ASSESSMENT OF THE SURFACE HEAT BUDGET COMPONENTS USING A MODEL OF THE SURFACE LAYER ENERGY BUDGET

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ABSTRACT

Verification of an energy-budget model of atmospheric boundary layer for calculation of the heat budget components was executed. A model was based on the Monin-Obukhov [1] similarity theory of the surface layer. All calculations were conducted on the basis of standard meteorological observations.

Keywords: atmospheric boundary layer, atmospheric surface layer, surface heat budget, radiation flows, turbulent flows

1. INTRODUCTION

The parameterization of physical processes of interaction between the atmosphere and the surface layer is one of the most important problems in the field of the development of atmospheric general circulation models. In the boundary layer models which are a compulsory part of global models, physical processes occurring at the boundary of "atmosphere-surface layer" are considered.

For solving this problem, the surface layer energy-budget model (SLEB) precisely redistributing the energy flows between components of the surface heat budget, is used [2, 3]. Using standard meteorological observations, the model identifies and elaborates the meso- and microscale processes of interactions.

The model allows:
1. To reveal relationships of spatial and temporal variability of components of the Earth’s radiation and heat budget in the meso- and microscale processes for series of many years of standard observations.
2. To reveal the features of the climatic fields of the turbulent fluxes of sensible and latent heat, momentum fluxes, heat flux in soil, surface air temperature and radiation budget components.
3. To assess the state of turbulent flow in surface and atmospheric boundary layers.

2. VERIFICATION OF THE SLEB MODEL

Before the SLEB meteorological model will be recommended for using in climate research, assessment of accuracy of calculation of the heat budget components must be done.

2.1. Radiant fluxes

The surface radiation budget determines the amount of energy that is expended to form heat fluxes on the interface between the surface and the atmosphere. Accurate assessment of the radiant flux ensures accurate assessment of the radiant energy that forms the flux of sensible and latent heat and heat flux in the soil.

For calculating components of the radiation budget standard meteorological observations for 2005 are used. Total radiation calculated by the SLEB model was compared with the data of actinometrical measurements, which were carried out on the weather station Odessa.

Figure 1 shows the correlation between the calculated \( Q_{\text{calc}} \) and measured \( Q_{\text{meas}} \) daily values of total short-wave radiation (\( N = 365 \) cases).
Figure 1. Correlation between the calculated (model) $Q_{calc}$ and observed (actinometrical measurement) $Q_{meas}$ values of daily sums of the total short-wave radiation (365 cases).

The figure shows that the calculated and measured sums of total radiation have relatively high correlations which equals $R = 0.93$ and the relative systematic errors of model data equals $\Delta Q = 2.5\%$.

Table 1 shows the daily sums of total radiation, which were monthly averaged. It can be seen that the difference between measured and calculated daily sums of total radiation $Q_{meas} - Q_{calc}$ does not exceed 1 MJ/m²/day and the relative systematic errors of model data varies between $\pm 5 - 7\%$, except February (14%). The average annual systematic errors of calculated daily sums are only 5%, and the average absolute difference is 0.5 MJ/m².

Table 2 shows calculated and observed monthly sums of total radiation. It can be seen, that the difference between measured and calculated monthly values of total radiation $Q_{meas} - Q_{calc}$ is 15-20 MJ/m²/month and the systematic errors of calculated monthly sums of total radiation, as well as for daily sums are 5%.

Figure 2 shows the annual variation of the calculated monthly averaged sums of shortwave radiation budget $Q_{(sb)}$ (dot line), measured $R_{meas}$ (red line) and calculated $R_{calc}$ (black line) of the total radiation budget.
The largest errors are fixed in the winter and the transitional seasons of the year with the maximum in February (36%). In these seasons abrupt changes in temperature and condition of soil occur: from snow cover period to freeze-thaw ones. On average systematic error of calculated data does not exceed 1% in a year.

Relative monthly averaged systematic error of total radiation budget \( \Delta R \), %, are larger than analogous systematic error of total radiation \( \Delta Q \), %, whereas the difference between measured and calculated values for the year is equal to \( (R_{\text{meas}} - R_{\text{calc}}) = -0.1 \).

Estimation of the effective radiation, which is obtained by indirect methods can sometimes be much more accurate than by direct methods, as the difference between the short-wave radiation and total budget includes the same error of calculation of their components. Therefore, on figure 2 the space between lines of short-wave and full radiation budget defines the annual changes of effective radiation in Odessa in 2005.

2.2. Land surface temperature

The land surface temperature and its temporal changes depend from the influx of radiant energy and the intensity of the flows, which expand radiant energy. To determine the part of energy, which will form one or other flow is difficult, because all of the flows being in the right side of the budget equation (1) are multi-dimensional functions of meteorological and geophysical variables, which are interconnected with each other in the interaction process in the system "surface-atmosphere".

\[
Q_{SW} + E_a = H(T_s, \zeta) + LE(T_s, \zeta) + G(T_s) + E_S(T_s)
\]  

(1)

Usually, such functions are not linear, and may even change sign, and therefore upset the budget in the surface energy budget equation.

The criterion of valid redistribution of energy between the flows \( H(T_s), LE(T_s), G(T_s) \) and is equality of the measured \( T_{SO} \) and calculated \( T_{sm} \) land surface temperature as the surface temperature is one of the basic physical quantities, the value of which depends on all the factors, which participate in the processes of transformation of radiant energy into heat.

If the surface temperature information is not required to calculate the short-wave \( Q_{SW} \) and long-wave \( E_a \) radiation flux, each of these fluxes of the budget equation, namely, the turbulent flow of sensible \( H \) and latent \( LE \) heat, the heat flux in the soil \( A \) and long-wave radiation from the surface \( E_S \), are defined with the surface temperature \( T_s \).

Comparison of the measured \( T_{SO} \) and calculated \( T_{sm} \) surface temperatures are shown in Table 3 and in Figures 3a, b.

<table>
<thead>
<tr>
<th>n/n</th>
<th>The statistic parameters</th>
<th>( T_{sm} )</th>
<th>( T_{SO} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Average</td>
<td>13.7</td>
<td>13.5</td>
</tr>
<tr>
<td>2</td>
<td>Max</td>
<td>59.7</td>
<td>58.9</td>
</tr>
<tr>
<td>3</td>
<td>Min</td>
<td>-20.0</td>
<td>-19.7</td>
</tr>
<tr>
<td>4</td>
<td>Standard deviation</td>
<td>13.4</td>
<td>13.8</td>
</tr>
</tbody>
</table>
Figure 3. Empirical distribution of the number of cases of calculated $T_{sm}$ (TSM) and measured $T_{s0}$ (TS0) soil temperatures for the warm (May-July) (a) and cold (November-February) period (b), Odessa, 2005

The accuracy of the surface temperature calculation by means of SLEB model is quite high. The average value of both measured and calculated temperature values differ by no more than one degree Celsius, for example, the average annual measured temperature is $T_{s0} = 13.5^\circ C$ and calculated temperature is $T_{sm} = 13.2^\circ C$. Close to each other and extreme values. So the maximum measured surface temperature in Odessa is $T_{s0,\text{max}} = 58.9^\circ C$ and calculated surface temperature is $T_{sm,\text{max}} = 59.7^\circ C$.

Figures 3 a, b shows the differential function of distribution of measured and calculated land surface temperatures. Temperature distributions completely coincide. And features of distribution law, which has two peaks, is coincided, too. These peaks separate two regimes of surface temperature condition for warm and cold season.

In the warm season the soil surface temperature varies from 5 to 60°C with a modal value which is equal to 22.5°C. In the cold season the soil surface temperature varies from -20.0 to 20.0°C with a modal value being about 5.4°C.

Figure 4 shows the correlation relationship between the calculated TSM and measured TS0 soil temperatures [4].

The angular regression coefficients are nearly equal to one. Correlation coefficient is at least $r = \sqrt{R^2} = 0.98$.

The greatest contribution (70%) of the total dispersion of surface temperature fluctuations are made with the radiation factor, wind speed change and soil moisture.

2.3. The heat flux in the soil

The heat flux in the soil in the model is estimated by the method proposed Hrgian [5]. Initial information for method are radiation budget $R$, soil surface temperature, volumetric heat capacity $C_{vol}$ and heat conductivity $\lambda$. 
Since temperature measurements at different depths are performed at meteorological stations, therefore it is possible to compare the calculated heat flow with measured flow. Heat conductivity \( \lambda \) was calculated for each of the observation.

The results of comparison are shown in Figure 5.

**Figure 5.** Comparison of measured \( A_{\text{meas}} \) and calculated \( A_{\text{meas}} \) heat fluxes in the soil, Odessa, 2005

The measured fluxes are greater than calculated ones by approximately 10%, which is not critical for the model estimates.

Table 4 shows the correlation between the heat flow, radiation budget, heat conductivity and soil moisture. There is a high correlation \( r = 0.9 \) between the calculated \( A_{\text{calc}} \) and measured \( A_{\text{meas}} \) flows from surface radiation budget. Correlation between the heat fluxes in the soil and the surface temperature is lower \( r \approx 0.7 \) as the volumetric moisture content of the soil practically does not depend on its temperature. Significant correlations between the fluxes and soil moisture \( r \approx 0.1 \), flux and heat conductivity are absent. The absence of such correlation does not mean the absence of physical interrelation between these values, as the heat flux in the soil increases with increasing soil moisture. The correlation between calculated and measured values of the heat flux in the soil is practically equal to one

\[ r = \sqrt{R^2} = 0.967. \]

<table>
<thead>
<tr>
<th>Option</th>
<th>( R )</th>
<th>( T_{\text{sm}} )</th>
<th>( A_{\text{calc}} )</th>
<th>( A_{\text{meas}} )</th>
<th>( W_g )</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>0.76</td>
<td>1.0</td>
<td>0.92</td>
<td>0.66</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.90</td>
<td>0.62</td>
<td>0.96</td>
<td>0.10</td>
<td>0.12</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>-0.10</td>
<td>-0.41</td>
<td>0.01</td>
<td>-0.12</td>
<td>-0.39</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Thus calculation of the heat flux in soil conducted with the SLEB model showed good agreement between the measured and calculated data. It confirms that the method reliably estimates two of four components in the heat budget equation.

The main factor on which the heat loss through evaporation depend, is, of course, the presence of moisture in the soil or on the vegetation elements. On the other hand, the main condition for reliable energy assessment, which will be spent on evaporation, is a physically correct parameterization of the processes being responsible for coming in moisture to the evaporating surface.

To make sure that the model reliably estimates the dependence of heat expenses for evaporation from soil moisture, consider how energy will redistribute between the turbulent flows with changes in soil moisture. Calculation is carried out for 5 categories of soil moisture from dry to over-wetted condition using a model. For the calculations the meteorological observations during the summer period (June-July) are used.

The results are shown in Figure 6 a,b. The flux of sensible heat for dry soil is directly proportional to the value of radiation budget. The regression dependence \( H = 0.9R - 2.5 \) has an angle coefficient which is equal to one, i.e., almost 90% of radiant energy absorbed by the surface, is spent on the sensible heat flow, and the remaining small part on the heat flow to the dry soil.

With increasing soil moisture sensible flux decreases, as most of the radiant energy are expended on the evaporation of water and when the soil becomes overwetted one sensible flow even changes sign (Figure 6a).
The relationship of the turbulent latent heat flow 
\( LE = f(R, W_s) \) from moistening the soil is the mirror image of the relationship 
\( H = f(R, W_s) \) (Fig. 7b). Under high moistening the soil a half of the radiant energy is spent on evaporation and the rest, 20-30%, is directed in the increasing heat flow to the wetted soil. Under decreasing the soil moisture heat expenditure on evaporation are reduced in 5-6 times, but evaporation does not stop as there is the water vapor in the soil at any level of moistening (usual southern chernozem).

![Figure 6. Relationship of turbulent fluxes of sensible and latent heat from the radiation budget and soil moisture](image)

### Table 5. Averaged values of the turbulent sensible and latent heat fluxes, the soil surface temperature (TSM), the Bowen number, \( Bo = H/LE \) and the ratio of the flow into the soil to the radiation budget \( A/R \)

<table>
<thead>
<tr>
<th>Categories of soil moisture</th>
<th>H, W/m²</th>
<th>LE, W/m²</th>
<th>TSM, °C</th>
<th>Bo=H/LE</th>
<th>A/R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very dry</td>
<td>320.76</td>
<td>0.00</td>
<td>49.7</td>
<td>-</td>
<td>0.038</td>
</tr>
<tr>
<td>Dry</td>
<td>307.5</td>
<td>14.7</td>
<td>42.3</td>
<td>20.84</td>
<td>0.04</td>
</tr>
<tr>
<td>Poorly wetted</td>
<td>283.2</td>
<td>41.1</td>
<td>41.0</td>
<td>6.88</td>
<td>0.06</td>
</tr>
<tr>
<td>Moderately wetted</td>
<td>232.2</td>
<td>93.0</td>
<td>38.2</td>
<td>2.50</td>
<td>0.1</td>
</tr>
<tr>
<td>Heavily wetted</td>
<td>151.1</td>
<td>166.5</td>
<td>33.5</td>
<td>0.91</td>
<td>0.21</td>
</tr>
<tr>
<td>Overwetted</td>
<td>74.0</td>
<td>229.9</td>
<td>28.6</td>
<td>0.32</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Medium loam. daily averaged values</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very dry</td>
<td>184.3</td>
<td>0.00</td>
<td>30.9</td>
<td>-</td>
<td>0.07</td>
</tr>
<tr>
<td>Dry</td>
<td>158.2</td>
<td>27.2</td>
<td>29.6</td>
<td>5.81</td>
<td>0.10</td>
</tr>
<tr>
<td>Poorly wetted</td>
<td>120.0</td>
<td>42.0</td>
<td>28.0</td>
<td>2.86</td>
<td>0.14</td>
</tr>
<tr>
<td>Moderately wetted</td>
<td>81.2</td>
<td>98.3</td>
<td>25.3</td>
<td>0.83</td>
<td>0.23</td>
</tr>
<tr>
<td>Heavily wetted</td>
<td>35.5</td>
<td>133.8</td>
<td>22.5</td>
<td>0.27</td>
<td>0.34</td>
</tr>
<tr>
<td>Overwetted</td>
<td>4.5</td>
<td>148.4</td>
<td>20.2</td>
<td>0.03</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>Heavy loam. daily averaged values</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very dry</td>
<td>205.5</td>
<td>0.00</td>
<td>31.5</td>
<td>-</td>
<td>0.051</td>
</tr>
<tr>
<td>Dry</td>
<td>173.3</td>
<td>33.7</td>
<td>30.0</td>
<td>5.14</td>
<td>0.08</td>
</tr>
<tr>
<td>Poorly wetted</td>
<td>135.7</td>
<td>69.1</td>
<td>28.0</td>
<td>1.96</td>
<td>0.14</td>
</tr>
<tr>
<td>Moderately wetted</td>
<td>77.9</td>
<td>114.3</td>
<td>24.9</td>
<td>0.68</td>
<td>0.25</td>
</tr>
<tr>
<td>Heavily wetted</td>
<td>25.3</td>
<td>146.2</td>
<td>21.7</td>
<td>0.17</td>
<td>0.39</td>
</tr>
<tr>
<td>Overwetted</td>
<td>8.2</td>
<td>155.6</td>
<td>20.5</td>
<td>0.05</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Figure 7. "Convergence" of surface heat budget for two versions for heat budget equation, namely, blue and black line for formula (2), the yellow and black line for formula (3). Odessa, 2005

Table 5 shows the averaged values of turbulent sensible and latent heat fluxes during the period in question for three soil types. Under changing the soil moisture, the both Bowen number and the surface temperature are changing. The highest temperature (50°C) is observed in dry sand. Temperature loamy soil is almost the same. The table also shows the change of ratio of the soil flux to the radiation budget $A/R$, depending on the soil moisture. All calculated values are in good agreement with various experimental data [5].

Figure 7 shows the annual variation of "convergence" of surface energy budget, which is carried out by the solution of surface energy budget equation, i.e., equality of inflows and outflows of energy. The balance closure was checked for two versions of heat budget equation:

$$Q_{SW} + E_a - A = H + LE + E_s,$$  \hspace{1cm} (2)

$$R - A = H + LE.$$  \hspace{1cm} (3)

Verification "equality" of the left and right side of energy budget equation is conducted with energy budget criterion (BC)

$$BC = \frac{Q_{CVI} + E_a - G(T_{si})}{H(T_s) + LE(T_s) + E_s(T_{si})}.$$  \hspace{1cm} (4)

If the conditional inequality $0.975 \leq BC \leq 1.025$ holds with an accuracy 2.5%, handling recursive functions to the functions containing a surface temperature is terminated. The figure shows that the sum of the left (black lines) and right (blue or yellow line) side of equation is equal.

3. CONCLUSIONS

Model reliably assesses the components of the heat budget and can be used in studies of long-term changes in energy processes in the system "atmosphere - surface".

REFERENCES


