A Revised Solar Transformity for Tidal Energy Received and Tidal Energy Dissipated Globally: Implications for Emergy Analysis.

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Abstract

Solar transformities for the tidal energy received and tidal energy dissipated globally were calculated by the same method used to calculate the solar transformity of the earth's deep heat. The annual emergy contributed by solar radiation (3.93 E24 sej y^{-1}) and the earth's deep heat (4.07 E24 sej y^{-1}) was divided by the difference between the total potential energy of the world oceans and the tidal energy dissipated in shallow water (21.4 E19 J y^{-1} - 5.2 E19 J y^{-1}) to obtain a transformity of 24259 sej J^{-1} for the part of the ocean's total potential energy generated by the solar heat engine if solar energy is the only emergy source and 49383 sej J^{-1} if both the solar heat engine and the earth's deep heat contribute. Since the potential energy of the world oceans is the same regardless of source, the transformity of the tidal energy dissipated is also 24259 sej J^{-1} or 49383 sej J^{-1}. The solar emergy used up globally by the dissipation of tidal energy is then 5.2 E19 J y^{-1} multiplied by 24259 sej J^{-1} or 49383 sej J^{-1} equaling 1.26 E24 sej y^{-1} or 2.58 E24 sej y^{-1}, respectively. The transformity of the gravitational energy of the sun and moon received by the earth is then 1.26 E24 sej y^{-1} or 2.58 E24 sej y^{-1} divided by 8.515 E19 J y^{-1} which equals 14797 sej J^{-1} or 30159 sej J^{-1}, respectively. Because the earth's deep heat makes a negligible

contribution to determining variations in the geopotential of the world oceans on time scales of less than 1.0 E6 years, the solar transformity for the tides based on solar energy alone is preferable for emergy analyses with short time frames of less than 10000 years. This new solar transformity for tidal energy establishes a new planetary baseline for emergy analysis (9.26 E24 sej y^{-1}). Spatial and temporal guidelines to avoid double counting in determining the emergy basis for local phenomena were suggested based on implications of the thinking used in this analysis.

Introduction

Emergy Analysis (Odum 1996) is an assessment method that can evaluate the contributions of humanity and nature to the overall well-being of an environmental system. This is accomplished by expressing all the products and services produced and consumed by a network of economic and ecological components and processes in terms of a single quantity, the energy of one kind, *e.g.*, the solar joules, that was required to produce them. This new quantity, called *emergy*, is defined as all the available energy of one kind previously used up directly and indirectly to make a particular product or service (Odum 1996). The emjoule or embodied joule (Odum 1986) denotes the use of a particular kind of energy in the past and thus it is the appropriate unit for emergy. Solar emjoules are commonly used as the emergy unit for evaluating environmental systems.

The *transformity* of a product or service is the emergy required to make a unit of that product or service, e.g., 18,199 solar emjoules (sej) are required to make one joule (J) of chemical potential energy in rain (Odum 1996). By convention the transformity of solar energy is 1. The available energy or exergy content of many natural and socioeconomic products and services has been tabulated and is widely available. These quantities can be easily converted to emergy by multiplying the exergy in joules by the appropriate transformity (sej J^{-1}). Therefore, transformities are the key pieces of new information needed to evaluate the emergy of environmental products and services. The future success of Emergy Analysis as a method for assessing environmental systems will depend on developing accurate and consistent methods for calculating transformities, documenting the uncertainty associated with these calculations, and developing a clear understanding of how to use these factors in determining the emergy basis for economic and ecological products, services, and systems.

The largest system of interest to us in calculating transformities for environmental products and services is the planetary web of processes that generates natural products such as the wind, rain, waves, tides, etc. (Figure1). These global products often supply much of the energy transformed to make other ecological and economic products and services. All products in the planetary web are created by the transformation of the earth's three primary independent sources of energy which are (1) solar radiation, (2) the earth's deep heat, and (3) the gravitational attraction of the sun and the moon. Furthermore, all natural products and processes on Earth are created by the transformation of the energies in the products of the planetary web. If these three primary energy sources to our earth are expressed in terms of a single kind of energy we can establish a planetary baseline for determining the transformities of products and services provided on a global basis. The planetary baseline itself is primarily of academic interest because as long as all transformities are determined relative to the same baseline the results of an analysis will change little if the baseline is moved. The more interesting question is how should the products of the planetary web be combined to determine the emergy basis for products and services without double counting. In an appendix to Campbell (1998) Campbell and Odum applied the method used by Odum and Odum (1983) to estimate the solar transformity of the earth's deep heat to calculate a revised transformity for the tidal energy received by the earth and the tidal energy dissipated, globally. In this paper I present the assumptions and calculations in more detail and consider the implications of this approach for Emergy Analysis. In addition, I suggest a rationale for combining the three independent energy sources to the planet to practically avoid double counting in the determination of the emergy basis for ecological products and services.

Methods

Odum and Odum (1983) used an elegant method to determine the solar transformity of the earth's deep heat. The key to making an equivalence between these two independent energy sources was to recognize that they both contribute to driving the geologic cycle of the earth's crust. The heat flux from the earth's crust is commonly measured by geologists (Lachenbruck and Sass 1977, Decker 1987). This heat flow is a product of the underlying geologic activity and the erosive action of wind and rain on the land surface. In addition, solar energy contributes to this heat flux through the burial of organic matter in sediments. Odum and Odum (1983) found that the flux of residual heat from the earth's mantle and the heat generated in the crust by radioactive decay had been estimated by Sclater et al. (1980). They estimated the solar transformity of the earth's heat driving deep geologic processes by subtracting the geologic heat fluxes (radioactive decay and deep heat) from the total heat flux from the earth's surface. The remaining heat flux from the crustal surface can be attributed to the part of the earth cycle driven by solar energy which passes energy downward into the crust as compression and chemical potentials (Odum 1996). The ratio of the annual solar energy input to the planet divided by this energy flux is then the solar transformity of the portion of the earth cycle driven by solar energy. Since both the solar engine and the earth's radioactive and residual heat contribute heat to drive the same geologic process, *i.e.*, the earth cycle of crustal movements, it is logical to assume that the solar transformity of the earth's radioactive and deep heat contributing to the earth cycle will be approximately the same as that estimated for the solar engine's contribution to the total crustal heat flux. In this paper I have used similar reasoning to determine the solar transformity of the tidal energy received by the earth and the tidal energy dissipated in the world oceans.

If the following four assumptions hold the method of Odum and Odum (1983) can be applied to determine the solar transformity of the tidal energy dissipated globally. (1) The available geopotential energy of the elevated water in worlds oceans is similar regardless of source. (2) On the time scale of one year the available potential energy of the world's oceans is in steady state, thus all the potential energy that is created in a given year is dissipated in that year. If this assumption was on average false, there would be an accumulation or decline of the total potential energy in the global ocean over a series of years and this is not observed. (3) The elevation of the ocean surface relative to a reference level at a depth of 1000m is primarily caused by the solar heat engine including its effect in delivering fresh water streams and the gravitational pull of the sun and moon. These two sources generate almost all the available potential energy in the world oceans. (4) The dissipation of tidal energy in the deep oceans is less than 0.001 of that in shallow water (Miller 1966). Given these assumptions, the solar transformity of the portion of the potential energy in the world oceans that is generated by the solar heat engine can be estimated if the fraction of the total potential energy generated by the tide is known. By the reasoning applied above the solar transformity of the tidal energy dissipated annually in the world ocean is approximately equal to that of the potential energy generated by the solar heat engine.

The calculations were performed as follows:

(1) Assume the total available gravitational potential energy of the world ocean equals a portion generated by solar heat engine plus a portion generated by the tide.

(2) Assume that almost all the potential energy generated by the gravitational attraction of the sun and moon is dissipated in shallow water of the earth's continental shelves and estuaries (Miller 1966).

(3) Subtract the tidal energy dissipated annually in shallow water from the total gravitational potential energy generated annually in the world oceans to get the gravitational potential energy generated by the solar heat engine.

(4) Divide the annual solar energy input to the earth by the joules of gravitational potential energy in the world oceans generated by the solar heat engine to obtain a transformity. Given that the total potential energy in the world ocean's is the same "stuff" this is also the transformity for the tidal energy dissipated.

(5) The transformity of the gravitational energy of the sun and moon received by the earth can be calculated knowing the solar emergy of the tidal potential energy generated in a year and the gravitational energy received by the earth, annually. Divide the solar emergy of the tidal potential energy in the world oceans by the joules of gravitational energy received to obtain the transformity.

(6) Determine the new solar emergy baseline for planetary processes by adding the estimate of the emergy of the tides to that of the earth's deep heat and solar radiation.

The process of determining a new transformity begins by identifying all the energy transformations that contribute to the formation of the product or service being evaluated. By definition the solar transformity is the solar energy required to make a joule of available energy in a product or service, so the next step is to determine the minimum set of required inputs that represents the maximum emergy contributed by independent emergy sources to produce a product, *i.e,* the emergy required without double counting. For example, many natural products are produced by the transformation of energy in a network (Figure 1). All products that are generated by the transformation of the external energy sources in the network are co-products of the same network of processes. Therefore, if more than one of these co-products contributes emergy to the formation of a product or service under evaluation only the product contributing the highest emergy is counted. If the emergy of other co-products is added to the emergy required to make the primary product, the emergy that the co-products contribute to the process will be counted more than once. The method of calculation used here leads to a consideration of practical methods for minimizing the problem of double counting in determining the emergy basis for natural products and services.

Results

If the solar energy flux to earth is 3.93 E24 joules y^{-1} (Odum 1996), the gravitational energy transmitted to the earth is 8.515 E19 joules y^{-1} (Munk and MacDonald 1960), the tidal energy transmitted to shallow water is 5.2 E19 joules y^{-1} (Miller 1966), and the available gravitational potential energy in the top 1000 m of the global ocean is 21.4 E19 joules y^{-1} (Oort et al. 1989), the method given above can be applied to calculate solar transformities for the tidal energy dissipated and the tidal energy received by the earth.

The fraction of the available gravitational potential energy of the oceans created by solar energy is equal to the total available potential energy minus the potential energy created by the tide. If almost all of the available potential energy produced by gravitational attraction is transmitted to shallow water and dissipated there the available potential energy produced by solar energy is 16.2 E 19 joules y^{-1}.

$$21.4\ \text{E19 joules y}^{-1} - 5.2\ \text{E19 joules y}^{-1} = 16.2\ \text{E 19 joules y}^{-1} \quad (1)$$

The solar transformity of this portion of the available gravitational potential energy created by the solar heat engine is then:

$$3.93\ \text{E24 joules y}^{-1} \div 16.2\ \text{E 19 joules y}^{-1} = 24259\ \text{sej J}^{-1} \quad (2)$$

This is also the transformity for the potion of the available gravitational potential energy in the world oceans generated by the gravitational attraction of the sun and moon. Transformity does not change when a system shifts energy from potential to kinetic form with conservation. Since almost all the tidal potential energy is transmitted to shallow water and dissipated there the solar transformity of the tidal energy absorbed is approximately the same as that of the tidal potential energy generated. The emergy contributed to the planetary baseline by the tides is then:

$$5.2\ \text{E19 joules y}^{-1} \times 24259\ \text{sej J}^{-1} = 1.26\ \text{E24 sej y}^{-1} \quad (3)$$

The solar transformity of the gravitational energy of the sun and moon received by the earth is then

$$1.26\ \text{E24 sej y}^{-1} \div 8.515\ \text{E19 joules y}^{-1} = 14797\ \text{sej J}^{-1} \quad (4)$$

The new planetary baseline using this revised transformity for tidal energy is:

$$3.93\ E24\ sej\ y^{-1} + 4.07\ E24\ sej\ y^{-1} + 1.26\ E24\ sej\ y^{-1} = 9.26\ E24\ sej\ y^{-1} \qquad (5)$$

These transformities are correct if the only important emergy sources required to produce the available gravitational potential energy in the oceans are the gravitational attraction of the sun and moon and the solar heat engine. However, it is well known that the elevation of the water surface also depends on the geometry and the distribution of land forms both locally and globally (Macmillan 1966). The distribution of landforms is a consequence of the earth cycle as discussed above which requires a major input of energy from radioactive and residual heat for its operation. This emergy contributed by the earth's heat is also required to produce a given quantity of gravitational potential energy in the world oceans. To see that there must be a geologic input to creating the potential energy of the oceans imagine an earth without continents and thus no geologic input to the upper zone. Would the oceanic geopotential energy created by the sun and moon be different?

If the deep heat energy input from the earth contributes to the formation of geopotential energy in the ocean by creating the distribution and geometry of the continental land masses and coastal shelves, the non-tidal emergy input should be 8.0 E24 sej y^{-1} (3.93 E24 sej y^{-1} from solar and 4.07 E24 sej y^{-1} from deep heat of the earth (Odum 1996). The solar transformity of the available gravitational potential energy in the oceans created by the solar heat engine is now:

$$8.0\ E24\ sej\ y^{-1} \div 16.2\ E19\ joules\ y^{-1} = 49383\ sej\ J^{-1} \qquad (6)$$

By reasoning similar to that applied above this transformity can also be applied to the available gravitational potential energy of the world oceans generated by the gravitational attraction of the sun and moon and to the tidal energy dissipated in shallow water globally. The solar emergy used up globally in the dissipation of available potential energy produced annually by the tides is then:

$$5.2\text{ E19 joules y}^{-1} * 49383\text{ sej J}^{-1} = 2.568\text{ E24 sej y}^{-1} \qquad (7)$$

and the solar transformity of the gravitational energy received by the earth is:

$$2.568\text{ E24 sej} \div 8.515\text{ E19joules y}^{-1} = 30159\text{ sej J}^{-1} \qquad (8)$$

The new planetary baseline using the transformity for tidal energy received that includes the contribution of earth processes is :

$$3.93\text{ E24 sej y}^{-1} + 4.07\text{ E24 sej y}^{-1} + 2.57\text{ E24 sej y}^{-1} = 10.57\text{ E24 sej y}^{-1} \qquad (9)$$

Discussion

Figure 1 illustrates the planetary web of interactions between the earth's three independent energy sources and the production systems of the land, oceans, and atmosphere.

The three planetary system components, oceans, atmosphere and land are completely interconnected with important feedbacks linking them together. For example, the land surface elevation and roughness affect wind movement in the atmosphere and the atmospheric winds erode the land and redistribute particles over the earth's surface. Many other examples of the connections between these planetary subsystems could be given but the important point is that all the global energy flows are the products of this interconnected web. Solar radiation interacts directly with all three planetary susbsystems, whereas, the earth's deep heat contributes energy primarily to the oceanic and terrestrial susbsystems. The gravitational attraction of the sun and moon interacts most strongly with the oceans, but it also results in lesser tidal effects in the atmosphere and land mass (Cartwright 1999). The relative magnitude of the contribution that each of these three independent energy sources makes to the production of eight global energy flows is shown in Table 1. The contributions are classified as (1) immediate meaning that changes in the annual energy supplied in the forcing function are reflected in the global energy flux in that year, (2) long term meaning that there is a substantial contribution of the present state of the environment to producing a global energy flow, but an energy input must act for thousands of years to result in enough change in the environment to cause a substantial change in the global energy flow, and (3) negligible meaning that the emergy supplied by a source is so small that it can be ignored for practical purposes. This table can be used to help avoid double counting in determining the emergy basis for local ecological and economic organization on our planet. For example, if one input is negligible for global energy flow, A, but makes an immediate contribution to energy flow, B, an another independent source makes an immediate contribution to A but has a negligible influence on B, the two may be counted together in determining the emergy basis of a phenomena without double counting. For example, the tidal energy absorbed and the chemical potential energy in rainfall can both be added to determine the emergy basis for organization in a coastal region without double counting (see Table 1). Emergy sources that make a long term contribution to a global energy flow do not need to be added to the emergy basis of organization in a region on time scales of less than their period of effective action. Effective action might be defined as the time needed to produce a 1% change in the global energy flow.

Questions about double counting can also be clarified by considering the separation of input emergies in space and time. Spatial separation of inputs avoids double counting. For example, the major emergy inflows are often different over the land and water portions of a system composed of a coastal body of water and its watershed. The primary emergy source for the water area is often from the tidal energy absorbed, whereas, over land it is often the chemical potential energy in rainfall. When these emergy inputs are determined based on their respective water and land areas there can be no double counting. According to the information in Table 1 the chemical potential energy of rainfall might be added over the water area as well as the land with little risk of double counting. However, the emergy in chemical potential energy of rainfall and the physical energy in wind could not be added over the same area without double counting, since they are both immediate co-products of the solar heat engine.

Separation in time is a second test to determine what emergy inputs should be counted as part of the emergy basis of a product, service, or system. In general transformities are calculated based on the inputs needed to produce a product or service quickly and efficiently. In some cases the amount of a product that is created depends on the energy previously used up over a very long period of time in a process that is a part of a much larger system, *e.g.*, the geologic input to the tidal energy of the world oceans as discussed above. In such cases there is a legitimate question of how these long term inputs should be handled. A simple test for the separation of processes in time is to compare the change in production that occurs as a consequence of a change in the long term input over a quick and efficient production time to the change in production caused by expected variations in the immediate inputs to the same production cycle. If the change in production caused by variations in the long term input are negligible compared with the expected changes caused by the immediate inputs, the long term input may be considered as a constant. In this case a negligible quantity of energy from the long term process is consumed over the production cycle. Energy from the long term process is being used up at infinitesimally small rate, and therefore, it can be omitted as an emergy input to production processes on short time scales. When the stored emergy in a long term product from a larger system is being used up at a rate much faster than it is being replenished, the contributions of the long term storage must be counted in the emergy basis for the product, *e.g.,* soil loss in agricultural production (Odum 1996).

Odum (1996) originally determined the transformity of the tidal energy dissipated by assuming that tidal currents had the same transformity as the current in a large river, *i.e.,* the Mississippi. He obtained a value of 27764 sej J^{-1} for tidal energy dissipated and 16,842 sej J^{-1} for tidal energy received. These numbers are 13.8% greater than the values calculated in this paper using solar emergy alone. The transformity of river current proves to be a good approximation for tidal current transformity, as calculated by this method. The present method follows that used by Odum and Odum (1983) to estimate the transformity of the earth's deep heat, therefore, the solar emergy contributed to the planetary baseline by the earth's deep heat and the emergy contributed by the tides have now been determined by the same method. Therefore, the transformities presented in this paper should be more accurate than those currently in use. However, two very different transformities for both the tidal energy received and tidal energy dissipated globally were calculated in the results section. A question remains as to which of these two alternatives should be used.

The argument on the temporal separation of emergy sources in a production process presented above leads to the conclusion that the transformities for the tidal energy dissipated and received globally based on solar emergy alone are best to use to determine the transformity of systems, products, and processes on scales of 10000 years or less. This assumes that the present configuration of the continents is essentially a constant over time periods of 10000 years or less so that the emergy contribution of the earth cycle to year to year variations in the gravitational geopotential of the world oceans is negligible. Effectively, no earth cycle energy is used up to produce the tides on such short time scales. The larger global transformity for tidal energy that includes the contribution of earth's deep heat is appropriate for processes operating on geologic time scales of 1,000,000 years or more over which the annual geopotential energy generated by the gravitational attraction of the sun and moon could change as a result of continental drift. The conclusion from this argument is that the emergy basis for a product or service may be determined differently if the nature of the inputs to the production process changes as a consequence of shifting time scales or some other relevant phenomena.

Acknowledgments

I thank H.T. Odum for his suggestions and counsel in developing these new transformities for tidal energy. The opinions expressed in this paper are my own and do not necessarily reflect those of the USEPA or anyone else. This paper is contribution number of the Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory.

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Table 1. An estimate of the contribution made by earth's three independent energy sources in producing global energy flows within the planetary web of processes.

Global Energy Flow	Independent Energy Source		
	Solar Radiation	Earth's Deep Heat	Gravitational Attraction
Wind	Immediate	Long term	Negligible
Rain, geopotential	Immediate	Long term	Negligible
Rain, chemical potential	Immediate	Negligible	Negligible
Waves	Immediate	Negligible	Negligible
Tides	Negligible	Long term	Immediate
Streams geopotential	Immediate	Long term	Negligible
Streams, chemical potential	Immediate	Negligible	Negligible
Earth cycle	Immediate	Immediate	Negligible

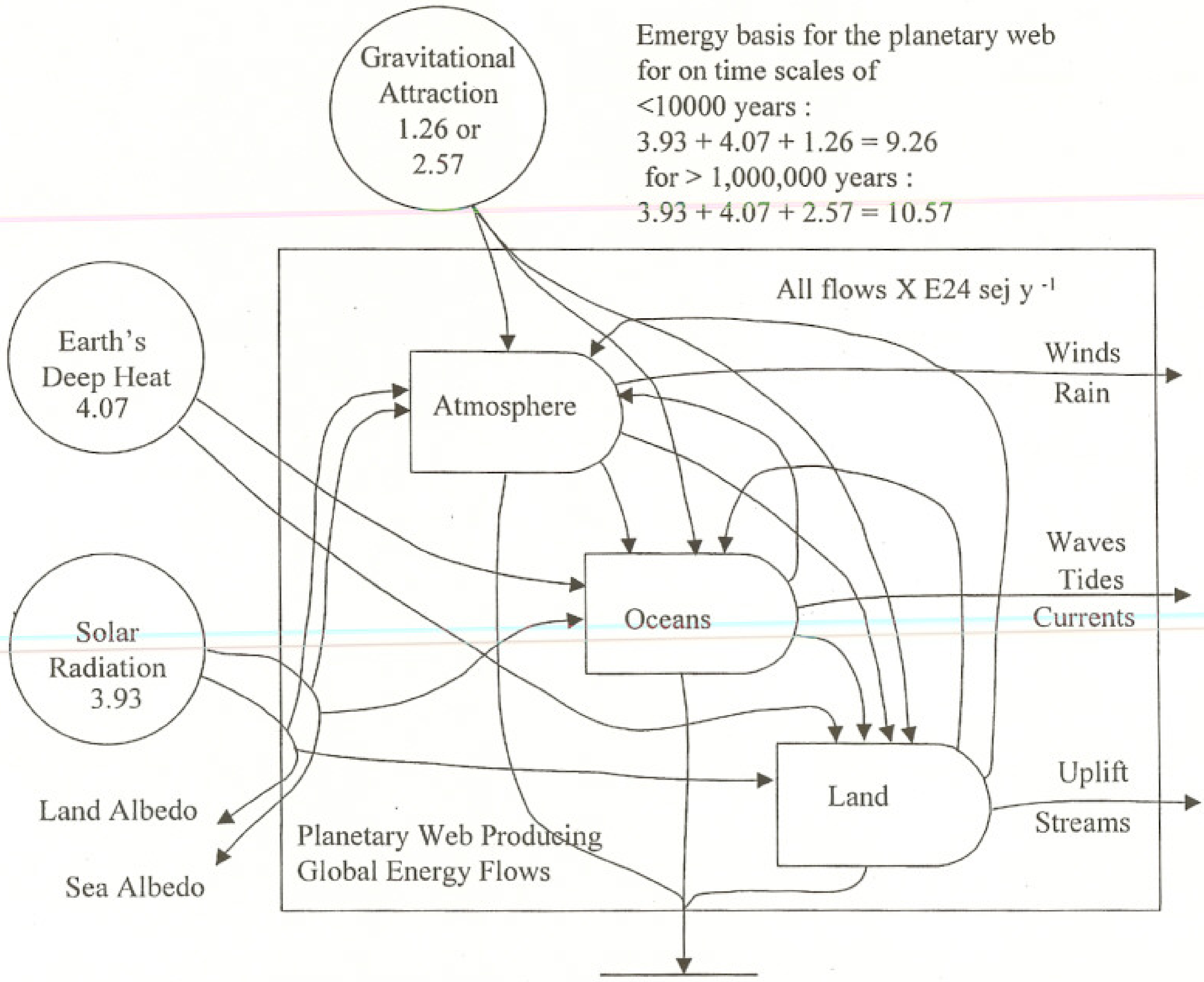

Figure 1. A partially evaluated diagram of the three independent energy sources supporting global energy flow. Short and long term planetary baselines are shown as discussed in the paper.