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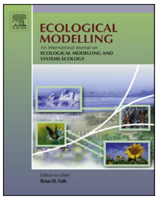

Assessing the global environmental sources driving the geobiosphere: A revised emergy baseline

Mark T. Brown[a,*], Sergio Ulgiati[b]

[a] Department of Environmental Engineering Sciences, University of Florida, United States
[b] Department of Sciences and Technologies, Parthenope University of Napoli & School of Environments Beijing Normal University, Beijing, China

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ABSTRACT

The empower that is derived from solar radiation, tidal momentum and geothermal sources drives the productive processes of the geobiosphere and is responsible for developing gradients of potential energy transformed into secondary energy and tertiary sources. In this paper we establish the geobiosphere emergy baseline (GEB) based on earlier methods proposed by Odum (2000) and refinements by Brown and Ulgiati (2010). After revising the solar exergy input and our previous interpretation of the sources and magnitudes of geothermal exergy, we compute a revised solar equivalent exergy and solar equivalence ratios (SERs) of geothermal and tidal inputs to the geobiosphere dynamic.

A Monte Carlo simulation that includes the revised solar exergy flow of geothermal inputs and uncertainty in the flows yields SERs of 26,300 seJ J^{-1} and 5500 seJ J^{-1} for tidal and geothermal sources respectively. The solar exergy remains 3.6 E+24 sej y^{-1}, while the solar equivalent exergy of tidal and geothermal sources were 3.1 E+24 seJ y^{-1}, and 5.4 E+24 seJ y^{-1} respectively, resulting in a GEB of 12.1 E+24 seJ y^{-1}.

1. Introduction

For several years more than one geobiosphere emergy baseline (GEB) has been promoted by various researchers (Odum, 2000; Campbell et al., 2005; Brown and Ulgiati, 2010) based on different quantification or inclusion of emergy sources driving the biosphere. The different GEB thus calculated were used by emergy practitioners resulting in different values of emergy indicators of products and processes, partially generating confusion and concern. After the Eighth Biennial Emergy Conference (January, 2014), the need for revisiting the procedures and assumptions used to compute the geobiosphere emergy baseline emerged very clearly as an urgent target to strengthen the emergy accounting method and remove sources of potential misunderstanding. The goal was to develop a synthesis document to clarify the baseline issue, potentially resulting in adoption of a single baseline (or baseline range). Several different approaches to the computations, carried out by a number of emergy practitioners, are likely to allow for accommodation of different perspectives and postulations related to integration of the three driving energies (solar, geothermal, and tidal momentum) into a single emergy baseline. Of course, given the significant uncertainty that exists in our understanding of the geobiosphere system as well as in the available data about global processes, we should not expect that each approach would yield the same baseline, but rather that results achieved through different procedures and assumptions may fall within an acceptable range of values showing the same order of magnitude. In so doing, a single agreed upon baseline could be selected to reflect a reconciliation of different perspectives within a scientifically sound uncertainty estimate.

When developing the emergy approach, H.T. Odum, at first, focused on solar radiation as the ultimate driving source of planetary dynamics and life on Earth (Odum, 1976). All calculations of resource convergence through planetary metabolism to yield "embodiment" factors (previously named transformities) were based on an estimate of the total solar radiation on Earth, after albedo was subtracted (Brown and Ulgiati, 2004). With the publication of Environmental Accounting (Odum, 1996) two more global sources were included as co-responsible of Earth phenomena, namely the gravitational potential energy of the Earth–Moon–Sun system (responsible for sea and earth tides and a portion of oceanic currents as well) and the heat flow from crustal weathering and erosion, radioactive decay in the mantle, and residual heat from the Earth's formation (primordial heat) in the Earth core (called deep heat). This solar budget was referred to as the solar emergy baseline and quantified as 9.44E+24 sej y^{-1}. Modeling the simultaneous

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* Corresponding author. Tel.: +1 352 3922424; fax: +1 352 3923624.
E-mail address: mtb@ufl.edu (M.T. Brown).

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support of these three energy sources yielded a new estimate of the biosphere baseline as 15.8E+24 sej y^{-1} (Odum, 2000) as the starting point for calculation of the transformities of solar radiation, heat crustal flow, and tide momentum. Finally, Brown and Ulgiati (2010) performed new calculations using the same driving energies, but based on updated estimates of Earth sources and their expression as available energy (exergy), according to Odum's definition of emergy (Odum, 1996), yielding a baseline of 15.2E+24 sej y^{-1}.

In earlier work, Campbell et al. (2005) suggested that more than one baseline is justified and proposed 9.26E+24 sej y^{-1} as an alternative to the baseline computed by Odum (2000). Also Campbell (2000) in another analysis suggested two baselines 9.26E+24 sej y^{-1} and 10.58 E24 sej y^{-1} for short and long period processes respectively. More recently Campbell et al. (2010) have argue that the 9.26E+24 sej y^{-1} baseline is the most appropriate because it assumes that only the sun and deep heat are responsible for generating geologic processes. Raugei (2013) proposed a scalar baseline where the three fundamental inputs of exergy to the geobiosphere (sunlight, tidal momentum, and geothermal) are kept separate at all times, not unlike the three independent axes of Cartesian space.

1.1. Conflicting baselines

Currently, the geobiosphere emergy baseline used in the emergy methodology is composed of the solar exergy received by Earth, geothermal exergy, and the exergy from dissipation of tidal momentum that results from the interaction of the earth, sun, moon system. From these three exergy sources the qualities of all other forms of exergy are computed. The conflicting baselines that have been proposed over the years have increased the difficulty of comparing results from one evaluation to another.

2. The geobiosphere emergy baseline (GEB)

The three main driving forces of sunlight, geothermal exergy and the dissipation of gravitational potential provide the total exergy (available energy, work potential) contribution to the geobiosphere.[1] These three driving sources are referred to as the *global tripartite* and are the primary sources of renewable exergy that support geobiosphere processes. By definition, the total exergy used up by a system process, expressed in common units, is the emergy of the final product or service (Odum, 1996). In order to represent tidal exergy and geothermal exergy on the same basis with solar exergy, we use a method of equivalence that expresses these two sources as solar equivalent exergy by means of appropriate *solar equivalence ratios* (SER). In so doing the three flows can be added to yield the geobiosphere emergy baseline (GEB).

When represented on the same solar basis, tidal and geothermal exergy are no longer actual exergy, but instead are *solar equivalent exergy*. The units of solar equivalent exergy are solar equivalent joules abbreviated seJ (note the capital J). Instead, all other emergy flows computed from the GEB (rain, wind, down to human made products) are expressed in solar emjoules, abbreviated sej (note the small j). The difference arises for consistency with the international energy and exergy nomenclature: according to International System of Units (S.I.: NIST, 2015) the word joule is never capitalized, but the abbreviation for the unit is capitalized (J); therefore, units of equivalent joules are abbreviated using a capital "J". On the other hand, emergy is no longer actual energy or exergy carried by a flow or item and cannot do further work or be degraded like exergy, for it is not measured using joule, but emjoule. The emjoule is the record of joules used in the past, thus the 'j' in the abbreviation for emjoule is not capitalized (sej).

In conclusion, we are suggesting the following convention. The exergy inflows of the tripartite are expressed in units called solar equivalent joules, abbreviated as seJ. This inflowing exergy is available to drive geobiosphere processes and its availability is "destroyed" as it is used up and assigned as emergy to secondary and tertiary renewable flows as well as to all the downstream chain of products. By definition, 1 seJ (solar equivalent exergy), when destroyed translates into 1 sej (solar emjoule); that is to say, one solar equivalent joule of inflowing exergy that drives the secondary, tertiary, etc. processes of the geobiosphere, when destroyed, becomes one solar emjoule, i.e. a record of the exergy destroyed. Mathematically, the conversion of units from seJ (solar equivalent exergy) to sej (emergy) is as follows:

$$X\,\text{seJ} \times \frac{1\,\text{sej}}{1\,\text{seJ}} = X\,\text{sej} \qquad (1)$$

where the quantitative amounts of flows (X) are derived from calculations.

2.1. The geobiosphere: a frame of reference

Interestingly, there is no standard definition of *geobiosphere* in the scientific literature. The *biosphere* is generally defined as the part of the earth's crust, waters, and atmosphere that supports life. *Geosphere* is the collective name for the lithosphere, the hydrosphere, the cryosphere, and the atmosphere. We therefore define the geobiosphere as "the ecological system that is the sum total of the living (biotic; including humans) components and non living (abiotic; including geologic, hydrologic and atmospheric processes) components of the Earth". The geobiosphere is the system where emergy gradients are generated and degraded, ultimately supporting a multiplicity of matter and energy transformations and storages on Earth.

2.2. Spatial boundary

We define the system boundaries of the geobiosphere to include Earth processes of the crust (to a depth of approximately 100 km) and the atmosphere (to a height of approximately 80 km) (see Brown and Ulgiati, 2010). In this way flows of available energy that cross this boundary are inputs to the geobiosphere.

When evaluating smaller areas of the Earth system, for example regional systems, or terrestrial ecosystems, it is appropriate to adjust the spatial boundaries to coincide with the temporal and spatial scales of system processes under study. For instance the input of available geothermal energy that affects surface processes within a region probably does not extend deeper than the deepest mines or oil wells. And the atmospheric input of available energy of wind generally does not need to extend higher than the atmospheric boundary layer taken as an average of approximately 1500 m (Garratt, 1992). If the study area is a single ecosystem (or agro-ecosystem) the lower boundary may only be the rooting depth. In all cases, when doing an emergy evaluation, it is absolutely necessary to specify the three-dimensional spatial boundaries of the investigated system.

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[1] While a concept put forth by Odum (1996), others have suggested that "all activity on Earth derives from four primary reservoirs of exergy that have existed since the formation of the solar system: fusible atoms in the Sun, fissionable atoms on Earth, the thermal energy of the Earth's interior, and the gravitational potential energy and relative kinetic energy of celestial bodies." (Hermann, 2006). Szargut (2007) describes the driving exergy as follows: Besides exergy losses derived from human activity, huge losses within the biosphere result from the irreversibility of natural phenomena "the absorption of solar radiation, the emission of thermal radiation, the irreversible heat transfer from inside the Earth to its surface and the braking of the planetary motion."

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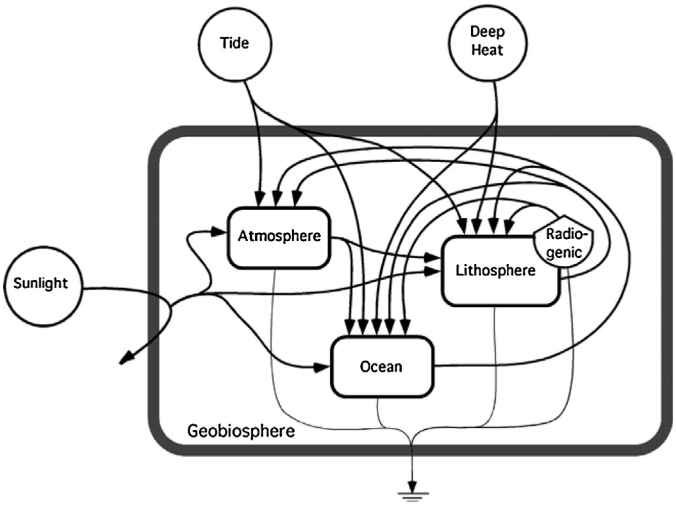

Fig. 1. Earth geobiosphere, a hierarchical web of components connected by flows of available energy, materials, and information that build potential energy and circulate materials.

2.3. *Temporal boundary*

A frame of reference for time is also important. When evaluating a product or service of the geobiosphere system, there must be a temporal frame of reference. In general, the temporal reference frame is related to the system of interest only and does not include all the evolutionary steps that may have gone before. In the emergy methodology, the timeframe is usually set by turnover time[2] of the system being evaluated. For many systems a time frame of one year is used. In evaluating the tripartite and the GEB, the temporal window is 1 year. For systems that have particular cycles, for instance forestry systems which provide a wood yield every 20 years, the time frame can be expressed as 20 years, but then it is often scaled to one year, by dividing all inputs and outputs over the 20 years by 20. Regardless of what time frame is used in an emergy analysis, the description of the system should include sufficient detail that the time domain is explicitly understood.

2.4. *Emergy flows of the geobiosphere*

The three renewable exergy inputs to the geobiosphere (Fig. 1) contribute to geologic, climatic, oceanic, and ecologic processes that are interconnected with flows of available energy and materials. In Fig. 1, the flows of available energy from air, land, and oceans interconnect these components, forming a mutually reinforcing web. Through these interconnecting pathways the main components of the geobiosphere cycle material and energy and each component receives inputs from and provides outputs to each of the others. After millions of years of self-organization,[3] the transformations of the driving energies by the atmosphere, ocean, and land are organized simultaneously to interact and contribute mutual reinforcements. This concept of mutual reinforcement is the basis for calculating unit emergy values (UEVs) for all the products of the geobiosphere, whether materials, energies, or information.

In our earlier paper (Brown and Ulgiati, 2010), the available energy of sunlight, tides and geothermal sources were evaluated based on the method first used by Odum (2000). Since Odum's evaluation in 2000, there had been considerable progress in measuring the solar constant and tidal momentum transferred to Earth yielding relatively precise estimates. However, the estimates of heat flow and the sources of that heat were still subject to relatively large uncertainty. In order to deal with this uncertainty, Brown and Ulgiati (2010) developed a Monte Carlo simulation of Odum's method of computing the transformities of the global tripartite that included all the uncertainty. The resulting transformities[4] were the median values from this Monte Carlo simulation. In the present paper we use the same Monte Carlo simulation with revised data based on our continued evaluation of the literature, especially related to the sources and magnitudes of earth's geothermal exergy.

3. Methods

3.1. *Brown and Ulgiati (2010) revisited*

We revisit the assumptions and computations of our earlier work primarily in light of further refinement of the estimates of the magnitudes and sources of geothermal exergy. In addition we have constrained the quantities of heat from the various geothermal sources, which has resulted in a far more stable model. The result is revised computations of the SERs of geothermal and tidal inputs to the geobiosphere. Fig. 2 shows the flows of exergy that are the basis for the re-evaluation of the geobiosphere baseline. Explanations of the changes in exergy flows are summarized below.

3.1.1. *Exergy of solar radiation*

In our earlier paper we reviewed the solar exergy used by researchers in their determinations of global exergy resources. The values varied from 160,000 TW to 173,300 TW and depending on the percent albedo (between 30% and 35%), yielded a net solar exergy between 104,000 TW and 120,400 TW (Table 1, Brown and Ulgiati, 2010). We then took the mean value yielding a solar exergy of 3.6E+24 J y^{-1}. We did not find any reason to alter the solar exergy driving the geobiosphere.

3.1.2. *Tidal exergy dissipated*

The exergy dissipated on Earth from the combined forces of attraction between the Earth, Moon, Sun system has been relatively well established (Munk and Wunsch, 1998) based on astronomical data of 3.7 TW (1.17E+20 J y^{-1}). We did not find data that would contradict these data in this re-evaluation.

3.1.3. *Geothermal exergy*

Geothermal exergy is composed of three separate sources of heat: the core or primordial heat (heat left over from the formation of the Earth), the radiogenic heat (heat produced by the radioactive decay of isotopes in the mantle and crust) and the heat flows from surface processes which are derived from tidal dissipation in the solid earth, differentiation of the crust and subduction of organic matter and other oxidized and reduced matter. We revisited the entire basis for geothermal exergy since much progress has been made in recent years regarding estimates of sources of geothermal energy (see Korenaga, 2011; Dye, 2012; Mareschal et al., 2012). Estimates of total global heat loss still range from 46 TW (Jaupart et al., 2007) to 47 TW (Davies and Davies, 2010); of which,

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[2] Sometimes called replacement time, or the amount of time required for replacement by a system's energy or material through-flow, and is calculated as the ratio of the system's content of that substance to its through-flow rate.

[3] Self-organization is the spontaneous emergence of order (Kauffman, 1993). In self-organizing systems, pattern at the global level emerges solely from interactions among lower-level components (Camazine et al., 2001).

[4] In our 2010 paper (Brown and Ulgiati, 2010) we referred to transformities when describing the ratio of solar equivalent energy to energy. We now realize that this is inappropriate, as transformity has been defined as the ratio of solar emergy to energy (sej J^{-1}). Since the solar equivalents of tidal dissipation and geothermal heat are not emergy, it is more correct to refer to the ratio sej J^{-1} as a solar equivalence ratio (SER).

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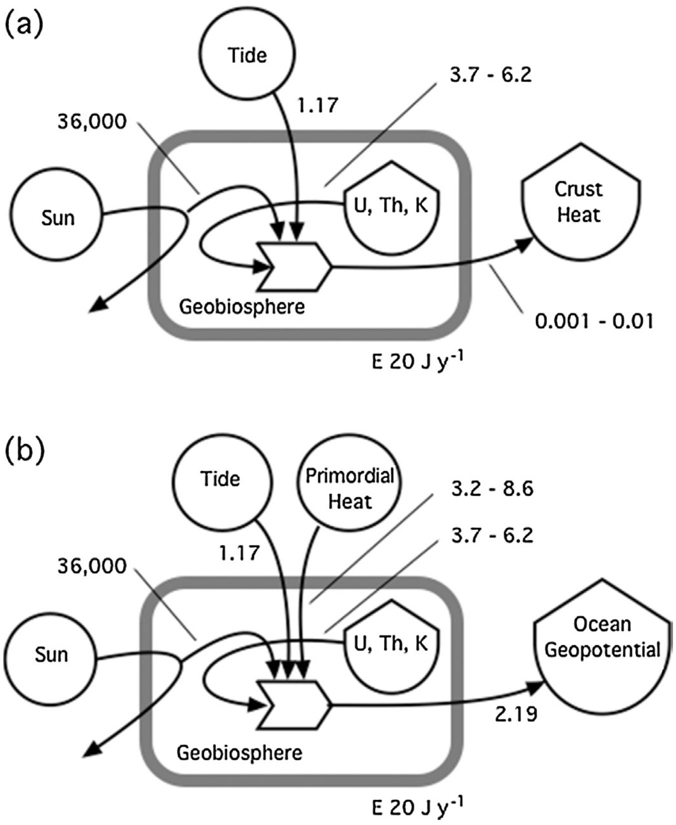

Fig. 2. Systems diagrams describing the relationships between global exergy sources generating (a) the exergy of crustal heat and (b) the exergy of ocean geopotential. Data in the figure refer to Table 1.

~32 TW through the ocean floor and ~14 TW through continental areas. After reevaluation of the heat flows supporting the geobiosphere, we also revised our previous interpretation of data from Sclater et al. (1980), by constraining the percent of total geothermal energy generated by surface processes from between 8.2 TW (2.6E+20 J y^{-1}) and 27 TW (2.69E+20 J y^{-1}) to between 0.1% and 1.0% (0.05–0.5 TW), primarily from tidal dissipation in the solid earth, differentiation of the crust and subduction of organic matter and other oxidized and reduced matter. Of the total geothermal energy input (47 TW; 1.5 E+21 J y^{-1}), we constrained primordial heat to between 4 and 15 TW and added mantle primordial heat of between 7 and 15 TW (Jaupart et al., 2007). Recent data from geoneutrino measurements (Dye, 2012) suggest that radiogenic heat is generated in both the crust (8 ± 1 TW) and mantle (12 ± 4 TW) yielding between 32% and 54% of total (15–25 TW) for radiogenic sources. As in our previous study, to express each of these sources as exergy we applied Carnot ratios $\eta_1 = (4500\,\mathrm{K} - 288\,\mathrm{K})/4500\,\mathrm{K} = 0.936$ (based on an average temperature of 4500 K) to core heat (Stixrude et al., 1997), $\eta_2 = (2750\,\mathrm{K} - 288\,\mathrm{K})/2750\,\mathrm{K} = 0.895$ to mantle heat (based on a average mantle temperature of 2750 K), and $\eta_3 = (750\,\mathrm{K} - 288\,\mathrm{K})/750\,\mathrm{K} = 0.616$ to surface processes and crust radiogenic sources (based on average of crustal temperature of 750 K) reflecting the difference in the temperature of each source (Rudnick et al., 1998; Jaupart and Mareschal, 1999; Poudjom Djomani et al., 2001). Carnot efficiencies where then applied to each of the sources in the Monte Carlo simulation to convert geothermal energy to exergy.

Finally, to compute the solar equivalent exergy contribution from geothermal sources, we subtracted the heat flows for surface processes from the total geothermal exergy, since to count them would be double counting the surface energy (sun and tide), thus the geothermal input reflects only the exergy of deep heat and radiogenic heat contributions to the geobiosphere. Table 1 summarizes the re-evaluated earth heat flows used in this simulation. Note that the exergy data are the inputs we use for the simulation and the computation of geothermal input and its SER.

Table 1
Energy, exergy and percent of total geothermal input for different sources.[a]

Source	Energy (TW)	Exergy[b] (J y^{-1})	Percent[c]
Crust			
Surface processes	0.05–0.5	9.7E+17–9.7E+18	0.1–1%
Radiogenic sources	7–9	1.4E+20–1.7E+20	21–27%
Mantle			
Primordial heat	7–15	2.0E+20–4.2E+20	21–44%
Radiogenic sources	8–16	2.3E+20–4.5E+20	24–47%
Core			
Primordial heat	4–15	1.2E+20–4.4E+20	12–44%

[a] Energy data are a synthesis of data from Hofmeister and Criss (2005), Jaupart and Mareschal (2007), Jaupart et al. (2007), Davies and Davies (2010), Korenaga (2011), Dye (2012), Mareschal et al. (2012).

[b] Exergy computed using the following Carnot ratios: crust = 0.616, mantle = 0.895, and core = 0.936.

[c] We computed percent of total based on total geothermal exergy of 9.8E+20 J y^{-1} (31 TW).

3.1.4. Oceananic geopotential exergy

Our re-evaluation of the literature related to ocean geopotential energy found no new information. In this simulation we continue to use the data from Oort et al. (1989), which is 2.19E+20 J y^{-1}.

Using these different estimates of solar radiation received by earth, and the quantity of exergy from geothermal sources, we reran the Monte Carlo simulations using the following equations, which were an adaptation of the equations first used by Odum (2000).

$$Sun(T_{rS}) + Tide(T_{rT}) + RadHeat(T_{rH}) = CrustHeat(T_{rH}) \tag{2}$$

where *Sun* is the exergy of net solar radiation; T_{rS}, transformity of solar exergy, 1.0 by definition; *Tide*, exergy of tidal momentum; T_{rT}, transformity of tidal exergy; *RadHeat*, exergy of radiogenic sources; *CrustHeat*, geothermal exergy flow that is generated from the crust (Carnot ratio ≈ 0.616); constrained to between 0.1% and 1.0% of total geothermal exergy; T_{rH}, transformity of geothermal exergy.

Radioactive decay is included in this equation because its contribution is in addition to the sun and tide. The sun and tide are responsible for surface processes that include buried oxidized and reduced substances, friction of plates, and compression of sedimentary deposits.

In Eq. (3), the production of oceanic geopotential exergy is a function of all three sources of exergy (solar, tidal, and deep heat) as well as radiogenic sources and thus the second equation is as follows:

$$\begin{aligned} &Sun(T_{rS}) + Tide(T_{rT}) + RadHeat(T_{rH}) + DeepHeat(T_{rH}) \\ &\quad = OcnGeoPot(T_{rT}) \end{aligned} \tag{3}$$

where *DeepHeat* is the exergy of primordial heat from the Earth's core (Carnot ratio ≈ 0.936) and mantle (Carnot ratio ≈ 0.895); T_{rH}, transformity of geothermal exergy; *OcnGeoPot*, oceanic geopotential exergy (2.19E+20 J y^{-1}, Oort et al., 1989); T_{rT}, transformity of tidal exergy.

3.2. Monte Carlo simulation

In order to assess the uncertainty of our results, we constructed a simulation model using Eqs. (2) and (3) in Visual Basic to vary each of the sources of geothermal exergy within the bounds described above (i.e., total geothermal energy = 47 TW, surface processes = 0.05–0.5 TW, primordial core heat = 4–15 TW, primordial

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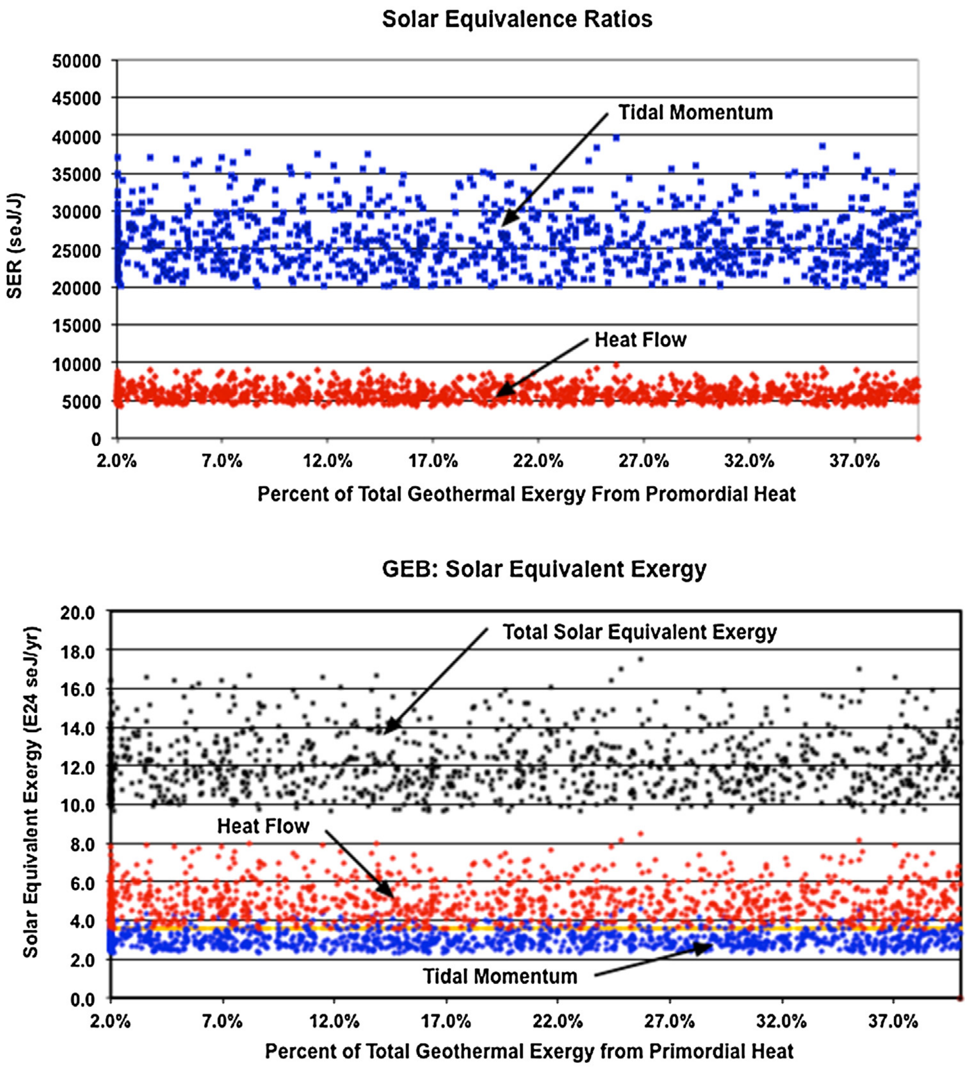

Fig. 3. Results of the Monte Carlo simulation of the geobiosphere energy equations (Eqs. (2) and (3)). Resulting solar equivalence ratios (top) and solar equivalent exergy (bottom).

mantle heat = 7–15 TW, radiogenic sources = 15–25 TW). Solar radiation and tidal exergy dissipated were set constant at 3.6E+24 J y^{-1} and 1.17E20 J y^{-1}, respectively. We assumed an equal probability distribution between each of the geothermal bounds since there was no suggestion in the literature of mean values for these sources. The model was run for 100,000 iterations randomly substituting values for each source within the bounds given. In all cases the total geothermal energy did not exceed 47 TW.

4. Results

Simulation of the Monte Carlo model yielded the results in Fig. 3. The top graph (Fig. 3a) shows the model estimated SERs for tidal momentum and geothermal sources for 1000 iterations of the model.[5] The bottom graph (Fig. 3b) shows the solar equivalent exergy of each of the sources and their sum. Each point in the graphs represents one simulation of the model. Since we reinterpreted the source and magnitude of heat flows and reduced the contribution from crustal heat sources to no more than 1% of the total heat flows, the stability of the simulation has been much improved over the simulation in our 2010 paper (Brown and Ulgiati, 2010).

The graphs in Fig. 4 are histograms of the output from the Monte Carlo simulation for 1000 iterations of the model. The top two graphs are histograms of tidal and geothermal SERs. Each bar in the histogram represents the number of simulation results that equal the range of SERs. Mean values for tidal and geothermal SERs were 5500 (±985) seJ J^{-1} and 26,300 (+3800) seJ J^{-1} respectively. The bottom graph is the histogram for total global empower, whose mean value was 12.1E+24 seJ y^{-1}. Evident in each histogram is a slight right skewness. Even taking into consideration the slight skewness, we used mean values for SERs and the GEB.

Table 2 lists the data from this revised Monte Carlo simulation (the last set of columns) compared with our previous results (Brown and Ulgiati, 2010) and those of Odum (2000). Overall the total geobiosphere empower of 12.1 E24 seJ y^{-1} represents a decrease of about 20% (from 15.2E+24 seJ y^{-1}) compared to Brown and Ulgiati (2010). More significant is the distribution of the changes. Solar exergy remained the same (3.6E+24 seJ y^{-1}), the emergy of geothermal sources increased by 65% (from 3.3E+24 seJ y^{-1} to 5.4E+24 seJ y^{-1}) and tidal dissipation decreased by 63% (from 8.3E+24 seJ y^{-1} to 3.1E+24 seJ y^{-1}).

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[5] We only show results for 1000 iterations of the model, while we ran the model for 100,000 iterations, the results were the same as for 1000. For clarity of the graphs, we limit the presentation to 1000 iterations.

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Table 2
Transformities and empower from previous evaluations compared with SER and solar equivalent exergy of this restudy.

Inflow	Odum (2000)			Brown and Ulgiati (2010)			This restudy[c]		
	Energy	UEV[a] (sej J^{-1})	Empower[b] (E+24 seJ y^{-1})	Exergy	UEV[a] (sej J^{-1})	Empower[b] (E24 seJ y^{-1})	Exergy	SER[a] (seJ J^{-1})	Solar equivalent exergy[b] (E+20 seJ y^{-1})
Solar energy absorbed	3.93E+24	1	3.93	3.59E+24	1	3.6	3.6E+24	1	3.6
Geothermal sources	6.72E+20	12,000	8.06	1.63E+20	20,300	3.3	9.78E+20	5500 (985)	5.4 (0.95)
Tidal energy absorbed	5.20E+19	73,700	3.83	1.17E+21	72,400	8.3	1.17E+20	26,300 (3800)	3.1 (0.44)
Total global empower[b]			15.83			15.2			12.1 (1.51)

[a] In the past the term unit emergy value (UEV) was applied to the tripartite, but with the publication of this paper, we recognize that the more appropriate term is solar equivalence ratio (SER).

[b] Empower was used in the past to refer to the inflow of each of the sources, but with the publication of this paper, we recognize that the more appropriate term is solar equivalent exergy.

[c] Numbers in parentheses are standard deviation.

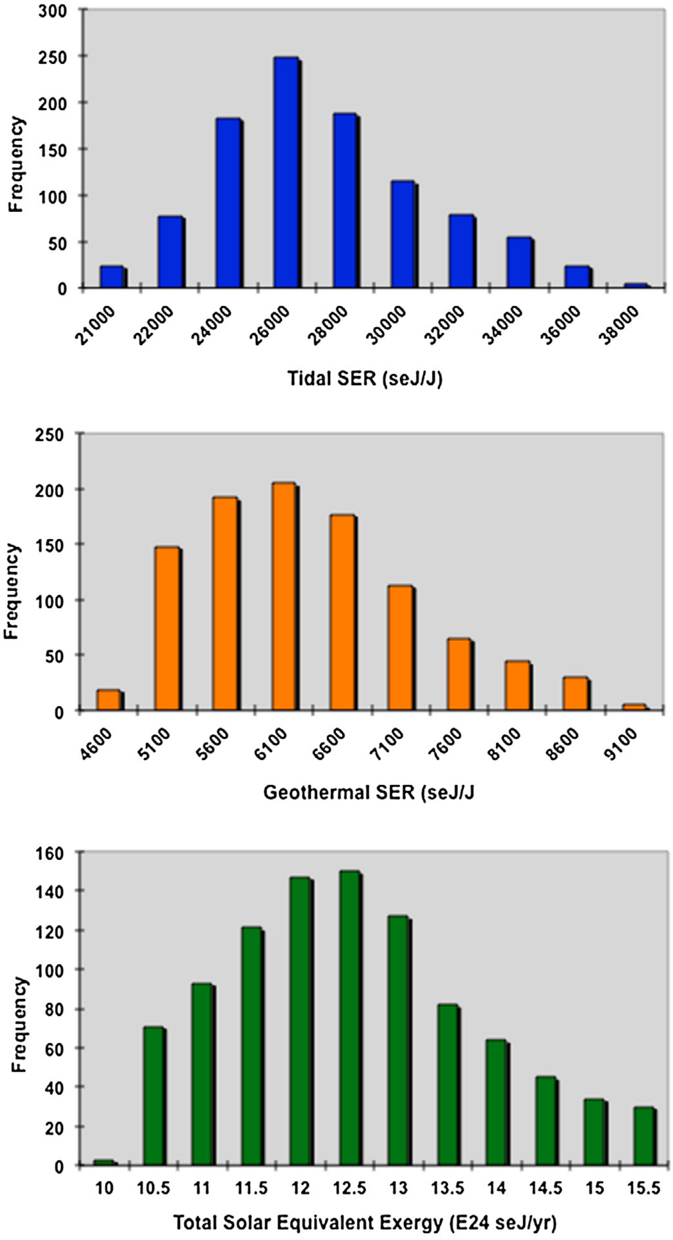

Fig. 4. Histograms of the Monte Carlo simulation results showing slight right skewness. Tidal SER (top), geothermal SER (middle) and total global solar equivalent exergy (bottom).

5. Summary and concluding remarks

5.1. *Solar equivalence vs solar emergy*

In order to express the exergy from tidal dissipation and geothermal sources on the same basis as solar exergy, we use a method of equivalence that expresses these two sources as solar equivalent energy. Solar equivalent energy is different from solar emergy. It has been pointed out by Raugei (2013) that tidal dissipation and geothermal inputs do not have a solar origin, and therefore, technically cannot be expressed as solar emergy. In fact, the method of computing their SERs and ultimately their contributions as sources to the geobiosphere is a method of equivalence. The result is solar equivalent joules; the abbreviation for which is seJ ("s", "e", capital "J"). The distinction we draw between solar equivalent exergy and emergy is not an arbitrary one, nor is it "splitting hairs". Solar emergy and solar equivalent exergy are not the same. On the one hand, emergy is the memory of available energy destroyed in the past, both directly and indirectly, to produce matter, energy or information. On the other hand, solar equivalent exergy is not available energy of the past, but is presently available and expressed in equivalence of one form, solar exergy.

5.2. *Geothermal unknowns*

In our 2010 paper (Brown and Ulgiati, 2010) we developed our model based on the current literature in geosciences. Since that time there has been much additional research and it appears that rather than remove some of the uncertainty, the latest publications have added to it. The most significant unknowns regarding the driving forces of the geobiosphere remain the source and magnitude of geothermal inputs. The literature is still somewhat ambiguous and while the estimate of the total heat flow seems to have been narrowed to 46 or 47 TW (we used 47 TW) the sources of that heat are still much debated and have wide variation. Using the most recent published literature we have revised our original formulation of the heat budget to include much higher radiogenic inputs, much reduced heat from surface processes and from primordial heat. In addition some of the latest research (Dye, 2012; Korenaga, 2011; Mareschal et al., 2012) suggest that radiogenic heat originates in both the crust and in the mantle, resulting in additional uncertainty. The place of origin of radiogenic heat is important since exergy inputs depend on Carnot ratios computed using the temperature differential between the Earth's surface and the average temperature of the crust and mantle, 487 K and 2737 K, respectively.

5.2.1. *The algebra of the equivalence method*

We use a relatively simple method of simultaneously solving two equations with two unknowns (the SERs of heat flow and tide)

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in a Monte Carlo model that substitutes various values for the different sources of geothermal exergy. We have adapted the method first introduced by Odum (2000) and include the uncertainty of the geothermal inputs to compute SERs and solar equivalent exergy for inputs to the geobiosphere from tidal dissipation and geothermal sources. Our contribution to the method was to separate radiogenic inputs from primordial heat and to introduce the uncertainty of these sources. The model estimates mean SERs and a confidence interval for each, and sums the solar equivalent exergy from the three sources resulting in the GEB.

We have assumed that the quality of the two geothermal sources (primordial heat and radiogenic heat) is the same regardless of its source. In a companion paper in this volume, using a different technique to compute SERs for geobiosphere inputs, the primordial heat and radiogenic heat have different SERs reflecting their different sources and quality (De Vilbiss et al., 2016).

6. Conclusion

In all, the field of systems ecology that uses emergy as its focus to evaluate energy flow through systems continues to evolve as more and more researchers apply its techniques and question fundamental properties. In this paper we revisited the GEB articulated 5 years ago in our 2010 paper (Brown and Ulgiati, 2010), and provide significant refinements of the SERs for the global tripartite which results in a revised emergy baseline of 12.1 (±1.43) E+24 seJ y^{-1} and revised global SERs for tidal dissipation and geothermal sources of 5500 (±985) seJ J^{-1} and 26,300 (±3800) seJ J^{-1} respectively.

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