From Muscles to Molecules: the Earth System has recently undergone a revolution

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Prologue

Imagine what Earth looks like from beyond our planet's boundaries. Imagine that you could have watched the evolution of our planet over the last 1000 or so years from a distance sufficient to see the planet as a whole rather than only subsystems of the planet at any given time.

This framework would extend our current observational hierarchy by embedding things that are going on on Earth in the context of at least the solar system. From this perspective, human intentionality at the scale of the individual would disappear while the outcomes of collective human activities would become central. If you got the scaling just right, it would be like the difference between watching the ant colony instead of individual ants.

Just as large and small scale maps highlight different elements of a particular region, so too this change in perspective will change how we look at the recent evolution of Earth and its occupants. The next section of this essay describes two important observations that are likely to have been prominent from this perspective. The penultimate section provides some commentary on those observations.

Observations

A single species came to dominate many aspects of the planetary system

The Earth System is a dynamic system which absorbs short wavelength energy radiated from the solar system's central star and re-radiates longer-wavelength heat. Biological organisms on Earth use this energy flux to fuel their biological cycles and to modify their local environments to their own advantage.

Human population and its influence on Earth grew rapidly

Since the year 1000, human population has grown from about 300 million to nearly 7 billion. The human population of Earth was less than 1 billion until the very beginning of the 19th Century; at the beginning of the 20th Century there were slightly less than 2 billion humans; and at the beginning of the 21st Century there were more than 6 billion. In recent decades, the total number of humans continued to grow, albeit at a slightly slower rate than that of the mid-20th Century.

In addition to the growth of their numbers, humans have extended their influence in the Earth system through the development of technology. While many Earth species modify their environments, humans are exceptional in their ability to harness materials and invent new methods of intervention. Human success on this front is so astonishing that for all intents and purposes, it is not useful to consider technology and humans separately.

There have been many bifurcation points in the evolution of humans and their technology. Just as biological evolution reflects complex interactions among species and

environments, the coevolution of humans and technology reflects the many complexities of human interactions with their environments, and with each other.

The scaling of human capacity has reached the scale of the planet itself

In addition to inventing new machines and techniques, humans have also evolved increasingly complex social organizations. These cooperative groups also extend the capacity of humans. Just as ants have evolved specialists and the means for coordinating their activities, these organizations make it possible for humans to specialize and for individual effort to be coordinated in such a way that the aggregate outcome is greater than the work of a similar-size collection of generalists.

In addition to increasing complexity, over time these social organizations have expanded their geographic scope from the scale of meters to the scale of the entire planet. Kilometer and smaller scale organizations have continued, but the largest scale has grown until it is now limited by the size of the planet itself. These expansions of scope and scale have resulted in humans becoming integrated into the Earth System at essentially all scales.

Earth's atmospheric CO2 concentration recently started rising rapidly

With the exception of a roughly 200 year excursion to lower levels, the CO2 concentration in Earth's atmosphere remained fairly stable for about 800 years beginning in 11th Century. Around the beginning of the 19th Century, Earth's atmospheric CO2 concentration began to climb rapidly. That increase has been inexorable and may be accelerating. Highly detailed observations reveal small variations in the rate of increase, but they do not reveal any significant departure from the new trend. At the beginning of the 21st Century, Earth's atmospheric CO2 concentration had increased by about 1/3 over its pre-19th Century average.

Transition from the Metabolic to the Molecular Ages

The change in Earth's atmospheric CO2 profile corresponds with a significant change in human energetic capabilities. In the Metabolic Age (the time prior to the 19th Century), human endeavor was limited by the metabolic rates of biological organisms. Energy technology advances were related to the efficiency of transferring the muscle power of humans and animals into other materials. During this period, energy usage at any given time, was closely tied to photosynthetic processes and to nutrient cycles. Energy availability was closely tied to the current food supply, which had a residence time of several seasons at most.

In this early period, carbon-based fuels were burned, but the heat of combustion was diffuse and used directly as heat rather than for mechanical advantage. Much of the burned fuel was plant material which may have stored solar energy for as long as several centuries, but not much longer. As the 19th Century approached, humans began to increase their use of fuels that had accumulated their energy millions of years earlier. As with plant material, the heat released from these fossil fuels was primarily used as heat rather than being converted into mechanical energy.

In the early 19th Century humans extended their energy capacity through technologies that converted the energy released from fuel burning directly into mechanical energy. This technological revolution replaced limits related to biological metabolic rates with technological limits related the efficiency with which the energy of combustion could be captured and redirected to human ends. And it signaled the beginning of the Molecular Age. With the transition from the Metabolic to the Molecular Age, humans moved from an energy system that

was rooted in energy stored in carbohydrates and other nutrients to one in which energy was usefully released from molecules with much higher energy densities.

In addition to molecular sources that had higher energy densities, the invention of molecular energy technologies also disconnected energy availability from the current state of the climate and of agricultural technology. Burning wood buffered energy availability over centuries, but the ability to harness the energy stored in coal and other fossil fuels, opened an energy reservoir that had been placed in storage millions of years earlier. Prior to the industrial revolution humans could not significantly alter Earth's total energy budget; as new technologies of the Molecular Age opened up stores of fossil energy, humans began to alter Earth's energy systems in significant ways.

From outside of the Earth System, it is clear that the industrial revolution opened an entirely new region in the Earth System phase space. Prior to the Molecular Age, biological metabolisms placed limits on parameters such as "CO2 emissions rate" and "average annual energy expenditure". The emergence of Molecular Age technologies significantly raised the limits on such parameters; as a result, Earth states that had hitherto been impossible began to be obtained and become common place.

In both the Metabolic and the Molecular ages there are waste products associated with energy usage. In the Metabolic age, those wastes could accumulate locally and disequilibrium could be maintained locally, but the limits imposed by reliance on current food supply and by relatively small human population maintained global equilibrium. Ignoring the small amount of fossil fuel burning, waste from energy production in the Metabolic Age was limited by mass balances in the atmospheric and surface systems of the planet.

This is no longer true with the advent of the Molecular Age. A side effect of the combination of new technologies and the fossil energy that they made available is that mass balances on Earth's surface are no longer in rough equilibrium. In particular, the rapid rise in Earth's atmospheric CO2 concentration is the inevitable result of the human-created conduit that rapidly moves carbon from reservoirs within Earth to reservoirs on the surface of the planet.

Commentary

Humans have misunderstood the nature of the CO2 profile of their planet

In recent decades humans have noticed the rapid rise in their planetary atmospheric CO2 concentration; furthermore, they have correctly understood the relationship between the release of fossil energy stores through combustion and the rise in atmospheric CO2. However, they have not fully comprehended the scale of the relationship.

It is the nature of human individuals to strive to improve their fortunes. Some groups and regions have been more successful at harnessing Earth's resources to their own betterment than others. While it is accurate to say that Earth as a whole has moved inescapably into the Molecular Age, many regions of the planet are still very dependent on Metabolic Age technologies and fuel. This

inequality / heterogeneity will drive continued expansion of Molecular technologies as humans in those regions strive to better their lot.

Recognizing that humans and their technology coevolve and that the human drive for betterment is innate leads to the conclusion that atmospheric CO2 concentration is an emergent property of the current configuration of the Earth System. Just as ants cannot re-engineer the basics of waste management in their colonies, humans cannot simply decide to emit less CO2. Those emissions are an innate reflection of the structure of planetary systems whose length scales encompass the entire planet.

Human managerial capacity has not yet reached planetary scale

Typical management systems employ viewpoints and decision-making frames whose hierarchical position is higher than that of the system to be managed. While complexity in the subsystem can complicate management, a viewpoint that encompasses the subsystem allows inputs and outputs to be monitored, desired system outcomes to be articulated, and at least a certain level of authority to be assumed by the managers. There are many subsystems of the Earth system that are controlled by human intentionality in this way.

Carbon is ubiquitous on Earth and it is fundamental to life processes. As CO2, it is well mixed in Earth's atmosphere; hence CO2 that is emitted to or removed from the atmosphere anywhere on Earth affects the entire system very quickly. Any management system devised to control CO2 will need to engage the scale and ubiquity of carbon itself. Atmospheric CO2 cannot be managed on scales smaller than the whole Earth system; this hierarchical fact places strong constraints on the relationship between human intentionality and the planet's atmospheric CO2 trajectory. Harking back to the earlier ant analogy, it is not even clear that "human intentionality" at the scale of the planet is meaningful.

The CO2 trajectory of Earth will change only when the fundamental relationships among the underlying drivers change. Such a change will be similar to what occurred in the early 19th Century. Human activity is likely to play an important role, but should such a revolution occur, it is unlikely that it will "planned" in the sense that human managers currently think about that concept.

Conclusion

If these observations and interpretations are correct, it is very likely that the functioning of many of Earth's subsystems will change in the coming centuries. It is likely that humans, with their technological extensions, will survive these changes; however it is unlikely that their current technological portfolios and social organizations will be well suited to future conditions.

Humans have an exceptional ability to imagine the future; they also have a propensity to yearn for the past. Wisdom in the current situation would emphasize the imagining and minimize the yearning. Humans should imagine technologies and social organizations that better our lot on a planet that is very different from that of Earth in the 20th Century.