

The Flux You Say?

Comments on “The Integrated Carbon Observation System in Europe”

Andrew S. Kowalski

AFFILIATIONS: Kowalski—Departamento de Física Aplicada, Universidad de Granada, and Andalusian Institute for Earth System Research (IISTA-CEAMA), Granada, Spain

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Corresponding author: Andrew S. Kowalski, andyk@ugr.es

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Heiskanen et al. (2022) present the Integrated Carbon Observation System (ICOS) employing a familiar contraction—shortening “flux density” to “flux.” This shorthand is recognized in the American Meteorological Society (AMS) Glossary of Meteorology (American Meteorological Society 2022), and its use is widespread (e.g., Kowalski et al. 2021), convenient, and sometimes obviously desirable (or we would give names like “FLUXDENSITYNET” to grids of flux-density towers). But it also has its pitfalls, and ICOS, with its ambition to harmonize flux observations globally, may impede the advance of knowledge if it does not navigate them carefully. The abbreviation conflates derived quantities whose basic natures differ in important ways.

In meteorology (American Meteorological Society 2022), a flux (F) is a time rate of exchange of mass (kg s^{-1}), energy (W), substance amount (mol s^{-1}), or momentum (kg m s^{-2}). It has the same tensor properties as the quantity being exchanged; fluxes of mass, substance, and energy are scalars, while those of momentum are vectors. By contrast, a flux density (ϕ) defines a rate of exchange of these quantities through surfaces of unit area and with particular orientation. Thus, ϕ 's of mass ($\text{kg m}^{-2} \text{s}^{-1}$), substance ($\text{mol m}^{-2} \text{s}^{-1}$), and energy ($W \text{ m}^{-2}$) are vectors whose directions describe those of transport, while ϕ 's of momentum ($\text{kg m}^{-1} \text{s}^{-2}$) are second-order tensors describing directions of 1) the momentum being exchanged and 2) its transport. The units specified above also reveal that F and ϕ are dimensionally dissimilar—a key distinction in fluid dynamics—and related via a surface area that must be identified correctly.

A telling example regarding photosynthetically active radiation (PAR) is the relationship between surface area and the photon flux density (ϕ_p) and flux (F_p). Above an ecosystem, the vector ϕ_p describes the intensity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) and direction of a stream of spectrally confined photons that may determine plant productivity. Such influence is conditional because it also depends on ecosystem surface orientation relative to ϕ_p . The

luminous determinant of ecosystem photosynthesis is F_p ($\mu\text{mol s}^{-1}$), defined as the scalar product of two vectors,

$$F_p = \boldsymbol{\phi}_p \cdot (A_e \mathbf{n}_e), \quad (1)$$

where the ecosystem surface area has magnitude (A_e ; m^2) and direction described by its normal unit vector (\mathbf{n}_e). To be clear, $\boldsymbol{\phi}_p$ describes the sunshine, independent of any particular surface, whereas F_p describes sunshine interaction with a surface and is modulated by surface orientation. Instrument manufacturers claim, and many scientists have accepted (e.g., Kowalski et al. 2003), that PAR sensors such as photodiodes can measure $\boldsymbol{\phi}_p$. But simply scaling up the diode's flux to that of a unit surface of identical orientation (assuming sunshine homogeneity) yields only a lone component of the vector $\boldsymbol{\phi}_p$, and furthermore in a direction that may be inappropriate. If the PAR sensor and ecosystem are not parallel, then the measured flux systematically misrepresents the ecosystem flux.

A simplified depiction illustrates this with two ecosystems of equal area on either side of a hill, a grassland on the sunny side and a forest growing in the hill's shadow (Fig. 1). For simplicity, the sunshine is presumed to be predominantly direct, with negligible diffuse radiation. Both hillsides have 11° slopes like the ICOS ecosystem station Renon (Feigenwinter et al. 2010) and are exposed to the same $\boldsymbol{\phi}_p$, with a 45° solar zenith angle. However, when scaled to a unit surface and compared with what perfectly leveled sensors would measure ($|\boldsymbol{\phi}_p| \cos[45^\circ]$)—as specified by ICOS protocols (Carrara et al. 2018)—this geometry yields solar fluxes that are 17% greater on the grassland ($|\boldsymbol{\phi}_p| \cos[34^\circ]$), and 21% reduced on the forest ($|\boldsymbol{\phi}_p| \cos[56^\circ]$). The need to measure radiative fluxes with sensors that are aligned, not horizontally but parallel to the ecosystem surface, is easily overlooked when conflating F and $\boldsymbol{\phi}$.

The vector nature of flux densities is also relevant in eddy covariance (EC) data. Coordinate-system specification has been the subject of much research (McMillen

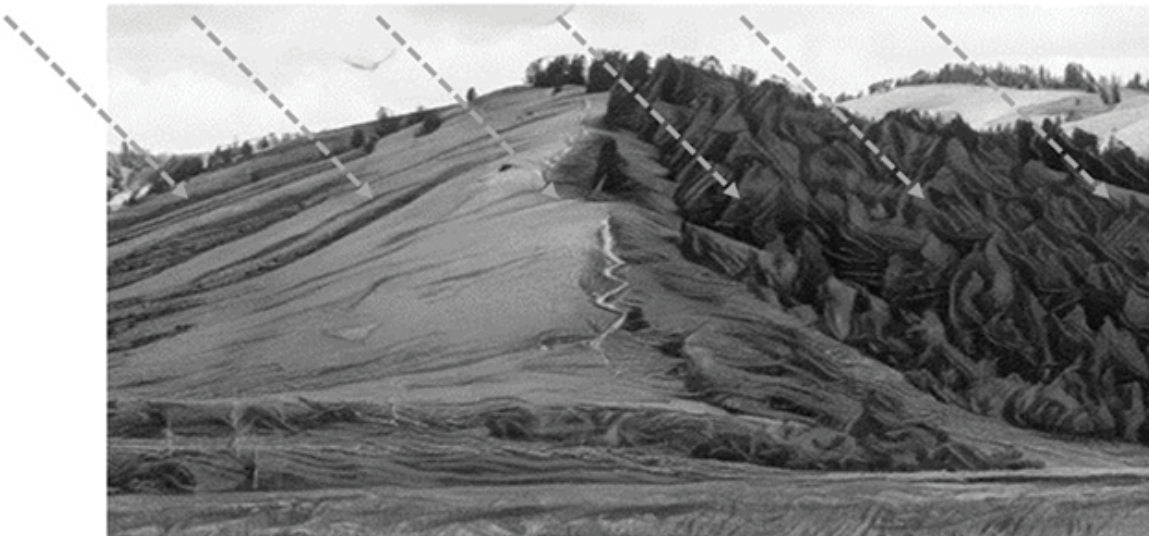


Fig. 1. Depiction of a hill with two ecosystems of equal surface area exposed to the same photosynthetic photon flux density ($\boldsymbol{\phi}_p$; dashed lines) but with distinct photosynthetic photon fluxes (F_p). The equatorward slope is a grassland, while the poleward side is a forest. Each hillside has an 11° slope, and the solar zenith angle is 45° . For simplicity, the solar azimuth is in the same plane as the normal vectors for the two hillside surfaces.

1988; Kowalski et al. 1997; Wilczak et al. 2001; Finnigan et al. 2003; Rannik et al. 2020) particularly regarding the CO₂ fluxes of sloping ecosystems. If the turbulent CO₂ flux density from EC takes the form $\boldsymbol{\phi} = \phi_x \mathbf{i} + \phi_y \mathbf{j} + \phi_z \mathbf{k}$, with coordinates defined by unit vectors \mathbf{i} (streamwise), \mathbf{j} (transverse), and \mathbf{k} (normal to the ecosystem), the primary interest is in the ϕ_z component, taken to represent the ecosystem flux per unit of surface area. The magnitudes of ϕ_x and ϕ_y are oft neglected; they make no appearance in ICOS protocols (Sabbatini et al. 2018) and generally are not reported, recorded, or made available in open-access data products. However, EC methodologies are not yet definitive, and scientists should remain open to the possibility that they may yet evolve. In this regard, one issue that has arisen recently is the possible entanglement of turbulent and nondiffusive transport processes due to methodological errors associated with “Reynolds averaging” (Kowalski et al. 2021). Given that nondiffusive CO₂ transport is predominantly in the \mathbf{i} direction (following coordinate rotation), excluding ϕ_x from data available at the ICOS portal inhibits the investigation of such possible entanglement within the ICOS dataset.

These examples demonstrate that, if at times it may be semantically acceptable to abbreviate “flux density” with “flux,” at other times it is worth the effort to state “flux density” and avoid errors that can arise when forgetting the distinctions between the two. It is sensible to record and report flux densities quantified using three-dimensional sonic anemometers as vectors. On the other hand, fluxes measured by single-surface radiation sensors should not be confused with vectors, and such sensors should be oriented with care to ensure that the measured flux corresponds to the flux of interest. For these reasons, it is recommended to change two entries in the Glossary of Meteorology (American Meteorological Society 2022) to the following:

- *Flux*: The time rate of exchange of some quantity, with the atmosphere usually energy (W; scalar), mass (kg s⁻¹; scalar, whether water vapor or other chemical species), or momentum (kg m s⁻²; vector).
- *Flux density*: The time rate of transport of some quantity crossing a plane surface of unit area with particular orientation, in the atmosphere usually energy (W m⁻²; vector), mass (kg m⁻² s⁻¹; vector, transport of water vapor or other chemical species), or momentum (kg m⁻¹ s⁻²; second-degree tensor). In radiation, the intensity and direction of solar radiation.

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