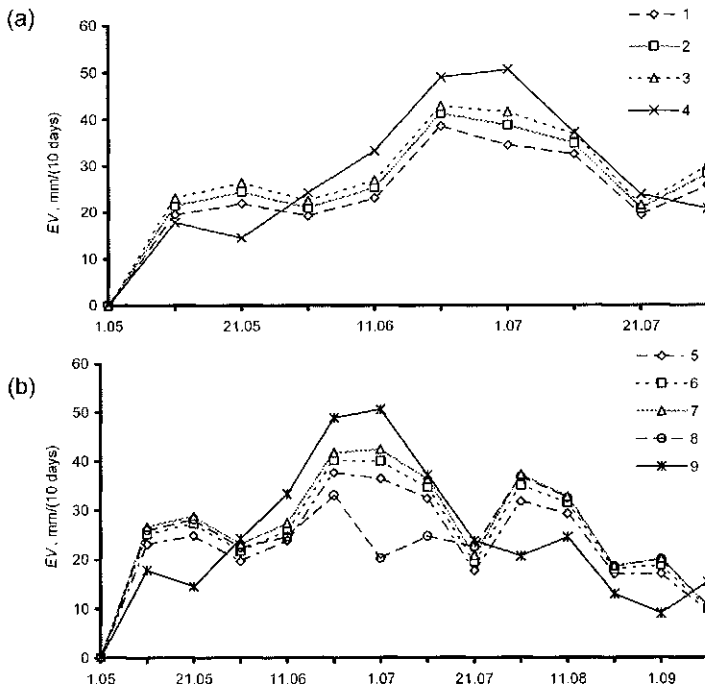


Fig. 3 Calculated evapotranspiration, EV , for 1997 vegetation season for: (a) winter wheat; and (b) grass at Petrinka agrometeorological station for different values of LAI_{max} : (1: 2.5; 2: 3.5; 3: 4.5; 5: 3.0; 6: 4.0; 7: 5.0; 8: $LAI_{max} = 4.5$ with 3 week shift cutting datum; 4 and 9: measured EV for water balance plot.)

LAI relative value by 0.1 induces changes in LST of about 1.0–1.2°C and changes in EV of about 2 mm per 10 days; the decrease in LAI from 0.8–1.0 to 0.1–0.2 after cutting causes an increase in LST of about 2.8–3.0°C and decrease in EV of about 8–10 mm per 10 days. The behaviour of EV during the vegetation season is displayed in Fig. 3. As can be seen, the difference between values of EV for grass plots before and after cutting may reach 15 mm per 10 days, and more. In view of such sensitivity, the LAI values need to be specified or corrected using satellite-derived LST values. The effects of A_s and A_v on EV and LST were also found to be significant. Variations of A_s by 0.2 caused changes in EV of about 1.2–2.3 mm per 10 days for different vegetation types and changes in LST of about 1.2–3.3°C; moreover, the latter values are greater than the satellite LST retrieval errors. Similarly, A_v variations induce 1.5–4.5 mm per 10 days changes in EV and 2–3 and even 5°C changes in LST in individual cases. The effects of E_s and E_v variations as on modelled EV and LST were found to be negligible.

Thus the specification of the HC model parameters using satellite LST data allows one to improve the feasibility of modelled vertical water and heat fluxes for each grid element and for the whole river basin.

Acknowledgement This work was carried out with support of the Russian Foundation of Basic Research—grant no. 00-05-64480.

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