

The thermodynamics of Earth

Albert Einstein considered thermodynamics to be among those principles unlikely to be changed by future scientific discoveries. “It is the only physical theory of universal content,” he wrote, “concerning which I am convinced that within the framework of the applicability of its basic concepts, it will never be overthrown.”

Today, thermodynamics may not be the most fashionable area of science, but it still provides a set of bedrock principles with important implications for anything from protein folding to the physics of black holes. It is also a source of valuable insight into the physics of the Earth system, as a recent book makes clear. *Thermodynamic Foundations of the Earth System*, written by physicist Axel Kleidon, examines what goes on in the Earth’s atmosphere, oceans, geosphere and biosphere from the perspective of energy and entropy flows. Kleidon draws on a wide range of research to help clarify in quantitative detail how thermodynamics shapes the entire Earth system, and, in particular, how humanity has come to play a central role in the Earth’s physics.

The power of thermodynamics rests on the understanding that fundamental consequences follow from how the energy is organized within a system, as reflected in its entropy, a measure of the dispersal of energy across microscale degrees of freedom. The bulk of Kleidon’s book examines how radiant energy is progressively converted to various forms of higher-entropy energy in a cascade through the Earth system, creating temperature gradients, mass flows, phase changes and rich chemistry. The low-entropy energy changes entropically as it moves through the Earth system. Radiant energy arriving from the Sun gets converted into chemical, kinetic and thermal energy, stirring myriad entropy-producing flows.

The energy ultimately leaves as high-entropy heat waste that radiates back into space. The overall energy balance (roughly) leaves the total energy unchanged, yet the net flow of entropy away allows the organization and structure we see on Earth. The radiant solar energy emitted from the Sun at 5,760 K ends up as radiant thermal energy at about 255 K; roughly 23 times more photons get emitted back away from the Earth as arrive to it, and these carry away net entropy.



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Where do people fit in? As Kleidon argues, a proper thermodynamic perspective reveals that we play a very significant role in Earth system physics. Getting that proper perspective requires distinguishing raw energy from free energy — the component available for doing useful work, driving dynamics, and converting energy from one form to another.

Considering raw energy flows, humanity’s activities naively look quite small compared to other physical flows. For example, our total energy use is approximately 17 TW, which is roughly 10,000 times less than the power of the radiant solar energy arriving at the upper atmosphere. Yet, as Kleidon makes clear, things look very different in terms of free energy.

Humans draw free energy in two fundamentally different ways. First, we use energy to support the basic metabolisms of billions of people, based on the consumption of low-entropy food created as a product of farming and photosynthesis. The total energy dissipated by human metabolism turns out to be comparable to the energy driving oceanic circulation. Second, we also draw on low-entropy sources of energy — from fossil fuels, nuclear fission and renewable energy sources — for external purposes such as building, manufacturing, transport, heating, lighting and so on. Our total power consumption in this domain is 10–100 times larger than for metabolism.

In standard economic analyses, energy in these two broad domains is simply taken as a resource much like any other; entropy is ignored. Thermodynamics implies, however, that our energy use faces distinct limits within each domain. In the case of food production, the limit emerges from the possible efficiency of photosynthetic conversion of energy into nutritious biomass. Thermodynamics limits this efficiency to a maximum of about 12%, although real plants only achieve about 3%. Not all of the resulting biomass can be used to generate useful sugars, fats and

proteins; estimates put the optimum at around 40%. Putting these numbers together yields a maximum for food production of about 0.3% of incoming energy producing useful food energy. For today’s population, this translates into a minimum of about 2% of the entire productive land surface being required for food production, if we converted energy with maximum efficiency.

As Kleidon points out, we don’t achieve such efficiency in practice, and as a result already exploit more than 33% of the available land surface, largely through grazing of animals, which harvests energy at much lower efficiencies. Yet the 2% limit makes it clear that humans, even if operating at optimal efficiencies, make significant demands in the Earth’s energy flows.

In the case of external energy, the numbers again show that human primary energy demands are already comparable to other fundamental free energy flows in the physical environment. We currently derive most of this energy from fossil fuels. If, in the future, we were to generate comparable energy from, say, harnessing winds, this would mean taking roughly half of the entire free energy available in winds, with dramatic slowing and alteration of those winds a certain consequence.

What does the future hold? Kleidon considers the thermodynamic limits for energy conversion from winds, tides, geothermal and solar, and shows that direct conversion of solar energy offers by far the greatest source of available energy, because it draws directly on low-entropy radiation. This simply reflects the fact that other sources of energy result from conversion of the radiation stream to another free energy flow — of mass or heat, for example — with efficiency loss at each stage.

Human societies draw the attention of, among others, sociologists, anthropologists, economists, psychologists and political scientists; not so much physical scientists. Yet humanity is undeniably subject to physical law, and we thrive only due to the far-from-equilibrium conditions on Earth. We’re “a dissipative process that is embedded within the functioning of the Earth system,” as Kleidon puts it. This important book fills a crucial gap by drawing out the implications of the second law of thermodynamics for the whole Earth system. □

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