Energy Balance Closure Analysis Based on Eddy Covariance Flux Tower Observations

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Abstract

Energy balance closure is a fundamental principle in micrometeorology, ensuring that all energy fluxes within an ecosystem are properly accounted for. The eddy covariance (EC) method, widely used for measuring land – atmosphere exchanges of energy and mass, often exhibits energy closure discrepancies, particularly across different timescales. This study investigates ecological year energy closure using flux tower data collected over multiple years at Skukuza, Kruger National Park. Energy closure was assessed using the fundamental balance equation $R_n - G = H + LE$, where net radiation (R_n), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE) were analysed across different timescales. Radiation shields and soil heat flux sensors were employed to capture variations in energy fluxes. Statistical analysis of multiple ecological years revealed that energy closure varies significantly with seasons, with wetter years exhibiting lower energy imbalances compared to drier years.

The findings indicate that energy closure improves with increased turbulence (frictional velocity) but remains incomplete due to measurement uncertainties, sensor sampling scales, and ecosystem heterogeneities. Results highlight a persistent energy closure gap, with an average closure of approximately 80%, consistent with other EC studies globally. The study underscores the challenges in achieving full energy balance closure and emphasizes the need for improved sensor calibration, turbulence parameterization, and data correction techniques. These insights are crucial for refining EC methodologies and enhancing the accuracy of land-atmosphere energy exchange assessment in semi-arid ecosystems.

1 Introduction

Measurements of Eddy Covariance (EC) flux are essential for estimating the flow of energy, water, and carbon between ecosystems and the atmosphere. They support the validation of climate models and the evaluation of ecosystem responses to climate change. EC data enhance estimates of the global carbon budget and facilitate remote sensing applications.

This approach improves our knowledge of land-atmosphere interactions and informs climate policy. Evapotranspiration (ET) includes evaporation and transpiration, which is the process by which water moves from the soil to the atmosphere through plants, evaporation from the capillary fringe of the groundwater table, and water evaporation from the soil surface and water bodies into the atmosphere. When plants absorb liquid water from the soil and release water vapour into the atmosphere, this process is known as transpiration. Because ET connects the energy, carbon, and water cycles, it has a major impact on the interactions between the atmosphere and the terrestrial surface. Particularly in arid and semiarid habitats, where it may be responsible for almost the whole surface water budget, ET controls the energy and water balance of the Earth's hydrosphere, atmosphere, and biosphere (Fisher et al., 2017; Oki and Kanae, 2006; Morillas et al., 2013).

Because warmer air carries more water vapour that is transpired by plants and evaporates from the soil surface, warming of the land and atmosphere fundamentally alters ET. This causes changes in the seasonality and patterns of precipitation and soil moisture, which alter the equilibrium of the water cycle's constituent elements and could lead to severe weather conditions like floods. Landslides, wildfires, and droughts. For instance, drought conditions are made worse in arid and semiarid regions when there is little precipitation. Determining agricultural and ecosystem water use, detecting drought, quantifying land-atmosphere feedback, evaluating the impact of human activity on the water cycle and surface energy budget, and validating and refining the parameterization of land surface models all depend on accurate ET estimation (Purdy et al., 2018). Generally, the water balance or energy balance is used to estimate ET.

2 Methodology

2.1 The study Area- The Skukuza Eddy Covariance flux tower, Kruger National Park

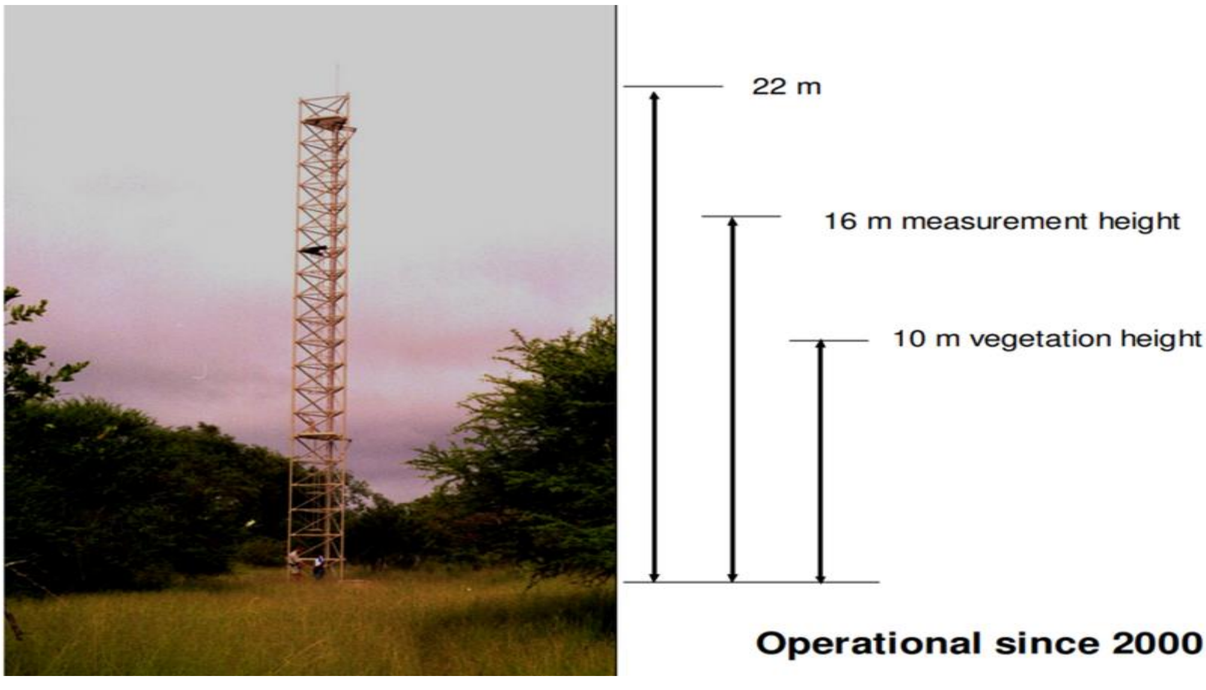

Figure 1. The Skukuza FLUXNET tower. Located in the Kruger National Park, within the semi-arid savanna biome. Vegetation: Combretum and Acacia trees. Climate: Distinct wet and dry seasons. Continuous EC measurements since 2000.

Table 1: The Skukuza covariance flux tower parameters and instrumentation.

Measurement Type	Instrument(s)
Gas fluxes	LI-7500 infrared gas analyzer
Wind & heat fluxes	Gill Wind Master Pro & Campbell CSAT3 ultrasonic anemometers
Radiation	Kipp & Zonen albedometers and pyrgeometer
Micrometeors	Air temperature, humidity, rain gauge
Soil moisture	CS615L TDR probes at multiple depths
Data handling	Data loggers, tower-top computers, periodic on-site visits

2.2 Energy Balance Closure

Energy Balance Closure (EBC) refers to how well the measured incoming and outgoing energy components at the Earth's surface balance out, according to the law of conservation of energy. Energy balance closure is a fundamental principle in micrometeorology, ensuring that all energy fluxes within an ecosystem are properly accounted for.

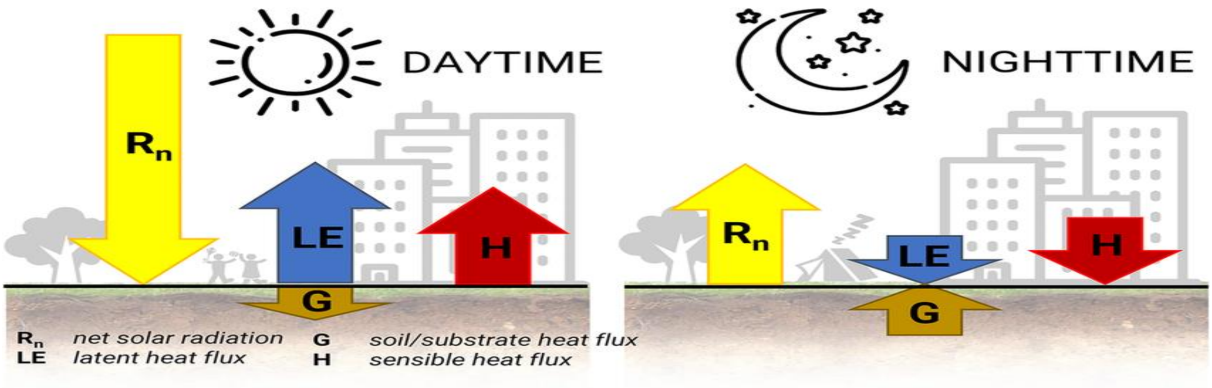

Figure 2. Illustration of a typical surface energy balance with key flux components based on the daytime and nighttime fluxes.

Energy closure was assessed using the fundamental balance equation:

$$R_n - G = H + LE \quad (1)$$

Where net radiation (R_n), soil heat flux (G), sensible heat flux (H), and latent heat flux (LE).

Lack of energy balance closure undermines the reliability of micrometeorological measurements, especially in flux networks like FLUXNET, and makes it harder to use the data confidently for research, agriculture, and climate Modeling. The problem of not having Energy Balance Closure (EBC) arises when the measured energy inputs and outputs at the land surface do not balance, meaning:

$Rn - G \neq H + LE$ - no closure (2)

$Rn - G = H + LE$ - energy closure (3)

This form is often used to assess the partitioning of net radiation into turbulent heat fluxes only.

$Rn - G = H + LE + G$ - Surface energy closure (4)

$Rn = H + LE$ - simplified form of the surface energy balance equation. When the time scale is long enough (daily or longer), so G ≈0

3 Results and Discussion

Energy balance closure is a quality check for eddy covariance data used in climate, hydrology, and ecosystem studies. Poor closure could indicate incomplete or biased measurements, reducing confidence in results like evapotranspiration rates or carbon fluxes.

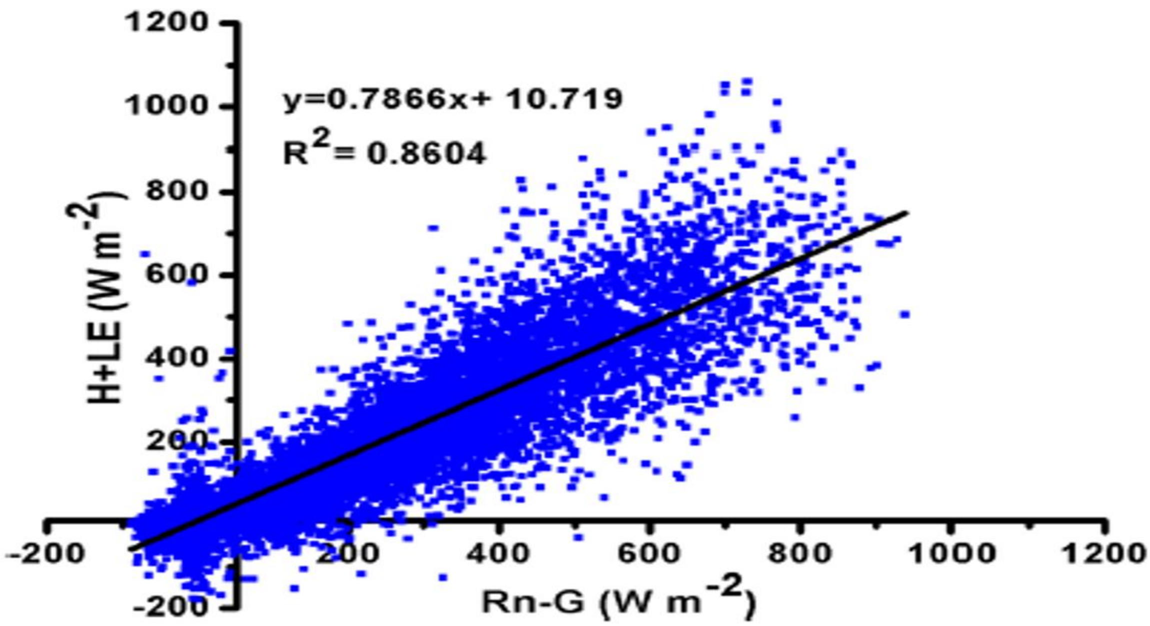

Figure 3. Energy balance closure for the entire study period, considering half-hourly averaged data.

In a study conducted in the semi-evergreen primary forest of Kaziranga National Park, Assam, India (Feb 2016–Jan 2017), energy balance closure reached up to 83% under neutral conditions. Latent heat flux dominated, showing strong evapotranspiration and reliable surface energy flux measurements.

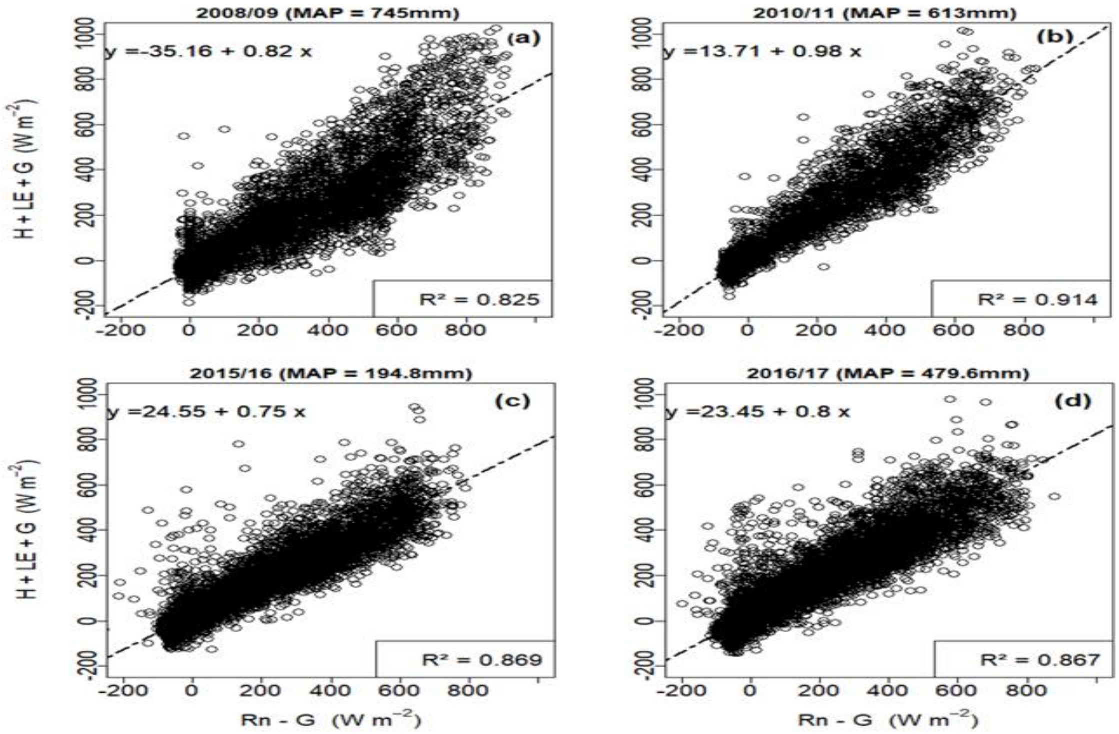

Figure 4. Combined plot of Monthly Energy Balance Closure (EBC) for Skukuza, Kruger National Park, across four years.

In Figure 4(a), 2008/09 Mean Annual Precipitation (MAP) = 745 mm, $R^2 = 0.825$; Moderate correlation with a slope of 0.75 indicates ~74% of net radiation is converted into turbulent fluxes, but energy imbalance remains. Figure 4(b) 2010/11 (MAP = 613 mm), $R^2 = 0.914$; Very strong correlation with near-unity slope (0.96) suggests best energy balance closure and accurate turbulent energy partitioning. figure 4(c) 2015/16 (MAP = 194.8 mm), $R^2 = 0.8404$; Strong correlation with a slope of 0.869 under dry conditions shows good energy relationship despite reduced rainfall and lower energy closure. Figure 4(d) 2016/17 (MAP = 479.6 mm), $R^2 = 0.867$. High correlation with a slope of 0.78 reflects improved energy balance under moderate rainfall, but still underestimates full closure.

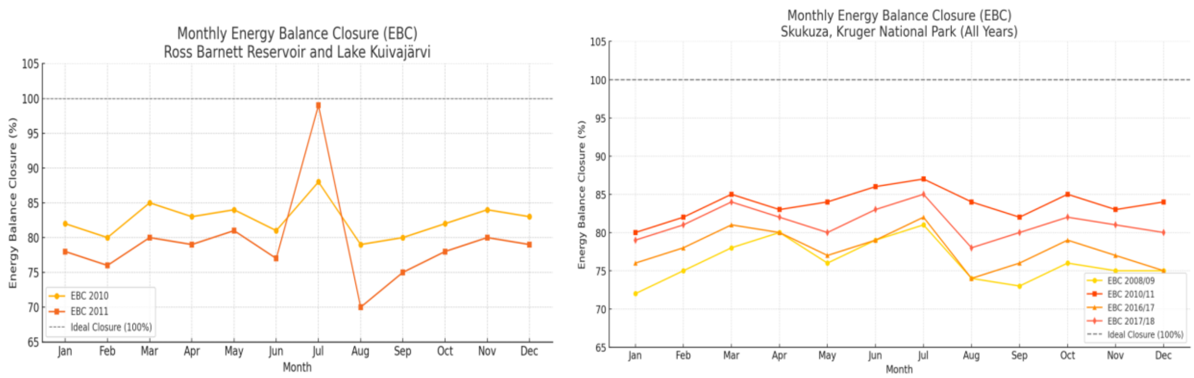

Figure 5. Comparison of the Combined plot of Monthly Energy Balance Closure (EBC) for Skukuza, Kruger National Park across four years and Monthly Energy Balance Closure (EBC) for 2010 and 2011 at Ross Barnett Reservoir and Lake Kuivajärvi.

Observations show seasonal variation, with July–October often having higher EBCs. 2010/11 and 2017/18 had the highest closure values (up to ~87%). All values are below the ideal 100% closure, which is typical due to surface heterogeneity, instrument limitations, and energy storage terms. In another similar review of studies at Ross Barnett Reservoir and Lake Kuivajärvi showed monthly energy balance closure ranged from 70% to 99%, with annual averages of 83% (2010) and 79% (2011). The effective transfer coefficients for heat are aligned with previous lake studies, validating the use of bulk transfer models (Nordbo et al., 2011; Xiao et al., 2013).

Table 2: Summary of Skukuza findings of results

Year	R^2	Slope	Interpretation	Reason for Energy Non-Closure
2008/09	0.739	0.75	Moderate EBC; ~74% of Rn partitioned to H+LE	Surface heterogeneity, storage terms (G, biomass), instrument error
2010/11	0.874	0.96	Best EBC; strong coupling of Rn to H+LE	Minimal imbalance; underestimation of minor energy sinks
2015/16	0.840	0.73	Good EBC despite drought; weak moisture fluxes	Sparse vegetation, reduced LE, soil moisture limitations
2016/17	0.836	0.78	High EBC; ~78% closure	Residual storage (G), unmeasured advection, canopy effects

Causes of unclosed energy balance

- Inaccurate Flux Estimates Eddy covariance (EC) systems may underestimate latent and/or sensible heat fluxes, especially under complex terrain or atmospheric conditions.
- Uncertainty in Evapotranspiration (ET)Latent heat flux (LE) is used to estimate ET. If the energy balance does not close, ET estimates may be wrong, affecting water resource management and climate modelling.
- Model Calibration Errors: Land surface and climate models rely on correct flux data. An unclosed energy balance can lead to biased model parameters or incorrect conclusions about surface processes.
- Misinterpretation of Ecosystem Function Energy imbalance may give false impressions of ecosystem productivity, stress, or water-use efficiency.
- Difficulty in Comparing Sites or Years Without closure, comparing flux data across sites or seasons becomes problematic because you cannot distinguish between true variation and instrumental or methodological errors.
- Data Correction Challenges Researchers often apply post-processing corrections (e.g., Bowen ratio energy balance closure, residual methods), which introduce assumptions and potential biases.

4 Conclusion

Study at Skukuza (Kruger National Park), shows energy balance closure ranged around 80% across years, with better closure during wet seasons. For example, 2010/11 showed improved closure compared to 2008/09, indicating seasonal and interannual variability in energy partitioning. Challenges were due to turbulence, sensor placement, and terrain. The suggestion is to integrate EC with remote sensing, upscaling and modelling. This study is highly relevant for improving the accuracy of climate models and understanding ecosystem responses to climate variability. It supports better water resource management, especially in arid and semi-arid regions facing increased climate stress. Enhancing energy balance measurements informs sustainable land-use planning and agricultural practices. Future studies can build on this data to advance remote sensing integration and climate adaptation strategies.

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