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Long-Term Global Heating From Energy Usage

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Even if civilization on Earth stops polluting the biosphere with greenhouse gases, humanity could eventually be awash in too much heat, namely, the dissipated heat by-product generated by any nonrenewable energy source. Apart from the Sun's natural aging—which causes an approximately 1% luminosity rise for each 10^8 years and thus about 1ºC increase in Earth's surface temperature—well within 1000 years our technological society could find itself up against a fundamental limit to growth: an unavoidable global heating of roughly 3ºC dictated solely by the second law of thermodynamics, a biogeophysical effect often ignored when estimating future planetary warming scenarios.

Today's civilization runs on energy for the simple reason that all ordered, complex systems need energy to survive and prosper. Whether galaxies, stars, planets, or life forms, it is energy that keeps open, nonequilibrium systems functioning—to help them, at least locally and temporarily, avoid a disordered state (of high entropy) demanded by the second law of thermodynamics. Whether living or nonliving, dynamical systems need flows of energy to endure. If stars do not convert gravitational matter into fusion, heat, and light, they collapse; if plants do not photosynthesize sunlight, they shrivel and decay; if humans do not eat, they die. Likewise, society's fuel is energy: Resources come in and wastes go out, all while civilization goes about its daily business.

Throughout the history of the universe, as each type of ordered system became more complex, its normalized energy budget increased. Expressed as an energy rate density (watts per kilogram), a clear ranking in energy usage is apparent among all known ordered structures that have experienced, in turn, physical, biological, and cultural evolution: stars and galaxies (10^{-4}–10^{-2} watts per kilogram), plants and animals (0.1–10 watts per kilogram), humans and society (~10^2 watts per kilogram). Figure 1 places these and other energy budgets into a broad perspective [*Chaisson*, 2003].

Rising Energy Use on Earth

Of relevance to the issue of global warming is the rise of energy use within the relatively recent past among our hominid ancestors, continuing on to today's digital society and presumably into the future as well [*Simmons*, 1996; *Christian*, 2003]:

- hunter-gatherers of a few million years ago used about 1 watt per kilogram (0.05 kilowatt per person);
- agriculturists of several thousand years ago used roughly 10 watts per kilogram (0.5 kilowatt per person);
- industrialists of a couple of centuries ago used about 50 watts per kilogram (2.5 kilowatts per person);
- citizens of the world today, on average, use approximately 50 watts per kilogram (2.5 kilowatts per person); and
- residents of the affluent United States use around 250 watts per kilogram (12.5 kilowatts per person).

Such energy rate metrics have clearly risen over the course of recorded and prerecorded history. The cause of this recent rise is not population growth; these are power density values caused by the cultural evolution and technological advancement of our civilization. Figure 2 maps today's per capita rate of energy consumption, globally [*Energy Information Administration*, 2006].

All of the above suggest that the total energy budget of society on Earth will likely continue growing for three reasons. First, world population is projected to increase until at least the late 21st century, when it

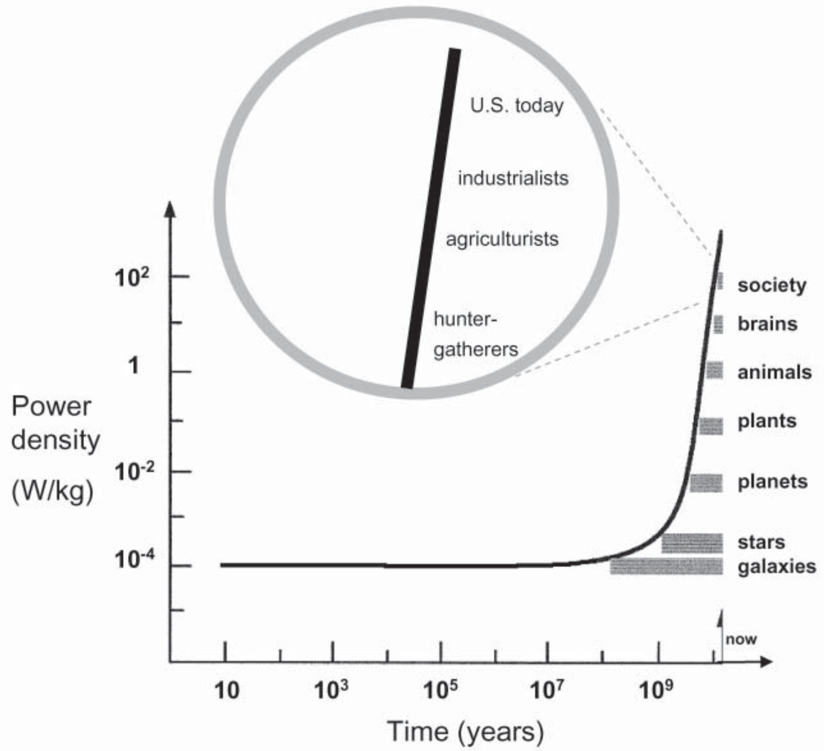

Fig. 1. Temporal dependence of energy rate density for a wide spectrum of energy-using systems over billions of years, including (within the circle, which magnifies part of the curve at top right) per capita power usage during the cultural advancement of human society in much more recent times. Adapted from Chaisson *[2003].*

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might level off at approximately 9 billion people [*United Nations Department of Economic and Social Affairs*, 2006]. Second, developing countries will mature economically, perhaps for the next several centuries, until equity is achieved among the world community of nations. And third, the per capita energy rate will probably continue rising for as long the human species culturally evolves, including conditioning our living spaces, relocating cities swamped by rising seas, and sequestering increased greenhouse gases—which implies that even if the first two reasons for growth end, the third will continue increasing society's total energy budget, however slowly.

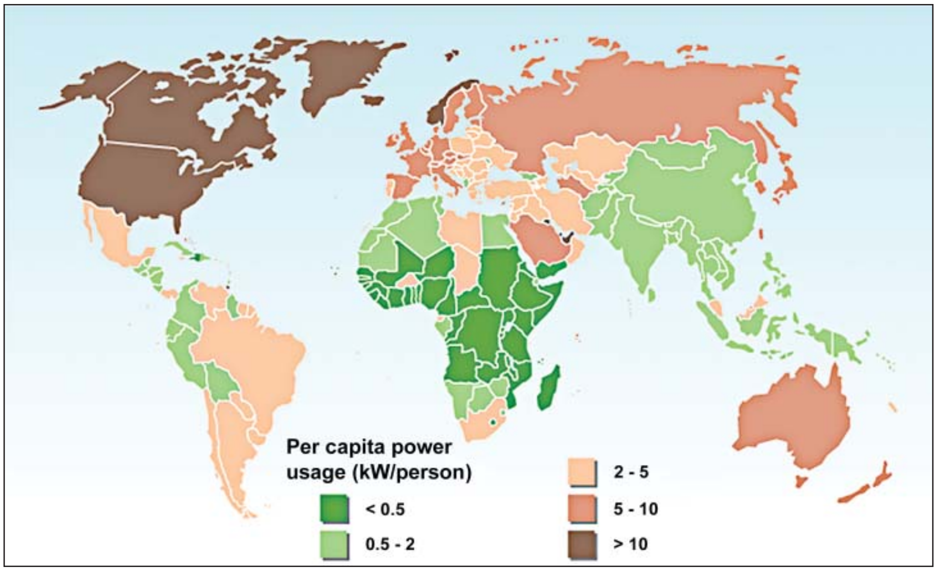

Fig. 2. Spatial dependence of energy rate density, or per capita power usage, across the globe today. Data from Energy Information Administration *[2006].*

Heat By-Products

Current fears of energy shortfalls aside, in the long term our true energy predicament is that the unremitting and increasing use of energy from any resource and by any technique eventually dissipates as heat at various temperatures. Heat is an unavoidable by-product of the energy extracted from wood, coal, oil, gas, atoms, and any other nonrenewable source. The renewable sources, especially solar, already heat Earth naturally; but additional solar energy, if beamed to the surface, also would further heat our planet.

Regardless of the kind of energy utilized, Earth is constantly subjected to heat generated by our industrial society. We already experience it in the big cities, which are warmer than their suburbs, and near nuclear reactors, which warm their adjacent waterways. A recent study of Tokyo, for example, found that city streets are about 2°C warmer when air conditioning units not only suck hot air out of offices but also dissipate heat from the backs of those inefficient machines [*Ohashi et al.*, 2007]. Everyday appliances—including toasters, boilers, and lawn mowers—all generate heat while operating far from their theoretical efficiency limits. Electricity production is currently about 37% efficient, automobile engines are roughly 25% efficient, and ordinary incandescent lightbulbs are only around 5% efficient; the rest is immediately lost as heat.

Even every Internet search creates heat at the Web server, and each click of the keyboard engenders heat in our laptops. Information data processing of mere bits and bytes causes a minuscule rise in environmental temperature (owing to flip/flop logic gates that routinely discard bits of information). Individual computer chips, miniaturized yet arrayed in ever higher densities and passing even higher energy flows, will someday be threatened by self-immolation.

Such widespread inefficiencies would seem to present major opportunities for improved energy conversion and storage. But there are limits to advancement. No device will ever be perfectly efficient, given friction, wear, and corrosion that inevitably create losses. Conversion and storage devices that are 100% efficient are reversible and ideal—and they violate the laws of real-world thermodynamics. Just like perpetual-motion machines, they cannot exist. To give but one example of less than ideal devices, today's photovoltaics currently achieve 10–20% efficiency, and when optimized they might soon reach 40%, yet the absolute theoretical (quantum) limit for any conceivable solar device is approximately 70%. Even with improved efficiencies, per capita and therefore societal demands for energy have continued to rise—and, in any case, all nonrenewable energy used must be eventually dissipated.

As we increasingly pollute the air with heat, adverse climate change could conceivably occur even in the absence of additional greenhouse gases. How much energy can all of our cultural devices—automobiles, stoves, factories, whatever—produce before Earth's surface temperature increases enough to make our planet potentially hellishly uncomfortable?

Global Temperature

The equilibrium temperature T at Earth's surface is reached when energy acquired on the dayside equals energy radiated away isotropically as a black body:

$$(k/r^2)\pi R^2(1 - A) = (\varepsilon\sigma T^4)4\pi R^2$$

where k is the solar constant at Earth (1370 watts per square meter), r is the distance from the Sun (in astronomical units), A is Earth's albedo (0.31), R is Earth's radius, ε is the effective surface emissivity (0.61), and σ is Stefan's constant. The result, including effects of natural greenhouse heating, is 288 K, or a globally averaged temperature for Earth's surface of 15°C. This is the surface temperature value that has risen during the twentieth century by around 0.7°C [*Intergovernmental Panel on Climate Change*, 2007]. Albedo changes are now and will likely continue to be negligible globally.

Nature's power budget on Earth is dominated by the Sun. Compared with our planet's solar insolation of 120,000 terawatts (absorbed by the land, sea, and air, and accounting for Earth's albedo of 31%), our global civilization currently produces an imperceptible 18 terawatts (approximately), about two thirds of which is wasted. But with humanity's power usage on the rise (~2% annually [International Energy Agency, 2004]) as our species multiplies and becomes more complex, society's energy demands by the close of the 21st century will likely exceed 100 terawatts—and much of that energy will heat our environment.

Note that utilizing solar energy that naturally affects Earth (including solar-driven tides, wind, and waves), without generating any further energy via nonrenewable supplies, would not cause additional heat. But if we do generate heat from other, nonrenewable energy sources, in addition to the Sun's rays arriving daily—or if we use space-based arrays to redirect additional sunlight to Earth that would normally bypass our planet—then the surface temperature will rise. That is, even if we embrace coal and sequester all of its carbon emissions, or use nuclear methods (either fission or fusion) that emit no greenhouse gases, these energy sources would still spawn additional heat above what the Sun's rays create naturally at Earth's surface.

Heating Scenarios

Estimates of how much heat and how quickly that heat will rise rely, once again, on thermodynamics. Because flux scales as σT^4, Earth's surface temperature will rise about 3°C (an IPCC "tipping point") when $(291/288)^4$, namely, when about 4% more than the Sun's daily dose (4800 terawatts) is additionally produced on Earth or delivered to Earth. Such estimates of energy usage sufficient to cause temperature increases are likely upper limits, and hence the times needed to achieve them are also upper limits, given natural greenhouse trapping and cloud feedbacks of the added heat. How far in the future, if ever, such heating might occur depends on assumptions [*Chaisson*, 2007]:

- If global nonrenewable energy use continues increasing at its current rate of about 2% annually and if all greenhouse gases are sequestered, then a 3°C rise will still occur in roughly 8 doubling times, or about 280 years (or ~350 years for a 10°C rise).
- More realistically, if world population plateaus at 9 billion inhabitants by 2100, developed (Organisation for Economic Cooperation and Development, or OECD) countries increase nonrenewable energy use at 1% annually, and developing (non-OECD) countries do so at roughly 5% annually until east-west energy equity is achieved in the mid-22nd century, after which they too will continue generating more energy at 1% annually, then a 3°C rise will occur in about 320 years (or 10°C in ~450 years), even if carbon dioxide emissions end.
- If greenhouse gases continue soiling our atmosphere beyond the current 380 parts per million of carbon dioxide, all of these projected times decrease.
- If around 4% additional solar energy is beamed to Earth, the surface temperature would quickly rise 3°C (or ~10°C for an additional 14% solar energy beamed to Earth).

Even acceding that the above assumptions can only be approximate, the heating consequences of energy use by any means seem unavoidable within the next millennium—a period not overly long and within a time frame of real relevance to humankind.

More than any other single quantity, energy has fostered the changes that brought forth life, intelligence, and civilization. Energy also now sustains society and drives our economy, indeed grants our species untold health, wealth, and security. Yet the very same energy processes that have enhanced growth also limit future growth, thereby constraining solutions to global warming. Less energy use, sometime in the relatively near future, seems vital for our continued well-being, lest Earth simply overheat.

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Riverine Flow and Lake Level Variability in Southern South America

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Considerable attention was directed during the 1920s to the remote connection that appeared to exist between the Southern Oscillation (SO) and anomalous rainfall over southern Brazil, Paraguay, and northern Argentina [*Mossman*, 1924]. It was Gilbert Thomas Walker's group, then in India seeking the prediction of monsoonal dynamics, that made the observation—seen with skepticism—that high volumes of flow along the Paraná River, as measured at the downstream Rosario (Argentina) gauging station, tended to occur during the negative phase of the SO, when surface level pressure (SLP) was anomalously high around Australia [*Bliss*, 1928]. Such high surface level pressures, when associated with unusual low pressure along South America's coast, tended to cause droughts in regions bordering the equatorial Pacific Ocean and heavy rainfall in other parts of the Americas and the world.

The idea of such a large-scale link in weather patterns subsided somewhat during the following decades until *Bjerknes* [1966] and others established the now widely known linkage between the SO and El Niño events (ENSO). Many works have expanded our knowledge on such processes, particularly since the early 1980s, when one of the strongest ENSO events ever occurred in the equatorial Pacific Ocean region.

In this brief report we review the present hydrological knowledge over South America in view of the current understanding of climate change. In particular, what are the hydrological trends and discernible connections with periodic interannual or decadal events, like ENSO, over southern South America?

Climate Features Over Southern South America

A monsoon-like system affects the atmospheric circulation over the Río de la Plata drainage basin (see Figure 1, region A), whose major feature is the South Atlantic Convergence Zone (SACZ) [*Carvalho et al.*, 2004], which normally runs along the basin's northeastern boundary (between about 20°S and 25°S). Also important in the regional climatic pattern is the southbound low-level jet that transports moisture along the corridor framed between the Andes and the Brazilian plateau. This corridor's southwestern border is the transitional "arid diagonal" (dashed line in Figure 1), south of which westerlies control the atmospheric circulation.

The main result of the transition is that an austral summertime rainfall regime prevails northeast of the diagonal. However, in Patagonia, weather patterns are dominated by austral autumn-winter precipitation.

Hydrological Trends and Periodicities in the Río de la Plata Drainage

Existing discharge records for southern South America's rivers, including the 100-year-long record for the Paraná, show variable trends in their historical records. Figure 1 presents, with darker and lighter shades of gray and also with hatching, the varying trends in river discharges for drainage basins in southeastern South America, as determined by *Pasquini and Depetris* [2007].

Most of the basins in Figure 1 show a positive annual trend, meaning that their mean annual runoff tends to increase with a slope greater than zero, significant in statistical terms. The Pilcomayo River (the drainage basin with no shading in Figure 1, located in the northwestern corner of the Río de la Plata drainage) is the only exception that does not show a positive annual trend. In the Río de la Plata headwaters, the statistical significance of positive trends seems to decrease as one moves toward the west. When applied to Paraná River discharge data at the city of Paraná (~600 kilometers upstream from the river's mouth), the seasonal-Kendall test, which allows us to establish if there is a significant increase (or decrease) in specific months, implies that such a yearly flow increase occurs mainly during the low-flow months of March and April (Figure 1, inset 2). Similar to the