MEETING REPORT

Thermodynamics of the Earth system*

Emergent patterns and predictable features of the Earth system, such as climate classifications and surface energy balance partitioning, despite their being the outcomes of a sequence of complex processes, engender the belief that they are driven by some deeper lying principles or laws of nature. All living and performing systems in the universe are sustained by performing work by drawing energy from some available energy source to create other forms of energy, albeit of lower potential. The ordering principle must, therefore, reside in the processes of energy transformation and the resulting arbitrage, subject to the overriding condition of the conservation of energy. Therefore, the key to understanding these principles lies in the constraints imposed by the laws of thermodynamics on Earth system processes.

It is particularly the second law which sets the direction of natural energy conversions and limits the maximum possible work that can be performed under a thermodynamic disequilibrium. While the dynamics of Earth system processes are known to be constrained by physical laws like conservation of energy, mass, and momentum, a quantitative analysis of the work performed by these processes in the Earth system provides novel insights into Earth system functions ranging from surface energy balance, hydrologic cycling, biosphere activity, anthropogenic effects on these process as well as the effects of climate change. The resulting view of the Earth as a thermodynamic, interconnected system opens up insightful ways to communicate the essentials of Earth system science in a simple yet physical way.

The idea of the workshop was prompted by the expectation that abstraction of the quintessential features of major Earth system processes: the atmosphere, the hydrosphere, the climate, ecosystems and human society, had the potential to reveal some optimality principles in energy transfer that may illuminate approaches to better understand and manage such systems, particularly those engineered by humans. It was delivered through ten lectures, two each in the morning sessions and five, 150 min long afternoon sessions devoted to hands-on problem-solving.

The workshop began with the inaugural address of Shakil Romshoo, the Vice Chancellor of IUST, in which he highlighted the challenges posed by global warming and climate change to work and livelihood issues faced by the people and administrative agencies in the Kashmir region. These problems underlined the importance of the workshop in directing the course of research and development in directions that would directly contribute to empowering people with knowledge of the evolving nature of environmental hazards in the region, as well as imaginative approaches to harness the value of regional resources. It was followed by an overview of the science of thermodynamics by V. K. Gaur, who illuminated the pathways of its growing conceptual space from the abstraction of the idea of energy transaction costs, to its rootedness in molecular organization and variabilities of state, whose measurability has shown us the way to design insightful algorithms for AI applications.

In the subsequent lecture, Axel Kleidon expounded on the role of entropy and the second law of thermodynamics from finite to infinitely possible degrees of freedom. Thus, he explained how three different processes mediated the transaction costs of the incoming solar radiation: (i) the few high energy photons to many of lower energy (radiation entropy), the molar entropy, related to electrons organization in molecular configurations, and the commonly known thermal entropy (related to the random motion of molecules). He highlighted the relevance of these entropy forms in Earth system processes, noting that even though photosynthesis and photovoltaic transformations were not heat engines, they are still governed by the second law of thermodynamics. Later, in the afternoon sessions, the concepts explained in these lectures were worked out individually by participants through exercises that Tejasvi Chauhan and Sarosh Alam Ghausi had designed.

The aforementioned structure was followed on the remaining four days, applied to other major Earth system components, as follows.

In the next lecture, Axel Kleidon explained how the disequilibrium on Earth caused by the differential radiative heating of the Earth's surface was dissipated by the work performed by the vertical turbulent fluxes and poleward heat transport, shaping surface temperatures and the large-scale circulation patterns respectively. However, the resulting heat transport, in turn, reduced the driving temperature differences, resulting in the maximum possible work that can be performed by the atmosphere to maintain the motion and exchange of heat. This limit on work yields a 'maximum power' limit from which simple yet realistic temperature variations can be inferred.

In the following lecture, Sarosh Alam Ghausi demonstrated that the atmosphere operates close to this thermodynamic limit of maximum power using real data. He showed that this approach works very well in estimating temperatures, from the diurnal to climatological scale, their spatial and temporal variability, as well as their sensitivity to global warming.

In explaining the thermodynamics of the hydrological cycle, Axel Kleidon highlighted the role of saturation as the reference state of thermodynamic equilibrium and how deviations from it, lead to hydrological cycling. In the evaporation phase, evaporation from the warmer surface depletes the disequilibrium of unsaturated air in the atmosphere, while in the precipitation phase, condensation releases heat within the colder atmosphere, fuels a moist heat engine, and performs the work to dehumidify the atmosphere and to generate the disequilibrium. The maximum power limit discussed above yields an expression for potential evaporation that compares very well to observations under unconstrained water supply.

Expanding on Kleidon's analysis, Tejasvi Chauhan attempted a broader view of the hydrological cycle from the perspective of climate change and discussed its sensitivity to global warming. He then related the thermodynamic view to the conventional hypotheses of how the hydrologic cycle changes with global warming and, in particular, as

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