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Thermodynamics and civilization: from ancient rivers to fossil fuel energy servants

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Abstract Civilization can be at least partially determined by climatic constraints upon net primary productivity and heat dissipation from the human body (Kleidon 2009). I discuss how these "metabolic" limitations were historically overcome: first, because large rivers in dry regions provided water to ancient civilizations; second, because fossil fuel energy servants working externally to muscle-limited bodies have produced economic well-being in a number of world areas.

1 Introduction

Kleidon (2009) has produced an innovative paper about metabolism, environmental thermodynamics, and human lifestyles. Specifically, in a modeling study he explores the relationship between the capability of a location to produce food (proportional to net primary productivity, NPP) and the ability for we human heterotrophs who consume food to dissipate waste metabolic energy to the environment.

Kleidon determines NPP primarily as a function of both temperature and water. The NPP decreases from the tropics to the poles as a function of temperature and the details of that pattern are determined by water availability. Thus areas of particularly low NPP occur in the very high latitudes and in the world's deserts.

A human heterotroph might have abundant food to consume yet be limited by the inability to dissipate waste heat in hot climates. This potential dissipation, opposite in sign to the decreasing latitudinal trend in NPP, will in general increase from the tropics to the high latitudes. Potential dissipation is also affected by water availability. In Kleidon's formulation, deserts are poor in this aspect as well, because of low

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turbulent mixing and from lack of water for heat dissipation through sweat (Kleidon, personal email communication).

Kleidon finds that a general decrease from tropics to poles in potential food and a general increase in potential dissipation (again, with many significant large-scale "local" details determined by water) results in broad sites in mid-latitudes for optimal human activity. Because large amounts of physical labor were necessary in the early stages of human civilization, Kleidon points to similarities between the maps generated by his model and historical sites of origin. Without citing details for time periods, he judges that his "simulated high levels of human metabolic activity match reasonably well the location where higher civilization developed, namely in Europe, China, and at high altitudes in the Andes."

In this springboard essay, I will "take off" from several topics that Kleidon noted in passing as potentially important. But he did not cover these because they were outside the main scope of his paper. The first topic I will briefly address is the benefits of large rivers and their ability to provide large supplies of water in the desert regions, allowing humans to overcome limitations imposed by low rainfall. Then I will go into the topic of fossil fuels and energy in general that we have put into place outside the limits of human or animal metabolism. We thereby overcome the thermodynamic constraints imposed by a location on Earth. Kleidon mentions this issue using the example of air conditioning, which allows for a level of comfort and activity that otherwise would be hindered by the inability to lose significant amounts of metabolic heat. I will take this point to discuss our fossil fuel energy servants (Volk 2008) and their impact on modern life.

2 The control of water and the origin of civilizations

At least 3 of the 6 classic areas usually discussed as relatively independent sites for the origins of civilizations have very low rainfall: the Tigris-Euphrates valleys of ancient Mesopotamia (Sumer, etc.), the Nile valley of ancient Egypt, and the Indus valley between modern Pakistan and India (the site of the ancient Indus civilization). These regions are quite dry and at times during the year they are very hot. In Kleidon's formulation these are areas that offer low NPP and low potential for the dissipation of metabolic heat. They should have been poor places for the development of civilization. But yet they were historically crucial crucibles for civilizations because of the presence of large rivers coming from distant highlands.

The rivers were literally gifts of life from the geophysical structure of the biosphere, facilitating both high local NPP and also water to drink. With adequate drinking water, the human skin can evaporate enough sweat to cool the body by latent heat transfer and thus dissipate heat, allowing the hard physical labor that was necessary for early massive architectural constructions and other public works projects.

The case of Peru is particularly instructive in this regard. Peru is another one of those 6 original, independent sites for the origin of civilization. Kleidon points out the thermodynamic advantages to higher altitudes in Peru. Indeed, the Inca and the earlier Chavín were both civilizations literally high up, allowing better conditions for heat dissipation than would have been possible at lower, hotter altitudes. And the lack of water in the driest of the low altitude sites of Peru would also have been a constraint to heat dissipation if humans simply did not have enough to drink.

But it is in the Norte Chico area along the Peruvian coast north of Lima where we find the origin of the oldest known civilization in the Americas (Wikipedia 2009). Starting about 3200 B.C.E. there was "large-scale human settlement and communal construction," which predated the above-cited highland civilizations by thousands of years. The Norte Chico region is remarkably dry. It should have been devoid of civilization. But large, steady rivers that flow out of the Andes were harnessed by the people there. With water, one can irrigate, grow crops, and, for heat dissipation and life, have enough to drink.

The thermodynamic constraints that Kleidon points to ultimately can produce heat illness, the most dangerous form of which is heatstroke. Heatstroke is a medical emergency in which the body's temperature can rise to 106°F (41°C) and death can swiftly ensue (Helman and Habal 2009). Typically heatstroke and preceding heat illnesses such as heat exhaustion occur under hot conditions with high humidity, which stifles both sensible and latent heat loss. But these problems also occur if one has not enough to drink. With enough to drink, desert conditions can actually provide a large potential to dissipate metabolic heat through sweat evaporation.

Kleidon's maps show where humans would be abundant as pre-cultural animals, and are most relevant to some of his discussions about the evolution of earliest humans and other mammals. But with culture all bets changed. In the Paleolithic ice-age Europe, for example, Cro-Magnon cultures had fire and fur clothing to compensate for the cold. The origins of culture itself, at least by the time of symbolic artifacts, are debated (Balter 2009). But culture certainly predates "state" civilizations by, at minimum, tens of thousands of years.

We see the importance of the human control of water availability. As Kleidon does recognize, of course, and I here emphasize, we are not just organic metabolic beings who must cope with the given environment. The classic civilizations—and ancient China must also be included here—had a large degree of control of water, with irrigation of crops to ensure adequate crop-NPP and with water in aqueducts for drinking. With food and heat dissipation through adequate sweat, even in dry, hot regions humans were able to labor hard and build the earliest civilizations.

3 Fossil-fuel energy servants

Humans manipulate the external environment to overcome what would be their "natural" metabolic thermodynamic limitations from living as animals in the biosphere. There is probably no more dramatic example of this than the ways in which fossil fuel consumption has allowed lifestyles of abundance far beyond what the biological body could produce through muscle power.

Architect, systems-thinker, and futurist Buckminster Fuller used the term "energy slaves," which I softened into "energy servants" (Volk 2008). The focus here is on these fossil-fuel energy servants, because fossil fuels account for approximately 80% of global energy consumption.

Conceptually, energy servants are sources of energy external to the human body. For a full account throughout history of the increasing deployment via cultural evolutionary processes of the full range of energy servants, we should include draft animals and biomass. We perhaps would leave out biomass combustion devoted to cooking food, because cooking is necessary to satisfy nutritional needs for our current bodies. Furthermore, the issue of cooked food is not a recent innovation but one that occurred deep in pre-human history and as such is outside the scope of this essay.

To get to the crux of the matter at hand: Fig. 1 shows per capita gross world product from the years 1000 to 2006, as calculated by the German historical economist Angus Maddison (Maddison 2009). In year 1000, the GWP per capita was $470 (in 1990 US$). Maddison does have a data point for year 1 C.E., and that "dollar value" was the same as year 1000 (3% higher, so indistinguishable). By 1700 global per capita growth had barely budged upward. It was only $615 then, despite all those intervening centuries of the European Middle Ages, the European Renaissance, the Aztec empire, the Chinese empires and those of India and elsewhere. All of history's battles, intrigues, art, architecture, and engineering for weapons and defense, and even innovations such as crop rotations—all these together had only barely increased human economic well-being.

Figure 1 also shows the per capita carbon emissions as CO_2 from fossil fuel combustion. These were 0.013 tC/capita in 1820, from the data set of the Carbon Dioxide Information Analysis Center (CDIAC 2009). I have assumed zero for the data before then. Whatever was going on in terms of energy consumption before about 1800, including the windmills and watermills of old Europe, the use of draft animals, and the combustion of biomass (assumed to be primarily for cooking, because the heat engine for mechanical thrust had not been invented), the average wealth of the average world citizen had increased by only 30% over nearly 2,000 years.

In the 1800s, drama ensues for both per capita GWP and per capita fossil fuel emissions. Both skyrocket. My point is not to closely analyze the details of these trends in terms of efficiency improvements or of the substitution of wood power (not included) for coal and then the emergence of oil as important and, more recently, natural gas as a player. It is clear and well-known that wealth is ultimately rooted in energy being transformed from more concentrated to more degraded forms to process materials and to transport materials and people. And fossil fuels, because of their prevalence and convenience, began to be the forms of energy that have given us (or, some of us) such relatively enormous wealth. The global per capita GWP stood

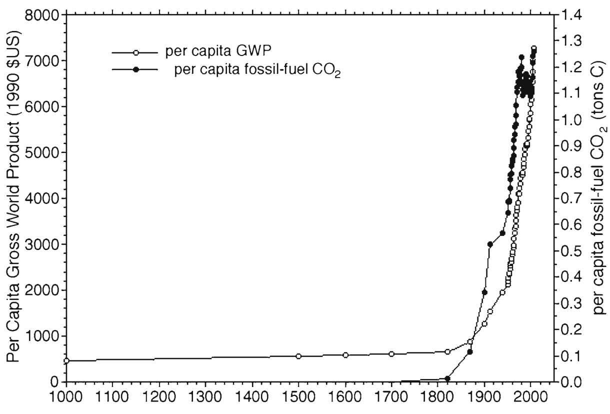

Fig. 1 The last 1,000 years for per capita gross world product in 1990 $US (Maddison 2009) and for per capita fossil-fuel carbon emissions (CDIAC 2009). The per capita GWP for year 1 C.E. was essentially the same as in year 1000

in 2006 at $7,300 (again, 1990 $US). That was nearly 16 times what it was during the long interval from 1 C.E. until year 1000.

As Kleidon points out, we are metabolic organisms who live by transforming the free energy from photosynthesized hydrocarbons (which might have first gone into other animals we consume). We change the reduced carbon in these hydrocarbons into CO_2 that we release as a waste gas. In this way, as chemical converters we are like our fossil fuel combusting engines, from roaring cars to humble gas stoves to gigawatt power plants.

We can compute the power of our fossil fuel energy servants by putting them in terms of human equivalent power units. The annual release of carbon as metabolic CO_2 by an average person who consumes 2,500 kcal of food per day is about 250 g of carbon per day, or about 90 kg-C per year. About 80% of this is exhaled directly as metabolically produced CO_2 (Volk and Rummel 1987). The other 20% is excreted in liquid and solid wastes, and this carbon, too, ends up as CO_2 produced primarily by respiring bacteria in soils or in municipal waste processing facilities.

Current per capita fossil-fuel CO_2 emissions, globally, are 1.26 tC. Thus the average global per capita number of fossil fuel energy servants is $1.26/0.09 = 14$. This is roughly like each having 14 human servants supply our daily needs. That is for every man, woman, and child on Earth.

Not all nations are equal in possessing the fossil fuel energy servants (Volk 2008). The US average citizen has about 60 such servants. An average person in Bangladesh or Rwanda, by contrast, has less than 1. There is more than a factor of 60 between the average person in the world's richest nation and the average person in several of the poorest nations. China, by the way, is approximately at this point the world's average nation. For a sense of what the average state of the world is, call up images of Mexico, Turkey, China, Bulgaria, or Romania.

4 Conclusion

Axel Kleidon has provided new insights into the issue of the evolution of encephalization in mammals and hominids as developed by Schwartzman and Middendorf (2000). Kleidon's analysis has possible applications to the rise and successive waves of civilizations. To put Kleidon's ideas into full proper perspective would require a close analysis of competing, perhaps complimentary factors. Kleidon cited the theories of Diamond (1997), but a point by point comparison has yet to be done. One would also want a careful analysis of the times of emergence of civilizations and the climate regimes of those times. Ideas such as theories about "hydraulic civilizations" propounded by Karl A. Wittfogel (and also his critics), with emphasis on irrigation as the civilizing trigger would have to be examined.

Arnold Toynbee, in his monumental *A Study of History*, suggested that the challenges of winter in the northernmost America colonies of Massachusetts, Connecticut, and Rhode Island made those colonies into the seed beds for what would become the innovative center of the young US, not the warm, agrarian south with its easier agricultural conditions. Yet, according to Toynbee, where winters were too severe, as in the land of the Inuit around Greenland and northern Canada, harshness was not stimulating but debilitating. These ideas are not the same as but complimentary to Kleidon's emphasis on net primary productivity and ability to dissipate metabolic heat. All ideas will need to be contrasted and we will need to have ways to evaluate multiple factors that contribute to the history that we know happened. Ultimately as well, the biological givens and proclivities of the human mind in a human brain will have to be folded into an understanding of this history (Smail 2008). Clearly the invention of technologies and the means to get energy sources to run those technologies will be crucial as well.

We are no longer purely animals with "natural skins" in a "natural field" of environmental conditions. Kleidon has identified two major factors in those conditions, namely food supply and heat dissipation, and showed that their counter-trends with latitude predict sites of maximum metabolic activity. Kleidon acknowledges the importance of a number of factors he did not consider, such as irrigation to ensure water supply and energy for such climate-modifying technologies as air conditioners. What I have attempted to do in this essay is to elaborate on these other factors, which I have demonstrated to be hugely important. I discussed water supply that allowed several ancient civilizations to originate in regions that would otherwise seem inhospitable, and I demonstrated how fossil fuel combustion allowed the gains in wealth many of us enjoy from the deployment of energy servants. More and more we are creating our own environments, some by design, and others—such as global warming—inadvertently. Considering the wealth generated by energy systems outside those of muscle power, we need to figure out how to enable everyone in the world to be well-off in the future (Sachs 2008). This is a tremendous challenge.

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