Handbook of Emergy Evaluation

A Compendium of Data for Emergy Computation
Issued in a Series of Folios

Folio #2
Emergy of Global Processes

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Preface, Handbook of Emergy Evaluation

Emergy, spelled with an "m," is a universal measure of real wealth of the work of nature and society made on a common basis. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use (maximum empower). To aid evaluations, this handbook provides data on emergy contents and the computations on which they were based. A series of Folios are to be issued. Folio #1 introduces concepts and evaluates the empower of the geobiosphere.

There may be Folios by many authors, who take the initiative to make new calculations or assemble results from the extensive but dispersed literature. Data on emergy content are in published papers, books, reports, theses, dissertations, and unpublished manuscripts. Tabulating unit emergy values and their basis is the main purpose of this handbook. Presentations document the sources of data and calculations. As received, Folios will go to reviewers, back to authors for revision and back for publication. Each will have an index to indicate the page where emergy is evaluated. Each Folio should be usable without reference to other Folios.

Policy on Literature Review and Consistency

This handbook is based on emergy evaluations assembled from various reports and published literature plus new tables prepared by Folio authors. Our policy is to present previous calculations with due credit and without change except those requested by original authors. This means that unit emergy values in some tables may be different from those in other tables. Some tables may be more complete than others. No attempt is made to make all the tables consistent. Explanatory footnotes are retained. The diversity of efforts and authors enriches the information available to users, who can make changes and recalculate as they deem desirable to be more complete, update, or otherwise revise for their purposes.

The increase in global emergy base of reference to 15.83 E24 sej/yr (Folios #1 and #2) changes all the unit emergy values which directly and indirectly are derived from the value of global annual empower. Two alternatives are suggested when using the values from this handbook with previously published unit emergy value: Either increase the older values or decrease the new values by a factor for the change in the base used. For example, to use unit emergy values based on the 1996 solar empower base (9.44 E24 sej/yr), multiply those values by 1.68. Or, multiply the emergy values of this handbook by 0.60 to keep values on the older base. – Howard T. Odum and Mark T. Brown

Introduction to Folio #2

This Folio #2 evaluates emergy for some of the physical processes of the geobiosphere. The solar emergy of tidal energy and deep earth heat were estimated by the special procedure of setting two inputs making the same product as equivalent. The atmosphere, ocean, and plastic earth each contain a hierarchy of coupled operating units on different scales that build potential energy and circulate materials. Tables are given evaluating emergy of these energy hierarchies, which include oceanic heating, winds and storms, ocean currents, and earth cycles.

An *emergy equation* sets the empower of inputs into an energy transformation process equal to the empower of an output, where each term contains a flow multiplied by its emergy/unit. For example, the empower of global rain equals the sum of empower input terms for solar energy, tidal energy, and energy from the earth below the crust. If there are common terms, two or more emergy equations can be used to determine unit emergy values. Patterson (1993, 1996) and Collins (1997, 1998; Collins and Odum, 2000) developed matrix procedures for determining a set of unit emergy values from a set of equations for energy flows. In the first part of this Folio, two emergy equations are used to calculate the unit emergy of tidal energy and deep earth heat.

1. Inputs to the Geobiosphere

Three main emergy inputs to the geobiosphere are the solar energy, the tidal energy, and the deep earth heat. An emergy equation was written for the joint contributions of these inputs to crustal heat and another for the joint contributions to the geopotential energy of ocean water. With the transformity of solar equal one, by definition, the two equations are used to evaluate transformities of global tidal energy and global deep heat contribution.

Emergy of Heat in the Crust

Pictured in Figure 1 are the main processes contributing 13.21 E20 J/yr heat to the earth's crust as given by Sclater et al. (1980). By subtracting the estimate for radioactivity generation (1.98 E20 J/yr) and heat flux up from the mantle (4.74 E20 J/yr), the remaining annual flow of 6.49 E20 joules per year can be attributed to the sources from above, the sun and tide that drive the atmosphere, ocean, hydrological, and sedimentary cycles. These processes contribute heat downward by burying oxidized and reduced substances together, by friction, and by compressing sedimentary deposits. In the following emergy equation, each term is a product of solar transformity and energy flow. T_{rh} is the transformity of the crustal heat flow and T_{rt} the transformity of the tidal input.

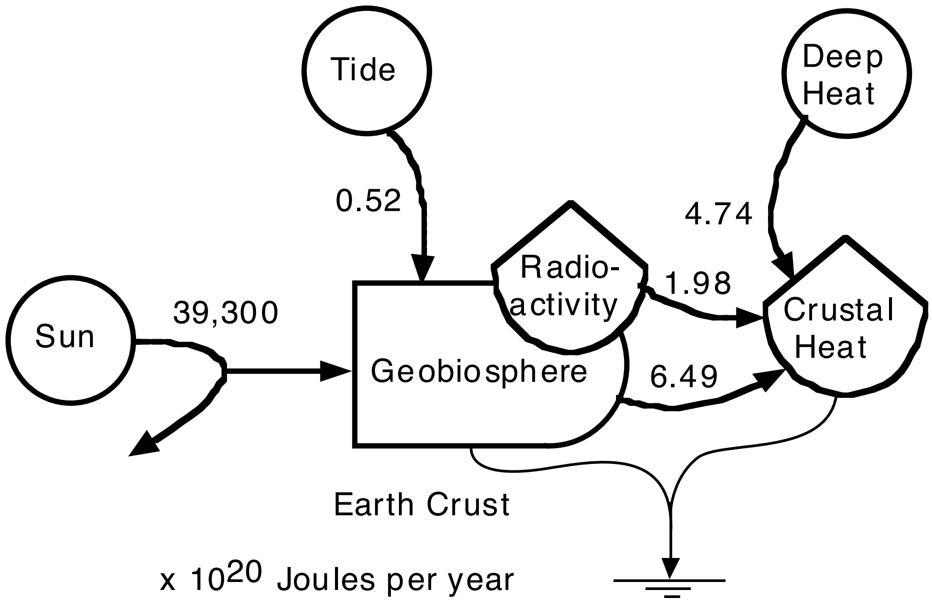

Figure 1. Energy diagram of sources of crustal heat used in equation (1):

Solar emergy + Tidal emergy = Emergy of the heat generated by the surface processes

$$(39{,}300 \text{ E20 J/yr})(1 \text{ sej/J}) + (0.52 \text{ E20 J/yr})*T_{rt} = (6.49 \text{ E20}) *T_{rh} \qquad (1)$$

Emergy of Tidal Energy Inflow and Use

Tidal energy is contributed to the geobiosphere by the gravitational forces of moon and sun that pull air, earth, and especially the ocean, relative to the rotating planet, causing friction and heat dissipation. Included in Figure 2 is the interaction of tidal energy with the ocean to generate potential energy which drives currents and is dissipated in the shallows of the coastal zone. Campbell (1998, 2000) used recent data on oceanic energy to infer the emergy of the tidal inflow and currents. Emergy of tide, solar-heating, sun driven wind stress, and earth energy contribute to gravitational potential energy (elevated waters) in the oceans. The earth contributes landform to the dynamics of the atmosphere-ocean.

As shown in Figure 2, an emergy budget equation for oceanic geopotential energy includes solar emergy, tidal emergy, and the contribution of the earth to the global process. The earth contributes 6.72 E20 J/yr (4.74 E20 J/yr deep heat and 1.98 E20 J/yr radioactive heat. Each term in the equation is a product of an annual energy flow in J/yr times the appropriate transformity. T_{rt} is the transformity of the contributions to the elevated ocean areas including the tide. T_{rh} is the solar transformity of the crustal heat.

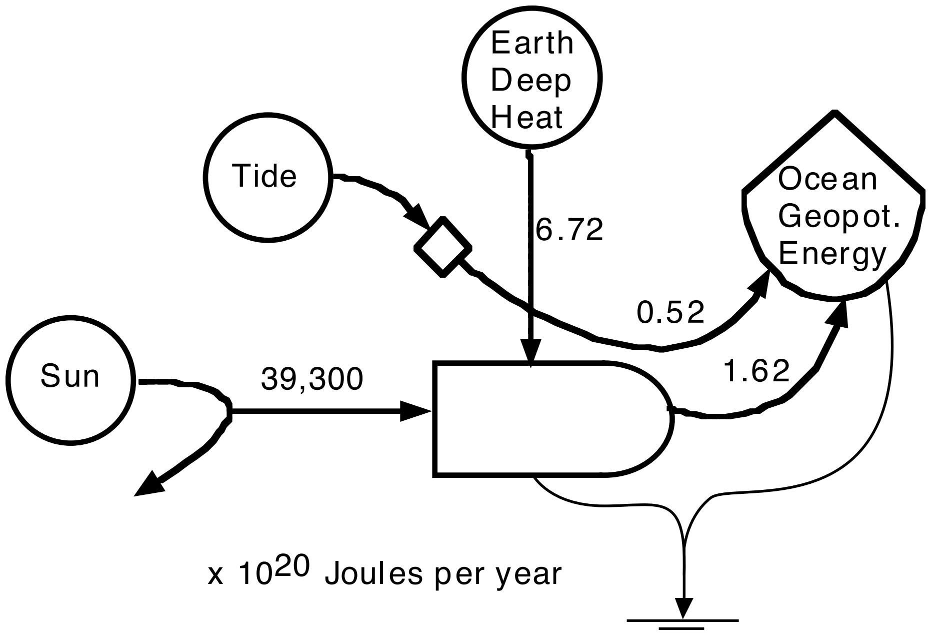

Figure 2. Energy diagram showing sources of oceanic geopotential used in equation (2):

Solar emergy + Tidal emergy + Deep Earth emergy = Oceanic geop. emergy

$$(39{,}300\ E20)*1.0 + (0.52\ E20)*T_{rt} + (6.72\ E20)*T_{rh} = (2.14\ E20)*T_{rt} \qquad (2)$$

<u>Combining Equations</u>

To obtain the unit emergy values (solar transformities), equation (1) was subtracted from equation (2) to obtain:

$$(6.72\ E20)*T_{rh} = (2.14\ E20)*T_{rt} - (6.49\ E20)\ T_{rh}$$

From this the solar transformity for tide was found to be

$$T_{rt} = 6.17\ T_{rh}$$

which was substituted in equation 1 to obtain the solar transformity of crustal heat:

$$T_{rh} = 11{,}981 \text{ sej/J}$$

and the solar transformity of tide:

$$T_{rt} = 6.17*11{,}945 = 73{,}923 \text{ sej/J}$$

Transformities of renewable inputs to the geobiosphere are summarized in Table 1. These were also used in Folio #1 to estimate the total annual emergy budget of the geobiosphere as 15.82 E24 sej/yr (solar emjoules per year).

Table 1
Emergy of Inputs to the Geobiosphere

Note	Inflow	Solar Transformity sej/J	Empower* 10^{24} sej/yr
1	Solar energy absorbed	1	3.93
2	Crustal heat sources	1.20×10^4	8.06
3	Tidal energy absorbed	7.37×10^4	3.83
	Total Global Empower	–	15.83

sej/J = solar emjoules per joule
* Global annual energy flow times solar transformity

Footnotes for Table 1

1 Transformity is 1.0 by definition; energy flow: 3.93 E24 J/yr based on solar constant 2 gcal/cm^2/min, 70 % absorption, and 1.27 E14 m^2 cross section facing the sun.

2 Transformity from emergy equation for crustal heat solved in previous section; heat release by crustal radioactivity 1.98 E20 J/yr plus 4.74 E20 J/yr heat flow from the mantle (Sclater et al., 1980) (Figure 1)

3 Transformity from emergy equation for geopotential of oceans in previous section. Energy flow 0.52 E20 J/yr (Miller, 1966) (Figure 2)

2. Emergy of Atmospheric Circulation

The abundant small circulation cells of the atmosphere converge and trans-form their energy into larger scale storms. These have less total energy flow but higher concentration, more potential energy storage, kinetic energy, transformity, and control action. Then these converge, concentrate, and transform into even larger circulation units that last longer and impact more. Low level circulation over the broad ocean surface collects latent heat which contributes to the convection over land, somewhat higher in the energy hierarchy. Table 2 evaluates transformities for the kinetic energy of the atmosphere.

Table 2
Energetics of Atmospheric Circulation Units

Note	Circulation Unit	Kinetic Energy Flow J/yr	Transformity[a] sej/J
1	Over ocean circulation		
	Latent heat into air	9.3 E23	12
	Kinetic energy used	2.33 E21	192
2	Cumulus land circulation	9.45 E21	485
3	Mesosystems	1.73 E22	912
4	Temperate cyclones	4.9 E21	3230
5	Hurricanes	6.1 E20	6487
6	Hemisphere general circulation		
	Surface winds	1.61 E22	983
	Average circulation	6.4 E21	2473
	Tropical jets	3.7 E21	4278
	Polar jet	1.61 E21	9832

Abbreviations: J/yr = joules per year; sej/yr = solar emjoules per year

a Solar transformity indicates position in the levels of energy hierarchy and quality. All or an appropriate fraction of the global annual e<u>m</u>ergy (15.83 x 10^{24} sej/yr) was divided by the annual energy flow for that earth process.

Footnotes for Table 2

1 Latent heat from low level ocean circulation:
Latent heat of whole ocean from Peixota and Oort (1992 p.172)
(1066 mm/yr)(1000 g/m^2/mm)(0.58 kcal/g)(4186 J/kcal)(3.6 E14 m^2/ocean) = 9.3 E23 J/yr latent heat into air

(0.2 w/m^2)(3.7 E14 m^2 ocean)(3.15 E7 sec/yr) = 2.33 E21 J k. energy use
Transformity: emergy split by energy 96% latent, 4% kinetic and 71% of area.
Latent heat (0.96)(0.71)(15.83 E24 sej/yr)/9.3 E23 J/yr = 11.6 sej/J

Vertical circulation, kinetic energy
(0.04)(0.71)(15.83 E24 sej/yr)/2.33 E21 J/yr = 192 sej/J

2 Land cumulus circulation: eddy kinetic energy flow from Peixota and Oort (1992) and Reiter (1969) for land, 2 watts/m^2
(2 J/m^2/sec)(1.51 E14 m^2 land) (3.15 E7 sec/yr) = 9.45 E21 J/yr
Transformity for land area (0.29)(15.83 E24)/9.45 E21 J/yr = 485 sej/J

3 Mesosystems: kinetic energy generation and use (Lin and Coover, 1988; Lin and Shen, 1991). Large thunderstorm, 13.5 w/m^2; squall line, 8.1 w/m^2; area of earth occupied by mesoscale storms 1%)
(10.8 J/m^2/sec)(3.15 E7 sec/yr)(5.1 E14 m^2/earth)(0.01) = 1.73 E22 J/yr

4 Dissipation of extra-tropical cyclones, 9780 cyclones/5 yr
(Wiin-Nielsen and Chen, 1993)
(0.3 J/m^2/sec)(3.15 E7 sec/yr)(5.21 E14 m^2/earth) = 4.9 E21 J/yr
Transformity: (15.83 E24 sej/yr)/(4.9 E21 j/yr) = 3230

Related data:
Palmen and Holopainen (1962) kinetic energy generation
(11.7 E13 J/sec)(3.15 E7 sec/yr) = 3.7 E21 J/yr

Related data:
Palmen and Newton (1969), generation rate16-21 w/m^2;
assume 15% of earth in temperate storms:
(18 J/m^2/sec)(3.15 E7 sec/yr)((5.1 E14 m^2/earth)(0.15) = 4.3 E22 J/y

Related data:
Eddy dissipation in zonal analysis (Wiin-Nielsen and Chen, 1993)
(1.8 J/sec)(3.15 E7 sec/yr)(5.21 E14 m^2/earth) = 2.95 E22 J/yr

Smith (1980) summary of extra-tropical cyclone kinetic energy dissipation
(6.3 J/m^2/sec)(3.15 E7 sec/yr)(5.21 E14 m^2/earth) = 1.01 E23

5 Tropical hurricanes, kinetic energy flow in global hurricanes
Chang (1972, page 103): 2-6 E19 J/day of latent heat release;
at 3% conversion to kinetic energy and dissipation: 0.6-1.8 E18 J/day. Riehl (1979) kinetic energy dissipation 1.29 E18 J/day.
With 78 storms/yr and lifetime of 6 days
(1.3 E18 J/day)(6 days/storm)(78 storms/yr) = 6.1 E20 J /yr
Split of the whole-earth emergy: assume the area and time for hurricanes requires 25% of earth in course of a year.
(15.83 E24 sej/yr)(0.25)/6.1 E20 J/yr = 6487 sej/J

6 Hemisphere circulation:
Surface winds, kinetic energy dissipation: 1 w/m^2

(1 J/m^2/sec)(3.15 E7 sec/yr)(5.1 E14 m^2/earth) = 1.61 E22 J/yr
Transformity: (15.83 E24 sej/yr)/(1.61 E22 J.yr) = 983 sej/J

Average circulation, zonal dissipation of general circulation:
Wiin-Nielsen and Chen (1993) 8.8 E20 J/yr standing kinetic energy
quotes Oort composite diagram on page 82
(0.4 J/sec)(3.15 E7 sec/yr)(5.21 E14 m^2/earth) = 6.4 E21 J/yr

Kinetic energy of main wind flow dissipation from Peixota and Oort (1992)
(0.18 J/sec/m^2)(5.1 E14 m^2/earth)(3.15 E7 sec/yr) = 2.9 E21 J/yr

Kinetic energy production in cross latitude circulation
(Palmen and Newton, 1969)
Winter 19 E13 watts; summer 1 E13 watts;
(10 E13 J/sec)(3.15 E7 sec/yr) = 3.15 E21 J/yr
Transformity 15.83 E24/3.15 E21 = 5025 sej/J

Tropical jet: Krishnamurti (1961); Wiin-Nielsen and Chen (1993)
Rate of dissipation of mean flow of tropical jet: 0.23 w/m^2
(0.23 J/sec/m^2)(3.15 E7 sec/yr)(5.1 E14 m^2/earth) = 3.7 E21 J/yr/jet

Polar jet: zonal kinetic energy dissipation (Oort and Peixoto (1974)
(0.1 J/m^2/sec)(3.15 E7 sec/yr)(5.12 E14 m^2/yr) = 1.61 E21 J/yr
Transformity: (15.83 E24 sej/yr)/(1.61 E21 J/yr) = 9832 sej/J

Emergy of the Circulation Units in the Atmosphere

Extensive research in recent decades has estimated the transformations of energy into available potential energy and the resulting kinetic energy of circulation. Circulation units of different size form an energy hierarchy.

Energy flow is largest with small scale circulation, often marked by cumulus clouds near the surface over land and ocean. Mesoscale systems such as large thunderstorms, squall lines and fronts, have less energy but higher transformities. Temperate cyclones and tropical hurricanes are next in the global hierarchy. The upper westerlies and jet streams have least energy, highest transformity and control actions, a familiar property among forecasters who find the movements of the smaller systems are controlled by the air flows above.

Table 2 evaluates energy flows for the various kinds of circulation and derives transformities. Where the main categories of circulation are necessary to the whole system, the emergy budget of the whole geobiospere is appropriate for estimating unit emergies. As footnotes indicate, some categories were identified as in parallel and calculated as splits. Items are arranged from top to bottom in order of increasing scale and transformity. In general, the scale and transformities increase with altitude.

Emergy of Latent Heat Flux and Rain with Altitude

Air high in the atmosphere is supported by air underneath. Like air in a stack of pillows, the air at the bottom is compressed by the weight above. The populations of molecular motions at the bottom support those higher up. Even for this static situation, more energy is involved at the bottom to support less at the top. Available energy flows from the solar-heated earth surface upward, much of it in the latent heat of evaporated water, especially from the oceans. Some of the water vapor that carries the heat of vaporization drawn from the sea surface is transferred upward as part of successive transformations in larger and larger whirlcells. The energy-containing water vapor is converted into rain at each stage as part of what is necessary to transfer a smaller amount to the next altitude. As a result, water vapor at high altitudes has higher transformity as suggested by Table 3, which estimates the average water vapor with altitude, the annual flux of latent heat reaching these altitudes, and the transformity of that latent heat, based on global annual emergy budget.

Table 3
Emergy of Global Water Vapor Flux with Altitude

Note	Level m	Emergy* E24 sej/yr	Latent Heat E23 J/yr	Transformity** sej/J
1	Surface	15.83	12.9#	12.2
2	990	15.83	7.4	21.4
3	1950	15.83	6.3	25.1
4	3010	15.83	3.7	42.7
5	4200	15.83	1.4	113.0
6	5570	15.83	0.90	176.0
7	7180	15.83	0.65	244.0

* Solar emergy inputs (solar empower) to the geobiospheric system from Table 1 of Folio #1 not including non-renewable consumption (fossil fuel and mineral use).

Global latent heat, evapotranspiration 1020 mm/yr,
(1020 mm/yr)(1000 g/m^2/mm)(0.58 kcal/g)(4186 J/kcal)(5.21 E14 m^2)
= 1.29 E24 J/yr

** Solar transformity calculated by dividing emergy flow from column 3 by the latent heat flux in column 4.
Abbreviation: sej/yr = solar emjoules per year

2-7 Latent heat reaching levels in the atmosphere calculated in proportion to the fraction of surface water vapor at each level. Precipitable water for each level was calculated from a global diagram of water vapor with pressure and latitude from Newell et al. (1972) given by Houghton (1977). Water vapor with altitude was calculated for pressures, temperature and density of standard atmosphere (Berry et al., 1945):

Altitude m	Mixing Ratio g/kg	Absolute Humidity g/m^3	Fraction of Surface %
110	7.72	10.3	100
990	5.43	6.0	58
1950	4.94	5.0	49
3010	3.28	3.0	29
4200	2.11	1.1	11
5570	1.06	0.7	7
7180	0.83	0.5	5

Precipitation varies with altitude, is affected by mountains, and depends on the weather systems in complex ways. For example, Glazir (1997) found the rainfall varying with altitude in mainland Asia. Rainfall increased with altitude in summer, but decreased with altitude in winter. Rains and snows that fall at high altitudes have higher real wealth value because of the high transformity of the processes in the upper air. In order to estimate global emergy per unit rainfall with altitude, the percent of global rainfall at each altitude was assumed to be proportional to the percent of surface latent heat flux reaching that altitude (last two columns in Table 3). These values of emergy per unit rain by altitude are useful for estimating inputs to mountain landscapes.

The evaluations in Table 3 are for the whole earth with 70% ocean. Regarding the land to be a higher level in the hierarchical organization of the geobiosphere, then rain over the land represents a convergence of oceanic resources. From line 1 in Table 4, transformity of continental rain is 2.9 E4 sej/J, and emergy/mass is 14.5 E4 sej/g.

Table 4
Evaluation of Continental Rainfall with Altitude*

Note	Level m	Emergy* E24 sej/yr	Rain# E20g/yr	Emergy/Mass E4 sej/g	Transformity** E4 sej/J
1	Surface	15.83	1.09	14.5	2.9
2	990	15.83	0.63	25.1	5.0
3	1950	15.83	0.53	29.9	6.0
4	3010	15.83	0.31	50.3	10.0
5	4200	15.83	0.12	131.0	26.1
6	5570	15.83	0.08	198.0	39.5
7	7180	15.83	0.05	315.0	63.1

* Emergy flow based on flux of latent heat in Table 3.

Continental rain at each level is estimated by multiplying the total continental rain (1.09 E20 g/yr from Ryabchikov, 1975) by the percentage of global latent heat flux above that level from note 2-7 in Table 3.

** Solar transformity calculated by dividing the emergy/mass in column 5 by 5 joules Gibbs free energy per gram of fresh water relative to sea water.

<u>Emergy of Dry Air</u>

Organization of the atmosphere cascades water vapor upward in its up currents, but it also generates dry air in parts of its circulation, in descending air, over deserts, removing waters from air masses by chilling and condensing in upper altitudes and at the poles. Dry air has available energy relative to wet surfaces. Thus, dry winds are a principal energy source, driving transpiration of water from stomata of leaves, the predominant integrating process in terrestrial photosynthetic production on land. The potential energy in dry air is the Gibbs free energy of the saturation deficit (difference between the air's vapor pressure and saturation vapor pressure). Especially when rains are not limiting, energy of dry air in wind flows is a valuable resource, one of the reasons for rapid growth of trees in New Zealand and the west coast of the United States. The energy of dry air contributes to the rapid geological cycles of arid areas.

Tilley (1999) evaluated the energy and transformity of dry air over land (Table 5). Transformity of dry air energy increases with elevations, since properties at higher levels are mostly based on the emergy contributed to the atmosphere at the surface. Higher altitudes contain higher levels in the energy hierarchy.

Table 5
Emergy of Saturation Deficit with Altitude over Land
(Tilley, 1999)

Note	Height m	Saturation Deficit Millibars	Energy* 10^{19} J	Energy Flux# 10^{21} J/yr	Transformity** sej/J
1	0	8.1	36.1	16.1	982
2	1,500	6.2	10.9	13.6	1,163
3	3,010	4.0	8.5	8.8	1,798
4	4,750	1.3	8.7	5.0	3,166
5	7,200	0.3	2.2	1.14	13,885

* Energy at each level calculated with data on atmospheric temperature and humidity over land from global climate data set (New et al., 1998) and upper air (Peixoto and Oort, 1996 and Haurwitz and Austin, 1944) were used to prepare a table of wa-

ter vapor pressure (e) and saturation deficit ($e-e_s$) by latitude and altitude. Saturation vapor pressure e_s = air pressure/622.
Gibbs free energy G was calculated for vapor pressure difference in J/g:
$G = (1/m)RT \text{ Ln } (e/e_s)$
$= (1/18 \text{ mole/g})(8.33 \text{ E3 J/mole-deg})(T \text{ deg K})(\text{Ln } e/e_s)$.
Energy in saturation deficit for air volumes at each altitude level was obtained from the product of air density, vapor mixing ratio, and energy per mass: (g/m^3 air)(g vapor/kg air)(G in J/g vapor)/1000

#Energy flux replacing dry air energy at the level and above; 0.35 E19 J above the 7,200 m level. Sum of energy at the level and above from column 4 was divided by 8.2 days replacement time and multiplied by
365 days/yr.

**Global annual emergy budget, 15.83 E24 sej/yr from Table 1 divided by flux, to replace the dry air energy at and above the altitude in Column 5.

1 Mean annual saturation deficit energy in whole atmosphere: 36.1 E19 joules; turnover time 8.2 days; mean value/turnover time = 16.1 E21 J/yr

2-5 Altitudes from standard atmosphere for levels with air pressures 1000, 850, 700, 550, and 400 millibars

3. Emergy of Ocean Processes

This section evaluates emergy flows in the ocean.

Emergy of Ocean Circulation
The circulation of the oceans is a major part of the geobiosphere. Like the atmosphere, it forms a hierarchy of circulation units. Available energy for ocean currents comes from the stress of atmospheric winds, from differences in geopotential density gradients from differential heating, from density differences due to salinity gradients (river discharges, melting ice, and differential evaporation), from tidal energy, and geomorphology of the ocean basin affected by earth processes. The most energy is in the small scale circulation at the ocean surface. Less energy and higher transformities are in the mesoscale gyrals (medium scale eddies in coastal waters and eddies from jets). The large scale general circulation of the oceans have highest transformities, with less energy overall, especially as emergy is converged in jets like the gulf stream.

Table 6 uses data from various sources to evaluate the transformities of four categories of circulation. Transformities for kinetic energy of ocean currents are much higher than those for winds on which they partly depend. Values for ocean currents are similar in magnitude for those in the largest rivers

Table 6
Energetics of Ocean Circulation[a]

Note	Circulation Unit	Annual Energy J/yr[b]	Transformity[c] sej/unit[d]
1	Surface eddies, J	3.0×10^{20}	5.3×10^{4} sej/j
2	Mesoscale gyrals, J	1.78×10^{19}	8.9×10^{4} sej/J
3	Sea Ice, g	3×10^{19}	5.3×10^{5} sej/g
4	Sea ice, J	9.0×10^{19}	1.76×10^{5} sej/J
5	Ocean circulation, J	8.5×10^{17}	1.87×10^{7} sej/J
6	Jet currents, J	1.67×10^{17}	9.4×10^{7} sej/J

a Ocean mass: 1.37×10^{24} g; surface area, 3.61×10^{8} km^2; average depth 3,795 m (Monin et al., 1977). One meter per second (m/sec) = 2.237 miles per hour (mph)

b Abbreviation: joules per year = J/yr

c Solar transformity indicates position in the levels of energy hierarchy and quality. Global annual emergy (15.83×10^{24} sej/yr) divided by the annual energy flow from column 3.

d Abbreviation: solar emjoules per joule = sej/J

Footnotes for Table 6

1 Energy in surface eddies for the area of all oceans, from wind waves, heating, density differences, etc. Energy in transient eddies to 200 m depth from Oort et al. (1989): 2.5 E 18 J; assume replacement time 3 days:
(2.5 E18 J/eddies)(121 eddies/year) = 3.025 E20 J/yr

2 Coastal gyrals, Gulf Stream eddies, scale about 10-300 km
Sample of kinetic energy in mesoscale eddies of the northwest Atlantic Ocean from coast to central ocean from Richardson (1993)
(165 cm^2/sec^2/g)(1 E6 cm^3/m^3)(1.025 g/cm^3)(1000 m thick)/1 E7 erg/J)

= 16,500 J/m^2 stored energy
Energy replacement time, Oort et al., weeks to months: 0.33 year
(16,500 J/m^2)(3 times/yr)(3.6 E14 m^2/ocean) = 1.78 E19 J/ocean/yr

3 Sea Ice; estimates from N. Untersteiner in Fairbridge (1966):
Mean total mass of sea ice: 4.5 E4 km^3; annual freezing and melting:
3 E4 km^3/yr (67%).
(3 E13 m^3/yr/earth)(1 E6 g/m^3) = 3 E19 g/yr/earth

4 Sea Ice, reversible energy of crystallization relative to meltwater;
(3 E19 g/yr)(0.080 kcal/g ice)(4186 J/kcal) = 1.0 E22 J/yr (state change).
Calculation of transformity made on the premise that sea ice is a necessary component of the oceanic-atmosheric system.

Ice energy in note 4 is available energy when advection of surrounding air and water temperature is different from 0 deg C. Calculation uses 5 deg C difference to estimate Carnot fraction (5 deg/278 deg Kelvin = 0.018) and operation of energy transfer at optimum efficiency = half of Carnot)
(1.0 E22 J/yr)(0.018)(0.5) = 9.0 E19 J/yr.

5 Total current energy of the oceans estimated by Oort et al. (1989) as
1.8×10^{18} J based on average velocity of 5.0 cm/sec. Replacement time assumed 2 years:
(0.5)(1.37×10^{21} kg)(0.05*0.05 m^2/sec^2)(2 yr) = 8.5 E17 J/yr

6 Jet Currents estimated for 5 oceans based on Gulf Stream transport (Monin et al., 1977); energy based on assumed velocity 0.5 m/sec:
(0.5)(8.5 E6 m^3/sec)(1000 kg/m^3)(0.5*0.5 m^2/sec^2)(3.15 E7 sec/yr)
(5 oceans) = 1.67 E17 J/yr

Heated Surface Waters and Ocean Thermal Energy Conversion (OTEC)
The available energy between the heated upper waters of tropical seas and the colder waters below has been much studied as a potential energy source for operating a heat engine for mechanical or electric power. Table 7 is the result of an OTEC evaluation of a proposed land-based installation in Taiwan, where detailed economic evaluations were made. Trans-formities of the warmed surface waters of the ocean are small. The trans-formity found for electric power is similar to the average of many other power generating processes (Odum, 1996, appendix).

Table 7
Transformities of Surface Ocean Heat*

Note	Available Energy sej/J	Solar Transformity
1	Warm-cold stratification	3.7
2	Available energy in ocean heat	60
3	Electric power from OTEC	1.76 E5

* Modified from Odum (2000)

Footnotes for Table 7

1 Annual production of energy of thermal difference: triangular hypsographic section multiplied by half of area of ocean and the temperature difference and divided by 1 year replacement time
(0.5)(1000 m)(0.5)(1.5 E14 m^2)(27.5 deg)(1 gcal/cm^3/deg)
(1 E6 cm^3/m^3)(4.186 J/gcal) = 4.3 E24 J/yr

Transformity using earth emergy from Table 1 Folio 1.
(15.83 E24 sej/yr/earth)/(4.3 E24 J/yr) = 3.7 sej/J

2 Earth Emergy input divided by half the Carnot fraction of the heat production from note #1
(11.82 E24 sej/yr)/[(0.5)(27.5/300.5)(4.3 E24 J/yr)] = 60 sej/J

3 Electric Power transformity from sum of emergy inputs divided by net power output.

Input emergy of equipment, services, and investment costs estimated by Tseng et al. (1991) multiplied by emergy/money ratio for Taiwan (2 E12 sej/$): 1.46 E19 sej/yr.

Aluminum pipe use per yr, with 2 E10 sej/g: 0.046 E19 sej/yr

Warm water use times heat content and Carnot fraction: 3.0 E16 J/yr
Emergy from available energy in water times transformity from Note 2
(3.0 E16 J/yr)(60 sej/J) = 0.12 E 19 sej/yr

Emergy input sum: (1.46 + 0.46 + 0.12) E19 = 2.04 E19 sej/yr

(Empower: 2.09 E19 sej/yr)/(Net power, 1.19 E14 J/yr) = 1.75 E5 sej/J

4. Emergy of Earth Processes

After several billion years of development, the land of the geobiosphere has been self organized into a hierarchy of components and cycles on many scales. Circulation of the land is driven by the atmosphere, ocean, hydrological cycle, and deep convection of the hot mantle below. Emergy of the geobiospheric engines converge materials to build rock and sustain continents against the flows of dispersal and recycle. Included are processes of chemical concentration and crystallization and erosion. Within the continents, mountains are hierarchical energy centers. In this section data from the literature are used to evaluate the emergy of principal parts of the earth cycles. Available energy is stored and transformed in geopotential and chemical potential form. For many purposes emergy evaluations on a mass basis (emjoules per gram) are the most useful for making calculations. Tables 8-10 evaluate the flows supporting the main features of the solid earth, the global hydrological cycle, and some principal ores and mineral resources of the earth.

Emergy of Main Features of the Land

Some major categories such as sedimentary cycle and mountain building can be evaluated in the aggregate as necessary to and requiring the global emergy budget (Table 8). An average annual emergy value of land is obtained from the average rate of erosion and replacement.

Table 8
Emergy of Continental Parts of the Global Energy System

Note	Componetnt and Units	Emergy* E24 sej/yr	Production Units/yr	Emergy/Unit sej/unit
1	Earth heat flux, J	15.83	2.74 E20	5.8 E4 sej/J
2	Glaciers, mass, g	15.83	2.48 E18	6.4 E6 sej/g
	crystal heat, J	15.83	8.3 E20	1.91 E4 sej/J
	geopotential, J	15.83	2.11 E19	7.5 E5 sej/J
	available heat, J	15.83	1.38 E19	1.14 E6 sej/J
3	Land area sustained, ha	15.83	1.5 E10	1.05 E15 sej/ha
4	Land, global cycle, g	15.83	9.36 E15	1.69 E9 sej/g
5	Continental sediment, g	15.83	7.4 E15	2.13 E9 sej/g
6	Volcanoes, g	15.83	3.05 E15	3.8 E9 sej/g
7	Mountains, g	15.83	2.46 E15	6.43 E9 sej/g
8	Cratons, g	15.83	0.81 E15	19.5 E9 sej/g

* Main empower of inputs to the geobiospheric system from Table 1, not including non-renewable consumption (fossil fuel and mineral use).

Footnotes for Table 8

1 Earth heat flux out from the land 2.74 E20 J/yr (Wylie, 1971)

2 Glaciers: 2.406 E16 m^3; replacement time 9700 yr (Voskresensky, 1978); mass/turnover time = 2.48 E12 m^3/yr
(2.48 E12 m^3/yr)(1 E6 g/m^3) = 2.48 E18 g/yr

Reversible energy of heat of Crystallization:
(0.080 kcal/g)(4186 J/kcal)(2.48 E18 g/yr) = 8.3 E20 J/yr

Geopotential energy of elevated glacier relative to sea level
(870 m avg. land elevation)(9.8 m/sec^2)(1 E3 kg/m^3)(2.48 E12 m^3/yr)
= 2.11 E19 J/yr

Available heat if surroundings of ice are 5 deg C warmer. Heat of crystallization times Carnot fraction: ($5^o/300^o$ K)(8.3 E20 J/yr) = 1.38 E19 J/yr

3 Land area sustained: annual global emergy budget divided by the area of the land sustained in hectares: 1.5 E10 ha/yr.

4 Land cycle: 2.4 cm/1000 yr from Garrels et al. (1975); density 2.6 g/cm^3
(0.0024/yr)(2.6 g/cm^3)(1.5 E18 cm^2 land area) = 9.36 E15 g/yr

5 Continental sediments; calculation by McGrane (1998): mass from Ronov and Yaroshevskiy (1976) 1850 E21 g; turnover time 2.5 E8 yr from Veizer (1988); mass/turnover time = 7.4 E15 g/yr

6 Volcanoes: 25.3% of mountains = 3.41 E23 g; turnover 112 E6 yr
Mass/turnover = 3.05 17 g/yr

7 Moutains: from Veizer (1988): mass in orogenic zones 1.35 E24 g; turnover time 548 E6 yr; mass/turnover time = 2.46 E15 g/yr

8 Cratons: Continental blocks of metamorphic and igneous rock; calculation after McGrane (1998). 20.1 E24 g from Ronov and Yaroshevskiy (1976); turnover time: half life 1.73 E9 years/0.693 (Veizer (1988); mass/turnover time = 0.81 E15 g/yr

Emergy and the Spatial Organization of the Land

Because of the spatial organization of earth processes there are large differences in rates of earth cycle, energy flux, and unit emergy between the high energy mountain centers and the broad low level areas in between. The larger scale features have longer turnover times, mass storages and unit emergy values. Figure 3, from Chorly et al. (1984), shows the erosion rates increasing with altitude. Here higher altitude means more mass converging as uplift (Figure 3b), balanced on the average by higher rates of geologic replacement from below. Higher land elevation represents smaller total quantity but circulating at higher concentration per area.

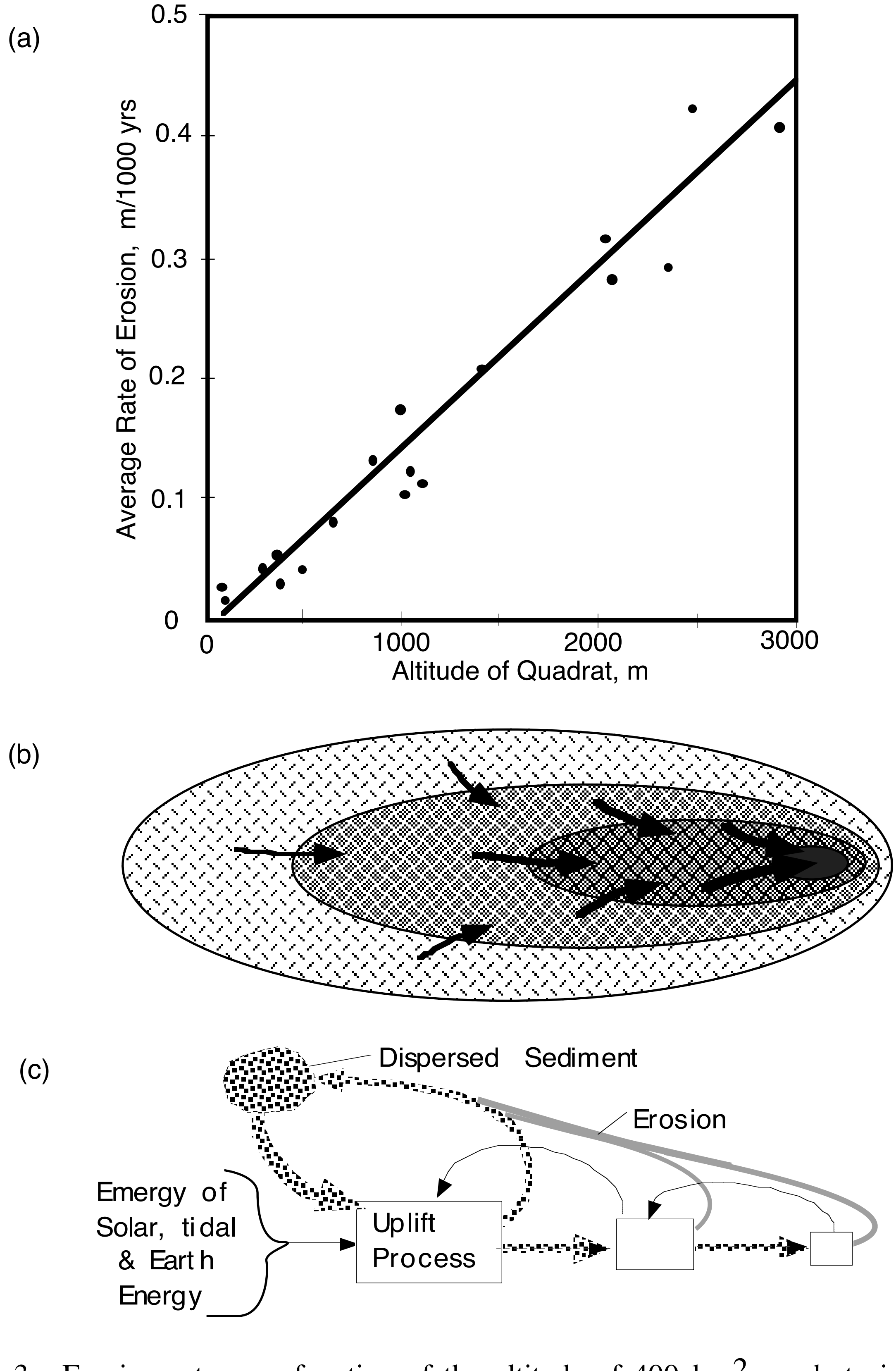

Figure 3. Erosion rate as a function of the altitude of 400 km^2 quadrats in the United States and Europe (Chorly, 1984, using data of Schumm, 1963.

Land area from the earth's hypsographic curve (area of land versus altitude) was multiplied by the erosion rate from Figure 3a to obtain the areal distribution of earth cycling. This pattern of mass flow is interpreted as the result of successive energy transformations by the lower altitudes supporting uplift at higher altitudes (Figure 3c). Hence, the mass flow at each level is related to the whole earth emergy to obtain the emergy per mass with altitude (Table 9). The unit emergy values are also appropriate for evaluating sediments generated in the earth cycle.

Table 9
Annual Emergy Contributions to Elevated Lands*

Altitude km	Area[a] 10^{12} m2	Erosion Rate[b] 10^3 g/m^2/yr	Mass Upflow[c] 10^{15} g/yr	Emergy/mass[d] 10^9 sej/g
0	148.1	–	9.36	1.7
1	42.3	0.15	6.34	2.5
2	19.7	0.29	5.71	2.8
3	8.5	0.44	3.74	4.2
4	2.7	0.60	1.62	9.8
5	0.5	0.76	0.38	41.6

Abbreviations: sej = solar emjoules; yr = year; E3 means multiplied by 10^3

a From global hypsographic curve for land (Scheidegger, 1963)

b See Figure 3 from Chorly et al. (1984). Y = 0.1535 X - 0.0108

c Product of column #2 and #3

d For sea level, average value for earth replacement from item 4, Table 8 For upper levels: 15.83 E24 sej/earth from Table 1 divided by mass flow in column #4

Emergy of Rocks

The self organizational processes of the earth circulation generate many kinds of rock. Sediments become cemented, reefs are generated by eco-systems, sedimentary rocks are metamorphosed, etc. Table 10 estimates unit emergy for some rocks which are major, necessary components of the earth cycles for which the total earth emergy was assigned, a procedure appropriate for co-products. Perhaps evaluation of rock types with data from smaller scale case histories can be assembled in the future for comparison.

Table 10
Emergy of Sediments and Rocks

Note	Component and Units	Emergy* E24 sej/yr	Production E15 g/yr	Emergy/Unit E9 sej/g
1	Global land cycle, g	15.83	9.36	1.69
2	Continental sediment, g	15.83	0.4-9.4	1.7-42
3	Pelagic-abyssal sediment, g	15.83	9.7 E15	1.63
4	Shale	15.83	3.9 E15	4.1
5	Sandstone	15.83	1.87 E15	8.5
6	Limestone	15.83	1.68 E15	9.5
7	Evaporites	15.83	0.094	169.0
8	Oceanic basalt, g	15.83	63.4	0.25

* Main empower of inputs to the geobiospheric system from Table 1 not including non-renewable consumption (fossil fuel and mineral use). Total global emergy budget is used for items believed mutually necessary to the global system as presently organized to be regarded as co-products.

1 Total land cycle repeated from item #4 in Table 8: 9.36 E25 g/yr

2 Continental sediment values for different altitudes from Table 7

3 Pelagic Sediment: storage 0.63 E24 g; turnover time 64.9 E6 yrs (Veizer, 1988; storage/turnover time = 9.7 E15 g/yr

4 Shale: mass circulation = 42% of continental area (item #1)

5 Sandstone: mass circulation = 20% of continental area (item #1)

6 Limestone:mass circulation = 18% of continental area (item #1)

7 Evaporites: mass circulation = 1% of continental area (item #1)

8 Oceanic basalt: Storage 5.4 E24 g; turnover time 85.1 E6 yrs (Veizer, 1988); storage/turnover time = 63.4 E15 g/yr

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