

The Science Behind CAU's Energy Balance Module

Jessica Paxton¹, Dr. Randal Mandock²

¹Millersville University, Millersville, PA 17551 ²Clark Atlanta University, Atlanta GA 30314
Research Experience for Undergraduates: Summer 2004, Clark Atlanta University

Introduction

The Earth System Science Program (ESSP) at Clark Atlanta University (CAU) has designed a module based upon lectures and laboratory assignments, quizzes and examinations, and projects used in the Physics 445 course at CAU: *Introduction to Micrometeorology*.

Micrometeorology is the study of atmospheric processes with time scales from milliseconds to hours and spatial scales from millimeters to kilometers. Examples of the processes include evaporation, sensible heat transport, thermal conduction into the ground, turbulent diffusion of scalars in the atmospheric boundary layer, radiative heating and cooling of thin layers of atmosphere near the ground, and others. .

A graphical user interface (GUI) has been developed which is used to model each of the components (net radiation, sensible and latent heat fluxes, ground heat flux, storage, anthropomorphic and residual) necessary to understand the partitioning of energy at the air/land and air/sea interfaces. The energy balance diagram consists of sky elements (sun, moon, clouds), a line representing the air/land or air/sea interface and arrows which indicate magnitude and direction of each of the energy fluxes. Storage components are represented as boxes when present.

The energy balance model has been applied to numerous (33 at present) scenarios which vary by (1) climate or microclimate, (2) day or night, (3) cloud cover, (4) land or water surface, and (5) freezing or non-freezing air temperatures. Upon completion, the module will be available in two levels of rigor: (1) an elementary level (Level I) and (2) an advanced level (Level II). In the Level I module, only fixed arrow lengths (e.g., zero, ¼, ½, ¾, 1) will be available to express flux magnitude. This allows a qualitative illustration of the energy balance components. The Level II module will require the student to calculate arrow magnitudes and directions from diffusion, evaporation, radiative transfer, source strength, and energy storage equations.

Objective

The objective of this project is to develop an interactive module which will introduce and supplement studies of the local energy balance of the earth/atmosphere system. This module is composed of interactive scenarios as well as quizzes to stress effective learning of the material.

Calculations

The sign convention used in CAU's Local Energy Balance Module is based upon S. Pal Arya's text *Introduction to Micrometeorology**. The module begins with a welcome screen that explains Arya's sign convention. Throughout the module all radiative fluxes are positive when directed toward the surface and negative when directed away from the surface. Non-radiative fluxes are positive when directed away from the surface, and negative when directed toward the surface.

This module consists of 8 groups and 33 scenarios. The are as follows:

- Bare Soil
- Short Grass Canopy
- Thick Forest Canopy
- Desert
- Oasis
- Urban Canopy
- Pacific Ocean
- Arctic Ice Pack

In general terms, the following equation describes the energy balance of a system in terms of a heat budget:

$$R_N = H + H_L + H_G$$

where

- R_N = net radiation
- H = sensible heat flux
- H_L = latent heat flux
- H_G = ground heat flux

This general form of the equation does not take into account a canopy layer.

To begin the partitioning of fluxes, net radiation needs to be determined. Roland B. Stull's text *An Introduction to Boundary Layer Meteorology* works through the process of calculating R_N in the following manner:

$$R_N = K_{S\uparrow} + K_{S\downarrow} + I_{\uparrow} + I_{\downarrow}$$

where

- $K_{S\uparrow}$ = downwelling shortwave radiation
- $K_{S\downarrow}$ = upwelling shortwave radiation
- I_{\uparrow} = downwelling longwave radiation
- I_{\downarrow} = upwelling longwave radiation

Net radiation is based upon specifications set in each of the scenarios. Cloud cover, time of day, time of year, latitude and longitude are parameters necessary to complete the calculations. The following equations are necessary to obtain the net radiation at the surface:

$$d_s = F_i \left[\cos \frac{2p(d-d_i)}{d_y} \right]$$

This equation determines the sun declination angle based upon the day of year and time of day.

$$\sin(?) = \sin(F) \cdot \sin(d_s) - \cos(F) \cdot \cos(d_s) \cdot \cos \left(\frac{p \cdot t_{UTC} - ?}{12} \right)$$

This equation determines the angle above the local horizon for the time of interest. Degrees latitude and longitude are positive when in degrees west and north, respectively.

Cloud cover is an important factor because it determines how much of the sun's energy passes through the atmosphere to the surface. High, , middle, , and low, , cloud cover are recorded in fraction form and placed into the following equation to determine the sky transmissivity:

$$T_K = (0.6 + 0.2\sin(?)) \cdot (1 - 0.4d_{CH}) \cdot (1 - 0.7d_{CM}) \cdot (1 - 0.4d_{CL})$$

These equations are combined to determine the total downwelling shortwave radiation.

$$K_{S\downarrow} = S \cdot T_K \cdot \sin(?)$$

In order to determine such values, many constituents would need to be provided. To cut down on the complexity of the module, these values will be given after being gleaned from various sources, such as the rooftop of the Earth Systems Science Program at CAU, the Automated Environmental Monitoring Network (AEMN), and the NOAA Global Energy and Water Cycle Experiment (GEWEX).

After net radiation is given, it is easy to work backwards to determine the portioning of longwave and shortwave radiation.

Another constituent that is given is the surface albedo. Such values include:

- Bare soil = 0.30
- Grassland = 0.20
- Forest = 0.14
- Cool water = 0.07
- Warm water = 0.08

- Ice = 0.80
- Urban areas = 0.07
- Desert = 0.37

From here, the Bowen Ratio is used to determine the partitioning of the fluxes into sensible and latent heat fluxes. The Bowen ratio is the ratio of sensible heat to latent heat and is defined as

$$\beta = \frac{H}{H_L}$$

The Bowen ratio will also be given and is defined as

- Semi-arid regions ~ 5
- Grasslands and forests ~ 0.5
- Irrigated orchards or grass ~ 0.2
- Oceans ~ 0.1
- Oasis < 0

Latent heat fluxes are dependent upon evapotranspiration, and sometimes using the Bowen ratio is not as accurate as other equations. One such example of a more accurate approach is taken from Deardorff 1978 where he uses evaporation rates from the foliage as well as the shading factor of the vegetation to change the net radiation equation.

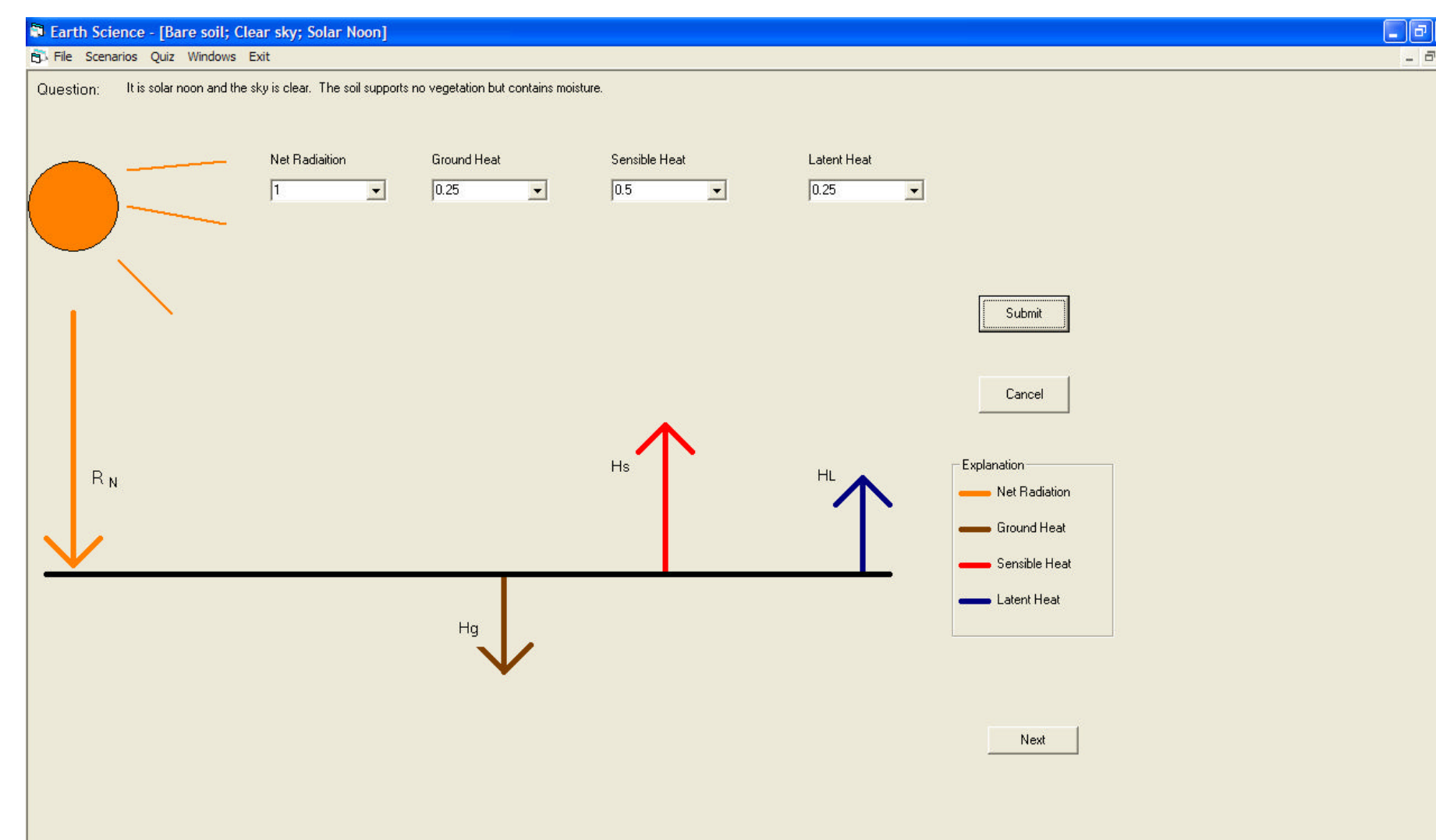
When R_N , H, H_L are known, it is easy to figure out the amount that goes into the ground. This is done by simply plugging the numbers into the equation and solving for H_G .

So far, this only gives the basic components to determine the energy balance for a bare soil scenario. When different components of the scenarios are added in (i.e., grass, trees, buildings), then a heat storage term, ΔH , comes into play. Additional terms are added in as well for different scenarios, especially urban areas. These terms are anthropogenic effects and advection.

Module level one is designed for undergraduates. It makes use of the basic knowledge of the radiative transfer equations to approximate the flux ratios by choosing an arrow magnitude and direction representing each of the fluxes. After each group is completed, there is a short multiple choice quiz to test the comprehension of the energy balance of the scenario group.

Module level two is designed for upper-classmen undergraduates and graduate students. It allows for the use the previous equations to complete the scenario, then input to check accuracy.

An example of a module screen is shown below.



Future Work

Currently under development is the Level II module. This module will include a GUI similar to that of the Level I module; however, exact numerical answers are needed to display the arrows correctly.

Beginning in the Fall '04 semester, the module will be introduced as an online instruction tool that will be incorporated into CAU physics and science education courses, available through the campus server. A procedure will be added to automatically score the answers and deliver correct answers upon demand. Feedback from both professors and students will be a fundamental online assessment tool.

Once all improvements have been made to the CD ROM version as well as the online version, CD ROMs will be offered to partnering institutions in Talladega, Alabama and Atlanta, Georgia. The institution may then duplicate and distribute the CDs to their students. The online module will also be accessible to the partnering institution. From here, any additional corrections will be made and the revised versions will be redistributed.

The module will leave the realm of the theoretical when real meteorological observations are incorporated. These observations will come from primarily three sources: (1) meteorological observations from the ESSP's rooftop laboratory, (2) Georgia Automated Environmental Monitoring Network (AEMN) website, and (3) NOAA Global Energy and Water Cycle Experiment (GEWEX) website.

Conclusion

The Local Energy Balance Module has been designed to assist students to learn the basics of energy conservation: energy that flows into a layer must balance the energy that flows out of a layer; any unbalance constitutes a flux convergence or divergence. The module will consist of two levels of rigor: (1) an introductory level and (2) an advanced level. It is required to modify diagrams correctly to demonstrate the transfer of energy through the earth/atmosphere system by shifting the direction and adjusting the magnitude of arrows. For further emphasis, quizzes between each group of scenarios and at the end of the program are available. This module is expected to enhance the science and science education courses at CAU.

Acknowledgements

Dr. Gerald Grams, Dr. Lucia Lu, Mr. Steve Fischer, Miss Omolara Fayanjuola, Miss Brenda Chee Wah

Earth System Science Program, Clark Atlanta University

National Oceanic and Atmospheric Administration Grant # NA030AR4810132.

National Science Foundation Grant # ATM-0139649

Universities Space Research Association Grant #NAG5-12434 Subagreement #05107-08

Reference

- Arya, S. Pal. [Introduction to Micrometeorology](#). 2nd ed. San Diego: Academic Press, 2001.
- Stull, Roland B. [An Introduction to Boundary Layer Meteorology](#). The Netherlands: Kluwer Academic Publishers, 2003.
- Deardorff, J.W., 1978: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *Journal of Geophysical Research*, 83 C4, 1889-1903