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## Surface Energy Balance of the Danube Region

### Assessment of changes between 1961-1990 and 1991-2020 using General Systems Theory and Climatic Energy Balance Diagram

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#### Abstract

The surface of the Earth is heated by solar radiation (shortwave radiation) passing through the atmosphere. The air near the earth's surface is heated from below using this energy converting the shortwave radiation to other forms. According to the law of conservation of energy, the incoming and outgoing energies are equal. Continents are warming faster than the global average warming as published in an IPCC 2019 report. These facts encourage us to examine energy transport processes and their changes applying Ludwig von Bertalanffy's General System Theory. The input of the system is net shortwave radiation and the outputs are distributing this energy via different processes after transformation (thermal radiation, sensible heat and latent heat).

Major terms of this surface energy distribution system are compared in the Danube Region in two thirty-year periods. The energy input to the system has increased, resulting in an increase on the output side as well. If we use the evaporation fraction as an indicator to evaluate the performance of the distribution process, we can see that the efficiency of the distribution process – illustrated by the Climatic Energy Balance Diagram – is roughly the same. However, this is not enough to remove the increased energy from the surface: both latent heat and sensible heat have increased.

If we decompose the energy increase between the two periods into components on the output side, another problem becomes visible. The excess energy no longer leaves the surface in the form of evaporation at the same rate as before, but at a smaller rate, and the proportion of energy converted into sensible heat increases. In summer the availability of water for evaporative cooling becomes a problem. The role of plants and transpiration is being appreciated, a paradigm shift is needed. They provide the most important environmental services.

**Keywords:** Surface Energy Balance; General Systems Theory; Climatic Energy Balance Diagram; Latent Heat; Sensible Heat, Evaporative Cooling

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#### 1. Introduction

The surface of the Earth is heated by solar radiation (short-wave radiation) passing through the atmosphere. This is the main energy source for life on Earth. This incoming energy is partially reflected back and the remaining part is converted into other forms of energy. The air near the earth's surface is heated from below. Data published by the IPCC in 2019 shows that the air over land is warming faster than the average warming of the Earth's atmosphere (IPCC 2019). This

suggests that something is happening differently on land than over the oceans, which cover most of the Earth's surface.

The aim of the study is to examine the land surface as a complex system, determine its function, and identify its main subsystems and processes. General Systems Theory seems to be an effective tool for analysis (Bertalanffy 1968, Báder 2023). Too much energy is just as harmful to life as too little, so understanding the role of the subsystems becomes key for maintaining a sustainable environment. Note: The topic of work focuses on the Earth's surface, choosing the temperate Danube region as a case study.

## 2. Material and method

According to the law of conservation of energy, in a state of equilibrium, the incoming and outgoing energies of the system are equal. The inextricably linked atmospheric and hydrological cycles together with the vegetation form an inseparable climatic energy transport and distribution system on the continents. The structure and core functions of this system can be identified by applying General Systems Theory.

Fig. 1a shows the energy balance model of vegetated land (Ryplová et al. 2024), this model is used to determine the key subsystems. Incoming shortwave (solar) radiation ( $R_s\downarrow$ ) is partially reflected in the same form ( $R_s\uparrow$ ). This net shortwave radiation is considered as energy input to the surface. Some of the energy, after being converted into heat, leaves the surface as long-wave radiation ( $R_nL$ ). The "rest" of the energy stays at or near the surface, and is called net radiation ( $R_n$ ). Most of the net radiation is converted into latent heat of evaporation (LE) or sensible heat that warms the air (H). A small fraction of solar energy (no more than 1%) is bound by photosynthesis into biomass (P) and heats the biomass of the vegetation (J). Another part of the energy heats the ground (G = ground heat flux) during warm seasons, but during cold periods it gives this energy back.

Considering the total amount of shortwave energy reaching the surface, we could interpret  $R_s\downarrow$  as input, and all other terms as output (eqv. 1). This is the interpretation on Fig 1a.:

$$Input = R_s \downarrow = R_s \uparrow + R_nL + (LE + H + J + P + G) = Output \quad (1)$$

Note: net radiation terms (all the terms that are converted on the surface to other forms of energy) are shown in the bracket:  $R_n = LE + H + J + P + G$

Another option is to consider net shortwave radiation on the input side, and all the other terms on the output side (eqv. 2). In the later part of the study, this interpretation was selected for analysis applying the General Systems Theory. A simplification was used, where the smaller terms J, P and G are not shown separately, but are included in the H term:

$$Input = R_s \downarrow - R_s \uparrow = R_nL + R_n = R_nL + LE + H = Output \quad (2)$$

Data used in this study are from the ECMWF ERA5-Land reanalysis database (Muñoz-Sabater, 2019) with spatial resolution of  $0.1^\circ \times 0.1^\circ$  (approximately  $9 \text{ km} \times 11 \text{ km}$  in the study area). Monthly averaged data for the Danube basin were downloaded between  $8.0^\circ - 29.9^\circ$  E longitudes and  $42.0^\circ - 50.3^\circ$  N latitudes (a  $84 \times 221$  grid matrix for each month and each parameter). ERA5-Land "ssr" parameter represents net shortwave radiation: Incoming solar radiation ( $R_s\downarrow$ ) less reflected ( $R_s\uparrow$ ). Short- and long-wave radiation parameters ("ssr" and "str") were used to calculate net radiation ( $R_n = \text{ssr} + \text{str}$ ). The evapotranspiration ("e") variable was used for LE. Sensible heat (H) was calculated as  $H = R_n - LE$ , so this component of the energy balance equation includes all other smaller items (photosynthesis, ground heat flux and heating the biomass). All flux measurement units were converted to water-depth equivalents via the latent heat of vaporization (2,48 MJ / kg). One kg of water represents a unit mm water depth over one  $\text{m}^2$ . The slight dependence of the latent heat of vaporization on temperature was not considered.

The efficiency and effectiveness of the natural processes cooling the surface can be examined using a simple Climatic Energy Balance Diagram (CEBD), showing the ratio of latent and sensible heat compared to the energy available at the surface:  $LE/R_n$  respectively  $H/R_n$  (Báder 2025a). Long-wave thermal radiation is not considered in CEBD, as it is not directly available for use on the surface, the focus is on the level of the  $R_n$  energy and the split between latent and sensible heat ( $LE$  and  $H$ ).

Fig. 1b shows the monthly averages of the major terms over a thirty-year period (the smaller terms are embedded in sensible heat). The yellow envelope curve shows the energy input per month, and the stacked bars show the output energy terms (Báder 2025b).

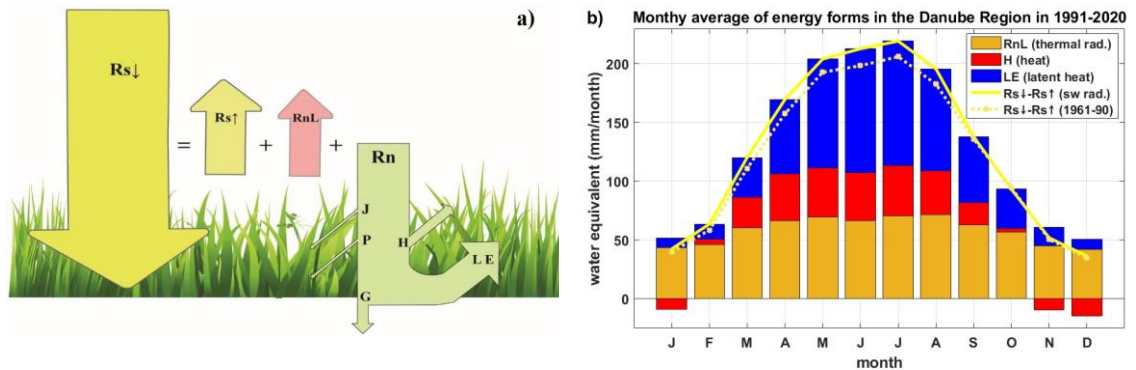


Figure 1: Main components of the surface energy distribution process: shortwave solar radiation ( $R_{s\downarrow}$ ) reflected solar radiation ( $R_{s\uparrow}$ ), net thermal radiation ( $R_{nL}$ ), net radiation ( $R_n$ ), latent heat of evaporation ( $LE$ ), sensible heat ( $H$ ), photosynthesis into biomass ( $P$ ), heating of the biomass of vegetation ( $J$ ) Fig 1a (left): The surface energy balance diagram (source: Ryplová et al. 2022).

Fig 1b (right): 30-year monthly average of energy forms in the Danube Region (ERA5-Land data). The yellow envelope curve shows the incoming energy, the bars show the outgoing energy (Báder 2025b)

### 3. Results

A high-level model of the surface energy distribution process can be formulated based on the principles of General Systems Theory. The model aims to help better understand climate and weather processes and their phenomena. Some definitions and boundary conditions need to be given at the beginning of the model development.

The subject of the System is the surface of the Earth. The name of the system can be Surface Energy Distributions System. The Function of the System is energy distribution; managing the transfer and transformation of energies on the surface to maintain energy balance. Key parts of a system are inputs and outputs. These are the interfaces of the system to the outside world. Our System consists of one input (net shortwave radiation,  $R_s$ ) and three outputs (Latent heat, sensible heat and net thermal radiation). Within the System, there are Subsystems that perform transformations. In this simple example we eliminate the details how shortwave energy turns into heat, how thermal emission transfers energy, how water evaporates, how plant transpiration works etc. Covering any further details (such as feedbacks, regulation processes, etc.) exceeds the scope of this work. This simple setup is still sufficient to make observation and draw some conclusions.

Fig. 2a shows the segmentation of annual values of net radiation ( $R_n$ ) on the Climatic Energy Balance Diagram (CEBD). The two components of  $R_n$ , latent heat of evaporation ( $LE$ ) and sensible heat ( $H$ ), are the axes of the diagram. The values of  $LE$  and  $H$  determine a working point for each year, which always falls on the  $R_n$  diagonal line of that year. The lines representing annual  $R_n$  values for the period 1961–1990 are marked in blue, and the lines for the period 1991–2020 are marked in yellow. The thirty-year averages are in bold blue and red respectively, where the lines projected onto the axes also show the ET and H values.

The figure clearly shows that with the increase in net radiation, both latent and sensible heat values increased. The shift of the 30-year average working point from 1961-1990 to 1991-2020 is

indicated by a red arrow (Báder 2025a). The figure also illustrates that if we want to maintain the sensible heat value even if net radiation increases (keep it under control and prevent warming), then the latent heat value would have to be significantly increased. This is indicated by the vertical grey arrow. Similarly, if we want to maintain the latent heat value (not allowing evaporation to increase), then the sensible heat value will increase significantly. This is indicated by the horizontal grey arrow.

Fig 2b shows the monthly distribution of changes in the outgoing energy terms between the two thirty-year meteorological normal periods. The orange, red and blue stacked bars indicate changes in thermal radiation (RnL), sensible heat (H) and latent heat (LE) respectively. The shift in proportions is striking: of the main energies leaving the surface, the rate of evaporation has noticeably decreased in the summer months, while the rate of sensible heat has increased.

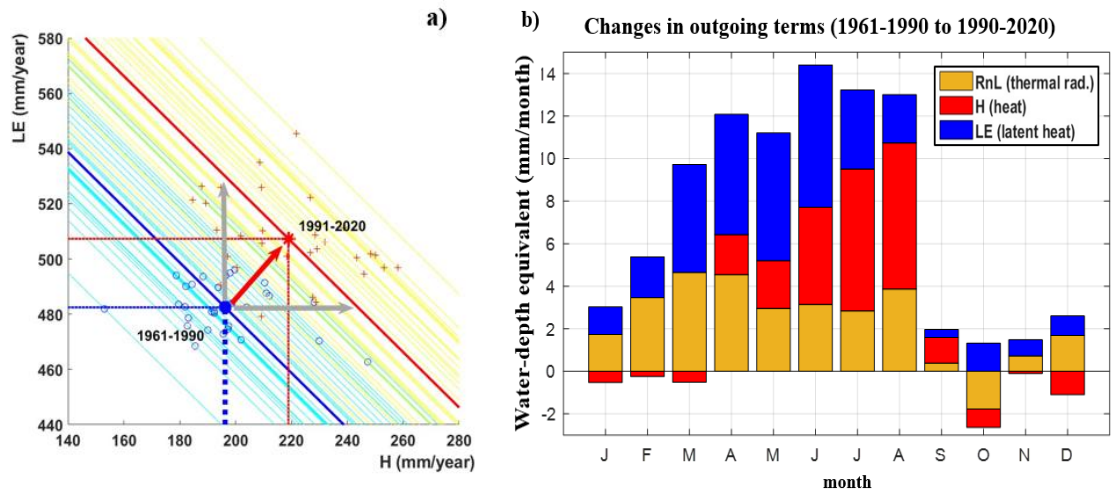


Figure 2: Changes in the main outgoing components of the surface energy distribution system of the Danube Region (ERA5-Land data). Unit of measure is in mm of water-depth equivalent.

Fig 2a (left): Detail of the Climatic Energy Balance Diagram. The shift of the 30-year average working point from 1961-1990 to 1991-2020 is indicated by a red arrow (Báder 2025a).

Fig 2b (right) Segmentation of the changes in the monthly average outgoing energy forms comparing periods 1961-1990 and 1991-2020 (Báder 2025b):.

#### 4. Conclusions and discussion

Examining the process of atmospheric warming from a systems perspective, we started from the energy distribution processes of the earth's surface, where the warming of air around us begins. A simple model based on the General Systems Theory helps to segment and visualize the main elements of the system consisting of one input (net shortwave radiation) and three outputs (latent heat, sensible heat and net thermal radiation). The monthly share of these terms to energy distribution and their changes become tangible.

Although average evaporation has increased somewhat in the Danube region, the sensible heat has also increased. The conditions and indicators of the surface energy distribution system have changed during 30 years: the availability of water for evaporative cooling in summer becomes a problem. The current amount of evaporation in the Danube basin is not sufficient to remove the incoming excess energy. This situation suggests that there is not enough (cooling) water left in the landscape for the hottest period.

Climate change has an impact on water balance on continents. Hydrological processes play an important role on life on Earth, they supply plants with water. Plants can effectively participate in maintaining environmental conditions through their evaporative cooling effect (Ellison et al. 2024). "Plants ensure water circulation on the Earth, retain water in the landscape and influence significantly our climate" (Ryplová et al. 2024). In efforts to combat climate change, sustainable

solutions therefore also require that sufficient water reaches the landscape and remains available for the warmer seasons at all points in the landscape.

Saving water in the landscape referring to climate change is a contra productive approach, a self-destructing trap of civilizations. The efficiency and effectiveness of the surface energy distribution process is eroding with each drop of water which we leave out of the small water circle. Paradigm shift is needed. The abundant water supply of thriving biologically active surfaces supports dynamic self-regulatory processes.

Further research is needed to clarify the feedback mechanisms and regulatory effects – such as cloudiness, surface temperature, moisture recycling, biologically active surfaces, etc. – whose deterioration causes the tipping points leading to significant changes. But above all, people should appreciate natural processes much more. Modern man, having moved away from nature, feels less the importance of natural cycles, considers them a given. Water is not only a resource for human activities, but a fundamental condition for life on Earth. The extraordinary physical properties of water, its specific heat and heat of vaporization, make it essential in itself for maintaining a habitable terrestrial environment.

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