ENERGY HIERARCHY OF THE EARTH

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Abstract

That all structures and processes form an energy transformation series in energy hierarchy has been offered previously as a general systems concept, a fifth energy law. Position in this universal energy hierarchy is measured by transformity (emergy /energy) which defines the energy scale. Insight on the organization of the earth is sought by evaluating transformities of atmosphere, ocean, continental earth. In order of increasing scale and transformity are the biogeochemical cycles of atmosphere, ocean, freshwater and ice, sediments, and crystalline rock Spatial organization in centers, pulsing system reinforcement, and energy-aligned material cycles appear to be characteristics of earth self organization on every scale. Transformities are also used as practical shortcuts for evaluating real wealth in emjoules and emdollars. Values increase from low values in sunlight to very high values in high mountains, scarce chemicals, and earth memory (genetic information).

Keywords: Energy hierarchy, biogeochemical cycles, watersheds, earth, atmosphere-ocean

1. Introduction

The concepts of energy hierarchy and transformity have been introduced to this society in previous years, and a summary book on emergy (spelled with an "m") was published (Odum, 1996). The theory suggests that on every scale phenomena are self organized to include energy-aligned material cycles, concentrations in centers, and pulsing concentrations in time. In a series of papers Veizer and associates (1988a, 1988b,1989) placed many earth processes in their appropriate scale of time and space by ingenious evaluations of turnover time of the cycles from the half lives of substances remaining in the geological strata. By calibrating geochemical simulation models that generated plausible pulses since Cambrian time, numerical modelers such as Francois et al. (1993) placed many features of the earth system in scale (parts up modeling). McGrane (1998) simulated overview models (top down) also considering alternative scenarios of the past and future for the earth.

For visualizing systems in a simple enough way for the human mind to understand complexity, words are not adequate because they loosely aggregate too many related concepts. Thus various systems languages have been developed to represent networks. One of these, energy systems language, already familiar to this society (Odum, 1983,1993), was designed to combine properties of other systems languages and represent energy hierarchy with symbols arranged in diagrams increasing from left to right in order of transformity. Placing geobiospheric phenomena in an energy systems framework allows well-understood features of earth science to be identified with general systems concepts that apply to other kinds of systems as well. This paper proposes ways the main structures and processes of the scales of the earth's geobiosphere are coupled to the energy hierarchy and located on the universal energy scale by the transformities (emergy/energy) and mass emergy (emergy/mass). Energy is part of every science and every scale. Perhaps it is time that relationships of these sciences be recognized on the energy scale. This paper examines the energetic hierarchical position of the main phases of atmosphere, ocean, hydrological cycle, sedimentary, and hard-rock cycles. Transformities are given in units of solar transformity, solar emjoules per Joule (abbreviated sej/J)

The work of the geobiosphere generates the real wealth of environmental resources (minerals, water resources, fuels, soils, forests, fisheries, etc.), but economic policy has often been based on short term perceptions of need, utility, and shortage by humans acting through market values. By putting all work on a common basis expressing work in units of one kind of energy, the concept emergy (spelled with an "m") provides a common measure of value that applies to nature and humans and to all scales. Emdollars, the monetary equivalent of emergy, is being used now to help resolve the controversies in public policy arena over alternatives in the use of the geobiosphere. Emergy of earth components is readily calculated from transformities and mass emergy values. By putting earth phenomena in their position in the energy hierarchy on energy systems diagrams, this paper may make it easier to interpolate among measured transformities and evaluate emdollars.

2. Definitions

Starting with classical concepts of energy, work, and power, Table 1 provides definitions including the newer concepts of emergy, transformity, and emdollars. Power is measured in useful energy flow per time, but more scale-independent concept is empower (emergy flow per time)

Table 1. Emergy and Related Definitions (Odum, 1996)

Heat = the collective motions of molecules, whose average intensity is the temperature, which may be measured by expansion of matter in a thermometer.

Energy = anything that can be 100% converted into heat.

Available Energy = Potential energy capable of doing work and being degraded in the process
(Units: kilocalories, joules, BTUs, etc.)

Useful Energy = Available energy used to increase system production and efficiency
(units: available joules, kilocalories, etc.)

Power = Useful energy flow per unit time (units: joules per time)

Time's Speed Regulator: Power in an energy transformation depends on the work load. Maximum output power occurs with an optimum intermediate efficiency.

Emergy = Available energy of one kind previously required directly and indirectly to make a product or service (units: emjoules, emkilocalories, etc.)

Empower = Emergy flow per unit time (units: emjoules per unit time)

Maximum Empower Principle (4th Law?): In the competition of self organization processes, network designs prevail that maximize useful power, where useful means to reinforce intake power and efficient use.

Work = An energy transformation process which results in a change in concentration or form of energy.

Transformity = Emergy per unit available energy of one kind (units: emjoule per joule)

Energy Transformation Hierarchy (5th law?): Energy flows of the universe are organized in an energy transformation hierarchy, measured with transformities of one kind

Solar Emergy = Solar energy required directly and indirectly to make a product or service
(units: solar emjoules)

Solar Empower = Solar emergy flow per unit time (units: solar emjoules per unit time)

Solar Transformity = Solar emergy per unit available energy (units: solar emjoules per joule

Emdollar = emergy divided by the emergy/money ratio of the economy

3. Transformations, Cycles, Centers, and Pulsing

First, from previously argued general systems papers, consider the way the properties of systems in self organization generate energy transformation units, material cycles, spatial concentration in centers, and regimes which store and pulse. The properties and evaluations of a network aggregation depend on the way the human mind has elected to make the aggregation. For the purposes of this paper only overview units are used which are mutually necessary for the functions of the others units as they are currently operating. Each unit is assumed to include all of the population of units of similar type. The rounded box in each diagram represents the window of attention in which discussion and calculations are made.

3.1 Energy Transformation Unit

Our attention in Figure 1 is placed on one energy transformation unit. It shows the connections between lower levels of energy hierarchy on the left and higher levels on the right. On the left energy flows are greater but more dilute; on the right energy flow is less but higher quality (in the sense of requiring more previous work from the left). If the feedback from the right ultimately came from the same original Type A source as implied by the dashed-line box, then there is only one source and the transformity of the transformed energy B passing to the right is 100 /10 = 10 type A emjoules/Joule. The used energy without work potential is shown leaving the system through an irreversible pathway symbol called a heat sink. No materials pass through this symbol. The other pathways may involve a pure energy flow such as sunlight, earthquake wave, or tide or they may be pathways in which the energy is associated with a flow of material as in rain or volcanic emission.

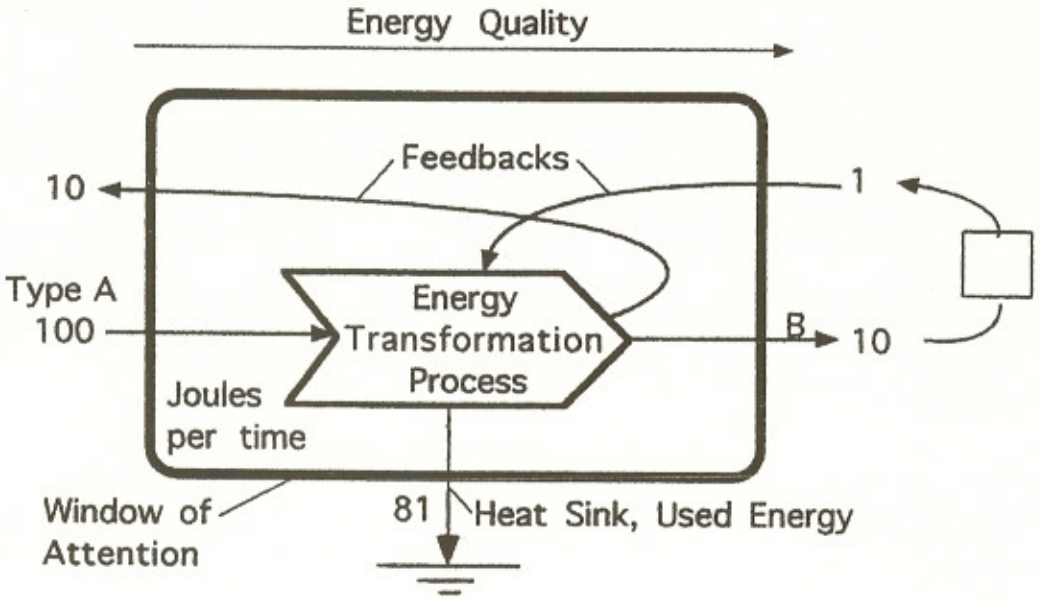

Figure 1 An energy transformation unit in steady state showing pathway connections and typical values

Most energy transformations involve a multiplicative interaction between the low transformity (high energy flow) input from the left and the high transformity (lower energy) inflow from the right joining in the interaction symbol. Matching of inputs of different transformity (and quality) appears to maximize the output flow of production of intermediate quality B.

The universal energy hierarchy consists of the network of units like that in Figure 1 connected into a web. The total energy decreases from left to right while the transformity increases to the right. A familiar example is the ecological food chain.

3.2 Material Cycles

In Figure 2 the window of attention is on the flow of materials arranged from left to right according to the energy hierarchy. Materials are more concentrated or higher quality form on the right than on the left. Although all the energy flows are not shown in this figure, the concentrating process requiredemergy.
Mass concentration is higher on the right. We can refer to this as an energy aligned diagram because the units and material flows are organized according to the energy hierarchy. A biogeochemical cycle has an energetic asymmetry when drawn with high transformity and concentrations on the right.

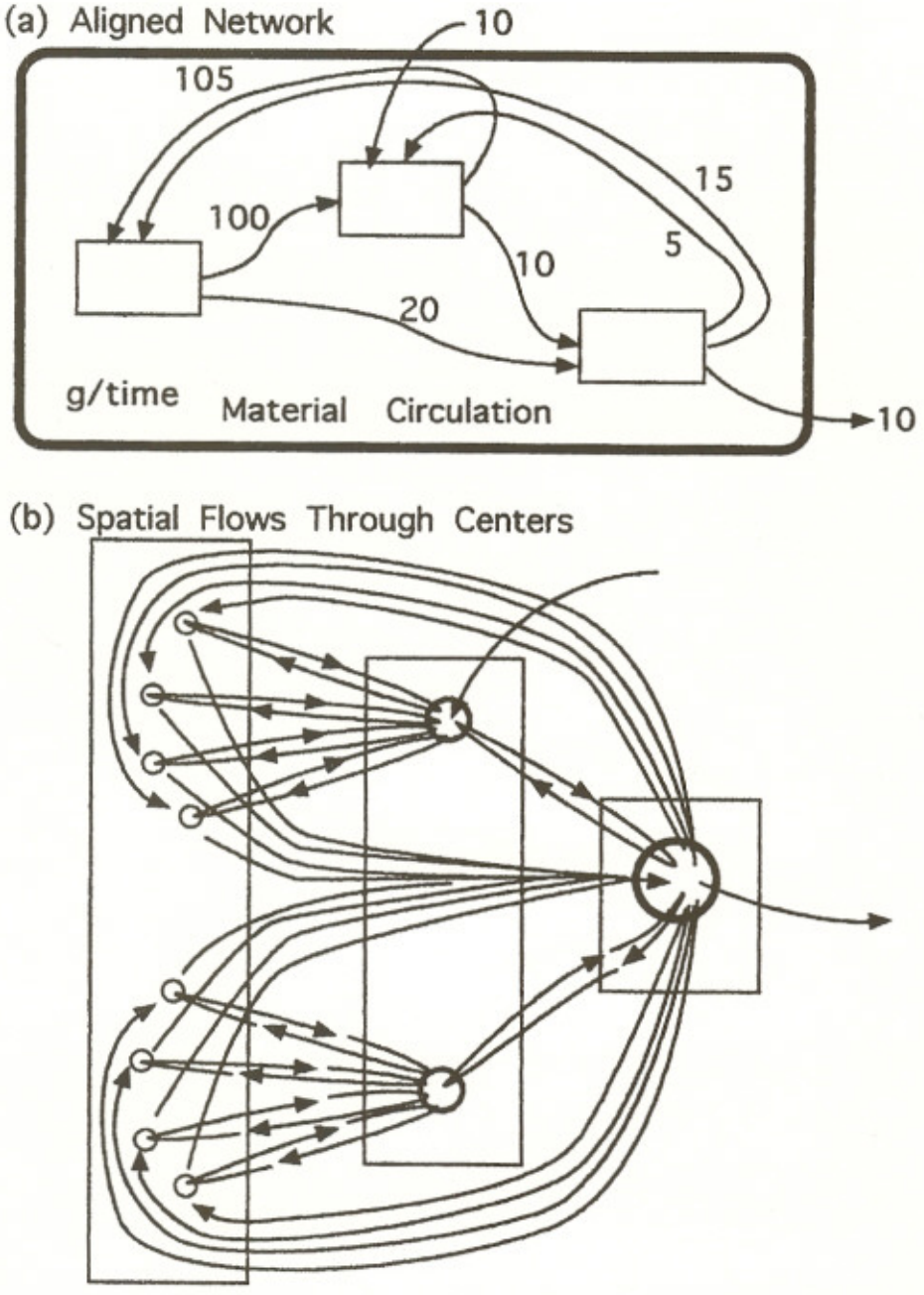

Figure 2 Aligned circulation of materials. (a) flows at steady state; (b) spatial converging to centers on the right and diverging return to support areas

When a material is incorporated into another product as a necessary part, it carries the emergy of that product. When that material is released as a recycling coproduct it carries that emergy. This method of cycle evaluation can be used to estimate the emergy per unit mass of a material in the environment that is sustained at higher concentration by the work done during the concentrating part of its cycle. However, as the material disperses (flows back to the left in the diagrams), it is losing concentration, emergy, and transformity. At any point the emergy necessary to reconcentrate it from that state might be calculated and this emergy subtracted from the concentrated value to obtain a transformity or emergy per mass.

Many chemical substances are dispersed in very dilute condition throughout the geobiosphere. Such concentrations have no available energy or emergy relative to their environment, since they are already at the background concentration used as reference in geobiospheric evaluations.

3.3 Spatial Centers

Self organization is observed to generate spatial centers in all levels of hierarchies (example: material circulation in Figure 2). Not only are materials converging and diverging, but other kinds of work are being converged transformed and the products sent back as feedback amplifiers. Concentrating flows spatially give the lesser quantity of transformed energy the means to feed back more commensurate effect. For example, storms organize their pressure distributions, which bring in more emergy-containing air. Mountains feedback their structures catching more hydrological energy from rains, driving the sedimentary cycle to generate new rocks.

3.4 Pulsing

Self organized systems are observed to accumulate storages that are subsequently consumed with a sharp pulse of use and growth of consumer structure before the cycle repeats. For one reason, the concentrating of consumer action gives a lesser quantity of transformed energy the means to feed back more commensurate effect. Familiar examples are storms, earthquakes, volcanoes, and civilizations. The longer the period of accumulation of inputs, the sharper and stronger the pulse (Examples: earthquakes from Gutenberg and Richter, 1949 and plankton from Kang, 1998). Longer periods of inputs generate a higher transformities by accumulation. Alexander (1979) estimated transformities for the pulses of disasters ranging from 1.1 E5 sej/J for an urban fire to 1.4 E7 sej/J for a volcanic emission.

4. Atmosphere

Main features and energy transformation processes of the atmosphere and ocean are drawn in aggregate form in Figure 3. Although traditionally studied separately, the atmosphere and the ocean are a single system in the coupling of winds to drive the sea and the sea to store and transport solar energy (Figure 3) The net effect is to develop streams of air mass and water masses of contrasting temperature thus fueling atmospheric-oceanic heat engine fluid structure, forces, and kinetic energy to reinforce empower processing.

With most of the global water in the ocean, self organization maximizes the surface area which can capture the more solar insolation to drive the evaporation that transfers heat energy into atmospheric vapor. The sea represents the background reference for geopotential energy of water. Because of 3.5 percent salt or more the fresh water in the sea and in pore waters of many sediments is at lower concentration than fresh water. The water in the sea is also the reference zero for the chemical potential energy (Gibbs free energy) of water.

The diagram of atmosphere and ocean in Figure 3 has flows on its right that connect with those on the left of the land diagram in Figure 4. The hexagon symbol in these figures is for recognizable units known to have inside processes that transform, store, and feedback reinforcements to intake. The tank symbol represents stored quantities (example: genes in Figure 4; ecosystem assets in Figure 5).

The suns insolation aided by the atmospheric-oceanic circulation and its other emergy inputs (deep heat, tide, and deep earth energy connecting by the land) distills the sea water into vapor and successive transformations to clouds, storms, precipitation, rivers and glaciers. In this atmospheric transformation series, the scale of turnover time, territory, of units increases as more smaller units are converged to generate the larger ones. Water vapor initially distributed widely over the sea is converged and transformed by the storms and general circulation. Example: small convection cell, thunderstorm, mesoscale storm, hurricanes, general circulation. Atmospheric phenomena with high transformities include high wind velocities, lightning, tornadoes, and hail.

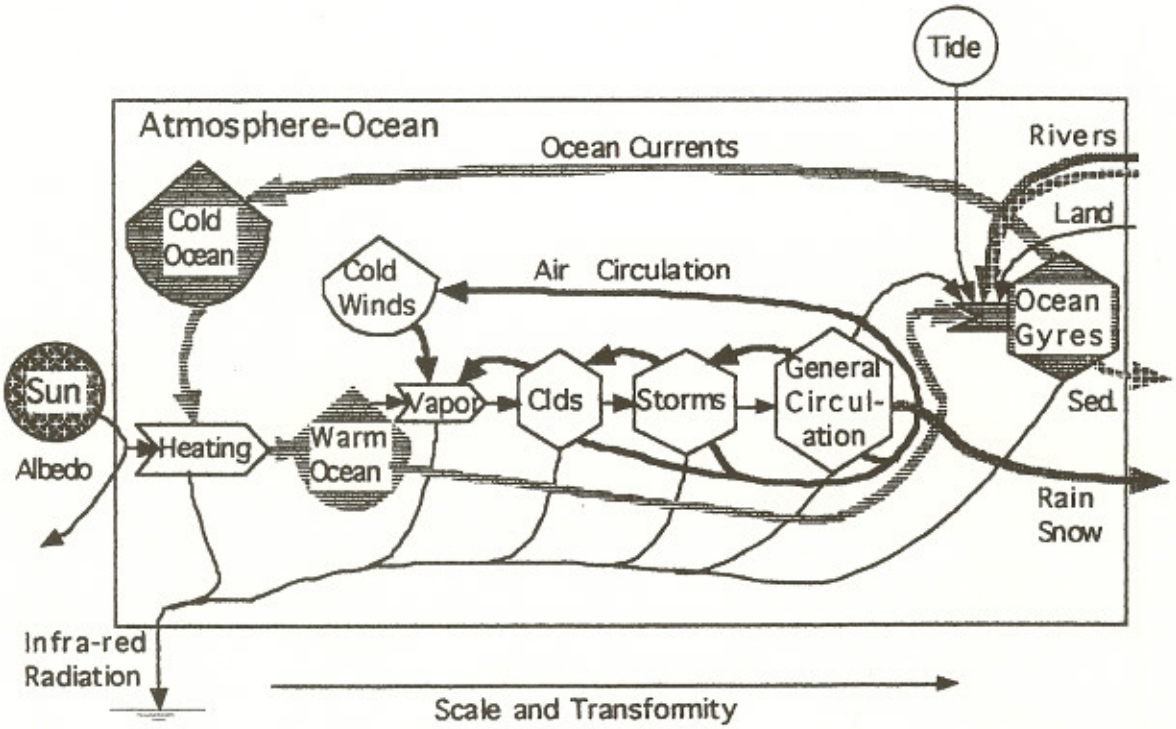

Figure 3. Coupled system of atmosphere and ocean arranged according to the energy hierarchy, showing main cycles of air, water, and sediment

5. Ocean

In the overview (Figure 3) ocean water converges from large areas of small current (low transformity) to a few places of intense current. The initial heating of the sea produces small temperature gradients which have small transformities and weak ability to drive currents, but after the solar energy is transferred to atmospheric vapor and concentrated as it is transformed into winds and rains, the atmospheric system returns work to the sea setting up global water circulation that converges further to generate high transformity Gulf Stream and its frontal vortices. Other places in the sea where there are convergences of empower are the beaches and reefs which receive and utilize strong wave energies. High transformity injections enter the sea with undersea volcanic emissions such as those in mid ocean ridges. Emergy is concentrated where the tidal wave is converged by the land configuration as in the Bay of Fundy. Mouths of rivers deliver high emergy in the freshwater (relative to sea water), river sediments, and its contained organic matter (from the upper right in Figure 3). The transformities increase along the food chains from sunlight to phytoplankton to zooplankton to small invertebrates to fishes to seals and whales. An interesting question is how is the energy hierarchy directed in going from the sea surface down to the deeps. Certainly total energy is less, but the scale and turnover times of physical and living phenomena may increase. The periods of flashing luminescent are greater in the deeps.

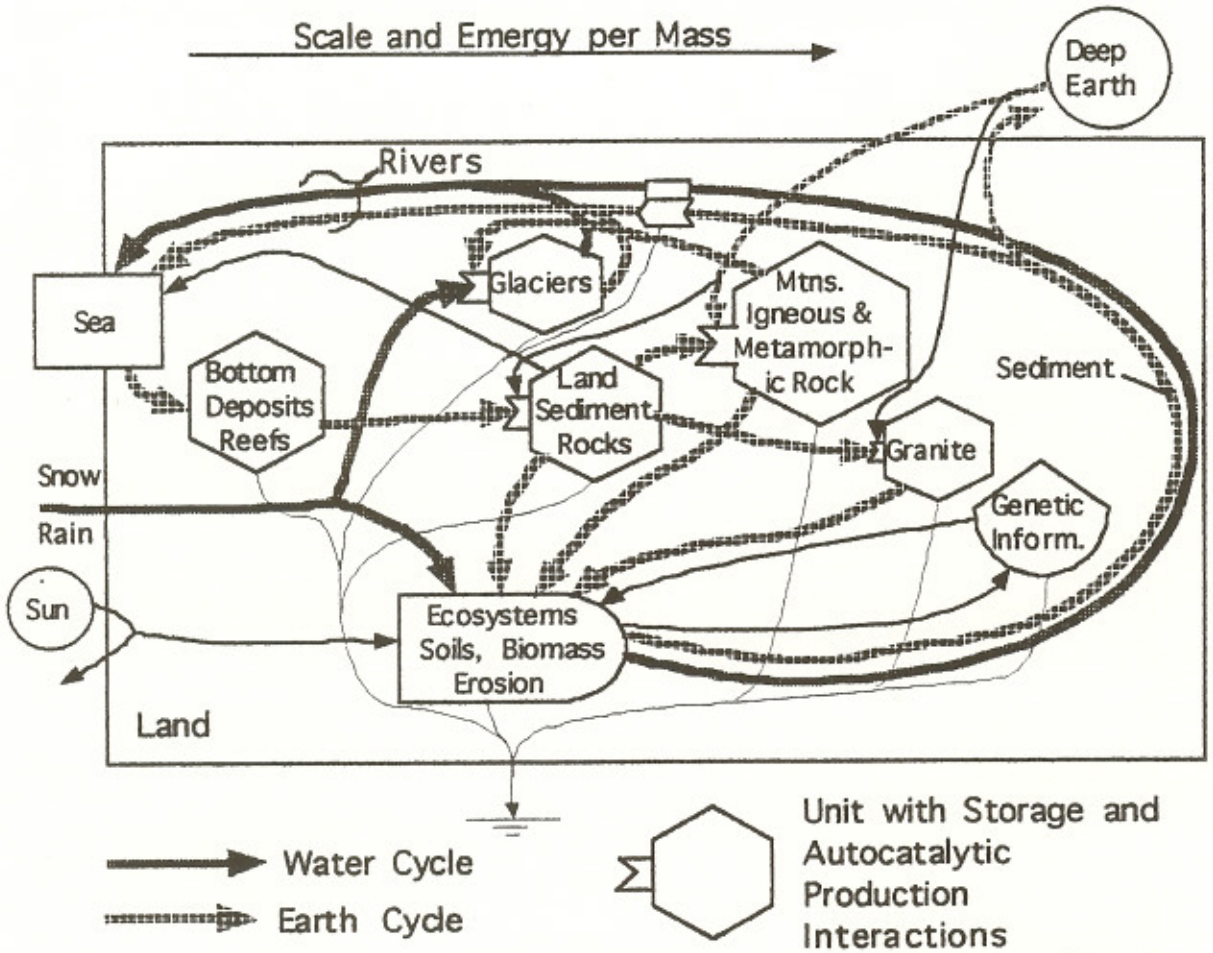

Figure 4. Main features of the energy hierarchy of the land including the sedimentary cycle, the ecological systems, the mountains, the genetic information, and the controlling role of the hydrologic cycle.

6. Land

Land is a concentrated product, of high emergy developed over million year periods by converging emergy from the deep earth energy sources, the tides, and the solar energy operating the hydrologic cycles. Items in the system of land maintenance are shown with their main interactions in Figure 4. Note the cycle of water from the precipitation through glaciers and rivers returning to the sea carrying sediments. The loose sediments reaching the sea consolidate and move in the earth cycle to form sedimentary rocks elevated as land. These converge into the more intensive mountain building centers of metamorphism and volcanic action. High emergy is accumulated where very gradual recrystallization develops plutonic crystalline rocks like granites of great age emerging slowly in the heart of continents. The oldest unit on land is the genetic information that carries the shared basic plan of life which was formed in symbiotic mutualism with the land evolution (Gaia concept). Floods, volcanic actions, earthquakes, and the concentrating of scarce minerals in rich ores have high transformities.

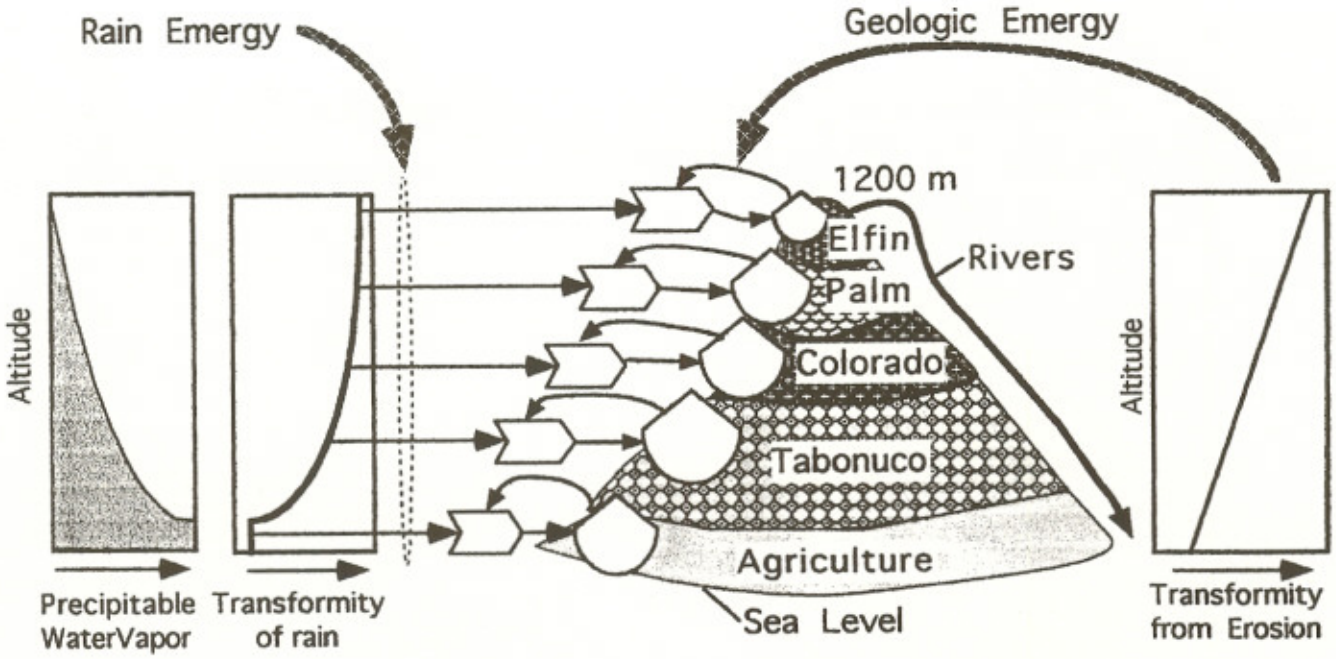

Figure 5. Luquillo Mountains of eastern Puerto Rico showing evaluation of annual empower from the sum of rain and geologic emergy inputs. Both inputs have transformities increasing with altitude.

7. Watersheds

Recent studies of watershed have evaluated the emergy characteristics starting with dispersed rain in mountains, converging in rivers to their mouths, diverging in wetlands, distributaries, and coastal waters. Sylvia Romitelli (1997) used empower density and transformity maps to show the spatial pattern of the energy hierarchy. Transformities increase from 20,000 to 500,000 solar emjoules/Joule because the self organization of water with landscape used geopotential energy to carved watershed patterns that can deliver flood pulses capable of maximum geologic work. By spreading out in the wetlands and deltas, these pulses maximize the use of chemical potential of waters and nutrients for wetland development and productivity. With this design geopotential emergy is used to increase the use of chemical potential. Dams that divert the geopotential energy as electricity leave the chemical potential without a means of spreading so that its potentials go to the sea without its normal high quality interaction with land. Day et al. (1997) used emergy to evaluate alternatives in the Mississippi River delta.

Figure 5 shows the way the input emergy and transformity was calculated for the runoffs from the Luquillo Mountains of eastern Puerto Rico. The rainfall is a function of altitude as it is affected by the mountains and vegetation. The transformities of rain increase with altitude since the water vapor at higher altitudes requires more convergence from below. The water vapor next to the earth's surface supports the water vapor that reaches higher altitudes through a cascade of transformation processes that pass water vapor to higher levels, vapor decreasing "exponentially" with height (Figure 5).

Like other self organized entities a developed watershed is an autocatalytic unit drawing on the emergy of the rain and that of the geological input that formed the mountains. Geologic emergy is usually delivered to the surface in pulses scattered over million year periods. Since geologic actions are on a longer time scale than the usual window for consideration of watersheds, the input to the contemporary transformations is from past storages. Its emergy can be added in proportion to the land use measured by its erosion.

Mountains are a hierarchical center with more convergence, uplift and corresponding erosion. In the Luquillo Mountains shown in Figure 5 there are 4 main vegetation types each of which has different emergy input from of the rain used in transpiration and geologic input from erosion). These inputs were related to the ecological productivities to get transformities, emergy, and emdollars for the ecosystems and the runoff waters used in the cities (Doherty, 1995, Scatena et al, 1998). The high values of the river outflow is a main environmental matching for the fossil fuel-basedeconomy of San Juan Puerto Rico.

8. Chemical Substances

Well known is the hierarchy of abundanceof chemical elements. (Elements of low atomic weight are abundant but elements of high atomic weight are scarce). This distribution comes from the energy hierarchy of nuclear processes in the stars with more emergy requiredto make the scarce higher atomic weight elements. The cosmic pattern of scarcity is somewhat reflectedin the concentrations in the earth's surface. Tennenbaum(1993) used the average abundanceof 21 metals in the earth to allocate a fraction of the earth's annual emergy budget. The result was values of emergy per mass ranging from 2 E9 solar emjoules per gram for iron to 2 E14 solar emjoules per gram for platinum.

Genoni and Montague (1995) and Genoni (1997) explored the concept that chemicals have effects correlated with their transformities presumably because of the mutual reinforcement patterns that survive self organization. Chemical substances with high transformity such as heavy metals and drugs have large effects per unit mass.

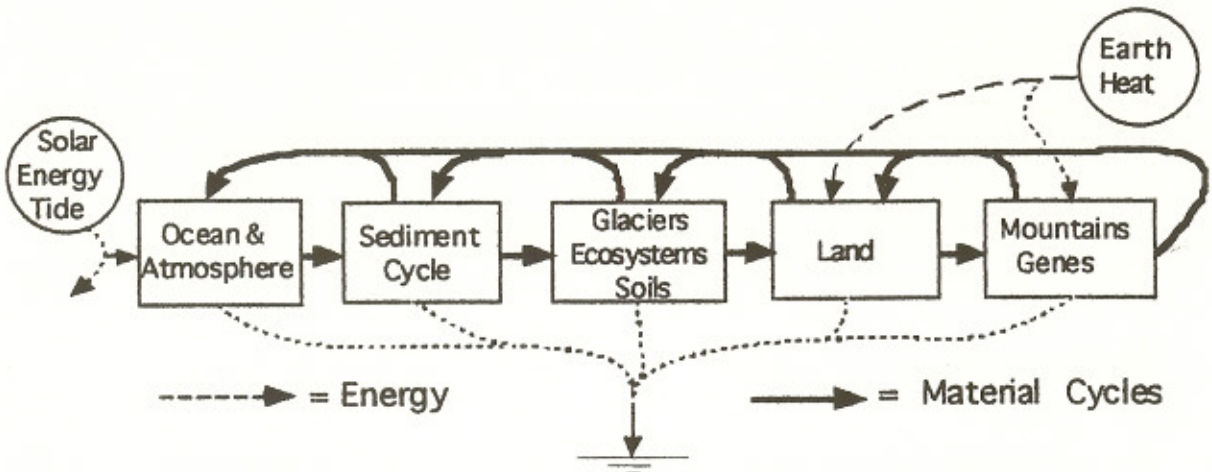

Figure 6. Summary view of the energy hierarchy of the geobiosphere

9. Summary

As a summary we can aggregate the geobiosphere energy web as a single series (Figure 6) although it may be misleading to do so. Transformities increase from left to right, but each unit has a wide range of transformities that overlap the other blocks. Each material cycle has an appropriate place in this series according to its emergy per mass. Depending on its transformity, each circulating element has an appropriate zone of operation in which it interacts with other inputs to production with mutual amplification. Cycles on the right have less mass. If materials are displaced out of the range appropriate for their transformity, they have less utility and may be a stress, a pollution. The principle of appropriate transformity and mass emergy may be useful for management of waste cycles in the development of ecological engineering and industrial ecology to make a more symbiotic joining of economy and environment.

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