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Posted Date: 25 March 2026

doi: 10.20944/preprints202602.1676.v2

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Pre-Biotic Earth and a More Complete Theory of Heat Transformation, Part I

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Abstract

The emergence of biological complexity from abiotic chemistry remains thermodynamically unexplained. Existing frameworks, such as Prigogine's minimum entropy production theorem, the maximum power principle (Lotka and Odum), and exergy (Rant) each capture one aspect of a dissipative structure, but none has quantified all its thermodynamic properties as a coherent set derived from a single physical model. This paper introduces the gravitational dissipative structure (GDS) and provides that complete quantitative framework. Grounded in Clausius's interior/exterior work distinction and his force-balance reversibility criterion, the GDS model derives six thermodynamic properties, including complexity yield, specific heat quality, and heat transformation effectivity, and proves two theorems: first, that dissipative structures are more effective at transforming heat into stored energy at greater local heat sink temperatures; second, that the ratio of real efficiency to Carnot efficiency is constant regardless of boundary temperatures. Applied to Earth's tropospheric water and air cycles, the model yields auto-powering capacities of 82 W/m^2 and 345 W/m^2, with 98.8% of initial heat quality retained. Their combined heat quality outputs estimate the actual measure of jet stream velocity to within the same order of magnitude, cross-validating the GDS model and the concept of heat quality networking. When GDSs network at planetary scale, the result is massive mixing, a geological-timescale concentration of dissolved salts, acids, bases, and minerals that provides the multiplicity of microstates and ergodicity of mixing required for spontaneous prebiotic chemistry. This is Part I of a four-part series; Parts II through IV build on these preconditions to demonstrate the inevitability of life. Earth is a naturally-organizing machine, driven by heat and conservative forces to generate life.

Keywords: dissipative structures; heat engines; thermodynamics; entropy; complexity; order; heat quality; gravity; sustainability; prebiotic Earth; evolution

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1. Introduction

1.1. Motivation

The theory of evolution is based upon a major assumption; as Charles Darwin stated it, "…probably all organic beings who have ever lived on this earth have descended from some one primordial form..." [1] (p. 484). This assumption has driven mainstream thinking toward the conclusion that intelligent life is unlikely in the universe because it requires a series of hard steps, events that had to occur on Earth for humans to evolve that are each independently unlikely [2–5]. Much of the literature agrees that abiogenesis, the development of a single life form from no life, is the first hard step [2,3,6–11]. The singularity thinking of evolutionary biology has had a major influence on related sciences, and there is broad scientific acceptance of this assumption, though any supporting evidence seems to be based on a dataset of one.

Space researchers searching the skies for life find no visitors, no communications, and no astrophysical phenomena that cannot be explained without invoking life [12–17]. If the signs we look for in space are based on the hard steps model, then we are looking for the very particular way in which the clades identified on Earth accomplished their hard steps. We tell ourselves that we have

doi:10.20944/preprints202602.1676.v2

measured many datapoints and found only one non-null result. But we have not measured other places in the universe thoroughly enough to treat them as valid data points. In no other science would we accept one datapoint as the validation of an assumption that something happens regularly by natural law, or does not happen at all.

What else are we to think? Mills et al. [18] raise the possibility that there are no hard steps, that the seeming appearance of singularities may be a result of a biospheric development that deterministically sequences windows of opportunity during which hard steps occur. To examine this proposal, the status of evolutionary innovations as true singularities needs to be more thoroughly questioned. The singularity assumption remains actively contested, with the leading RNA-first framework [19] competing with active alternative programs including metabolism-first [20,21] and lipid-first [22,23] hypotheses, each proposing a different chemical pathway to the same singular origin of life. This reinforces the need for a thermodynamic framework that does not depend on any single assumed pathway to explain the emergence of complexity.

The study of the evolution of life that is not based on assumptions of rarity requires a standard model that stands independent of the one that biological evolution is based on. Such a model must be based upon universal laws more fundamental than those developed from observed biology and paleontology. Appeal must be made to chemistry, and even more fundamentally to physics. Consider the concept of the last universal common ancestor (LUCA), the amalgam of all clades for which life is extant on Earth today. Recent studies [24,25] identify horizontal gene transfer from other life-forms not extant on Earth when it first evolves, suggesting that there is life present with LUCA when it first evolves. Even in these models, there is assumed to be a first universal common ancestor (FUCA) [26], a tree of life with a single trunk. How does the first individual of the FUCA population, the original FUCA (OG-FUCA) theorized by abiogenesis theory, survive and multiply? Each plausible mechanism for its survival (i.e., forming already equipped to replicate, surviving long enough for random mutation to confer that ability, or growing until physical forces cause it to divide by a process such as lipid polymorphism) requires a pre-existing physical and chemical support system to sustain the OG-FUCA and its offspring as the first living population, according to ecosystem theory.

The logical need for an ecosystem to sustain a first living population can be probed backward prior to the abiogenesis of the OG-FUCA in a causal chain to simpler and simpler molecular systems in a molecular storm that is the prebiotic Earth. The sustainability of today's Earth and its ecosystems suggests that the first life and its associated ecosystem must have had that same property. Without it, life becomes even more unlikely than theory currently claims. Pushing the bounds of the logical argument extends to a pre-biotic Earth that sustains the transformation of the elements that coalesced into Earth out of a protoplanetary system into molecules of progressively greater complexity. The logic leads to an inescapable conclusion: what is needed is not merely a mechanism for the spontaneous formation of complex molecules, but a pre-biotic chemosystem of self-sustaining chemical processes that precedes life and provides the material foundation from which life can emerge and persist. What does such a planet look like, and how does a chemosystem and eventually an ecosphere come into being on a planet in a sustainable way?

1.2. Scope and State of the Art

This paper is the first part of a series that addresses this question using thermodynamics and the extension of physical theory into ecological theory. It is important to state explicitly what this first paper does and does not do. This paper does not address the chemistry or biology of life's emergence directly. It establishes the thermodynamic and physical foundation of the gravitational dissipative structure (GDS) framework upon which the chemical argument is built in Part II and the statistical inevitability argument is built in Parts III and IV. This first paper establishes that Earth has gravitational systems that provide the material and energy capacities to achieve the multiplicity of microstates [27] (pages 49-121) and ergodicity of mixing [28] required to instantiate opportunities on Earth for pre-biotic molecular synthesis [29]. To do so, the paper develops six thermodynamic properties specific to dissipative structures: auto-powering capacity, auto-restoring order, specific universal entropy (with three forms), complexity yield, specific heat quality (with six forms), and heat transformation effectivity The paper proves two theorems regarding the performance of dissipative structures relative to conventional heat engines. Theoretical definition and demonstration is provided of complexity that is the cyclic storage and decay of energy, growth of complexity being associated with thermodynamic properties of state and process. The second paper establishes that all types of chemical reactions can occur spontaneously on a pre-biotic Earth. Ecological thermodynamics is applied to chemical system networking with gravitational systems to achieve an effective use of dissipating heat with no degradation in efficiency. The third and fourth papers develop in detail the questions of how pre-biotic niches achieve multiplicity and ergodicity such that chains of chemical reactions occur spontaneously. Gravitational and chemical system networks are shown to result in the development of complex chemicals. These networks determine a limited set of what are known today as canonical amino acids and nucleotides and establish their functionality in organized structural systems that lead to life. What is shown in this series of papers is that species of chemicals and eventually life occurs spontaneously. These papers provide a basis for a standard-model theory with mathematically developed quantities that have their basis in the thermodynamics of energy storage caused by heat dissipating out of the potential energy wells of conservative force fields.[30]

Existing frameworks for quantifying the thermodynamic behavior of the dissipative structure (DS), a concept first introduced by Prigogine [30], share a common and consequential limitation. Each framework captures one aspect of a DS: either its power intake, its entropy production, its organizational complexity, its energy quality, or its efficiency. However, none has ever quantified all six of these properties as a coherent, internally consistent set derived from a single physical model of the DS cycle. The maximum power principle [31–36] quantifies energy intake but provides no per-unit-mass intensive property and no connection to the conservative force that restores the DS to its initial state. Prigogine’s minimum entropy production theorem [37] characterizes the steady-state entropy of near-equilibrium linear systems but breaks down entirely in the far-from-equilibrium regime where DSs operate and does not yield a measurable state property for any individual DS. Exergy [38–40] and its ecological extensions [36,41] quantify available energy relative to a local dead state but define that dead state as the local environmental temperature, not the universal heat sink at 2.7 K, and therefore cannot track the remaining potential of heat as it flows through a network of DSs from the universal heat source to the universal heat sink. Efficiency measures from Carnot [42] through Curzon and Ahlborn [43] and into dissipative chemistry [44] characterize system performance relative to thermodynamic optima but uniformly predict that efficiency decreases when the local heat sink temperature increases, a prediction that, as this paper shows, does not apply to DSs driven by conservative force fields. No prior work has identified the six properties defined here, proved that heat transformation effectivity equals the local heat sink temperature (Theorem 1), or established that the ratio of real to Carnot efficiency is constant and independent of local boundary conditions for DSs (Theorem 2). This paper does all of these things for the first time, working from first principles within the gravitational dissipative structure model and demonstrating the results numerically for the tropospheric water cycle and the tropospheric air cycle. Tabulations S1 through S6 in the Supplementary Materials present detailed descriptions of existing frameworks that are prior art and are grouped into six tables based on how they relate to the six new properties developed in this paper. Limitations identified in the literature are listed for each framework. Explanations of how each new property related to the existing frameworks addresses these limitations are provided in Sections 4.3, 4.4, and 4.5, below, where the new properties are developed.

The theory presented is of the growth of Earth to what it is today from where it started as stardust in a proto-planetary disk around a young star. In attempting to name such a theory to assist with communication, it is important to avoid confusing it with other existing theories that have canonical interpretations. To avoid confusion with biological evolutionary theory, the word evolution will not be used in this theory unless referring specifically to biological growth of complexity. The word evolution comes from the Latin word evolutio meaning “an unrolling and reading of a scroll.” Though poetic, it is not a meaning that this theory intends to imply. The theory presented in these papers is based in the physical sciences that frequently use Greek root words for naming. Rudolf Clausius used the Greek word entropia to name the property of state now called entropy. Entropia means “a turning or a transformation,” a meaning that the theory intends to imply. However, we can’t call it entropy theory, considering that is Clausius’s innovation. Entropy has a central meaning of loss of heat quality. That is a meaning that this theory will leverage and rework. As such, the objective of this theory is to present an explanation of how heat dissipation out of conservative force fields results in both entropy and order, resulting in a growth of complexity. As a theory of growth that is a result of the transformation of heat, these papers will use the name heat transformation theory, a theory of the transformation of Earth that is driven by heat dissipation and conservative forces.

1.3. Notations and Conventions

A complete list of abbreviations and mathematical notation used in this manuscript is provided in the Abbreviations table at the end of the paper.

Throughout this paper, absolute values are used in mathematical expressions of the first law of thermodynamics. This convention is adopted to aid the reader in tracking the direction of process properties, i.e., heat entering or leaving a system, work performed on or by a system, and the sign of state property changes. Where a quantity increases, its change is positive; where it decreases, its change is negative. The absolute value notation makes these directions explicit in the expressions themselves rather than requiring the reader to carry sign conventions implicitly through derivations.

This paper introduces four novel thermodynamic quantities that have no established symbols in the literature. Their symbols are defined here before their first appearance in the text:

- $\mathbb{T}^{APC}$ and $\mathbb{T}^{ARO}$ — auto-powering capacity and auto-restoring order
- $\mathscr{s}^{DS}$ — specific universal entropy
- σ^{DS} and $\Delta\sigma^{DS}$ — specific heat quality output and specific heat quality drop
- $\Delta \mathscr{u}_{Cx}^{DS}$ — complexity yield
- $\mathcal{T}_{eff}^{DS}$ — heat transformation effectivity

The symbols S, $\mathscr{s}$, and σ cform a deliberate symbolic family. S is Clausius’s established symbol for entropy. The script lowercase $\mathscr{s}$ extends this to specific universal entropy, following the standard thermodynamic convention of using lowercase for specific (per-unit) quantities. The symbol σ is the Greek letter corresponding to the Latin S, and is used here for specific heat quality to reflect the conceptual relationship between heat quality and the entropy framework from which it is derived. The three symbols are distinct quantities but belong to the same theoretical lineage.

This paper uses various forms of T to represent a few different properties. The standard T is used to represent temperature. $\mathcal{T}_{eff}^{DS}$ is heat transformation effectivity, listed above. It has simplified units of temperature. Finally, there is the symbol for auto-powering capacity and auto-restoring order, listed above. They are like and related to the symbol used for flow, $\mathbb{T}_{i,j}$, a standard symbol used in network ecology.

System entropy and universal entropy, two forms of entropy developed in this paper, are defined under distinct calculation conventions established in Sections 2.3 and 2.4.

2. A Growth Postulate

2.1. Evidence of Pre-Biotic Spontaneous Growth

The goal is to understand how the natural world grows from simple aqueous molecules to the more complex organic molecules that are magnitudes of scale larger and longer as seen in biology, today. Considering the current theories of how Earth forms [45,46], it seems reasonable to postulate that pre-biotic chemical reactions start with relatively simple molecules in the protoplanetary accretion disk of the solar system and results in progressively larger and longer molecules developing on Earth. Evidence suggests that some molecules such as simple salts, carbon monoxide, ammonia, simple organic molecules, amino acids, and single nucleotides can form following a supernova or following coalescing as smaller celestial bodies in space [47–51] before coalescing under the attractive force of gravity to form Earth. All theory must start with molecular hydrogen. Early in the universe, molecular clouds of hydrogen-2 with trace amounts of helium forming star nurseries with the earliest stars around 100-million years following the big bang [52–55]. These stars undergo fusion followed by collapse to supernova, resulting in the formation of all the nuclides of the elements of the periodic table of chemistry. Recent evidence from asteroid Bennu suggest that chemical reactions involving hydrogen and elements heavier than helium, helium being chemically inert, commence within the stellar nursery before forming into planets circling stars. This suggests that supernovas and the turbulent regions immediately surrounding supernovas have a level of multiplicity and ergodicity in mixing [56] that results in chains of reactions that lead to molecules as complex as short-chain polypeptides and nucleotides. It is within this mix that the Sun forms surrounded by a protoplanetary disk filled with all the ionic and molecular contents of the molecular cloud.

It is important to note that heat transformation theory treats Earth as an open system not only to energy exchange but to matter exchange, on the timescales of planetary formation and early geological history relevant to prebiotic chemistry. The elements and molecules that make up Earth today did not arrive all at once. Earth coalesced from the protoplanetary disk over geological time, continuously accreting material from the solar system as it swept up everything in its orbital path. The most dramatic single open-system event was the collision of Earth with a large planetoid that resulted in the formation of the two-body Earth-Moon system [45,57]. Evidence also indicates ongoing material exchange between Earth and Mars through impact ejection and subsequent capture [58–60]. Even after initial coalescence, Earth continued to receive material through ongoing bombardment. On these planetary formation and early geological timescales, Earth was genuinely and substantially open to matter exchange, not merely open to radiative energy exchange as is the case on present-day human timescales. The open-system modeling framework used throughout this paper is therefore not a simplification but a physically accurate description of the prebiotic Earth that the theory addresses.

In addition to matter exchange, Earth's position within the universe establishes its thermal boundary conditions. Regarding the universe as the thermal reservoir within which this open system operates: the observable universe, with its hot spots of stars and other celestial objects collected in clusters of galaxies, spread in a web of mass filaments, and within a cosmic microwave background radiation (CMBR) of 2.7 K, does not appear to have changed temperature appreciably over the course of Earth history. For the purposes of this paper, that limited time period of Earth history is sufficient to treat the universe as approximating an ideal thermal steady-state reservoir with its temperature constant on these timescales. The far-from-equilibrium open system of Earth operates within this space. Laying aside any current debates regarding what the universe is and whether it is an isolated system or an open system, the CMBR temperature stability over Earth history provides a physically grounded justification for this treatment.

A theory that explains the growth of the large and long-chain molecules present in life might start in space [61], but might also start on Earth [62] and must finish on Earth. The question is how to achieve multiplicity of microstates and ergodicity of mixing on Earth to achieve sustainable molecular growth and do so in such a way as to exceed what is accomplished in supernova mixing remnants that are present in asteroids. To substantiate a growth postulate from elements to simple molecules to complex molecules present in Earth life, it is apparent that it is gradual and in small steps at the molecular level that are individually probable at the statistical level of Earth and are scalable to bulk material levels in all properties. Limiting examination to the end result of such a prebiotic growth process is overwhelming to comprehend, but that is only because it proceeds through a great number of steps and a great number of levels of scaling. The path to understanding is a path that proceeds through understanding each step and each scale. It seems appropriate to start with fundamental physics and chemistry to "stick-build" models and thought experiments, starting with simple and progressively getting more complex.

2.2. The Starting Point for a Standard Model

In the universe, everything that exists is a result of the physical processes of heat and work move energy between materials, as established by James Joule in 1850 [63,64]. Heat and work are macroscopic process properties. In 1850, Rudolf Clausius re-examines Carnot's theory in light of Joule's findings, establishing that heat is not conserved but is partly converted into work [65,66], revealing that the universe acts according to the process properties of heat and work to materially build anything through the storage and release of internal energy. The form of the second law of thermodynamics simply states that heat can only dissipate from high temperature to low temperature.

Critically, Clausius's 1850 paper introduces a distinction that is foundational to the theory developed in this paper: the difference between interior work and exterior work [65]. Clausius explicitly recognizes that heat in dissipative processes bifurcates: some heat is consumed in performing interior and exterior work, while the remainder is transmitted from the hot body to the cold body. The properties of these two forms of work and their implications for non-equilibrium thermodynamics are examined in detail in Sections 2.3 and 2.4 below.

The initial form of the second law in 1850 addresses local heat transfer as a result of a local temperature gradient (or pressure gradient associated with a temperature difference), and does not differentiate on the involvement of non-equilibrium conditions that might be driving the heat direction. Furthermore, Clausius's initial analysis is explicitly restricted to permanent gases operating under the Mariotte-Gay-Lussac law [65] (pp. 505–510]), an ideal gas assumption that means his initial entropy formulation applies fully only under approximately equilibrium conditions.

Clausius subsequently notes that differences in temperature and pressure could be a result of a far-from-equilibrium condition. Such a far-from-equilibrium condition could move heat from a cooler system to a hotter system, seeming to contradict the original form of the second law of thermodynamics. Clausius refines his second law of thermodynamics, defining the state property of entropy and stating a second form of the second law of thermodynamics that the entropy of the universe tends to a maximum [67–69].

In his 1865 paper formalizing entropy, Clausius defines the property S through the equation $\delta S = \delta Q/T$, but makes a restriction that is critical to the theory developed in this paper: this formula applies only to reversible processes, what Clausius called *umkehrbaren Vorgängen* [67] (p. 353). The implications of this restriction, including Clausius's actual reversibility criterion and its consequences for far-from-equilibrium systems, are developed in detail in Sections 2.3.3 and 2.4 below.

This version of the law does not allow for work to reverse the entropy of the universe, which would be the case if heat spontaneously moved from a cold system to a hot system. Any such work that reverses the direction of heat dissipation produces its own heat dissipation and would still result in an increase in entropy.

In 1909, Ludwig Boltzmann develops a statistical form of mechanical theory [70] that explains entropy by examining near-equilibrium systems at the microstate level of particle positions and velocities. Boltzmann's theory in combination with Clausius's theory enables the calculation of entropy using either microstate properties or macrostate properties of thermodynamic systems.

2.3. Clausius's Three Papers: A Close Reading

The three papers by Clausius spanning 1850 to 1865 trace a 15-year development that, read together, contain the seeds of the non-equilibrium thermodynamics formulated in this paper. Before presenting heat transformation theory, it is useful to trace this development, because the present theory extends rather than contradicts canonical thermodynamics. This is demonstrated directly from Clausius's own texts.

2.3.1. Paper 1 (1850): Heat Bifurcates; Interior Work Is Path-Independent

In his first paper [65], Clausius challenges Carnot's assumption that the quantity of heat is undiminished in the production of work. His language is clear: "the latter part of this assumption, namely that the quantity of heat remains undiminished, contradicts our earlier principle, and must therefore, if we wish to maintain it, be rejected" [65] (pp. 500–501). By rejecting this assumption, Clausius recognizes that heat in dissipative processes bifurcates: some heat is consumed, i.e., converted into work or into changing the internal state of matter, while the rest is transmitted. Clausius develops this further through the interior work / exterior work distinction. Interior work overcomes intermolecular forces; it is path-independent, depending only on initial and final molecular states. Exterior work is performed against external resistance; it is path-dependent. This decomposition reveals that the path-dependence of heat in dissipative processes arises specifically from the work conversion component, and that the interior work component is in principle fully recoverable [65] (pp. 504–510).

2.3.2. Paper 2 (1851): The Limits of the State Postulate

In his 1851 paper [66], Clausius articulates the path-dependence of heat most clearly: "the quantity of heat necessary to bring a body from one condition into another depended, not upon the state of the body at the beginning and the end alone, but upon the manner in which the alterations had been carried on throughout" [66] (p. 5). He then clarifies the domain in which heat can be treated as a state function: this path-independence holds for "that portion only of the latent heat which corresponds to the interior work" [66] (pp. 5–6). The path-dependent component, exterior work, is precisely the component involved in far-from-equilibrium dissipative processes. Clausius's own analysis therefore shows that the entropy defined by $\delta S = \delta Q/T$ cannot fully characterize systems operating in the far-from-equilibrium, dissipative regime. This is known as the state postulate.

2.3.3. Paper 3 (1865): Entropy Restricted to Reversible Processes; Force Balance as the Reversibility Criterion

In his 1865 paper [67], Clausius formalizes entropy with the definition that S satisfies $\delta S = \delta Q/T$ for any reversible process (*umkehrbaren Vorgang*) [67] (p. 353). The explicit restriction to reversible processes is not incidental. It is a structural feature of the definition. Noteworthy for this paper is that Clausius states the reversibility condition in terms of force balance rather than speed: "For a process to be reversible, force and counter-force must be equal. Because the difference between them can be arbitrarily small, one can regard the case where absolute equality holds as the limit case" [67]. This condition, force equals counter-force, is not inherently a condition of slowness. The identification of reversibility with quasi-static conditions is a consequence of Clausius's piston examples. In those examples, maintaining force balance between the gas pressure and an adjustable external pressure requires slowing the piston to an infinitely slow quasi-static limit. However, quasi-static is a consequence of those specific mechanical systems, not Clausius's stated criterion.

2.4. Extending Clausius to Far-From-Equilibrium Open Systems

Across these three papers, Clausius consistently operates in the domain of near-equilibrium, reversible, or ideal-gas processes. His definitions are internally consistent and correct within that domain. However, his own analysis of dissipative processes in which heat is consumed rather than merely transmitted points toward a regime outside that domain. Heat transformation theory extends Clausius's framework into that regime.

Understanding why heat bifurcates, i.e., why some heat is consumed in interior work while the rest is transmitted, requires understanding the molecular-scale mechanism of heat transfer itself. James Maxwell's work in 1860 builds on Clausius's earlier work by showing that the difference in temperature between two systems is a difference in the microstate intensive property of average molecular kinetic energy of the particles of the two systems, the greater temperature system having particles with a greater average molecular kinetic energy [71,72]. When a cooler system comes into contact with a warmer system, meaning that heat can transfer between them by conduction, convection, or radiation, the kinetic particles in the warmer system transfer momentum to the kinetic particles in the cooler system, on average. This is because the particles in the warmer system are colliding with the particles in the cooler system, momentum is conserved in any collision of two particles, and greater momentum particles that are vibrating at greater kinetic energy transfer some of their momentum to lesser momentum particles that are vibrating at lesser kinetic energy. In the bulk interactions of two systems of particles at different macroscopic temperatures, molecular kinetic energy is passed on average from particles in the hotter system to particles in the cooler system. *On average* means that less than 50% of particles in the cooler system have a greater molecular momentum than particles in the warmer system that they interact with, resulting in more molecular momentum transfer into the warmer system than into the cooler system. The majority of particles have greater momentum in the warmer system than particles in the cooler system. Heat transfer is a net effect, so the macroscopic process property of heat is transferred from the warmer system into the cooler system.

The microscopic transfer of molecular momentum is fundamentally a result of a differential force of interaction between two particles, with the net force against the greater momentum particle slowing it down somewhat, and the net force against the lesser momentum particle speeding it up somewhat, according to Newton's second and third laws of motion from which conservation of momentum is derived. If these two systems are in contact through a perfectly-insulated, equal-surface-area, moving interface such as a piston and have differences in the macroscopic state intensive property of pressure (that could be a result of their differences in temperature), then the macroscopic process property of work is exhibited by the movement of the piston, resulting in the pressures tending to equalize by the bulk mass movement and acceleration of molecules. The macroscopic process property of work is performed. This molecular-scale force balance that is Newton's third law operating at the level of individual particle collisions is precisely the mechanism that Clausius's force = counter-force reversibility criterion formalizes at the macroscopic level.

Furthermore, what Clausius does not develop and what the mechanical systems he analyzes cannot illustrate is that force balance can be achieved dynamically, not by slowing a process until it approaches equilibrium at each step, but by choosing a physical medium in which the forces are conservative by nature and therefore balanced at every instant regardless of the speed of the process. Clausius's force = counter-force criterion revealed in Section 2.3.3 is satisfied exactly in conservative force fields, where the restoring force at every point equals the applied force. They satisfy Clausius's force-balance reversibility condition not as a limiting approximation but as a physical consequence of the nature of the forces involved. Heat transformation theory therefore identifies far-from-equilibrium processes that are implicit in Clausius, the physical classes of processes for which force balance is achieved exactly and dynamically and develops the thermodynamic properties of the far-from-equilibrium open systems in which such processes occur alongside irreversible heat-exchange stages.

Clausius applies his entropy formula within the convention of the universe as an isolated system, which is the same convention he uses in his gas piston analyses, where the combined system of gas piston plus thermally massive reservoirs is treated as isolated from whatever lies beyond the reservoir boundaries. Within this convention, this paper develops two specific forms of entropy: system entropy, a change of entropy of a system because of heat input to and heat output from the system through its system boundaries; and universal entropy, generated by irreversible heat dissipation from the universal heat source to the universal heat sink within the isolated system. The correct convention for calculating the change in entropy of any intermediate closed or open system between the universal heat source and the universal heat sink is to account for all heat transfers once dissipation to the universal heat sink is complete. The second law requires all heat entering an intermediate system to ultimately dissipate out of it to generate irreversible growth in entropy of the universe. The correct convention for calculating entropy of the universe is also to consider all heat transfers out of the universal heat source and into the universal heat sink to be complete. These conventions are first applied mathematically in this paper to the open-system simple heat transfer model to determine system entropy in Section 3.3 (Equation 9) and universal entropy in Section 3.4 (Equation 10). Further development system entropy and universal entropy for progressively more complicated models is in Sections 3 and 4.

With the first and second laws of thermodynamics firmly established from the late nineteenth century until now, science is now able to mathematically model effectively anything in the universe, because everything runs on energy release, energy capture, work, and heat dissipation. To stick build the prebiotic Earth, the place to start is with such models. What follows is a series of thermodynamic models that utilize work and heat and progressively add functional elements until a model is developed that is as close as possible to the environments of Earth. The analysis reveals understanding of how Earth achieves what heat transformation theory calls *massive mixing*, the level of multiplicity of microstates and ergodicity of mixing necessary to achieve the development of life.

3. Heat Dissipation Causes Growth

3.1. Open-System Simple-Heat-Transfer Model

The simplest model is the open-system simple-heat-transfer model of Figure 1.

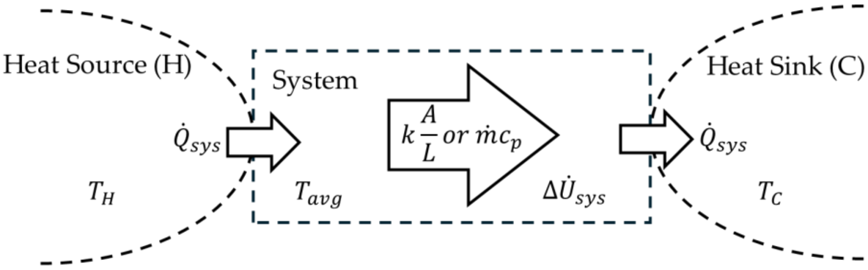

Figure 1. A model of an open system (subscript *sys*) with a heat source (subscript *H*) from which and a heat sink (subscript *C*) to which the open system undergoes a simple heat transfer process. The following variables are used: $\dot{Q}_{sys}$ – heat transfer rate into and out of the system, k – heat transfer coefficient of matter in system, A – cross-sectional area of system of matter, L – length of system of matter from heat source to heat sink, $\dot{m}$ – mass flow rate, c_p – specific heat capacity at constant pressure (subscript *p*) , T_H – temperature of the heat source, T_C – temperature of the heat sink, T_{avg} – average (subscript *avg*) temperature of the system, $\Delta\dot{U}_{sys}$ – the rate of change of internal energy of the system.

Heat transfer from the heat source to the heat sink through the open system is governed by the second law of thermodynamics. The heat source and heat sink are modeled as much larger than the open system and the open system has reached a steady state condition. This means that the heat source and heat sink are large enough that their temperatures do not change as they release or absorb heat. They are at thermal steady state. Their temperatures are constant reference temperatures for the entropy calculations; this constancy does not make them equilibrium systems in Clausius's sense, for which equilibrium entropy would apply. The heat source and heat sink temperatures do not change as heat transfers into and out of the open system. The heat source and heat sink together are considered to be the universe within which the open system exists (see Section 2.4 for discussion of Earth as an open system and the universe as a stable thermal reservoir on the timescales of Earth history). The open system contains homogeneous, gravitationally inert matter (at gravitational equilibrium), chemically inert matter (at electro-chemical equilibrium), and radioactively stable matter (at nuclear equilibrium). Because this model excludes conservative force fields, it addresses only the dissipating heat side of the Clausius bifurcation established in Section 2.3.1, the heat that is transmitted from a warm body to a cold one, generating universal entropy, without being consumed in interior work against a conservative force field. The conservative force and interior work side of the bifurcation is introduced in Section 3.5. The open system has dissipated heat long enough that temperatures have stabilized everywhere in the open system. Though the heat source and heat sink are idealized to be at thermal steady state, the open system is in a far-from-equilibrium steady state considering it is actively transferring heat at a fixed rate.

Consider a fixed time frame of constant heat transfer from the heat source (subscript *H*) through the open system (subscript *sys*) to the heat sink (subscript *C*) in an isochoric process according to the second law of thermodynamics. The conductive heat transfer equation,

$$\dot{Q}_{sys} = k\left(\frac{A}{L}\right)(T_H - T_C)\ , \tag{1}$$

assumes heat transfer by conduction only. If the heat transfer is occurring by convection resulting from a movement of mass into the system from the heat source and out of the system to the heat sink, then the heat transfer rate is provided by

$$\dot{Q}_{sys} = \dot{m}c_p(T_H - T_C) \tag{2}$$

for a homogenous distribution of flowing material.[1]

A fixed time frame of constant heat transfer allows us to put the model in terms of scalar changes in internal energy, net heat input, and net work output over the given time period. To develop a mathematical expression of this model, start with the first law of thermodynamics,

$$\Delta U_{sys} = \Delta Q_{sys} - W_{sys}\ , \tag{3}$$

that relates macroscopic process properties of heat and work to the macroscopic state properties of energy.

For an isochoric process, macroscopic work output from or work input to the system is zero, $W_{sys} = 0$, meaning there are no changes in pressure or kinetic energy within the open system as a result of the exertion of an external non-conservative force on the system. The change in the macroscopic state extensive property of internal energy, ΔU_{sys}, of the open system of matter is equal to the net heat transfer, ΔQ_{sys}, into the open system (i.e., the heat input from the heat source minus the heat output to the heat sink),

$$\Delta U_{sys} = \Delta Q_{sys}\ . \tag{4}$$

The definition of entropy is used to define the change in the macroscopic state extensive property of entropy of a system of matter of average temperature (subscript *avg*) with positive net heat transfer into the system or a negative net heat transfer out of the system,

$$\Delta S_{sys} \equiv \frac{\Delta Q_{sys}}{T_{avg}}\ . \tag{5}$$

Equation 5 is the mathematical form of system entropy for the open far-from-equilibrium system, the first of the two entropy forms introduced in Section 2.4. It applies Clausius's entropy formula $\delta S = \delta Q/T$ to the open system using the convention stated in Section 2.4 for calculating system entropy: all heat transfers into and out of the system are accounted for once dissipation to the universal heat sink is complete.

3.2. Explanation of Heat Capacity

Using the change in system entropy as a property of an open far-from-equilibrium system assists in understanding the heat capacity of the system. Combining the isochoric first law of thermodynamics, Equation 4, with the definition of change in entropy, Equation 5, results in a relationship of the change in internal energy of a far-from-equilibrium system being proportional to

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[1] An example of a real system that can be modeled as convective heat transfer in an open system simple-heat-transfer model is a Bénard cell [73]. A Bénard cell is an example of a dissipative structure that does not involve a conservative force field. DSs that utilize conservative force fields are discussed starting in Section 3.6

the change in system entropy, with the constant of proportionality being the steady-state average temperature of the open system of matter,

$$\Delta U_{sys} = T_{avg} \Delta S_{sys} \,. \tag{6}$$

This relationship means that the change in system entropy and the change in internal energy of the system are correlated. Considering the change in internal energy is due to a net heat input or output (or a non-isochoric process of a net work input or output that becomes heat as the work is dissipated), this change in internal energy is a result of the heat capacity of the system, which heat capacity is a measure of how much heat can be absorbed by a system of matter (i.e., how much molecular kinetic energy a system of matter can have) for each degree of temperature. The term $T_{avg}\Delta S_{sys}$ is related to change in internal energy by the net heat absorbed or released by the system based on its heat capacity. This equation also works for changes in internal energy and equilibrium entropy of a near-equilibrium system. The first law of thermodynamics sets no limits on the dynamics of the system.

3.3. Determining the Macroscopic Properties of State of the System

Heat entering the open far-from-equilibrium system in steady state from the high temperature heat source, Q_H , has a positive contribution to the first law of thermodynamics and is equal and opposite to the contribution of the heat leaving the system into the low temperature heat sink, Q_C ,

$$Q_C = -Q_H = |Q| \,. \tag{7}$$

The first law of thermodynamics reveals that the total change in internal energy of the open system in steady state heat transferring over a fixed time frame from the heat source through the open system to the heat sink is zero,

$$\Delta U_{sys} = \Delta Q_{sys} = Q_H + Q_C = |Q| - |Q| = 0 \,. \tag{8}$$

Finally, applying the definition of entropy, the system entropy change is zero, because of the stabilized average temperature and because the heat output from the system is equal to the heat input to the system,

$$\Delta S_{sys} = \frac{|Q|}{T_{avg}} - \frac{|Q|}{T_{avg}} = 0 \,. \tag{9}$$

Equation 9 uses the convention established in Section 2.4: with complete accounting of all heat transfers once dissipation to the universal heat sink is complete, heat in equals heat out of the system, and the net change in system entropy is zero. The zero result is not a special property of the simple heat transfer model. It is a general consequence of the second law of thermodynamics: all heat entering an intermediate system before reaching the universal heat sink must ultimately dissipate out of it. The convention established in Section 2.4 implements this by accounting for all heat transfers once dissipation is complete.

3.4. Determining the Macroscopic Extensive State Property of Entropy of the Universe

When determining the entropy generated in the universe as a result of heat being transferred through the open far-from-equilibrium system, it is universal entropy that is being calculated, the entropy generated beyond the system boundaries as heat dissipates from the universal heat source into the system and from the system to the universal heat sink. The second law of thermodynamics establishes that universal entropy always increases as heat dissipates from higher to lower temperature. Universal entropy production is the entropy of the isolated universe, always positive and increasing per the second law, calculated using the isolated system convention established in Section 2.4. Universal entropy is generated by irreversible heat dissipation. As such, it is a *production* quantity, not like a *change* in system entropy that is a difference quantity. Evaluating the entropy production of a universe made up of a universal heat source and universal heat sink, the decrease in entropy of the higher temperature heat source is less in magnitude than the increase in entropy of the lower temperature heat sink, resulting in the universal entropy production being positive,

$$S_{uni} = |Q|\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right) > 0\ for\ T_{uni-H} > T_{uni-C}\ . \tag{10}$$

Equation 10 expresses universal entropy production for the simplest open-system case as the second of the two entropy forms introduced in Section 2.4. The result $S_{uni} > 0\ for\ T_{uni-H} > T_{uni-C}$ is precisely the second law of thermodynamics as Clausius stated: the entropy of the universe tends to a maximum. The universal heat source temperature, and T_{uni-H} , universal heat sink temperature, T_{uni-C} , are the temperatures of the thermal steady-state reservoirs between which the open system operates, corresponding to the hot and cold reservoirs of Clausius's original second-law analysis, now applied to the non-cyclic open-system context.

3.5. Open-System Simple-Heat-Transfer Model in a Conservative Force Field

Sections 3.1 through 3.4 address the dissipating heat side of the Clausius bifurcation, heat transmitted from a warm body to a cold one, generating universal entropy. This section introduces the conservative force field, which is the physical realization of Clausius's interior work. Interior work, as Clausius established in his 1850 paper [65] presented in Section 2.3.1, is performed against intermolecular forces, is path-independent, and is fully recoverable. Conservative force fields satisfy this description exactly. By adding a conservative force field to the open-system model, this section introduces the physical mechanism by which heat can be stored and returned without generating entropy, completing the two-sided picture of the Clausius bifurcation in its simplest open-system form.

Now consider the same problem of a constant rate of heat transfer through an open system but with the presence of a conservative force field in the system of matter between the heat source and the heat sink , as shown in Figure 2.

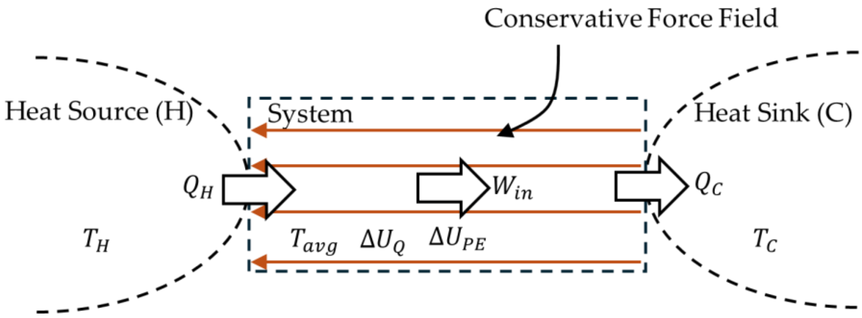

Figure 2. A model of an open system with a heat source from which and a heat sink to which the open system undergoes a heat transfer process in the presence of a conservative force field. The following new variables are introduced: Q_H – heat leaving the heat source and entering the system, Q_C – heat leaving the system and entering the heat sink, W_{in} – work input to the system, ΔU_Q – internal energy of heat capacity of the system, ΔU_{PE} – potential energy of the system associated with the conservative force field. The total energy contained by the system is $\Delta U_{sys} = \Delta U_Q + \Delta U_{PE}$.

As the heat dissipates through the matter from the heat source to the heat sink, it must do so in a way that allows it to dissipate in the direction opposite to the force of the conservative field. A graph of distance from the center of the source of the conservative field vs. potential energy stored in the conservative field looks like a well, shown in Figure 3.

This is called a potential energy well. The energy balance equation to be used combines the first law of thermodynamics with the work-energy theorem,

$$\Delta U_{Q-sys} + \Delta U_{PE-sys} = \Delta Q_{sys} + W_{in-sys}\ . \tag{11}$$

The left side of the relationship includes a change in potential energy (subscript PE) of the matter that holds the internal energy of the heating as the matter "rises" to the top of the conservative potential energy well, ΔU_{PE-sys}. To help keep track of ΔU terms, give the change in internal energy a subscript Q associated with heat, ΔU_{Q-sys}.[2] Assuming there is no initial macroscopic kinetic energy of material movement in the system, there must be a combination of heat input captured by internal energy of the material and heat movement through the system by way of conduction, radiation, or convection. Conduction is slow, and heat transfer by a material generating radiation tends to be less effective, as other surrounding material can tend to absorb the emitted radiation, effectively blocking it from transfer. Convection is more effective and must be driven by a work input (i.e., a negative work output) to move the material against the conservative force field for the heat to transfer "up" the gradient of the potential energy well to reach the heat sink, if possible. If not possible, it remains in the system until the system rises to a sufficiently high temperature to make the differential temperature with the heat sink high enough to force the heat to transfer. Within a potential energy well, heat tends to move by convection until the moving material that holds the heat gets high enough in the potential energy well to enable radiative heat transfer to become more effective at transferring the heat into the heat sink. The material movement implies that the material must be in a fluid state.

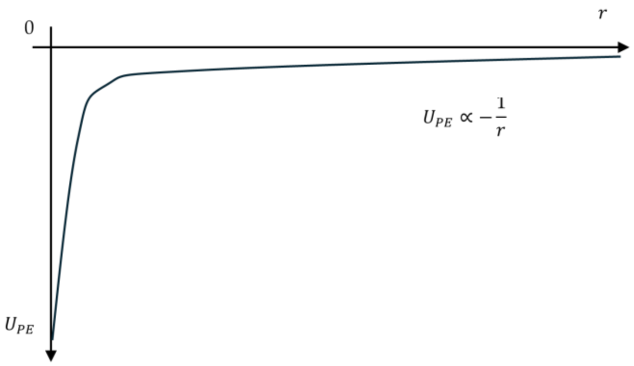

Figure 3. The potential energy function of a point source potential energy well. The potential energy is proportional to the negative inverse of the distance from the point source of a conservative force field.

For Equation 11, the work-energy theorem and first law of thermodynamics are combined to require a term of work input (subscript *in*) to the system, W_{in-sys}, that is a positive contribution of energy to the heat-bearing material to overcome the potential energy well to convectively move the heat captured by the internal energy of the system to the top of the gravity well where it can be released as radiation. Note that the increase in potential energy is a result of internal-energy-holding matter being displaced against the conservative force field. This corresponds to interior work in Clausius's terminology of Section 2.3.1 and Section 2.4. The model has no qualifier regarding whether the work input is a result of a conservative or a non-conservative force, and therefore whether it corresponds to interior or exterior work in Clausius's terminology. Both the work-energy theorem and the first law of thermodynamics allow for non-conservative work, though the work-energy theorem considers conservative forces to only be part of the change in potential energy term and the non-conservative forces to be part of the work term. For Equation 11, the change in potential energy term only includes consideration of the four standard conservative forces and the work input term includes all other forces.

Heat escape from a potential energy well is governed by this analytical model. Also note that this model allows for the work input to become either or both a change in internal energy and a

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[2] Textbooks and literature commonly symbolize both internal energy and potential energy using the term ΔU. The subscripts of Q, PE, and G are used to differentiate between the internal energy of heat capacity and the potential energy of gravity. What internal energy and potential energy have in common beyond the symbol is that they are both forms of stored, captured, or contained energy.

doi:10.20944/preprints202602.1676.v2

change in potential energy. The creation of an internal energy change, ΔU_{Q-sys}, by the work input, W_{in-sys}, would be a result of bulk kinematic motion caused by the work input to the fluid molecules of the material being quickly internalized to molecular kinetic energy as a result of the acceleration of the individual molecules. This bulk kinematic motion can also result in kinetic energy being quickly converted to potential energy of the material in the conservative force field, ΔU_{PE-sys}. By the time it reaches a location in the potential energy well where the heat can now escape by radiation, the convective heat transfer produced by the work input is converted into potential energy of the fluid material in the potential energy well and possibly some increase in internal energy. Therefore, the immediate heat output to the heat sink is equal in magnitude to the heat input from the heat source with possibly some additional heat output resulting from some of the work input.

The system now has potential energy in it. This is why the work is treated as an input. The potential energy is contained by the material that also contains the internal energy of heat capacity. For the sake of simplifying this model, assume the potential energy is released and converts to heat, with the heat being output from the system to the heat sink. The change in system entropy due to heat transfer into and out of the system is zero just as for the open-system simple-heat-transfer model, consistent with the convention established in Section 2.4 and confirmed in Section 3.3. The work input that becomes potential energy as the material is lifted in the potential energy well initially converts completely to kinetic energy, with the bulk kinetic energy of material then dissipating into additional heat output from the system, $|Q^{W_{In}}|$. This adds to the original heat input to the system from the heat source, resulting in additional universal entropy production. The result is that the universal entropy production for this model is somewhat greater than for the isochoric model,

$$S_{uni} = (|Q| + |Q^{W_{In}}|)\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right) > 0 \; for \; T_{uni-H} > T_{uni-C} \,. \tag{12}$$

3.6. Temporary Equilibrium with Stored Potential Energy

Now consider a system in which the potential energy is not released immediately. Assume the material that is transferring heat to the top of the potential energy well of the system is held in place by a normal force plateau that is a temporary equilibrium point for the material in equal opposition to the conservative force field at the point in the potential energy well where the heat leaves the system by radiation. This assumption fits real phenomena in nature known as dissipative structures (DSs). Prigogine, Wiame, and Nicolis first recognized the existence of DSs in nature as collections of material that organize and grow while dissipating heat [74–77]. Irons and Irons [78] (Figure 2) postulated that the DS is a far-from-equilibrium heat engine that drives against a conservative force field, resulting in a cycling of potential energy storage followed by a release that acts as an ideal pump in the return cycle of the heat engine. Conceptually for a DS to experience growth, there must be a work input. Work input to a system is the mathematical representation of growth or gain of system energy in physics. The existence of a normal-force plateau in the system that stores potential energy for some period of time fits the DS phenomenon. Thus, the model of an open-system simple heat transfer in a conservative force field with a temporary equilibrium plateau appears to be a good candidate for modeling a DS in nature.

The temporary storage of potential energy at the normal-force plateau is the physical realization of Clausius's interior work: the material is held in opposition to the conservative force field, force equal to counter-force, as established in Section 2.4, and the stored potential energy is fully recoverable without generating entropy. The DS therefore realizes, in a far-from-equilibrium open system, Clausius's force = counter-force criterion for zero entropy production.

With the development of these models, the progression is toward a model that looks like Earth with heat pouring onto it from the Sun and then dissipating from Earth back into space. This model of heat dissipation out of a conservative force field well with a temporary storage of potential energy matches the situation on Earth in which the heat from the Sun that strikes Earth escapes from the gravity well. What natural phenomenon produces the required work input of the model? The next step is to examine more closely the ways in which heat dissipates from Earth by modeling a gravitational dissipative structure (GDS).

4. Dissipation of Heat Through a Gravitational System

4.1. Heat Engine Model of a Gravitational Dissipative Structures (GDS)

When the force field in Figure 2 is replaced by gravity, it is a model of how the tropospheric water cycle (TWC) on Earth enables heat to escape the gravity well of Earth. The Figure 2 model does not include the entire TWC that is shown in Figure 4.

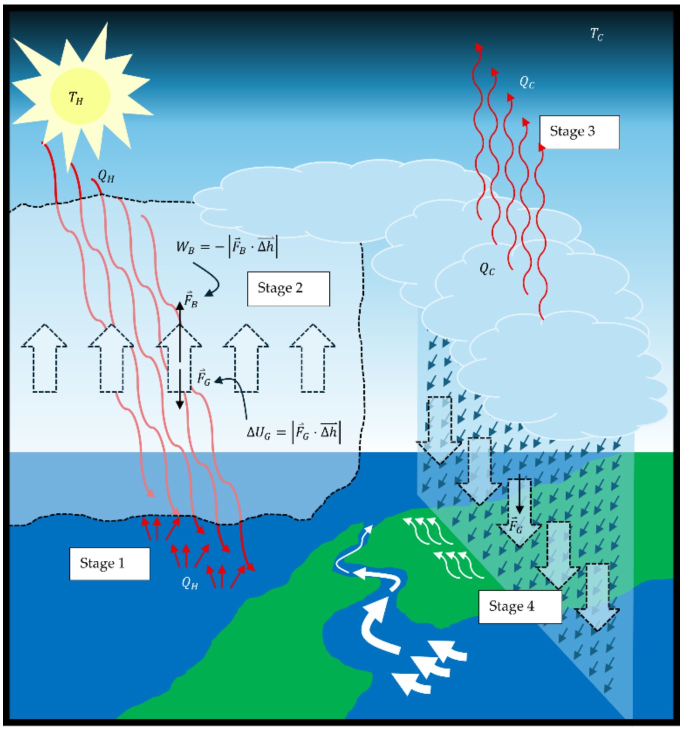

Figure 4. The tropospheric water cycle (TWC). At stage 1 (S1), liquid water absorbs the heat of solar radiation, Q_H, and evaporates into gaseous form. At stage 2 (S2), the buoyant force, $\vec{F}_B$, performs work on the water vapor, W_B, by lifting the water vapor to higher altitudes, $\overrightarrow{\Delta h}$. As this occurs, the force of gravity, $\vec{F}_G$, acts against the lift, resulting in an increase in potential energy of the water vapor, ΔU_G. At stage 3 (S3), the heat released by condensing water vapor, Q_C, dissipates into the upper atmosphere and space. At stage 4 (S4), the water falls back to Earth's surface as precipitation and flows to the lowest point in Earth's gravitational well that it can reach, returning to the beginning of stage 1 where it can again absorb solar radiation.

The TWC includes the return of the water to ground level. The TWC is a gravitational dissipative structure (GDS). A heat engine model of the TWC GDS is analyzed in Appendix A. Stage 1 (superscript *S1*), stage 2 (superscript *S2*), stage 3 (superscript *S3*), and stage 4 (superscript *S4*) of Figure 4 align with the same stages in Figure A1. This model is based on deep convective organization on the mesoscale in which the water cycle is driven by entraining plume buoyancy with layer lifting and deep in-flow mixing [79,80]. Application of the first law of thermodynamics and the work energy theorem to the model results in the energy balance (also Equation A5),

$$|\Delta U_Q^{S1}| - |\Delta U_Q^{S3}| + |\Delta U_{PE}^{S2}| = |Q_H^{S1}| - |Q_C^{S3}| - (-|W_{In}^{S2}|)\,. \tag{13}$$

The Sun is a heat source reservoir for Earth, because heat in the form of radiation is emitted by the nuclear fusion of hydrogen into helium in the Sun and travels at the speed of light as photons (electromagnetic packets of energy) to Earth with an energy equivalent to the temperature of the Sun at which it was radiated, T_H. A photon from the Sun comes into contact with the electric field of an atom on Earth and is thereby absorbed by the atom. The absorption of the energy of the photon by the atom causes the atom to increase the average speed of its vibration. An influx of such photons against a large mass of material, such as the surface of a lake, results in the temperature of the mass of material rising as its internal energy increases based on its heat capacity. This is stage 1 of the heat engine model of the TWC: heat input. The heat from the Sun, Q_H^{S1}, enters water on Earth's surface at stage 1 of the heat engine, increasing the internal energy of some of the water by an amount required to raise it to the temperature of vaporization and then transition its phase to water vapor (superscript *wv*), $\Delta U_Q^{S1} = \Delta U_Q^{wv}$.

The warm water vapor that is formed is less dense than the cooler air around it and above it. At stage 2, this difference in density creates a buoyant force upward on the water vapor in opposition to the gravitational force on the water vapor. The expansion of the water vapor also lifts the atmosphere with it by the displacement of the cooler air, just as bath water rises when you sit in it. The buoyancy and lift forces (subscripts *B* and *L*) together result in work input being done on the atmospheric column made up of water vapor and air (subscript *air*) (from Equation A8),

$$W_{in}^{S2} = W_B^{wv} + \delta W_L^{air} \,. \tag{14}$$

The buoyancy work pushes evaporated water skyward with the internal energy it holds in its kinetic-molecular molecules, ΔU_Q^{wv}. The work of the buoyancy and lift forces accelerates the molecules in the water vapor and air column, increasing the molecular kinetic energy of the water and air molecules, resulting in convective heat, $Q_{B/L}^{S2}$. The convective heat of the acceleration is simultaneously converted into the potential energy of gravity (subscript *G*) in an equal amount to the work of the buoyancy and lift (from Equation A13 and Equation A16),

$$\Delta U_{PE}^{S2} = \Delta U_G^{wv} + \delta U_G^{air} = W_B^{wv} + \delta W_L^{air} \,. \tag{15}$$

As it is lifted skyward, the water vapor continues to take in more heat from the solar radiation, even as it dissipates some heat to cooler air molecules around it. This maintains the water vapor at the lower density needed to produce buoyancy work that is converted into gravitational potential energy as it continues to rise. At various altitudes, dependent upon environmental conditions of the atmosphere, stage 3 occurs with the heat dissipation from the water vapor becoming greater than the heat transfer into the water vapor from solar radiation. Water vapor releases the latent heat of vaporization, ΔU_Q^{wv}, condensing and releasing the heat that ultimately dissipates to space, Q_C^{S3}.[3]

During stage 4, condensed water falls from the sky by the force of gravity. The total volume of water vapor decreases by the loss of vapor to condensation. This results in the lifted air falling as the total vapor bubble reduces in size. This is a gravitational leveling/rounding effect of the troposphere by the force of gravity (Figure 5), described by Irons and Irons [78] (Presentation 1). The energy balance for stage 4 just involves gravitational potential energy and heat (also Equation A23),

$$-|\Delta U_{PE}^{S4}| = -|Q_C^{S4}| \,. \tag{16}$$

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[3] Liquid water and even frozen water can result. Considering that some of the original evaporation/sublimation into water vapor comes from regions of snow and ice, effects of such subcooling into cold water and ice/snow are considered to be averaged out of this model.

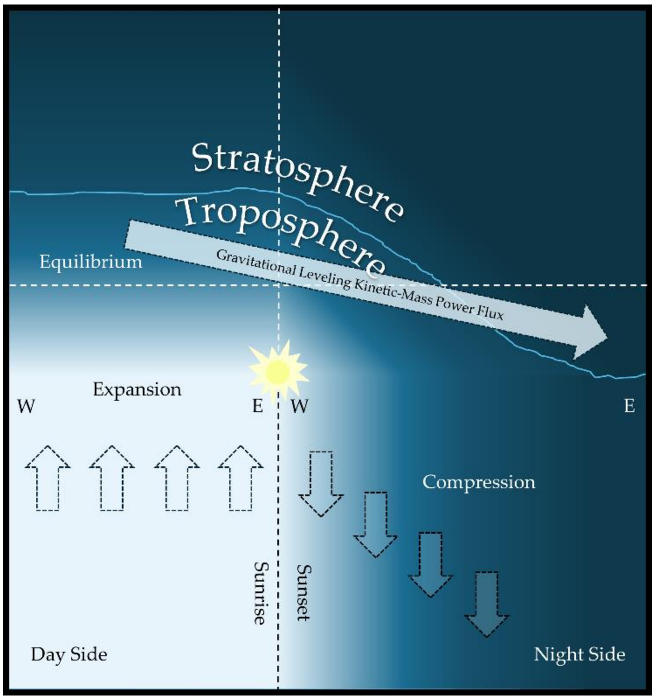

Figure 5. Atmospheric lift results from the expansion of water vapor that displaces dry air to higher altitudes. When the Sun sets and the night side of Earth loses solar insolation, water vapor remaining in the air contracts, resulting in the atmosphere compressing to lower altitudes. Air pressure at altitude adjusts conservatively based upon the weight of the air column under the influence of gravity (determined by the atmospheric density and depth). This causes the atmosphere to act like a conservative piston, considering gravity is not depleted by the lift and subsequent leveling.

The decrease of potential energy of rain as it precipitates (superscript *precip*) and lifted air as it atmospherically levels (superscript *atmlev*) at stage 4 is equal and opposite to the increase in potential energy of buoyant water vapor and lifted air during stage 2,

$$\Delta U_{PE}^{S4} = \Delta U_G^{precip} + \delta U_G^{atmlev} = -\Delta U_G^{wv} - \delta U_G^{air}\,. \tag{17}$$

Heat transformation theory refers to this as the decay part of the dissipative structure, because stored potential energy is being released. The potential energy is converted to the kinetic energy of bulk water, molecular water, and air, a continuation of the convective cycle started by the rising water vapor and air column in stage 2. The water hits the ground and sinks into the ground or flows over the surface to collect back into streams, rivers, ponds, lakes, and oceans from which the water evaporated, with all kinetic energy gained from the gravitational potential energy being converted into the internal energy of the water and air warming up (superscript *wu*),

$$\left|\Delta U_Q^{wu}\right| = \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|\,, \tag{18}$$

both from friction during the precipitation and leveling and from the impact of water hitting the ground, at which point its remaining kinetic energy is converted to internal energy The increase in internal energy then dissipates into the environment as heat. The energy balance gives the result that the heat dissipated into the environment at stage 4 due to the warmup is equal to the original increase in potential energy of the water vapor and air during stage 2,

$$\left|Q_C^{wu}\right| = \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|\,. \tag{19}$$

4.2. Characteristics of DSs

Three interesting characteristics of a DS are revealed by this model. The first characteristic is that the restoration of internal energy from stored energy that does not deplete another energy source or reduce the quality of the restored energy makes stage 4 of the DS act as an ideal pump, with conservative forces performing all work in the thermodynamic cycle. This means that the thermodynamic cycle of the DS is semi-reversible [78].

This semi-reversibility has its foundation in Clausius's own reversibility criterion, stated in his 1865 paper: a process is reversible when force and counter-force are equal [67]. In the conservative-force stages of the GDS (stages 2 and 4), gravity and buoyancy are the acting forces, and conservative force fields by their nature maintain this force balance at every point of the cycle regardless of the speed of the process. It is important to note what Clausius does *not* say: he does not say that reversibility requires quasi-static conditions. As established in Section 2.3.3, the identification of reversibility with quasi-static processes is a consequence of the mechanical piston examples Clausius used. In those examples, maintaining force balance between the gas pressure and an adjustable external pressure requires slowing the piston to an infinitely slow quasi-static limit. But quasi-static is a consequence of those specific examples, not Clausius's stated condition. The stated condition is force balance, and conservative forces satisfy it exactly and dynamically.

Sands [81] demonstrates this computationally. He shows that the canonical requirement that a Carnot cycle must be quasi-static to achieve reversibility is incorrect. Under idealized conditions of zero internal damping, an ideal gas in a piston changes state without net entropy production regardless of the speed of the piston. The cycle is dynamic rather than quasi-static, with the piston always in motion and never settling into static equilibrium. The universal entropy associated with such a dynamic Carnot cycle is zero whether run forward or in reverse. As Sands demonstrates, this result requires an ideal working fluid (no internal dissipation) and the absence of heat losses. It also requires precise control of when each stage of the cycle ends and the next begins; the literature indicates that such control mechanisms generate their own irreversible entropy through the erasure of the information they use to time the cycle [82], which is an additional entropic cost not addressed in Sands's framework.

The GDS reveals a way by which Sands's requirement of a zero-entropy control system can be physically satisfied, not by engineering a control system, but by eliminating the need for one. At stages 2 and 4, the conservative force field drives the energy storage and release automatically: the exact quantity of energy stored at stage 2 is returned at stage 4 with no reduction in quantity and no reduction in quality, because conservative forces are path-independent and the process is governed by the same force at both stages. No specific timing of the transition between stages is required, and no external control system is needed to enforce it. What the GDS achieves is reversibility under dynamic, non-quasi-static conditions, the physical substance of Sands's prediction, while dispensing with the Carnot cycle architecture and its associated control requirements entirely. Stages 2 and 4 are reversible in Sands's sense: no internal dissipation occurs, and the process changes state without net entropy production.

Stages 1 and 3 of the DS are irreversible and do generate universal entropy. They are governed by non-conservative processes that are the heat exchange with the universal heat source and heat sink respectively and are not controlled by path-independent energy storage. The irreversibility at stages 1 and 3 is not a failure of the DS; it is the thermodynamic cost that drives the cycle and satisfies the second law. The GDS as a whole generates positive universal entropy, as demonstrated throughout Section 4, because the irreversibility at stages 1 and 3 outweighs the zero-entropy contribution of stages 2 and 4.

This pattern of reversibility in the conservative-force energy-storing stages and irreversibility in the heat-input and heat-exhaust stages is a structural feature of all dissipative structures governed by conservative force fields. As will be shown in Part II, the identical structural pattern reappears in chemical dissipative structures (CDSs) in the general case: conservative electromagnetic forces between atoms govern the energy-storing bond-formation and bond-dissolution stages (stages 2 and 4, reversible), while the heat-input and heat-exhaust stages (1 and 3) involve heat exchange that can generate entropy.

In contrast, stages 2 and 4 of an engineered forced-convection heat engine are performed by non-conservative forces in constrained but non-isolated energy conversion systems. Heat dissipation and loss still occurs through scattering of work output at stage 2 into degrees of freedom of heat dissipation that do not perform work and through imperfectly insulated barriers as a result of dampening. If the work output of stage 2 of an engineered forced-convection heat engine were to be utilized to perform the work input at stage 4 to pump the heat transfer medium back to stage 1, the work input power available at stage 4 would be less than the work output power at stage 2 due to such heat dissipation and loss at both the stage 2 work output and stage 4 work input machinery, both losing power and generating universal entropy.

In Clausius's terminology established in Section 2.3.1, the work performed at stages 2 and 4 of an engineered forced-convection heat engine is exterior work, i.e., work performed against external resistance, path-dependent, and governed by non-conservative forces. Clausius's 1851 analysis shows that exterior work is inherently dissipative: the heat associated with it is path-dependent, cannot be fully recovered, and necessarily generates positive entropy (Section 2.3.2). This is the fundamental thermodynamic reason that stages 2 and 4 of the engineered heat engine generate universal entropy rather than achieving the zero-entropy result of the GDS's conservative-force stages. The GDS does not merely perform better in practice than an engineered heat engine, it operates by a physically different mechanism. At stages 2 and 4 of the GDS, conservative forces perform interior work: path-independent, fully recoverable, satisfying Clausius's force = counter-force criterion exactly. The contrast between interior work (zero entropy, conservative forces, GDS) and exterior work (positive entropy, non-conservative forces, engineered heat engine) is therefore not a matter of engineering efficiency but a direct consequence of the Clausius interior/exterior work distinction.

When considering the TWC GDS and the portion of heat input from the Sun that is non-reflective (i.e., only considering heat that must convectively escape Earth's gravity well), stage 2 and stage 4 of the GDSs occurring in the atmosphere have no such constrained, non-isolated energy conversion systems because the atmosphere acts as a whole, effectively isolating it from heat losses through any surface other than the stage 3 surface at the top of the troposphere. The buoyancy effect caused by density differences works because of pressure differences caused by the depth of a fluid in a gravitational field. The pressure differences drive motion by particle interactions of non-ideal fluids that can result in dissipation of the upward momentum of water molecules into transverse degrees of freedom, resulting in dissipation of the heat. However, greatly isolatable, single-dimensional motion of the water vapor results from barrier channeling. The vaporous ejections of high temperature water molecules from liquid water during evaporation are channeled in a common direction of the pressure gradient by the more compact and almost twice-as-massive air molecules made up mostly of diatomic oxygen and diatomic nitrogen that are also moving in the direction of the pressure gradient caused by a tropospheric air cycle (TAC) driven by the solar- heating of the air. The compact, massive, moving air molecules act like walls against the spread out, less-massive water molecules, resulting in water molecules giving up very little of their momentum to dispersion to degrees of freedom that are perpendicular to the pressure gradient. Thus, the water molecules mostly maintain their momentum along the pressure gradient that generally progresses vertically even as horizontal flow of air occurs barometrically. This upward movement of water vapor can be physically experienced by the bump of an airplane flying over a river on a hot day.

As a result of dense air around sparse water, superheating of water vapor by solar radiation tends to be dissipated into air, and molecules of water that manage to continue to rise gradually vertically along the pressure gradient have sufficient internal energy to maintain their latent heat of vaporization. Dissipation of water vapor superheating being captured in the air of the atmosphere effectively still requires dispersed heat captured by air molecules to transfer along the pressure gradient to the top of the troposphere. For the proportion of solar heating that is absorbed by water and air, the only way to escape efficiently from Earth's gravity well is by convection of both water and air to the top of the troposphere where it is output at stage 3. Earth's gravity well has no heat losses of absorbed solar radiation that depletes natural convection of combined water vapor and air because it is a sphere with a radial conservative force field. Thus, though the combination of the TWC and TAC do not meet theoretical requirements of a zero-entropy cycle at stage 1 and stage 3, they do at stage 2 and stage 4. Thus, the postulate of the DS being a semi-reversible heat engine cycle as proposed by Irons and Irons is supported theoretically.

The second interesting characteristic of a DS revealed by the TWC GDS is that the conversion of buoyancy to heat and then to potential energy, Figure 6, without depleting an energy source or reducing the ongoing quality of action of the gravitational field reveals that buoyancy is an extension of the conservative nature of the gravitational force field.[4] Buoyancy is a force caused by a permanent differential pressure that does not dissipate, making it conservative. This conservative nature of the buoyant force is a result of being coupled to the force of gravity by the variation in depth pressure of matter in the presence of gravity. Unlike a temperature difference that results in a pressure gradient to drive heat convection until the temperature and pressure equalize because of heat dissipation, depth pressure never equalizes, due to the constant presence of gravity. Effectively, the gravidynamic energy of buoyancy and lift are added to the environment as new heat energy without depleting gravity or buoyancy. The moment the fallen water of stage 4 evaporates again at stage 1, the buoyant force returns, fully conserved.

$$\xrightarrow{buoyancy\ and\ lift\ work}\left|W_B^{wv}\right| + \left|\delta W_L^{air}\right|\xrightarrow{molecular\ \Delta KE}\left|Q_H^{B/L}\right|\xrightarrow{PE\ increase}\left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|$$

$$\xrightarrow{gravitational\ \text{work}} -\left|\Delta U_G^{precip}\right| - \left|\delta U_G^{atmlev}\right|\xrightarrow{molecular\ \Delta KE}\left|\Delta U_Q^{wu}\right|\xrightarrow{dissipates\ as\ heat}\left|Q_C^{wu}\right|$$

Figure 6. Buoyancy driven by atmospheric depth pressure performs work on water vapor and air. The work is converted to molecular kinetic energy, effectively acting as a source of heat input. The molecular kinetic energy of work-heat is converted into gravitational potential energy. Any water that condenses and falls at any time during the cycle is returned to ground level because of the conservative nature of the force of gravity. The work of buoyancy that is stored as gravitational potential energy converts back to molecular kinetic energy as water molecules are accelerated by gravity. This injects into the Earth system an amount of internal energy of heat capacity equivalent to the energy of work performed by the buoyant force in previously lifting water to higher altitudes in the atmosphere. The injected internal energy is then free to dissipate as heat into the environment.

The third interesting characteristic of a DS is that it operates as an open system on a closed state cycle. This means that the properties of matter making up the DS return to the same values the matter has at the start of stage 1 when the matter reaches the end of stage 4. The net change in temperature, net change in pressure, net change in volume, net change in internal energy, net change in stored potential energy, and net change in system entropy of a unit of matter completing the cycle back to the beginning of stage 1 is zero. This confirms that the convention established in Section 2.4 for change in system entropy always being zero holds not only for the simple open-system heat transfer model of Section 3.3 but also for the more complex heat engine model of a GDS.

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[4] Universal entropy is generated by the warmup heat expelled at stage 4, but buoyancy's fundamental conservative quality is not reduced. This reveals that gravity wells are endless sources of additional energy when heat from other sources dissipates through them. This is a seeming paradox to the definition of entropy in that universal entropy from released gravitational potential energy does not deplete the source of gravity. While there is mass available to form gravity wells and while there is heat of any quality available to fall into gravity wells, GDSs would seem to continue to exist. The presence of life within this enigma is an interesting correlation.

At steady state, the heat transfer rate out of the GDS equals the heat transfer rate into the GDS. It is at this steady state level where the DS achieves maximum universal entropy production equivalent to simple heat transfer. This is a principle of operation of DSs known as the *maximum entropy production principle* [83–87]. The model of the GDS demonstrates that this principle is a result of stage 4 decay occurring at the same rate as stage 2 growth upon reaching steady state, thus resulting in total heat output equaling total heat input. Although MEPP has been contested as a postulate, with information-theoretic derivation attempts [88] themselves drawing criticism [89,90], the GDS model derives this behavior as a consequence of the second law requirement for intermediate systems rather than assuming it. On the growth path to steady state, the GDS takes in an increasing amount of heat at stage 1. It outputs less combined stage 3 and stage 4 heat than it takes in at stage 1 due to stage 4 decay of stored potential energy lagging behind stage 1 and stage 2 growth of stored potential energy. This means that the average net change in stored potential energy at any moment of a DS going through a growth transient is positive and increasing. To understand the function of a GDS further, it is necessary for heat transformation theory to define mathematical equations for state properties. These equations assist in analyzing the functions of a GDS.

The GDS framework as developed in this paper applies under four structural preconditions. First, a universal heat source and universal heat sink must be present and maintained at thermal steady state. A star provides radiative heat input and the cosmic microwave background of space provides the ultimate heat sink. This precondition is a given, considering they are the conditions for Clausius's definition of entropy. Second, a conservative force field of sufficient strength must be present. In the gravitational case, a planet with substantial gravity providing the potential energy well through which heat must be transported. Third, the matter occupying that potential energy well must be capable of fluid motion, enabling convective transport against the conservative force at stage 2 and return at stage 4. A body whose matter is entirely solid cannot support a GDS cycle regardless of the strength of its gravitational field. Fourth, the physical properties of the system must provide a natural equilibrium plateau, a point at which matter can be held in temporary balance against the conservative force field between stage 2 storage and stage 4 release. Without such a plateau, a dissipative structure still forms and cycles through all four stages. However, stored potential energy cannot accumulate to a sustained level: the stage 4 decay follows stage 2 storage too rapidly for the DS to build stored energy. Where all four preconditions are met, the GDS framework applies. The underlying thermodynamics is the same for any planet around any star.

4.3. Auto-Powering Capacity and Auto-Restoring Order of a DS

The DS has six thermodynamic properties defined by heat transformation theory: (1) auto-powering capacity (APC), (2) auto-restoring order (ARO), (3) specific universal entropy, (4) complexity yield, (5) specific heat quality, and (6) heat transformation effectivity. The first two properties, APC and ARO, are developed in this section. The remaining four intensive state properties are developed in Section 4.4. Four of these properties are proposed at a high level in Irons and Irons [78] (pp. 2-6) as self-restoring order, capacity, entropy, and exergy. The following presents a refinement of terminologies, definitions, and mathematical developments of these properties.

The first two properties refined by heat transformation theory are associated with the extensive macroscopic properties of process of the GDS. *Auto-powering capacity* (APC), referred to as capacity in [78], is defined as the flow within the DS that is generated by heat transfer per unit area of a DS. *Auto-restoring order* (ARO), referred to as self-restoring order in [78], is the flow within the DS that is generated by the release of the potential energy gained by work input at stage 2 and released at stage 4 to return the DS to its starting conditions. Flow is a network ecology term that can be expressed many ways, such as in properties of mass, energy, or population (number of "individuals") and in quantities of sums, rates, or fluxes [91] (pp. 213-260). Flow ($\mathbb{T}_{i,j}$) is usually associated with a transfer between two nodes (subscripts i and j) of a network. A DS is the node of a network that receives $Q_{i-H}^{S1\to2}$ flows from i local heat sources and outputs stage 3 Q_{j-C}^{S3} flows to j local heat sinks. The APC and ARO are flows within the node that sum, re-divide, and route the $Q_{i-H}^{S1\to2}$ heat inputs to Q_{j-C}^{S3}

stage 3 heat outputs. Ecosystem networks on Earth today are made up of both physical (inanimate) and biological (animate) DS nodes. For a pre-biotic Earth, such a network is only comprised of physical components. Developing heat transformation theory in terms of network ecology gives advantages of leveraging the science of ecological thermodynamics to explain the growth phenomena covered by the theory and suits the context of pre-biotic evolution of inanimate material.

Equations for APC and ARO can be mathematically modeled by starting with the heat engine model of the DS in question. Specific DSs have unique heat engine models, the model developed in Appendix A for the TWC being an example. Using the heat engine model, thermodynamic equations specific to the model are developed for APC and ARO based upon heat inputs and work inputs seen in nature for the given DS.[5] The equations and empirical values are used to calculate values.

4.3.1. The Tropospheric Water Cycle (TWC)

For the TWC model of Appendix A, APC is driven by the heat input of stages 1 through 3 (also Equation A17),

$$\left|Q_{in}^{S1\to3}\right| = \left|\Delta U_Q^{wv}\right| + \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right| . \tag{20}$$

It is desired to put APC in terms of power fluxes, i.e., energy flow per unit time per unit area, considering these are common units used in the study of network ecology. Using Equation 20, APC (superscript *APC*) for the TWC (subscript *twc*) takes the form,

$$\mathbb{T}_{twc}^{APC} = \frac{\Delta \dot{U}_Q^{wv}}{A_{atm}} + \frac{\Delta \dot{U}_G^{wv}}{A_{atm}} + \frac{\delta \dot{U}_G^{air}}{A_{atm}} . \tag{21}$$

Calculation S1 in the Supplementary Materials provides the analysis, empirical research on Earth's energy budget [92–94], and calculations for these values. The result from Equation S32 in the Supplementary Materials calculates $\mathbb{T}_{twc}^{APC}$ of Earth to be,

$$\mathbb{T}_{twc}^{APC} = 82\,\frac{\mathrm{W}}{\mathrm{m}^2} . \tag{22}$$

For the TWC model of Appendix A, ARO is driven by the heat output of stage 4, Equation A32. Putting ARO (superscript *ARO*) in terms of power fluxes takes the form,

$$\mathbb{T}_{twc}^{ARO} = \frac{\Delta \dot{U}_G^{wv}}{A_{atm}} + \frac{\delta \dot{U}_G^{air}}{A_{atm}} . \tag{23}$$

Equation S34 in the Supplementary Materials calculates $\mathbb{T}_{twc}^{ARO}$ of Earth to be,

$$\mathbb{T}_{twc}^{ARO} = 2.1\,\frac{\mathrm{W}}{\mathrm{m}^2} . \tag{24}$$

Research on Earth's energy budget [92–94] indicates the Earth receives an average flow of radiative-heat-transfer-rate flux from the node of the Sun (subscript *sun*) to the node of the TWC of $\mathbb{T}_{sun,twc} = 80\,\mathrm{W/m^2}$. The result is an equivalent average convective-internal-energy-transfer-rate flux of rising water vapor through the atmosphere. This results in an average of $2.1\,\mathrm{W/m^2}$ of kinetic-mass power flux due to the work input of buoyancy and lift that goes into gravitational potential energy, which kinetic-mass power flux is associated with the average convective-heat power flux of evaporated water.

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[5] In the discussion of APC and ARO for GDSs, the calculations presented are based on present-day empirically determined solar insolation and average Earth budget values. The calculated APC and ARO are average steady state values. These calculations are provided as examples. Knowing the level of solar insolation for a pre-biotic Earth would enable similar calculations. The same equations would apply, considering the physics of gravity and heat transfer is the same for pre-biotic Earth as it is for contemporary Earth.

4.3.2. The Tropospheric Air Cycle (TAC)

Any heat dissipated away from causing superheating can also be utilized by other DSs in the environment, such as what happens when the superheating of water vapor is dissipated into the surrounding air. This dissipation of superheating away from water vapor becomes part of the $95\,\mathrm{W/m^2}$ of average convective-heat power flux due to solar heating of the air in the atmosphere [92–94].

The TAC is a result of the interaction of two collections of air molecules, one being a collection of warmer, low-altitude air and the other being cooler, high-altitude air. The interaction results in an upward natural convection due to the pressure difference. This convective gradient is a result of a differential pressure between the hotter, higher-pressure end of the system where the heat is input to internal energy of the air and the cooler end of the system at the top of the atmosphere where the pressure is lower and heat output occurs. The heat is carried by the mass convection of warmed air into the cooler, higher altitudes, carrying an internal energy of the air based on its specific heat capacity.

The work of natural convection that drives the air is driven by gravity and therefore conservative, and the resulting TAC is semi-reversible in the same way as explained for the TWC. Calculation S2 in the Supplementary Materials provides analysis, empirical research on Earth's energy budget [92–94], and calculations for these values. The reader is left to prepare their own TAC GDS heat engine model similar to that of the TWC in Appendix A. The result of Equation S51 in the Supplementary Materials calculates the APC for the TAC (subscript *tac*) of Earth to be,

$$\mathbb{T}_{tac}^{APC} = \frac{\Delta\dot{U}_{Q}^{air}}{A_{atm}} + \frac{\Delta\dot{U}_{G}^{air}}{A_{atm}} = 95\,\frac{\mathrm{W}}{\mathrm{m}^2} + 250\,\frac{\mathrm{W}}{\mathrm{m}^2} = 345\,\frac{\mathrm{W}}{\mathrm{m}^2}, \tag{25}$$

with the ARO of the TAC (Equation S53 in the Supplementary Materials) only including a gravitational-potential-energy-release-rate flux equal to the storage-rate flux,

$$\mathbb{T}_{tac}^{ARO} = \frac{\Delta\dot{U}_{G}^{air}}{A_{atm}} = 250\,\frac{\mathrm{W}}{\mathrm{m}^2}. \tag{26}$$

All power fluxes used in APC and ARO are proportional to the kinematic-mass-flow-rate flux of the natural convection (subscript *NC*) of air, $\dot{m}_{NC}^{air}/A_{atm}$ (Equation S43 in the Supplementary Materials), considering it only involves specific heat capacity with no phase change. The result is $250\,\frac{\mathrm{W}}{\mathrm{m}^2}$ of average kinetic-mass power flux that is driven by natural convection into a gravitational-potential-energy-storage-rate flux of air displacement that is almost triple the associated $95\,\frac{\mathrm{W}}{\mathrm{m}^2}$ of average convective-internal-energy transfer rate flux of heat-capacity-carrying air.

The specific heat capacity of air results in much less internal energy carrying capacity than that of water vapor with its latent heat of vaporization. Air is also denser than water vapor. These two factors result in the kinetic-mass power flux of air needing to be greater than that of water vapor by two orders of magnitude. This high kinetic-mass power flux of air compared to water vapor is what mitigates the superheating of water vapor with the two DSs working together to mix the atmosphere.

4.3.3. Kinematic-Mass-Flow-Rate Flux Proportionality and the Effect of TWC and TAC

The example of the TWC and TAC reveal an interesting aspect of GDSs. The kinetic-mass-flow-rate flux of the heat-carrying medium of a DS is proportional to both the APC and the ARO. For the TWC of Calculation S1 in the Supplementary Materials, the contribution of the kinematic-mass-power flux of air to APC and ARO is two orders of magnitude smaller than the total APC and one order of magnitude smaller than the total ARO. The lesser contribution of kinematic-mass-power flux of air to APC and ARO allows an approximation of proportionality. Therefore, all the power fluxes used in APC and ARO are treated as proportional to the kinematic-mass-flow-rate flux of water vapor as shown in Calculation S1 in the Supplementary Materials. The example of the TWC reveals that DSs in which the heat-carrying medium undergoes a phase transition require an estimation of proportionality. However, the TAC analysis in Calculation S2 in the Supplementary Materials shows that the APC and ARO are exactly proportional to the kinetic-mass-flow-rate flux, thus needing no approximation. GDSs that do not undergo a phase transition have this proportionality as an exact property.

For this approximation to be acceptable for the TWC in which the heat-carrying medium undergoes a phase transition, an assumption built into the calculations of Calculation S1 in the Supplementary Materials is that there is no superheating of the water medium of the DS (i.e., raising the temperature of the water above the vaporization temperature at atmospheric pressure). All the heat input from the heat source goes into the latent heat of vaporization of water with the temperature of the water vapor remaining at $373.15\ \mathrm{K}$, the temperature of phase transition of liquid water into gaseous water at standard temperature and pressure.

This assumption requires questioning, considering kinematic-mass-flow-rate flux is governed not only by the quantity of mass involved but also by the velocity of flow. Superheating allows for the carrying of more heat by the same amount of mass. However, superheating would also result in an increase in velocity of flow due to a decrease in the density of the water vapor and an increase in the buoyancy force. These are competing changes that make it difficult to determine what is exactly happening in the environment. To address this unknown in the analysis, the heat transformation theory defines superheating as the carrying of a heat load above and beyond the mechanism of the DS to transform the extra heat load to potential energy. Considering the purpose of the heat transformation theory is to understand the mechanism of the DS that transforms heat into potential energy, the element of superheating is not a function of the DS and, therefore, is assumed to not be included in the transfer of heat through the DS. This is a valid assumption in that the open-system nature of DSs, even those without phase transitions, results in any superheating above and beyond what the DS can use for energy storage dissipating out of the DS and into the surrounding environment to either be used by another DS or to engage more mass in the given DS.

Based on this, heat transformation theory excludes superheating from the APC calculations considering we are defining it as a capacity. In other words, it is a maximum engagement of available mass in the environment assuming no superheating. As a result, the kinematic-mass-flow-rate flux of a DS adjusts proportionally to changes in convective-internal-energy-transfer-rate flux by engaging a greater amount of mass from the environment or by passing the heat to other surrounding DSs for their use, both of which eliminate superheating from the function of the DS, making these fluxes proportional.

For the TWC and TAC that operate in the same space, any potential superheating of water vapor as a result of solar radiation continuing to heat the water vapor as it rises is transferred to the surrounding air and becomes part of the contribution of $95\ \mathrm{W/m^2}$ of solar radiation to heating the air. The APC flows of the heat engines that drive the TWC and the TAC power the cycles from stage 1 to stage 3 where the portion of the flow associated with the direct solar heating is dissipated to the tropopause (subscript *tropau*),

$$\mathbb{T}_{tropau}^{APC} = 82\,\frac{\mathrm{W}}{\mathrm{m^2}} + 345\,\frac{\mathrm{W}}{\mathrm{m^2}} = 427\,\frac{\mathrm{W}}{\mathrm{m^2}}\ , \tag{27}$$

and eventually to the stratosphere and upper layers of atmosphere, and to space. The ARO flows in the troposphere (subscript *trosph*),

$$\mathbb{T}_{trosph}^{ARO} = 2.1\,\frac{\mathrm{W}}{\mathrm{m^2}} + 250\,\frac{\mathrm{W}}{\mathrm{m^2}} = 252\,\frac{\mathrm{W}}{\mathrm{m^2}}, \tag{28}$$

release the potential energies and restore the internal energies of the DSs at stage 4, returning the DS to the state properties it has at the start of stage 1, thus maintaining Earth in average thermal steady state. The heat associated with ARO becomes part of the background environmental internal energy that supports average Earth temperatures. Combined, the APC and ARO of the TWC and TAC in the troposphere are substantially larger than the input flow from the radiative heat rate flux of the Sun to the troposphere. This makes up part of the total power flux that drives Earth weather.[6]

4.4. Specific Universal Entropies and Complexity Yield of a GDS

Sections 4.4 and 4.5 develop the four remaining properties. Table 1 provides a roadmap to assist the reader with following the development of all six properties through Sections 4.3 through 4.5.

Table 1. The six properties of heat transformation theory, numbered in order of first presentation and cross-referenced to sections and equations where they first appear.

Property Sequence	**Property Name**	**Symbol**	**Section Reference**
Property 1	Auto-Powering Capacity (APC)	$\mathbb{T}^{APC}$	4.3
Property 2	Auto-Restoring Order (ARO)	$\mathbb{T}^{ARO}$	4.3
Property 3	Specific Universal Entropy	$\mathscr{s}$	Section 4.4
	Specific Maximum Universal Entropy	$\mathscr{s}_{max}^{DS}$	Section 4.4, Equation 29
	Specific Conditional Universal Entropy	$\mathscr{s}_{con}^{DS}$	Section 4.4, Equation 37
	Specific Mutual Universal Entropy	$\mathscr{s}_{mut}^{DS}$	Section 4.4, Equation 41
Property 4	Complexity Yield	Δu_{Cx}^{DS}	Section 4.4, Equation 33
Property 5	Specific Heat Quality		Section 4.5
	Specific heat Quality Output		Section 4.5
	Specific Maximum Heat Quality Output	σ_{max}^{DS}	Section 4.5, Footnote 9
	Specific Conditional Heat Quality Output	σ_{con}^{DS}	Section 4.5, Equation 45
	Specific Mutual Heat Quality Output	σ_{mut}^{DS}	Section 4.5, Equation 46
	Specific Heat Quality Drop		Section 4.5
	Specific Maximum Heat Quality Drop	$\Delta\sigma_{max}^{DS}$	Section 4.5, Equation 58
	Specific Conditional Heat Quality Drop	$\Delta\sigma_{con}^{DS}$	Section 4.5, Equation 49
	Specific Mutual Heat Quality Drop	$\Delta\sigma_{mut}^{DS}$	Section 4.5, Equation 50
Property 6	Heat Transformation Effectivity	$\mathcal{T}_{eff}^{DS}$	Section 4.5, Equation 53

The last four properties of a DS as refined by heat transformation theory are intensive and associated with the macroscopic properties of state of the DS. Intensive properties are being used to reveal how the differences in matter and states of matter affect the dissipation of heat through a DS. The third property of heat transformation theory is *specific universal entropy*, $\mathscr{s}$, defined as the amount of universal entropy generated per unit mass of a DS. There are three quantities of specific universal entropy that assist in the analysis of the DS. Each applies the universal entropy production

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[6] The total additional gravidynamics power flux introduced to Earth is 252 Watts per square meter, which is greater than the 95 Watts per square meter estimated in [78]. The sum of the inputs to Earth by the solar power with the related gravidynamic response to solar power is 491 Watts per square meter. This is greater than the 334 Watts per square meter estimated [78].

convention established in Section 2.4, using T_{uni-H} and T_{uni-C} the thermal steady-state temperatures of the universal heat source and heat sink as the reference temperatures. The GDS heat engine model in Section 4.1 and Appendix A reveals that heat is taken in at stage 1 and released at stages 3 and 4. The specific universal entropy quantities that follow are determined based on these heat flows.

Specific universal entropy is a causal property of the DS system defined by the effect of the DS on universal entropy, and not by the DS system entropy. This follows heat engine theory in which entropy of the heat engine is calculated based upon output of heat from the heat source and input of heat to the heat sink. Unlike heat engine theory that uses local heat source and local heat sink temperatures, the thermal steady-state temperatures of the universal heat source and universal heat sink are used. Referring to this loosely as “the specific entropy of the DS” incorrectly suggests it is the specific entropy of the heat-carrying medium being calculated.

The first quantity of specific universal entropy to discuss is *specific maximum universal entropy*, $\mathscr{s}^{DS}_{max}$, defined as the maximum (subscript *max*) universal entropy generated per unit mass of the medium (subscript *med*) of the DS (superscript *DS*) involved in the heat transfer. It is the result of a total heat output from the universal heat source (subscript *uni-H*) that goes through a DS and is input to the universal heat sink (subscript *uni-C*),

$$\mathscr{s}^{DS}_{max} \equiv \frac{S_{max}}{m_{med}} = \frac{Q^{Tot}_{loc-H}}{m_{med}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right). \tag{29}$$

As discussed in Section 4.3, a DS can be a node in a network. The quantity of heat that is passed to the DS from its local heat source originated from the Sun. It is heat that is output from a universal steady state heat source and input to the GDS that is used to calculate universal entropy. Subscripting it as a local heat source (subscript *loc-H*) even though it originates from a universal heat source ensures inputs and outputs are properly tracked when the DS is analyzed in the context of a network. Notice, however, that the universal heat source temperature, T_{uni-H}, and universal heat sink temperature, T_{uni-C}, are used. These temperatures are used because the property is the amount of specific entropy that the DS is affecting on the universe.

In any given timeframe of operation of a DS that has achieved steady state, the same quantity of heat that is input is also output, such that the total heat input is equal to the total heat output. The equation could use either total heat input or total heat output, considering they are the same magnitude. For convention, the total heat input is used. To obtain $\mathscr{s}^{DS}_{max}$, the equation divides by the total mass of the heat-carrying medium of the DS (m_{med}). The property is in units of kilojoules per kilogram-Kelvin. The maximum universal entropy is exactly equal to that generated for simple heat dissipation from the heat source reservoir to the heat sink reservoir without passing through a DS, mentioned previously as the maximum entropy production principle [83,84], from which the heat transformation theory derives the name specific maximum universal entropy.

For $\mathscr{s}^{DS}_{max}$ of the TWC,

$$\mathscr{s}^{twc}_{max} = \frac{Q^{sun}_{H} + Q^{B/L}_{H}}{m_{med}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right). \tag{30}$$

$Q^{sun}_{H} + Q^{B/L}_{H}$ is the total sum of the heat inputs from stages 1 and 2, treated as originating from the universal heat source and that are input to the GDS from local heat sources that feed it. Section 5.2 provides the physical justification for using the same T_{uni-H} for all heat inputs to a GDS. To calculate specific maximum universal entropy for the TWC, $\mathscr{s}^{twc}_{max}$, it is convenient to put Equation 30 in terms of the empirical and calculated values of Calculation S1 in the Supplementary Materials,

$$\mathscr{s}^{twc}_{max} = \frac{\mathbb{T}^{APC}_{twc}}{\frac{\dot{m}^{wv}_{B}}{A_{atm}}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right) = \frac{82.1\,\frac{\mathrm{W}}{\mathrm{m}^2}}{0.000018\,\frac{\mathrm{kg}}{\mathrm{s\text{-}m}^2}}\left(\frac{1}{2.7\ \mathrm{K}} - \frac{1}{15\times10^{6}\ \mathrm{K}}\right)$$
$$= 1.69\times10^{3}\ \frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{31}$$

As discussed in Section 4.3.3 and in Calculation S1 in the Supplementary Materials, the APC and kinematic-mass-flow-rate flux of water vapor are approximately proportional as calculated empirically and based on the modeled assumption of no superheating of water vapor. The ratio is approximately the same as the ratio of Equation 30 of the total heat input of a fixed period of time and the mass of the heat transfer medium used in that time period. Note that the T_{uni-H} term is the temperature of the sun where fusion occurs, 15×10^6 K, the universal heat source of radiative heat for the TWC, and the T_{uni-C} term is the temperature of space as indicated by the cosmic microwave background radiation (CMBR), 2.7 K. $\mathscr{s}^{DS}_{max}$ for the TAC DS similarly follows using the empirical and calculated values of Calculation S2 in the Supplementary Materials,

$$\mathscr{s}^{tac}_{max} = \frac{\mathbb{T}^{APC}_{tac}}{\frac{\dot{m}^{air}_{NC}}{A_{atm}}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{uni-H}}\right) = \frac{345\,\frac{\mathrm{W}}{\mathrm{m}^2}}{0.0028\,\frac{\mathrm{kg}}{\mathrm{s\text{-}m}^2}}\left(\frac{1}{2.7\ \mathrm{K}} - \frac{1}{15\times10^6\ \mathrm{K}}\right) = 46\,\frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{32}$$

Total changes in maximum universal entropy over a given time-period are determined by the total amount of mass engaged in the medium of the DS in that time period. Considering the TAC has a kinematic-mass-flow-rate flux that is two orders of magnitude greater than that of the water vapor and air captured in the TWC, the reader can satisfy themselves that the maximum universal entropy production rate of the TAC is the same order of magnitude as the TWC, even though $\mathscr{s}^{DS}_{max}$ of the TAC is two orders of magnitude lesser than that of the TWC.

$\mathscr{s}^{DS}_{max}$ is governed by the temperature of the heat source and heat sink, not by the strength or type of conservative force field and not by the quantity of mass of the DS. A separate intensive property is needed to quantify the conservative force field element of a DS. The fourth property of the heat transformation theory is used to do this and differentiate the transformation of heat. *Complexity yield*, Δu^{DS}_{Cx}, related to *exergy* in [78], is a quantization of the ability of the DS to generate *complexity* (subscript *Cx*), i.e., conservatively store and release energy per mole of the heat carrying medium as a result of heat transfer through the DS,

$$\Delta u^{DS}_{Cx} \equiv \frac{\Delta U^{endo}}{n_{med}}\ . \tag{33}$$

This equation is a general form that can be applied to any DS with ΔU^{endo} being the energy that is stored during the endothermic stage of a DS (always stage 2 for GDSs) and n_{med} is the number of moles of heat carrying medium used in the storage of that energy. The reason for dividing by the number of moles rather than by mass is because Clausius's temperature-based entropy and Boltzmann's statistical-microstate-based entropy [70] are both based on particle dynamics and particle quantity, both based on molecular constitution. Temperature is a macroscopic intensive property that is based on molecular kinetic energy according to Maxwell [71]. Boltzmann statistical entropy is based on the number of accessible microstates that are determined by molecular aggregation and granularity, both properties of the numbers and varieties of molecules [29].

Δu^{DS}_{Cx} is a measure of the DS's ability to produce a change in stored energy. Δu^{DS}_{Cx} is a result of the energy that is stored or released in the interaction between the matter that is the heat transfer medium of the DS and the conservative force field of the DS as a result of a property of the matter that couples the interaction (e.g., the mass property of matter couples with the gravitational force). A DS transforms heat into stored energy. Stored energy, ΔU, can include a change in what is traditionally called internal energy in the context of chemistry that is held by the matter of the medium in addition to a change in what is traditionally called potential energy in the context of gravity. This is covered in part II of this paper series [95]. The work input of a DS is a result of universal heat source input to the DS. Therefore, conservation of energy using the first law of thermodynamics combined with the work-energy theorem requires that the change in stored energy is equal to the total heat input at stages 1 and 2 minus the heat output at stage 3 at steady state.

For complexity yield of the TWC,

$$\Delta u_{Cx}^{twc} = \frac{Q_H^{sun} + Q_H^{B/L} - Q_C^{wv}}{n_{med}} , \tag{34}$$

$Q_H^{sun} + Q_H^{B/L}$ is the total sum of the solar (superscript *sun*) and buoyancy and lift (superscript *B/L*) heat inputs from stages 1 and 2 that originate from the universal heat source and that are passed through the network and input to the GDS from the local heat source that feeds it and Q_C^{wv} is the heat output at stage 3.

To calculate complexity yield for the TWC, Δu_{Cx}^{twc}, put Equation 34 in terms of empirical and calculated values of Calculation S1 in the Supplementary Materials,

$$\Delta u_{Cx}^{twc} = M_{wv} \cdot \frac{\left(\Delta\dot{U}_G^{wv} + \delta\dot{U}_G^{air}\right)/A_{atm}}{\dot{m}_B^{wv}/A_{atm}} = M_{wv} \cdot \frac{\mathbb{T}_{twc}^{ARO}}{\dot{m}_B^{wv}/A_{atm}} = 18\ \frac{\mathrm{g}}{\mathrm{mol}} \frac{2.1\ \frac{\mathrm{W}}{\mathrm{m}^2}}{0.000018\ \frac{\mathrm{kg}}{\mathrm{s\text{-}m}^2}} \tag{35}$$
$$= 2.1 \times 10^3\ \frac{\mathrm{kJ}}{\mathrm{mol}} .$$

As discussed above and in Calculation S1 in the Supplementary Materials, the total gravitational-potential-energy-storage-rate flux and kinematic-mass-flow-rate flux of water vapor are approximately proportional as calculated empirically and based on the assumption of no superheating of water vapor. The ratio is approximately the same as the ratio of Equation 34 of the total heat input of a fixed period of time and the number of moles of the heat transfer medium used in that time period. This makes Δu_{Cx}^{DS} a constant property of the DS. Thus, the differences in the heat source and heat sink that affect s_{max}^{DS} do not affect how the DS converts heat to potential energy at a constant per-unit-of-matter ratio. Δu_{Cx}^{DS} is not defined by the heat source and heat sink of the DS. Δu_{Cx}^{DS} is an intensive state property of the DS that is a result of the properties of matter interacting with the conservative force field of the DS. However, the actual potential energy storage rate is extensive and is a portion of the APC. Complexity yield for the TAC, Δu_{Cx}^{tac}, similarly follows using the empirical and calculated values of Calculation S2 in the Supplementary Materials,

$$\Delta u_{Cx}^{tac} = M_{air} \cdot \frac{\Delta\dot{U}_G^{air}/A_{atm}}{\dot{m}_{NC}^{air}/A_{atm}} = M_{air} \cdot \frac{\mathbb{T}_{tac}^{ARO}}{\dot{m}_{NC}^{air}/A_{atm}} = 28\ \frac{\mathrm{g}}{\mathrm{mol}} \cdot \frac{250\ \frac{\mathrm{W}}{\mathrm{m}^2}}{0.0028\ \frac{\mathrm{kg}}{\mathrm{s\text{-}m}^2}} \tag{36}$$
$$= 2.5 \times 10^3\ \frac{\mathrm{kJ}}{mol} .$$

Both Δu_{Cx}^{twc} and Δu_{Cx}^{tac} calculations of multiply by the molar mass of the heat transfer medium to convert the denominator to moles per unit time per unit area.

This leads to a second form of specific universal entropy. The *specific conditional universal entropy*, s_{con}^{DS}, is defined as the universal entropy produced per unit mass of the heat transfer medium of the DS, which production is associated with direct pass-through heat that is not transformed to potential energy,

$$s_{con}^{DS} \equiv \frac{\triangle S_{con}}{m_{med}} = \frac{1}{m_{med}}\left(\frac{Q_{loc-C}^{S3}}{T_{uni-C}} - \frac{Q_{loc-H}^{S1\to 2}}{T_{uni-H}}\right). \tag{37}$$

It is a general form that can be applied to any DS in a network. As with s_{max}^{DS}, s_{con}^{DS} is determined by local heat source inputs and local heat sink outputs that are ultimately from and to the universal heat source and universal heat sink and by T_{uni-H} and T_{uni-C}. The term *conditional entropy* is specifically used to relate to the conditional entropy of information theory, covered in part II of this paper series [95]. Heat transformation theory defines s_{con}^{DS} specifically to address the heat leaving the system at stage 3. s_{con}^{DS} is a quantity that applies in exactly the same way to forced convection heat engines as it does to DSs. s_{con}^{DS} results from the exhausting of the remaining heat from the heat source that is carried as internal energy in the heat engine medium following the work performance of the heat engine.

For specific conditional universal entropy of the TWC, s_{con}^{twc},

$$\Delta\mathscr{s}_{con}^{twc} = \frac{1}{m_{med}}\left(\frac{Q_C^{wv}}{T_{uni-C}} - \frac{Q_H^{sun} + Q_H^{B/L}}{T_{uni-H}}\right), \tag{38}$$

the values of Calculation S1 in the Supplementary Materials are applied using similar ratios of power flux to mass flow rate flux as used for $\mathscr{s}_{max}^{DS}$,

$$\mathscr{s}_{con}^{twc} = \frac{1}{\frac{\dot{m}_B^{wv}}{A_{atm}}}\left[\frac{\frac{\Delta\dot{U}_Q^{wv}}{A_{atm}}}{T_{uni-C}} - \frac{\mathbb{T}_{twc}^{APC}}{T_{uni-H}}\right] = \frac{1}{0.000018\ \frac{\mathrm{kg}}{\mathrm{s\text{-}m^2}}}\left[\frac{80\,\frac{\mathrm{W}}{\mathrm{m^2}}}{2.7\ \mathrm{K}} - \frac{82.1\,\frac{\mathrm{W}}{\mathrm{m^2}}}{15\times 10^6\ \mathrm{K}}\right]$$
$$= 1.65\times 10^3\ \frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{39}$$

Specific conditional universal entropy of the TAC, $\mathscr{s}_{con}^{tac}$, is calculated using values in Calculation S2 in the Supplementary Materials,

$$\mathscr{s}_{con}^{tac} = \frac{1}{\frac{\dot{m}_{NC}^{air}}{A_{atm}}}\left[\frac{\frac{\Delta\dot{U}_Q^{air}}{A_{atm}}}{T_{uni-C}} - \frac{\mathbb{T}_{tac}^{APC}}{T_{uni-H}}\right] = \frac{1}{0.0028\ \frac{\mathrm{kg}}{\mathrm{s\text{-}m^2}}}\left[\frac{95\,\frac{\mathrm{W}}{\mathrm{m^2}}}{2.7\ \mathrm{K}} - \frac{345\,\frac{\mathrm{W}}{\mathrm{m^2}}}{15\times 10^6\ \mathrm{K}}\right] = 13\ \frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{40}$$

For these cycles, even though the heat of warmup as condensed water falls back to Earth and cooled air levels eventually ends up in space along with the heat from the Sun, only the heat carried by the medium from the Sun is considered in conditional entropy. This is because the warmup heat comes from the ARO of the heat engine, which ARO is a result of decay of the stored potential energy at stage 4. That warmup heat is not generated at the same time and place in stage 4 as the heat exhausted at stage 3. This difference in time and place of heat generation is consequential in heat transformation theory, especially in the case of GDSs that extend over great distances.

To understand the importance, warmup heat associated with decay of stored potential energy must be tracked separately by a third form of specific universal entropy. The *specific mutual universal entropy*, $\mathscr{s}_{mut}^{DS}$, is defined as the difference between $\mathscr{s}_{max}^{DS}$ and $\mathscr{s}_{con}^{DS}$ and is the universal entropy produced per unit mass of the heat transfer medium of the DS, which is mutual to the Δu_{Cx}^{DS} or mutual to the heat that is transformed by the Δu_{Cx}^{DS} ,

$$\mathscr{s}_{mut}^{DS} \equiv \mathscr{s}_{max}^{DS} - \mathscr{s}_{con}^{DS} = \frac{(Q_{loc-H}^{S1\to 2} - Q_{loc-C}^{S3})}{m_{med}}\left(\frac{1}{T_{uni-C}}\right) = \frac{(Q_{loc-C}^{S4})}{m_{med}}\left(\frac{1}{T_{uni-C}}\right). \tag{41}$$

This equation is a general form that can be applied to any DS in a network. It reveals that $\mathscr{s}_{mut}^{DS}$ is fixed to the constant T_{uni-C} . It is the quantity of $\mathscr{s}_{max}^{DS}$ that remains to be produced following the production of $\mathscr{s}_{con}^{DS}$ at stage 3. It is specific universal entropy resulting from the decay of complexity by ARO at stage 4. The word *mutual* is specifically used to relate to the average mutual information of information theory and is discussed in part II of this paper series [95].

In the case of the TWC and TAC, there is no stage 4 heat input. There is only a stage 4 output that is equal to the heat originally converted to stored energy in stage 2. For specific mutual universal entropy of the TWC,

$$\mathscr{s}_{mut}^{twc} = \left(\frac{Q_{loc-H}^{S1\to 2} - Q_{loc-C}^{S3}}{m_{med}}\right)\frac{1}{T_{uni-C}} = \left(\frac{Q_H^{sun} + Q_H^{B/L} - Q_C^{wv}}{m_{med}}\right)\frac{1}{T_{uni-C}}, \tag{42}$$

the values of Calculation S1 in the Supplementary Materials are applied,

$$\mathscr{s}_{mut}^{twc} = \frac{(\Delta\dot{U}_G^{wv} + \delta\dot{U}_G^{air})/A_{atm}}{\dot{m}_B^{wv}/A_{atm}}\frac{1}{T_{uni-C}} = \frac{\mathbb{T}_{twc}^{ARO}}{\dot{m}_B^{wv}/A_{atm}}\frac{1}{T_C} = \frac{2.1\,\frac{\mathrm{W}}{\mathrm{m^2}}}{0.000018\ \frac{\mathrm{kg}}{\mathrm{s\text{-}m^2}}}\cdot\frac{1}{2.7\ \mathrm{K}}$$
$$= 40\ \frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{43}$$

Specific mutual universal entropy of the TAC, $\mathscr{s}_{mut}^{tac}$, is calculated using values in Calculation S2 in the Supplementary Materials,

$$\mathscr{s}_{mut}^{tac} = \frac{\left(\Delta \dot{U}_G^{air}\right)/A_{atm}}{\dot{m}_{NC}^{air}/A_{atm}} \frac{1}{T_{uni-C}} = \frac{\mathbb{T}_{tac}^{ARO}}{\dot{m}_{NC}^{air}/A_{atm}} \frac{1}{T_C} = \frac{250\,\frac{\mathrm{W}}{\mathrm{m}^2}}{0.0028\,\frac{\mathrm{kg}}{\mathrm{s\text{-}m}^2}} \cdot \frac{1}{2.7\ \mathrm{K}} = 33\ \frac{\mathrm{kJ}}{\mathrm{kg\text{-}K}}. \tag{44}$$

The reader can verify that these values are exactly equal to the $\mathscr{s}_{max}^{DS}$ minus $\mathscr{s}_{con}^{DS}$.

The three types of specific universal entropy of a GDS presented above follow the convention of heat engine theory but use the thermal steady-state temperatures of the universal heat source and universal heat sink as the reference temperatures for the entropy calculations. For complete and honest disclosure, a conventional heat engine should use the universal heat source and the universal heat sink rather than its engineered heat source and heat sink to calculate its universal entropy and its best-case Carnot efficiency. This would reveal that real engine efficiency is far less optimistic than local calculations suggest. The fundamental difference between GDSs and conventional heat engines is that GDSs network together. The heat exhaust from upstream GDSs becomes the heat source for downstream DSs. Conventional heat engines waste their exhaust. Because the heat exhausted at stages 3 and 4 of a GDS does not immediately reach the universal heat sink, $\mathscr{s}_{con}^{DS}$ and $\mathscr{s}_{mut}^{DS}$ suggest a quality of heat that remains in the local environment to be picked up and used by another GDS. Heat transformation theory therefore needs far-from-equilibrium properties to track this remaining heat quality along a network of GDSs to the heat's end fate of maximum universal entropy production in the heat sink of space. These properties are developed in Section 4.5.

4.5. Specific Heat Qualities, Heat Transformation Effectivity, and Efficiency of a GDS

To address this need, the heat transformation theory proposes a fifth property called specific heat quality. Heat quality is another term that is occasionally used in the literature, typically to refer to the potential of heat to produce work based on the temperature of the local source of the heat. As such, it is related to entropy in that heat quality is considered to be lost as heat moves from higher temperature to lower temperature. Heat transformation theory defines and quantifies the specific heat quality available for use by a DS as the amount of heat available per unit mass per unit temperature. It has the same units as specific universal entropy. It is determined by considering the specific universal entropy that can be produced from the point where heat is made available to the DS by a local heat source. That local heat source may itself have received the heat from a universal heat source, perhaps through a network of DSs, before it ultimately dissipates to the ends of the universe. Specific heat quality is therefore a measure of the potential universal entropy that can still be generated from the available heat as it continues dissipating from its current location toward the universal heat sink.

In the equations of specific universal entropies, the heat source temperature of the Sun and the heat sink temperature of space are used, T_{uni-H} and T_{uni-C}. However, in calculating the specific heat quality depleted by a DS on Earth, the temperature of the heat source and heat sink of the local environment need to be used, T_{loc-H} and T_{loc-C}. The intent is to determine the amount of specific heat quality depleted by the DS and the amount remaining when the heat exhausts from the DS. Recalling that the heat quantities exhausted at stage 3 and stage 4 of a DS are different amounts and can be at different locations with different local temperatures, the specific heat qualities at stage 3 and stage 4 are considered separately.

Specific conditional heat quality output, σ_{con}^{DS}, is the quantity of heat per unit mass per unit temperature of the medium of a far-from-equilibrium DS receiving heat directly from the universal heat source, that is output at stage 3, and made available to the environment,

$$\sigma_{con}^{DS} \equiv \frac{1}{m_{med}}\left(\frac{Q_{loc-C}^{S3}}{T_{uni-C}} - \frac{Q_{loc-H}^{S1\to 2}}{T_{uni-H}}\right) - \frac{1}{m_{med}}\left(\frac{Q_{loc-C}^{S3}}{T_{loc-C}} - \frac{Q_{loc-H}^{S1\to 2}}{T_{uni-H}}\right) = \frac{Q_{loc-C}^{S3}}{m_{med}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right). \tag{45}$$

It is related to the APC (auto-powering capacity, Section 4.3) of the DS. The first term of the definition is the $\Delta\mathscr{s}_{con}^{DS}$. The second term of the definition that is being subtracted is the amount of specific conditional heat quality that is depleted as the heat moves from the universal heat source to the local heat sink of the DS. The difference is the amount of specific conditional heat quality remaining after the heat passes through the DS. It is the amount of heat quality that can be depleted between being output from the DS and the universal heat sink.

The form of this second term of Equation 45 is used to define a *specific conditional heat quality drop* of the DS,

$$\Delta\sigma_{con}^{DS} \equiv \frac{1}{m_{med}}\left(\frac{Q_{loc-C}^{S3}}{T_{loc-C}} - \frac{Q_{loc-H}^{S1\to 2}}{T_{loc-H}}\right). \tag{46}$$

Equation 46 is defined by starting with the second term of Equation 45 and replacing T_{uni-H} with T_{loc-H}.This equation represents the amount of specific heat quality depleted by the DS because of the down step from the T_{loc-H} to the T_{loc-C} of the environment at the location where the heat is released from the DS at stage 3. For a DS that is using a local heat source rather than heat directly from a universal heat source, it is important to recognize the network effect of subdividing the original heat from the heat source to go down multiple branching and paralleling paths that break up the heat into multiple flows. This network effect results in each subsequent DS having specific heat quality drops and specific heat quality outputs based on local heat sources.

For the cases of the TWC and TAC dissipating heat at stage 3, the local environment is the tropopause. The average temperature of the environment at the tropopause of 222.15 K (–51 °C). To calculate specific conditional heat quality output for the TWC, σ_{con}^{twc} , put Equation 46 in terms of the empirical and calculated values of Calculation S1 in the Supplementary Materials,

$$\sigma_{con}^{twc} = \frac{\frac{\Delta\dot{U}_{Q}^{wv}}{A_{atm}}}{\frac{\dot{m}_{B}^{wv}}{A_{atm}}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right) = \frac{80\,\frac{\text{W}}{\text{m}^2}}{0.000018\,\frac{\text{kg}}{\text{s-m}^2}}\left(\frac{1}{2.7\,K} - \frac{1}{222.15\,K}\right)$$
$$= 1.63\times 10^{3}\,\frac{\text{kJ}}{\text{kg-K}}. \tag{47}$$

The specific conditional heat quality output of the TAC, σ_{con}^{tac}, is calculated using values in Calculation S2 in the Supplementary Materials,

$$\sigma_{con}^{tac} = \frac{\frac{\Delta\dot{U}_{Q}^{air}}{A_{atm}}}{\frac{\dot{m}_{NC}^{air}}{A_{atm}}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right) = \frac{95\,\frac{\text{W}}{\text{m}^2}}{0.0028\,\frac{\text{kg}}{\text{s-m}^2}}\left(\frac{1}{2.7\,K} - \frac{1}{222.15\,K}\right) = 12.4\,\frac{\text{kJ}}{\text{kg-K}}. \tag{48}$$

Comparing these values to $\mathscr{s}_{con}^{DS}$ values, it is interesting to note that the TWC has a specific conditional heat quality drop, $\Delta\sigma_{con}^{twc}$, of 20 kJ/kg-K and the TAC has a specific conditional heat quality drop, $\Delta\sigma_{con}^{tac}$, of 0.2 kJ/kg-K. What is exhausted to the environment as σ_{con}^{DS} in both cases is 98.8% of the initial specific heat quality from the Sun. They each use 1.2% of the specific heat quality.

There are DSs in the layers of the atmosphere above the troposphere that can utilize the 98.8% of the remaining specific heat quality from stage 3 of the TWC and TAC. Between the troposphere and the stratosphere is another GDS that circulates the thinner, dryer air. This circulation is horizontal due to both the rotation of Earth and a temperature inversion in the stratosphere that prevents vertical convection.[7] The result is the phenomena of jet streams. Assume the jet streams are driven completely by heat delivered from stage 3 of TWC and TAC. The contribution of these heat inputs to drive the jet streams are estimated in Calculation S3 in the Supplementary Materials. The kinematic-mass-flow-rate flux of the combined TWC and TAC predicts a jet stream wind velocity that is in the correct order

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[7] The temperature inversion in the stratosphere is a result of a chemical reaction driven by solar radiation that generates Oxygen-3 (ozone). The ozone chemical reaction is stage 2 of a chemical DS (CDS). CDSs are discussed in Part II of this paper series [95].

of magnitude of measured values, with the gap between the calculated and measured velocities physically explained by needing to add the contribution of the gravitational drag of the spinning Earth on the atmosphere and the direct heating of the tropopause by solar radiation.

It is noteworthy in the calculations of Calculation S3 in the Supplementary Materials that a heat-quality-transfer-rate flux delivered from the TWC and the TAC to the jet streams is determined by multiplying the σ_{con}^{twc} and σ_{con}^{tac} by their kinematic-mass-flow-rate fluxes. How the jet streams receive this amount of power in the form of heat at this level of quality (i.e., per unit temperature) depends upon the quantity of air mass available as a heat transfer medium to the jet streams and the specific heat capacity of the air. A similar consideration applies to all transfers of specific heat quality outputs from upstream DSs as inputs to downstream DSs. This exhibits use of the specific heat quality output property in enabling tracking of heat quality drops through an ecosystem network.

The *specific mutual heat quality output*, σ_{mut}^{DS}, is the quantity of heat per unit mass per unit temperature of the medium of a far-from-equilibrium DS that is output at stage 4 and made available to the environment,

$$\sigma_{mut}^{DS} = \left(\frac{Q_{loc-C}^{S4}}{m_{med}}\right)\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right). \tag{49}$$

This equation developed similarly to the σ_{con}^{DS} of Equation 45 and is related to the ARO (auto-restoring order, Section 4.3) of the DS. It has the same units as specific universal entropy, suggesting that it also is a potential entropy, as the σ_{con}^{DS}. The *specific mutual heat quality drop* of the DS similarly follows,

$$\Delta\sigma_{mut}^{DS} = \left(\frac{Q_{loc-C}^{S4}}{m_{med}}\right)\left(\frac{1}{T_{loc-C}}\right). \tag{50}$$

based upon a T_{loc-H} rather than T_{uni-H} due to network effects. This equation represents the amount of heat quality that is depleted by the DS because of the release of stored energy as heat to the T_{loc-C} of the environment at the location of stage 4 and, therefore, an amount of specific heat quality that is no longer available to be used by other DSs.

For the cases of the TWC and TAC, again there is no stage 4 heat input. There is only a stage 4 output that is equal to the heat originally converted to stored energy in stage 2. The stage 4 heat output is to the local environment that is lower in the troposphere. The average temperature is 288.15 K (15 °C). To calculate specific mutual heat quality output for the TWC, σ_{mut}^{twc}, put Equation 50 in terms of the empirical and calculated values of Calculation S1 in the Supplementary Materials,

$$\sigma_{mut}^{twc} = \frac{\mathbb{T}_{twc}^{ARO}}{\dot{m}_{B}^{wv}/A_{atm}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right) = \frac{2.1\,\frac{\text{W}}{\text{m}^2}}{0.000018\,\frac{\text{kg}}{\text{s-m}^2}} \cdot \left(\frac{1}{2.7\text{ K}} - \frac{1}{288.15\text{ K}}\right) \tag{51}$$
$$= 43\,\frac{\text{kJ}}{\text{kg-K}}.$$

The specific mutual heat quality output of the TAC, σ_{mut}^{tac}, is calculated using values in Calculation S2 in the Supplementary Materials,

$$\sigma_{mut}^{tac} = \frac{\mathbb{T}_{tac}^{ARO}}{\dot{m}_{NC}^{air}/A_{atm}}\left(\frac{1}{T_{uni-C}} - \frac{1}{T_{loc-C}}\right) = \frac{250\,\frac{\text{W}}{\text{m}^2}}{0.0028\,\frac{\text{kg}}{\text{s-m}^2}} \cdot \left(\frac{1}{2.7\text{ K}} - \frac{1}{288.15\text{ K}}\right) = 33\,\frac{\text{kJ}}{\text{kg-K}}. \tag{52}$$

Comparing these values to $\mathscr{s}_{mut}^{DS}$ values, it is interesting to note that the TWC specific mutual heat quality drop, $\Delta\sigma_{mut}^{twc}$, is 0.4 kJ/kg-K and that of the TAC, $\Delta\sigma_{mut}^{tac}$, is 0.3 kJ/kg-K. What is exhausted to the environment in both cases is 99.1% of the initial specific heat quality from the Sun. They each use 0.9% of the specific heat quality that initially goes into Δu_{Cx}^{DS} and is exhausted following decay at stage 4.

The property of specific heat quality suggests an efficacy of heat in being transformable to stored energy and associated Δu_{Cx}^{DS}. Therefore, heat transformation theory defines *heat transformation* *effectivity*, $\mathcal{T}_{eff}^{DS}$, as a sixth property of a DS and defined as the effectiveness of the DS at transforming heat into stored energy based on the specific heat quality,

$$\mathcal{T}_{eff}^{DS} \equiv \frac{1}{M_{med}} \cdot \frac{\Delta\mathcal{u}_{Cx}^{DS}}{\Delta\sigma_{mut}^{DS}}. \tag{53}$$

The factor of one over the molar mass of the medium of the DS is used to put the numerator in terms of per unit mass just as the denominator. $\mathcal{T}_{eff}^{DS}$ is based on the heat storage occurring during stage 2. This definitional equation provides the first theorem of heat transformation theory when Equation 33 and Equation 50 are substituted into it, the *heat transformation effectivity theorem*,

$$\mathcal{T}_{eff}^{DS} = T_{loc-C}. \tag{54}$$

Theorem 1. *Heat transformation effectivity theorem: A greater local heat sink temperature results in a DS yielding the same complexity yield at a greater specific heat quality output.*

It reveals that a DS with a greater T_{loc-C} has a greater $\mathcal{T}_{eff}^{DS}$, Equation 54. Though the simplified units are in temperature, it is helpful to think of $\mathcal{T}_{eff}^{DS}$ in terms of units of $\Delta\mathcal{u}_{Cx}^{DS}$ per unit of specific heat quality.

Proof of Theorem 1. To understand the heat transformation effectivity theorem, it is helpful to do an analysis of how it changes with environmental conditions of the DS. For any DS in steady state, a greater T_{loc-C} also results in an equivalently greater average temperature of the DS and an equivalently greater T_{loc-H} to accomplish an unchanged local heat input and APC of the DS. This is because the internal energy of the local heat source that is available to be moved as heat is independent of the DS. The local temperatures are driven to increase or decrease for the heat source to reach a steady state in which its internal energy remains constant as it transfers heat into the DS. This results in the heat transfer from the local heat source to the local heat sink through the DS remaining constant with local changes in temperatures. Recall that the heat source and heat sink do not affect how the DS uses properties of matter to store energy, resulting in the $\Delta\mathcal{u}_{Cx}^{DS}$ remaining constant even if T_{loc-C} and associated $\mathcal{T}_{eff}^{DS}$ increase. A DS that involves the same conservative force field but has a greater $\mathcal{T}_{eff}^{DS}$ produces the same $\Delta\mathcal{u}_{Cx}^{DS}$ with a lesser $\Delta\sigma_{mut}^{DS}$. Also note that considering local heat input, $Q_{loc-H}^{S1\to2}$, does not change and the energy storage of the constant $\Delta\mathcal{u}_{Cx}^{DS}$ is only dependent on the properties of mass, this means that mass engagement is constant and local heat output at stage 3, Q_{loc-C}^{S3}, also does not change. Thus, a greater T_{loc-C} and associated $\mathcal{T}_{eff}^{DS}$ with the same local heat output at stage 3 results in a greater σ_{con}^{DS}. In summary, a greater T_{loc-C} results in a greater $\mathcal{T}_{eff}^{DS}$, which means that the $\Delta\mathcal{u}_{Cx}^{DS}$ of the DS does not change but the specific heat quality output increases.

$\mathcal{T}_{eff}^{DS}$ is not the same as real heat engine efficiency. $\mathcal{T}_{eff}^{DS}$ is a conversion ratio. Real heat engine efficiency, $\eta_{\mathcal{R}}$, is work output divided by heat input,

$$\eta_{\mathcal{R}} = \frac{Q_{loc-H}^{S1\to2} - Q_{loc-C}^{S3}}{Q_{loc-H}^{S1\to2}}. \tag{55}$$

The Carnot efficiency of an ideal heat engine,

$$\eta_{\mathcal{C}} = \frac{T_{loc-H} - T_{loc-C}}{T_{loc-C}}, \tag{56}$$

is the best possible efficiency that the DS could theoretically achieve if it were a dynamic zero-entropy cycle. As noted at the end of Section 4.4, Carnot efficiency of a given heat engine is historically based on T_{loc-H} and T_{loc-C}.

Putting $\mathcal{T}_{eff}^{DS}$ in terms of these efficiencies results in

$$\mathcal{T}_{eff}^{DS} = \frac{1}{M_{med}} \cdot \frac{\Delta\mathcal{u}_{Cx}^{DS}}{\Delta\sigma_{max}^{DS}} \cdot \frac{\eta_{\mathcal{C}}}{\eta_{\mathcal{R}}}, \tag{57}$$

for which the specific maximum heat quality drop[8] is

$$\Delta\sigma_{max}^{DS} = \Delta\sigma_{con}^{DS} + \Delta\sigma_{mut}^{DS} = \frac{Q_{loc-H}^{S1\rightarrow 2}}{m_{med}}\left(\frac{1}{T_{loc-C}} - \frac{1}{T_{loc-H}}\right). \tag{58}$$

Equation 57 provides a second theorem that is a corollary of the heat transformation effectivity theorem of Equation 54.

Theorem 2. *Corollary to the heat transformation effectivity theorem: Heat transformation effectivity is greater and the real heat engine efficiency is constant for a DS with a greater local heat sink temperature.*

Proof of Theorem 2. Relating Equation 53 and Equation 57 results in,

$$\frac{\eta_R}{\eta_C} = \frac{\Delta\sigma_{mut}^{DS}}{\Delta\sigma_{max}^{DS}}. \tag{59}$$

Equation 59 reveals how $\mathcal{T}_{eff}^{DS}$ and η_R, Equation 55, vary in relation to each other. As discussed previously, if the T_{loc-C} is greater for the same local heat input, then the steady state $\mathcal{T}_{eff}^{DS}$ is greater with Δu_{Cx}^{DS} being a constant of the DS. Unlike specific universal entropy that is calculated based upon the T_{uni-H} and T_{uni-C}, specific heat quality drop is affected by the conditions of the local temperatures. An analysis of $\Delta\sigma_{mut}^{DS}$ of Equation 50 and the $\Delta\sigma_{max}^{DS}$ of Equation 58 reveals the effects. Recall that regardless of how heat input might change, the ratio of any energy flow through a DS to the mass flow through the DS is a constant. Equation 53 shows an inverse relationship of a greater T_{loc-C} to a lesser $\Delta\sigma_{mut}^{DS}$ with a constant Δu_{Cx}^{DS}.

First examine the right side of Equation 59. For a greater T_{loc-C}, considering T_{loc-H} and T_{loc-C} must be greater by an equivalent amount, the difference $\left(\frac{1}{T_{loc-C}} - \frac{1}{T_{loc-H}}\right)$ must be lesser and, thus, $\Delta\sigma_{max}^{DS}$ must be lesser as shown by Equation 58. $\Delta\sigma_{mut}^{DS}$, Equation 50, goes as the inverse of T_{loc-C} multiplied by the heat output at stage 4. $\Delta\sigma_{max}^{DS}$, Equation 58, goes as the difference of the inverses of two different temperaturesT_{loc-H} and T_{loc-C} that are changing by the same amount multiplied by the total heat input at stage 1. This results in $\Delta\sigma_{max}^{DS}$ being lesser by a greater factor than $\Delta\sigma_{mut}^{DS}$. The result is that $\Delta\sigma_{con}^{DS}$, Equation 46, is lesser by the greatest factor, it being the difference between $\Delta\sigma_{max}^{DS}$ and $\Delta\sigma_{mut}^{DS}$. Therefore, the ratio on the right side of Equation 59 is greater when there is a greater T_{loc-C}.

On the left side of Equation 59, η_C of Equation 56 is lesser for equivalently greater T_{loc-H} and T_{loc-C}. The η_R does not change considering the local heat input and stage 3 heat output do not change. For heat engines that drive work output using non-conservative forces, a lesser η_R results from a greater T_{loc-C}. However, because of the fixed nature of the conservative work output per unit mass of a DS, T_{loc-C} does not affect the energy balance provided by the first law of thermodynamics, resulting in a constant η_R. This results in a greater ratio on the left side of Equation 59 equivalent to the greater ratio on the right side of the equation. DSs are just as efficient at any temperature and are more effective at great temperatures.

The two theorems of Equation 53 and Equation 57 are important to understand the function of DSs. DSs that operate in environments of greater local temperatures have less $\Delta\sigma_{con}^{DS}$ and $\Delta\sigma_{mut}^{DS}$ for the same Δu_{Cx}^{DS}. This also means that σ_{con}^{DS} and σ_{mut}^{DS} are greater even as local heat input and the local heat outputs at stage 3 and stage 4 do not change. Constant Δu_{Cx}^{DS} and local heat flows with greater specific heat quality outputs at greater T_{loc-C} means that the heat can support more DSs with their Δu_{Cx}^{DS} in downstream in a network of DSs before the specific heat quality is routed into the

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[8] $\Delta\sigma_{max}^{DS}$, Equation 58, is defined for convenience. A specific maximum heat quality output, σ_{max}^{DS}, is not defined for GDSs, considering that GDSs tend to extend over large distances with specific conditional heat quality output and specific mutual heat quality output affecting separate local heat sinks at different heat sink temperatures, at different times, and with different quantities of heat. For this reason, there is no explanatory value in calculating σ_{max}^{DS} for a GDS.

universal heat sink of space or "burns out."[9] This is discussed further in part II of this paper series [95].

Though higher T_{loc-C} is better for DSs operating in an ecosystem, this is not the case for non-conservative engineered forced-convection heat engines. The efficiency of the non-conservative engineered forced convection heat engine decreases for an increase in heat sink temperature. This means less work output is generated for the same heat due to the non-conservative nature of the involved forces. Together, these mean that the power of the heat engine drops even as the engine requires more fuel to be burned for the dropping power. Non-conservative engineered forced convection heat engines have greater power and greater efficiency with lesser heat sink temperatures, together resulting in less exhaust heat that is just waste, though at a lower specific heat quality output. The heat sink is usually the environment, and the environment is not always as cold as is needed for a heat engine to work at the power desired and without overheating and failing as a result. Contrary to the non-conservative engineered forced convection heat engine, the DS has the same efficiency with a greater specific heat quality output with greater T_{loc-C} resulting in greater complexity production on Earth due to a greater number of DSs with lesser specific heat quality drops.

4.6. Steady-State Seeking and Transient Growth of GDSs

To make it easier to develop the models and the properties associated with single DSs and networks of DS, the analyses used to initially develop the models are based on steady-state conditions. However, the models and associated equations are based on the laws of thermodynamics that apply to all conditions, including transient conditions. Therefore the models and equations of the properties also apply to transient conditions. Analyses of these models indicate that when transient conditions occur in the environment of a DS, the DS seeks to return to steady state, just as any heat engine, as governed by the laws of thermodynamics. This steady-state-seeking function shifts the properties of the DS to drive toward total heat output coming into equality with total heat input as the DS asymptotically approaches a maximum APC based upon the available heat and available materials of the DS's heat transfer medium. This characteristic prevents a cascading temperature effect and maximizes universal entropy production to an amount equivalent to simple heat transfer. The difference between the DS and simple heat transfer is that DSs have Δu_{Cx}^{DS}.

It is noteworthy that DSs are a result of two things, the first being collections of matter with properties that produce conservative force fields and the second being a universal heat source and universal heat sink that provide the ultimate temperature difference that drives heat through the collections of material. Without either, the DS does not exist. If both are initially present, and then either the source of matter or the source of heat are lost, the DS grows smaller and finally disperses. The matter with its conservative force fields can hypothetically be placed anywhere in the universe with any local solar or galactic heat source and the heat sink of space and still function to seek steady state heat dissipation while producing Δu_{Cx}^{DS}. The DS is as an emergent property of the unique combination of heat source, heat sink, and matter with its conservative force fields.

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[9] The poetic and literal meaning of "burns out" is that the heat is still one or more steps away from dissipating into the universal heat sink when the specific heat quality output is so low that the only thing the heat can do is dissipate into the average local internal energy of the Earth environment, its last use being to maintain average temperatures on Earth. It becomes a foundation for local heat temperatures of all the DSs in the network that the heat passed through to get to this point, similar to the heat generated in the Earth core, mantel, and crust that is left over from the initial formation of Earth, the heat that is generated by gravitational interaction of Earth with the Sun and Moon, the heat that is generated by friction of the spin of Earth, and the heat of augmentational activity [78] generated by humans and other tool-using animals on Earth. This is effectively the ultimate, last DS with the Δu_{Cx}^{DS} comprised of the storage of internal energy of Earth in the form of the heat capacities of the materials of Earth, and the final ARO, specific heat quality drop, and local heat output at stage 4 being the black-body radiation of Earth.

doi:10.20944/preprints202602.1676.v2

Imagine an Earth-like planet in orbit around a star that provides a greater or lesser heat rate flux or has a greater or lesser temperature. The gravitational field, structure, and material makeup of the Earth-like planet is the same, but the solar heat source is different due to the size of the star in combination with the distance of the planet from the star, reducing the solar flux as the inverse of square of the distance from the star. The DS of the planet will adjust its steady state average temperature to bring the total heat output from the planet equal to the total heat input to the planet by the entire network of DSs that form on the planet coming into quasi-steady state. This means that an Earth-like planet around some other star is driven by the same ecological thermodynamics. This science is not unique to Earth. It also means that over the course of the astro geological history of our solar system, as the heat generation rate and temperature of the Sun have varied, so has the average temperature of Earth to adjust up and down to maintain a steady state.

The steady-state-seeking behavior predicted by the theory is not merely a theoretical property, it is observable in Earth's climate system response to perturbations. When large volcanic eruptions inject sulfate aerosols into the stratosphere, reducing solar flux to the surface, the GDS network of the troposphere responds by reducing APC and heat output, and then recovering toward the prior steady state as aerosols dissipate. Such a response is documented in the post-eruption temperature records of events such as the 1991 Pinatubo eruption and the 1815 Tambora eruption [96,97]. Similarly, El Niño–Southern Oscillation cycles represent the coupled ocean-atmosphere GDS network seeking steady state after perturbations in sea surface temperature redistribute heat input asymmetrically across the troposphere [98,99]. In both cases, the direction and timescale of the recovery are consistent with the steady-state-seeking prediction of the GDS model: the network adjusts its APC to drive total heat output back toward equality with total heat input. These observations do not constitute a precise quantitative test of the GDS model, but they confirm that the qualitative behavior the theory predicts, i.e., perturbation followed by asymptotic recovery toward a steady-state heat balance, is the behavior Earth's GDS network actually exhibits.

The steady-state-seeking characteristic of a GDS results in a transient process associated with APC, ARO, Δu_{Cx}^{DS}, and heat outputs. The GDS grows as both additional mass and additional heat are available and shrinks as either mass or heat or both become unavailable. A growth process happens when either additional mass or additional heat is fed into a GDS that has existing excess heat or excess mass respectively available. This puts a GDS in a growth transient that increases APC. While in this transient, the GDS is using an increase in convective heat input and its Δu_{Cx}^{DS} to increase APC, resulting in an increase in energy storage rate that results in an increasing quantity of total stored energy. All heat input at stage 2 of a GDS is transformed into stored energy. The increase of heat input rate at stage 1 of a GDS results in an equivalent increase in heat output rate at stage 3. GDSs are heat movers. The effect of the GDS is to use buoyancy to move heat with a side effect of the buoyancy energy input being converted to stored gravitational potential energy.

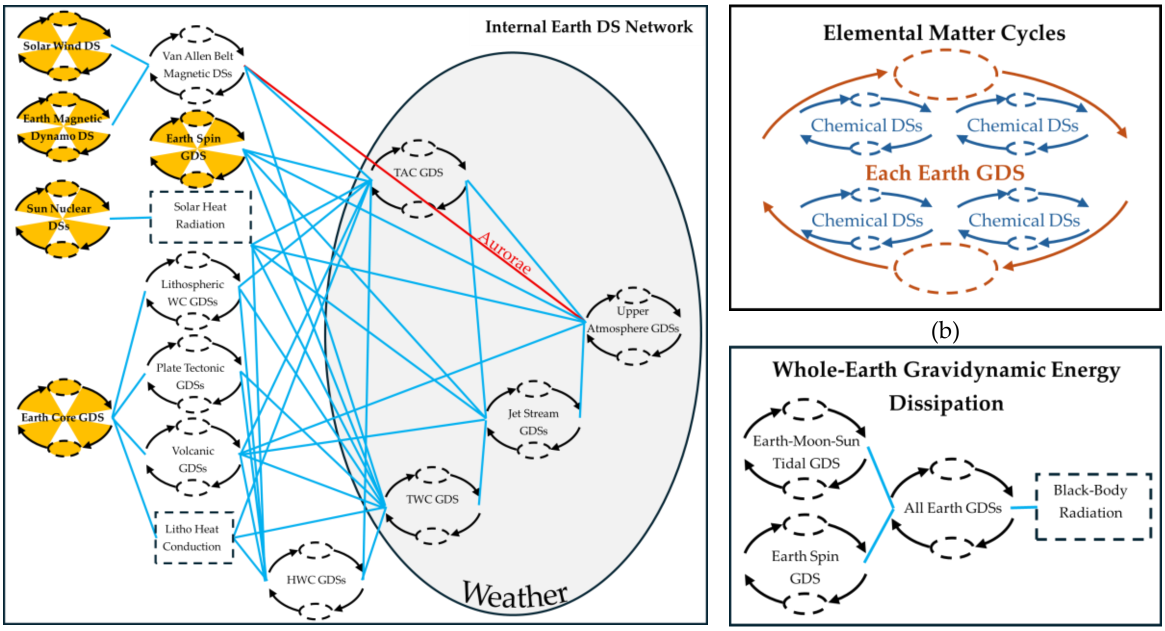
As is the nature of any physical cycling process, ARO will respond following any change in APC. During transient growth, a corresponding increase in heat output at stage 4 is delayed relative to the increase in heat output at stage 3, because the increase in the rate of the ARO decay process at stage 4 lags behind the increase in the rate of the APC growth process at stage 2. Heat output at stage 3 increases effectively immediately with the increase in APC. However, heat output at stage 4 does not start increasing until the decay process of ARO starts releasing the additional stores of energy that are collecting at the energy equilibrium plateau that is part of the structure of a DS as discussed in Section 3.6. ARO decay processes of DSs generally do not track close behind APC growth processes because of the equilibrium plateau. There must be a transition process of the stored energy that drives its release, and this can take additional time dependent upon the stability of the equilibrium plateau of the DS. The increase in the heat output at stage 4 of a GDS is therefore delayed until ARO increases to and eventually comes into steady state with APC, such that total heat input at stages 1 and 2 equals total heat output at stages 3 and 4.

Depending upon whether this growth is a result of an increase in the amount of available heat transfer medium material for the same amount of heat or an increase in the amount of available heat with excess inert heat transfer medium material standing by, this can affect local temperatures for GDSs that are more isolated from other GDSs. An increase in the availability of heat transfer medium material for the same amount of available heat could drive local heat source temperature down as the GDS is able to take in more heat from the local heat source and thereby decrease the internal energy of the local heat source. Recall that GDSs store the heat of buoyancy that is input at stage 2. They do not store any of the heat input from stage 1. The intake of more heat from the local heat source would result in more heat being delivered to the local heat sink of the GDS, thereby increasing local heat sink internal energy and temperature. However, considering the expanse of GDSs on Earth and the amount of energy moving through Earth as result, GDSs do not tend to become isolated from other GDSs, so the tendency of local temperature swings is dampened. Generally, local temperatures are largely driven by changes in heat inputs rather than changes in the availability of heat transfer medium material. Considering that specific heat quality drops and specific heat quality outputs are driven by changes in local heat source temperatures relative to local heat sink temperatures, local changes in available heat will tend to be the primary determinant of local changes in specific heat quality.

Heat transformation theory predicts a specific consequence for early Earth’s thermal history during and immediately following the period of the gravitational formation of Earth when GDSs were first forming across the planet. During this period when the lithosphere is more fluid because of the high temperatures and lower densities, the surface of Earth is covered with localized GDSs that form and dissolve as the excess heat of the gravitational collapse of Earth finds pathways of available fluid material to move the heat to the surface of the lithosphere. For any individual GDS, the eventual depletion of available heat transfer medium material results in the APC of the GDS going to zero and the structure of the GDS dissolving. “Gravi-systems” (i.e., local and regional systems of GDSs) made up of populations of various types of GDSs forming a mixed community seems to follow the same pattern as the ecosystems of the biological Earth. The environment on Earth at this time during and following the coalescence of Earth is consistent with geological and geochemical evidence for the thermal evolution of early Earth during the Hadean and Archean eons, when Earth’s interior heat production was substantially higher than today and the surface heat flow reflects a planet still approaching thermal steady state [100,101].

4.7. Networking of GDSs Results in Massive Mixing, Heat Delivery, and Complexity

Before heat released from a GDS on Earth can pass all the way to the universal heat sink, it must pass through a network of DSs (Figure 7).



(a) (b) (c)

Figure 7. (a) Internal Earth DS network. The GDS network of Earth extends well beyond the TWC and TAC developed in Sections 4.1 through 4.3. Lithospheric GDSs (including Volcanic GDSs, Lithospheric Water Cycle (LWC) GDSs, and Plate Tectonic GDSs) draw on the Earth Core GDS as a heat source and deliver heat to the surface where it enters the hydrospheric and atmospheric GDS networks. Hydrospheric Water Cycle (HWC) GDSs drive ocean currents that redistribute heat across latitude, longitude, and depth. The atmosphere connects to space and space weather: charged particles from the solar wind are captured in the Van Allen Belts of Earth's magnetic field and are funneled into the upper atmosphere, producing aurorae. **(b)** Elemental Matter Cycles. All GDSs transfer heat by moving matter, driving the cycling of elements through the periodic table (notably carbon, oxygen, nitrogen, and sulfur) creating the material flows along which Chemical DSs develop. **(c)** Whole-Earth Gravidynamic Energy Dissipation. The Earth Spin GDS and the Earth-Moon-Sun Tidal GDS input gravitational energy into all Earth-scale GDSs, contributing to massive mixing.

The source of the heat and material resources driving complexity on Earth is a network of DSs making up the solar system of the Sun (Figure 8). All GDSs produce what heat transformation theory calls *massive mixing*. The massive mixing is a phenomenon of the emergent property of *complexity* that is driven by the Δu_{Cx}^{DS} of each GDS. The mathematical basis of complexity is developed in part II of this paper series [95]. For the conceptual basis of complexity, consider the example of water entering the TWC from a lake high in a mountain range that is fed by a hot spring at the bottom of the lake. A separate lithospheric water cycle (LWC) GDS that is transferring heat from the mantel of Earth to the surface of Earth uses the water to lift the heat to the altitude of the lake, storing an increase in gravitational potential energy per mole of the water based on the change in distance from the center of Earth from the depth below the ground where the water received the heat from the mantel to the altitude of the mountain lake. That starting potential energy per mole of the water in the lake is transferred to the TWC when the water in the lake evaporates because of solar power and enters the TWC. That transfer of potential energy is what heat transformation theory defines as complexity. However, the potential energy per mole brought from the LWC with the water into the TWC is not included in the Δu_{Cx}^{DS} of the TWC. Δu_{Cx}^{DS} of the TWC is the amount of potential energy per mole that the TWC imparts to the water as it takes the water to its new level of potential energy at the top of the troposphere. The starting potential energy that the water had in the mountain lake is still with that water. Thus, the networking of the TWC with the LWC increases complexity. If the water goes on to feed into another DS from the top of the troposphere, the complexity is a combination of the potential energy per unit mole imparted by the Δu_{Cx}^{DS} of the LWC plus the potential energy per unit mole imparted by the Δu_{Cx}^{DS} of the TWC.

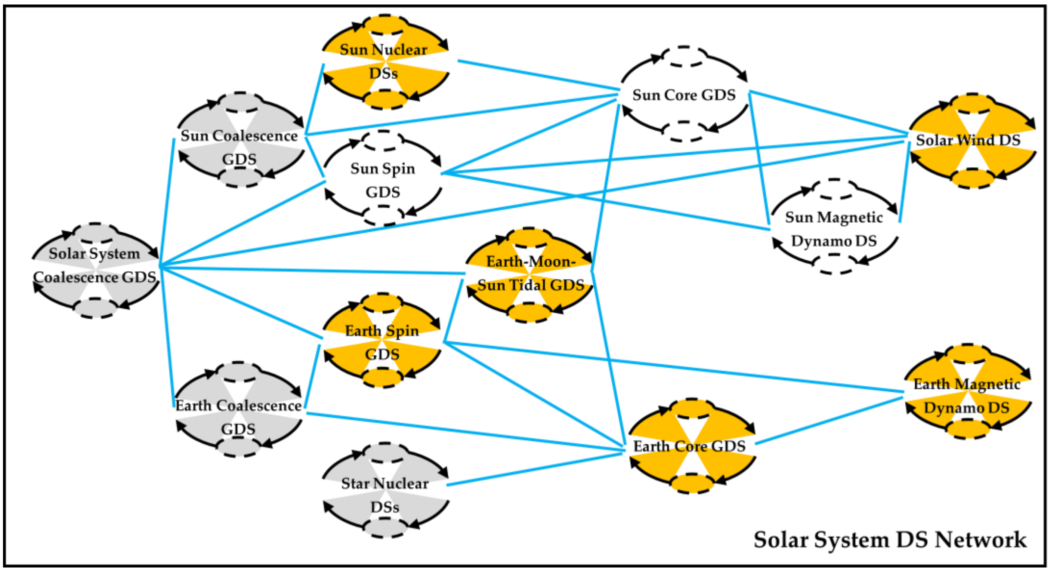


Figure 8. Solar system DS network. The Earth Core GDS receives heat and energy input from the internal energy left in the core from the original collapse of matter into the formation of the Earth (i.e., Earth Coalescence GDS), from Earth being pulled and squeezed by the gravity of the Sun and the Moon (i.e., Earth-Moon-Sun Tidal GDS), from friction driven by the Earth Spin GDS, and from the radioactive decay of elements in the mantel and crust of Earth. This radioactive decay is stage 4 of Star Nuclear DSs that start their cycles during the luminous life, collapse, and supernovae of stars that exist before the Sun and Earth.

On the decay portion of the TWC when the water precipitates, if it falls into a lake at the bottom of the mountain range and then flows downriver to an ocean, the amount of released potential energy per mole includes some of the potential energy per mole received from the LWC DS that lifted the water to the mountain lake. The remaining amount of stored gravitational potential energy per unit mole remaining in the water once its reaches the ocean is summative to the complexity of the network if it is taken up by another DS. The lesser amount of gravitational energy per unit mole that remains is transferred on the next DS as yet another positive, though lesser contribution to total network complexity. As the water continues to be passed from GDS to GDS, the total network grows in complexity as potential energy per mole stored in the water is passed along, taking heat with it. The same argument applies to lithospheric earth cycles (i.e., as in elements making up the mantel and crust) and atmospheric air cycles, as well as the cross connection from earth to water (e.g., magma to hot spring), water to air (e.g., TWC to jet stream), and water and air to earth (e.g., water and air penetrating and mixing with soil to start the carbon, nitrogen, and sulfur cycles).

The universal solvency and volatility of water ties the GDS network together as a material transport system. As developed in Sections 4.1 through 4.3, the TWC and TAC move water across the surface of Earth, lifting it from large bodies of water and depositing it over land as precipitation. As water travels, it soaks into the ground, runs in streams and rivers, rises in LWC GDSs as hot springs and hydrothermal vents, and cycles through ocean currents. It the process, it physically erodes earth materials and carries dissolved elements, minerals, and silt with it. The cumulative effect is that some of these materials settle into subterranean or surface deposits; others reach large bodies of water where they mix with materials accumulated over geological time and are redistributed by ocean-scale GDSs. This cross-connection between GDSs is what heat transformation theory calls massive mixing. As water, air, and earth are engaged in successive GDS cycles, the total network grows in complexity as the complexity yield of potential energy per mole is handed off and heat is carried along with it.

All massive mixing with water as the main solvent results in growing concentrations in the waters of Earth of simple chemicals that form when elements prevalent in the earth and in the air react with water: dissolved salts, acids, and bases made from elements from the first three lines of the periodic table and particulates of minerals that include heavier elements. These concentrations are a direct result of the APCs, AROs, and complexities of the GDSs driven by solar heating, buoyancy,

doi:10.20944/preprints202602.1676.v2

and the local heat sources in the Earth. The concentrations of simple chemicals grow over geological time, going through various surges resulting from large-scale events such as volcanoes, meteor strikes, and hurricanes. The more consistent growth toward high concentrations is a result of the regular, ongoing GDSs of the atmosphere, hydrosphere, and lithosphere driving either steadily higher or asymptotically toward a steady state of saturated concentrations that level out due to the plating out of minerals and the precipitation of salts.

The greater the complexity, the greater the massive mixing, the greater the material and heat carrying capacity as functions of the emergent property. The complexity of Earth resulting in massive mixing prevents superheating and mass disengagement by preventing localized hot and cold spots. T_{loc-C} is raised across the GDS network and applying available heat to available heat transfer medium material is maximized. The results discussed in Section 4.5 of a greater T_{loc-C} are favorable for heat transformation effectivity, efficiency of heat utilization, and specific heat quality. Massive mixing enhances the effects of GDSs, resulting in even more mixing.

The theory predicts that GDS-driven massive mixing on early Earth produced systematically increasing concentrations of dissolved chemical species (i.e., dissolved salts, acids, bases, and mineral particulates) over geological time at rates proportional to the APC of the GDS network operating at any given period of Earth history. This is a testable prediction against geochemical models of early ocean composition and hydrothermal system chemistry. The chemistry of modern hydrothermal vent systems that have been extensively characterized provides a present-day analog for the GDS-driven mixing processes the theory describes: mineral-laden water circulated by lithospheric GDSs delivers concentrated chemical species to the surface and ocean floor, creating the localized chemical gradients that the theory identifies as the precondition for prebiotic chemical reactions [102,103]. The concentrations observed in modern hydrothermal vent systems, when corrected for the higher GDS network APC of early Earth driven by higher internal heat production, provide an order-of-magnitude constraint on the chemical concentrations available to prebiotic synthesis.

5. Conclusions

With the development of the portion of the heat transformation theory dealing with dissipation of heat through a gravitational system, several conceptions of thermodynamics become decipherable. Ever since Schrödinger pondered about the nature of life [104], scientists have been discussing his concept of *negentropy*. There is also much debate in science about the nature of entropy in the universe. The following are the conclusions that could be drawn from Part I of heat transformation theory.

5.1. Apparent Negative Changes in Local Entropy

Local heat sources and heat sinks are open systems through which simple heat transfer occurs, carrying heat without converting any of the heat to stored energy. As mentioned at the end of Section 4.2, it appears that there is a transient reversal of local heat source and local heat sink system entropy during transient growth of the DS [78]. This apparent reversal is in stark contrast to the apparent maximum production of local heat source and local heat sink system entropy occurring when the DS is at steady state. This apparent local transient effect is suggested by

$$\Delta S_{loc} = \frac{|Q_C^{Tot}|}{T_{loc-C}} - \frac{|Q_H^{Tot}|}{T_{loc-H}} < 0 \text{ for } |Q_H^{Tot}| > |Q_C^{Tot}| \text{ and } T_{loc-H} \gtrsim T_{loc-C}\,. \tag{60}$$

The heat input increases relative to the heat output because heat output lags heat input during transient growth of the DS. This is due to a delay of the stage 4 decay part of the cycle. This apparent heat effect is compounded in Equation 60 for situations in which T_{loc-H} is equal to or not much greater than T_{loc-C}, which can be the case with massive mixing. During transient growth of the DS, the second term of Equation 60 is greater than the first term, resulting in local heat source and local heat sink system entropy appearing to reverse.

In his treatise on “What is Life?”, Schrödinger [104] discusses a property called negentropy that is related to the growth of forms of stored energy on Earth, including life. The steady-state-seeking process of a DS, in which transient stored-energy growth occurs with an apparent transient reduction in local heat source and local heat sink system entropy, fits the description of what Schrödinger called negentropy. However, the universal entropy is always greater than zero during transient growth of a DS,

$$\Delta S_{uni} = \frac{|Q_C^{Tot}|}{T_{uni-C}} - \frac{|Q_H^{Tot}|}{T_{uni-H}} > 0 \qquad (61)$$
$$\text{for } |Q_H^{Tot}| > |Q_C^{Tot}|\,, T_{uni-H} \gg T_{loc-H}\,, \text{and } T_{uni-C} \ll T_{loc-C}\,,$$

because of how much greater T_{uni-H} is relative to T_{loc-H} and how much lesser T_{uni-C} is relative to T_{loc-C} .

There are two misconceptions that appear in the scientific literature [76,104–106,41,107,108] that lead to the incorrect conclusion that DSs reduce entropy locally even as universal entropy increases.

The first misconception is that the combined local heat source and local heat sink can have a negative change in system entropy. Equation 60 appears to support this conclusion, showing $\Delta S_{loc} < 0$when heat input to the DS exceeds heat output during transient growth. However, this result is an artifact of incomplete accounting. Equation 60 considers only the heat transfers between the local heat source and the DS, and between the DS and the local heat sink, It does not account for the heat input to the local heat source from the universal heat source, nor for the heat output from the local heat sink to the universal heat sink. When these transfers are included, the accounting is complete: the heat input to the local heat source from the universal heat source is exactly equal to the heat output from the local heat source to the DS, so the net change in local heat source system entropy is zero. Equally, the heat input to the local heat sink from the DS is exactly equal to the heat output from the local heat sink to the universal heat sink, so the net change in local heat sink system entropy is zero. The full accounting, illustrated in Figure 9, gives:

$$\begin{aligned} \Delta S_{loc} &= \Delta S_{loc-H} + \Delta S_{loc-C} \\ &= \left(\frac{\left|Q_{uni-H-to-loc-H}^{Tot}\right|}{T_{loc-H}} - \frac{\left|Q_{loc-H-to-DS}^{Tot}\right|}{T_{loc-H}}\right) \\ &\quad + \left(\frac{\left|Q_{DS-to-loc-C}^{Tot}\right|}{T_{loc-C}} - \frac{\left|Q_{loc-C-to-uni-C}^{Tot}\right|}{T_{loc-C}}\right) = 0 + 0 = 0\,. \end{aligned} \qquad (64)$$

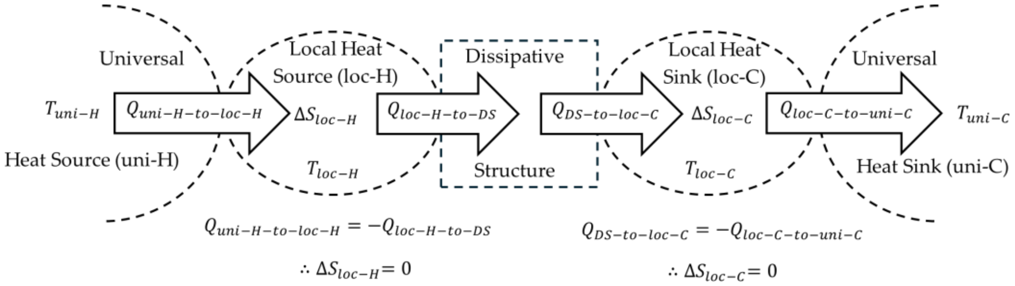


Figure 9. Heat input from the universal heat source to the local heat source is equal to heat output from the local heat source to the DS. These heat transfers into and out of the local heat source are equal and opposite, resulting in the change in local heat source system entropy being zero. The same argument applies to the local heat sink.

Modeling the complete heat transfer from universal heat source to universal heat sink reveals that there is no local negative change in local heat source or local heat sink system entropy per Clausius’s theory.

The second misconception is that dissipative structures can experience a negative change in DS system entropy. Erroneous reasoning treats the DS as a subsystem that can have a negative change in DS system entropy provided the positive change in universal entropy is greater, such that the net sum remains positive. This misapplies Clausius's heat bifurcation (Section 2.3.1): every subsystem, including a DS, contains only an interior work element, an exterior work element, and a heat dissipation element. The interior work element generates zero DS system entropy, not negative. This is because conservative force fields satisfy Clausius's force = counter-force criterion at every point of the cycle, making the process path-independent, fully recoverable, and incapable of generating either positive or negative entropy. Exterior work and heat dissipation elements can only generate positive entropy. A DS can only generate positive universal entropy by the irreversible processes of exterior work and dissipating heat. However, the accounting of total heat inputs to and total heat outputs from a DS once all heat has completed dissipating reveals that the change in system entropy of a DS is also zero for the same reason that the changes in local heat source and local heat sink entropies are zero. What appears in the DS to be an increase in system entropy due to taking in more heat than it puts out in an interim state is a diversion of heat into a recoverable form: stored energy at stage 2 delays but does not increase the system entropy, and when released at stage 4, completes the release of heat that makes the change in system entropy zero. Negative entropy production in a DS is not possible according to Clausius's definition of entropy and his interpretation of the second law of thermodynamics.

The Boltzmann statistical entropy framework describes that a system goes through a negative change in entropy during a reduction in access to microstates. The gravitational collapse of hydrogen gas to form a star or star dust to form a planet has been described as a reduction in available microstates of the collapsing matter and thus as a local decrease in entropy. The basis is that the material is constrained in its access to microstates by being pulled into a smaller volume of space. What can be said from the theoretical development presented in this paper is that this constrained material represents heat that has been transformed into stored potential energy and delayed in generating universal entropy. The force = counter-force criterion established above means the conservative force neither contributes to nor subtracts from entropy as defined by Clausius. The word conservative captures precisely this property: exact force balance that can neither produce nor reduce Clausius entropy. Why Boltzmann's entropy and Clausius's entropy do not agree on the action of conservative forces is addressed further in Part II of this paper series.

Mathematically modeling specific heat quality drop and specific heat quality output of the DS goes a step beyond Clausius's original concept of the second law of thermodynamics. Heat transformation theory defines specific heat quality drop and specific heat quality output to analyze far-from-equilibrium systems that entropy as defined by Clausius cannot. Specific universal entropy (s_{max}^{DS}, Equation 29; s_{con}^{DS}, Equation 37; s_{mut}^{DS}, Equation 41) is used to determine the worst-case performance of the universe in the use of heat to power the DS. Specific heat quality drop and specific heat quality output enable determining how the DS releases heat to the local environment to be used by another DS and how much quality remains before it is completely depleted in the universal heat sink. What is revealed is that T_{loc-C} is determinate in the extension of usefulness of heat. A DS has the same Δu_{Cx}^{DS} (i.e., stores the same amount of potential energy per mole) regardless of the T_{loc-C}, resulting in a constant efficiency determined only by the material properties associated with the conservative force field. However, the DS is more effective the greater the heat sink temperature, meaning the DS has a greater heat quality output. The greater the heat quality output, the more available the associated heat is to driving Δu_{Cx}^{DS} in downstream DSs. The TWC and TAC calculations of Section 4.5 quantify this concretely: the specific conditional heat quality output (σ_{con}^{DS}, Equation 45) retained after passing through either GDS is 98.8% (99.1% for specific mutual heat quality output) of the initial specific heat quality from the universal heat source, with only 1.2% depleted as specific conditional heat quality drop ($\Delta\sigma_{con}^{DS}$, Equation 46) (0.9% for specific mutual heat quality drop) This numerical result illustrates that the GDS framework does not merely predict that heat quality is largely preserved through conservative-force dissipative structures. It calculates the fraction retained to within the precision of the empirical inputs, providing a directly verifiable prediction for any GDS whose APC and local heat source and sink temperatures are known.

5.2. Sources of Heat and the Universality of the Universal Heat Source and Universal Heat Sink

Section 4.4 and subsequent sections use T_{uni-H} throughout the specific universal entropy calculations for GDSs, assigning it the value of solar fusion temperatures, 15×10^6 K. This section provides the physical justification for that value and demonstrates that the specific universal entropy calculations of this paper are thermodynamically self-consistent.

The elements that make up Earth and become the heat transfer media of GDSs originate in a molecular cloud that formed the first stars before the Sun ever existed (Figure 10). The gravitational formation and nuclear fusion of those first stars operating at temperatures of the same order as the Sun generated the elements of the periodic table and the heat energy stored in them. Once these elements are incorporated into Earth by gravitational collapse, they become the source of the lithospheric heat of radioactive decay and Earth's core. Heat transformation theory therefore treats all local heat sources on Earth as intermediate, having been originally sourced from stellar core fusion temperatures of the same order as the Sun. $T_{uni-H} = 15 \times 10^6$ K is the physically appropriate temperature for all terrestrial heat sources when calculating their specific universal entropy contributions.

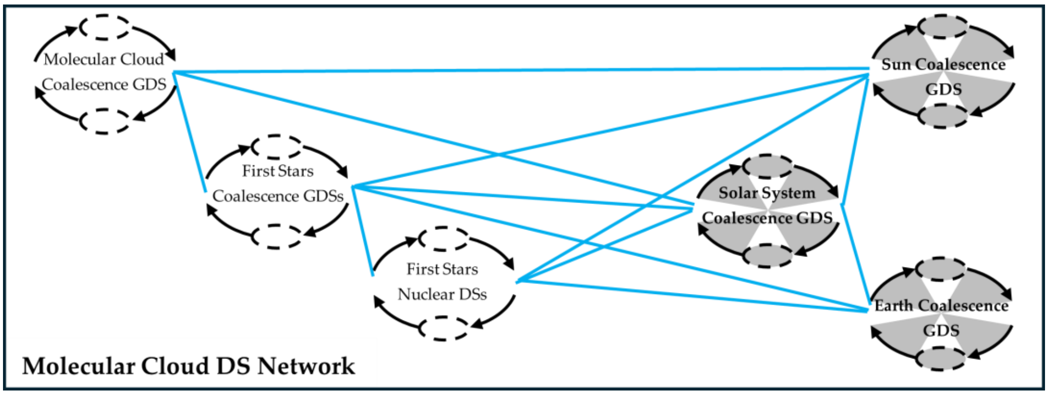


Figure 10. Molecular Cloud DS Network. A local molecular cloud formed following the big bang and, within it, the first local stars. The collapse and supernovae of these stars produce all the elements of the periodic table and the turbulence needed to form the Sun, Earth, and solar system. As noted in Section 2, the first chemicals form in space as a result of the fused and ejected elements and mixing caused by the supernovae. The formation of these chemicals occurs within GDSs within the molecular cloud, just as depicted in Figure 7b for Earth GDSs. The darkened GDSs in this figure match the darkened GDSs in Figure 8, revealing how all DSs are networked across space and time to the big bang. All energy that produces all heat today is originally sourced from the big bang.

The traceability chain of heat delivery can be extended further. The molecular cloud itself received its gravitational and nuclear potential energy from the generation of elementary particles and hydrogen following the big bang. This makes the big bang the ultimate universal heat source from which all heat in the universe traces its origin, including all heat that has ever passed through a GDS on Earth. The total universal entropy is positive and increasing from the moment of the big bang as heat dissipates through the expanding universe toward a low-temperature universal heat sink.

Clausius's entropy formula is based on the convention of the universe as an isolated system, and the objective within this convention is to identify the peak temperature of the universe for use as T_{uni-H} in the specific universal entropy calculations. Tracing the origin of all terrestrial heat to stellar fusion establishes $T_{uni-H} = 15 \times 10^6$ K as the physically appropriate value, and tracing further to the big bang suggests that an even higher temperature might be more appropriate. However, in every specific universal entropy property defined in Section 4.4, T_{uni-H} appears in a term of the form Q/T_{uni-H}. At stellar fusion temperatures of 15×10^6 K this term is effectively zero: even for large values of Q representing the full heat throughput of a GDS, dividing by 15×10^6 K yields a contribution that is negligible compared to the Q/T_uni-C term, where $T_{uni-C} = 2.7$ K. Inspection of

Equations 29, 37, and 41 confirms that the specific universal entropy properties of GDSs are dominated entirely by the universal heat sink term and are insensitive to the precise value of T_{uni-H} at or above stellar fusion temperatures. Whether one uses stellar fusion temperatures, the temperature of the molecular cloud's gravitational collapse, or the peak temperature of the big bang, the result is thermodynamically indistinguishable. Stars are therefore selected as the working value for T_{uni-H} as both a pragmatic and physically grounded choice: the thermodynamic result is identical to any more primordial selection.

5.3. Chemical Dissipative Structures and Networks

The massive mixing capacity of GDSs established in this paper raises the question of whether that mixing is sufficient to achieve the multiplicity of microstates and ergodicity required for spontaneous chains of chemical reactions to produce the biochemistry of life. If it is, then the probability arguments that any given sequence of chemical reactions leading to a complex molecule is improbable in nature may be reframed entirely by the thermodynamic framework developed here. What remains to be understood is whether the Clausius framework of force = counter-force applied to gravitational dissipative structures extends to the molecular scale of chemical reactions, and whether the heat quality properties developed in this paper can characterize the thermodynamic behavior of chemical dissipative structures as they do for gravitational ones. Beyond the individual reaction, it is an open question of how complexity yield and specific heat quality enable networks of GDSs and CDSs to produce molecules of increasing complexity. These questions are addressed in Part II of this series.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/doi/s1, Tabulation S1: Prior Art related to Auto-Powering Capacity (APC); Tabulation S2: Prior Art related to Auto-Restoring Order (ARO); Tabulation S3: Prior Art related to Specific Universal Entropy; Tabulation S4: Prior Art related to Complexity Yield; Tabulation S5: Prior Art related to Specific Heat Quality; Tabulation S6: Prior Art related to Heat Transformation Effectivity; Calculation S1: The Auto-Powering Capacity and Auto-Restoring Order of the Tropospheric Water Cycle; Calculation S2: The Auto-Powering Capacity and Auto-Restoring Order of the Tropospheric Air Cycle; Calculation S3: Transfer of Specific Heat Quality Output from Tropo-spheric Water and Air Cycles to the Jet Stream.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: No data were generated for this study.

Acknowledgments: The author thanks Morgan Irons for many hours of coworking, listening to ideas, and providing feedback.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

APC	Auto-powering capacity
ARO	Auto-restoring order
atmlev	Atmospheric leveling
C	Heat sink
CDS	Chemical dissipative structure
CMBR	Cosmic microwave background radiation
Cx	Complexity
con	Conditional
DNA	Deoxyribonucleic acid

DS	Dissipative structure
FUCA	First universal common ancestor
G	Gravity
GDS	Gravitational dissipative structures
H	Heat source
HWC	Hydrospheric water cycle
in	Input
L	Lift
loc-H	Local heat source
loc-C	Local heat sink
LUCA	Last universal common ancestor
LWC	Lithospheric water cycle
max	Maximum
med	Heat carrying medium of a dissipative structure
mut	Mutual
NC	Natural convection
out	Output
OG-FUCA	The original individual of the first universal common ancestor
PE	Potential energy
precip	Precipitation
Q	Internal energy of heat capacity
S1	Stage 1
S2	Stage 2
S3	Stage 3
S4	Stage 4
Sys	System
TAC	Tropospheric air cycle
tac	Tropospheric air cycle
tropau	Tropopause
trosph	Troposphere
TWC or twc	Tropospheric water cycle
uni	Universal
uni-H	Universal heat source
uni-C	Universal heat sink
wu	Warm up
wv	Water vapor

Appendix A. The Tropospheric Water Cycle (TWC) GDS Model

Figure A1 is a heat engine model of the tropospheric water cycle (TWC) as a GDS. The following is a physical and mathematical analysis of the model.

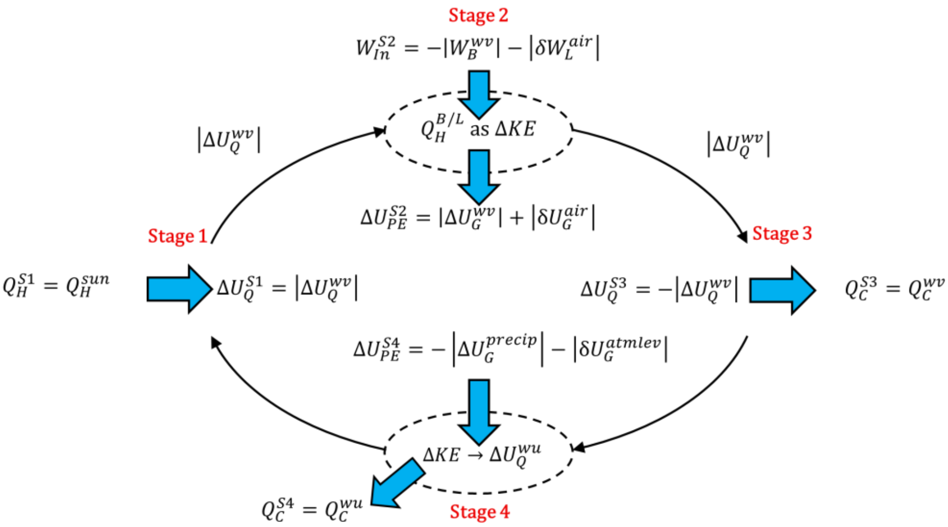


Figure A1. The tropospheric water cycle (TWC) gravitational DS (GDS) model. At stage 1, liquid water absorbs solar radiation and evaporates into gaseous form. At stage 2, buoyancy lifts the water vapor to the top of the troposphere, also lifting the atmosphere as it expands and displaces dry air. At stage 3, the heat of the water vapor is released and dissipates into the upper atmosphere and space. At stage 4, the water falls back to Earth's surface as precipitation as the atmosphere relevels due to the contraction of water vapor. The water flows to the lowest point in Earth's gravitational well that it can reach, returning to the beginning of stage 1 where it can again absorb solar radiation.

Appendix A.1. Analysis of Stages 1 Through 3 of the TWC

Start with applying the first law of thermodynamics and the work-energy theorem from Equation 11 to the system (subscript *sys*) for stages 1 through 3 (superscript $S1 \rightarrow 3$),

$$\Delta U_{Q-sys}^{S1\rightarrow 3} + \Delta U_{PE-sys}^{S1\rightarrow 3} = \Delta Q_{sys}^{S1\rightarrow 3} + W_{in-sys}^{S1\rightarrow 3}\,. \tag{A1}$$

Total system energy change is the sum of state energy changes of internal energy of heat capacity and potential energy occurring during the stages. There are two changes in state property of internal energy of heat capacity (subscript Q) at stage 1 (superscript S1) and stage 3 (superscript S3) and one change in the state property of potential energy (subscript PE) at stage 2 (superscript S2),

$$\Delta U_{Q-sys}^{S1\rightarrow 3} + \Delta U_{PE-sys}^{S1\rightarrow 3} \rightarrow \left|\Delta U_Q^{S1}\right| - \left|\Delta U_Q^{S3}\right| + \left|\Delta U_{PE}^{S2}\right|\,. \tag{A2}$$

The process property of net heat exchange of the system is the difference in heat input from the heat source (subscript H) at stage 1 and heat output to the heat sink (subscript C) at stage 3 (superscript S3),

$$\Delta Q_{sys}^{S1\rightarrow 3} \rightarrow \left|Q_H^{S1}\right| - \left|Q_C^{S3}\right|\,. \tag{A3}$$

The process property of work output is the difference between work output and work input. Gravitational work is included in the state property of potential energy according to the work-energy theorem. There is no work output, but there is work input at stage 2,

$$W_{sys}^{S1\rightarrow 3} \rightarrow -\left|W_{In}^{S2}\right|\,. \tag{A4}$$

Substitute Equation A2, Equation A3, and Equation A4 into Equation A1 to obtain the energy balance for stages 1 through 3 of the model (also Equation 13),

$$\left|\Delta U_Q^{S1}\right| - \left|\Delta U_Q^{S3}\right| + \left|\Delta U_{PE}^{S2}\right| = \left|Q_H^{S1}\right| - \left|Q_C^{S3}\right| - \left(-\left|W_{In}^{S2}\right|\right)\,. \tag{A5}$$

At stage 1, heat comes from the Sun (superscript *sun*),

$$|Q_H^{S1}| = |Q_H^{sun}|\,, \tag{A6}$$

heating and evaporating water, resulting in water vapor (superscript *wv*) with an increase in internal energy,

$$|Q_H^{sun}| \rightarrow \left|\Delta U_Q^{S1}\right| = \left|\Delta U_Q^{wv}\right|. \tag{A7}$$

At stage 2, the buoyancy (subscript *B*) and lift (subscript *L*) of the atmosphere (superscript *air*) accelerate molecules into molecular kinetic energy that is heat generated by both (superscript *B*/*L*),

$$\left|W_{in}^{S2}\right| = |W_B^{wv}| + \left|\delta W_L^{air}\right| \xrightarrow{molecular\ \Delta KE} \left|Q_H^{B/L}\right|. \tag{A8}$$

Substitute Equation A6 and Equation A8 into Equation A5:

$$\left|\Delta U_Q^{wv}\right| - \left|\Delta U_Q^{S3}\right| + |\Delta U_{PE}^{S2}| = |Q_H^{sun}| - |Q_C^{S3}| - \left(-\left|Q_H^{B/L}\right|\right). \tag{A9}$$

Rearrange right hand side of Equation A9,

$$\left|\Delta U_Q^{wv}\right| - \left|\Delta U_Q^{S3}\right| + |\Delta U_{PE}^{S2}| = \left(|Q_H^{sun}| + \left|Q_H^{B/L}\right|\right) - |Q_C^{S3}|\,, \tag{A10}$$

revealing that the heat input (subscript *in*) for stages 1 through 3 is

$$\left|Q_{in}^{S1\rightarrow 3}\right| = |Q_H^{sun}| + \left|Q_H^{B/L}\right| \tag{A11}$$

and the heat output (subscript *out*) is

$$|Q_{out}^{S1\rightarrow 3}| = |Q_C^{S3}|\,. \tag{A12}$$

Displacement of water vapor and air becomes gravitational (subscript *G*) potential energy,

$$|\Delta U_{PE}^{S2}| = |\Delta U_G^{wv}| + \left|\delta U_G^{air}\right|. \tag{A13}$$

At stage 3, water condenses,

$$\Delta U_Q^{S3} = -\left|\Delta U_Q^{wv}\right|, \tag{A14}$$

and loss of internal energy becomes heat output,

$$\left|\Delta U_Q^{wv}\right| = |Q_C^{wv}| = |Q_C^{S3}|\,. \tag{A15}$$

Substitute Equation A7, Equation A8, Equation A13, Equation A14, and Equation A15 into Equation A10,

$$|Q_H^{sun}| + \left|Q_H^{B/L}\right| = |\Delta U_G^{wv}| + \left|\delta U_G^{air}\right| = |W_B^{wv}| + \left|\delta W_L^{air}\right|. \tag{A16}$$

To obtain the heat input and heat output for stages 1 through 3, substitute Equation A16 into Equation A11 (also Equation 21),

$$\left|Q_{in}^{S1\rightarrow 3}\right| = \left|\Delta U_Q^{wv}\right| + |\Delta U_G^{wv}| + \left|\delta U_G^{air}\right|, \tag{A17}$$

and substitute Equation A15 into Equation A12,

$$|Q_{out}^{S1\rightarrow 3}| = \left|\Delta U_Q^{wv}\right|. \tag{A18}$$

Appendix A.2. Analysis of Stage 4 of the TWC

To analyze stage 4 (superscript S4), apply the first law of thermodynamics and the work-energy theorem,

$$\Delta U_{sys}^{S4} = \Delta Q_{sys}^{S4} - W_{sys}^{S4}\,. \tag{A19}$$

Total system energy change is due to one change in potential energy,

$$\Delta U_{sys}^{S4} \rightarrow -|\Delta U_{PE}^{S4}|\,. \tag{A20}$$

The net heat exchange is due to a heat output,

$$\Delta Q_{sys}^{S4} = -|Q_C^{S4}| \,. \tag{A21}$$

There is no work performed other than what is already included in the change in potential energy,

$$W_{sys}^{S4} = 0 \,. \tag{A22}$$

Substitute Equation A20, Equation A21, and Equation A22 into Equation A19 to obtain the energy balance (also Equation 16),

$$-|\Delta U_{PE}^{S4}| = -|Q_C^{S4}| \,. \tag{A23}$$

There is no heat input for stage 4,

$$|Q_{in}^{S4}| = 0 \,. \tag{A24}$$

There is a heat output for stage 4. The following analysis determines the quantity of this heat output,

$$|Q_{out}^{S4}| = |Q_C^{S4}| \,. \tag{A25}$$

At stage 4, water precipitates (superscript *precip*) and causes the atmosphere to level (superscript *atmlev*),

$$-|\Delta U_{PE}^{S4}| = -|\Delta U_G^{precip}| - |\delta U_G^{atmlev}| \,. \tag{A26}$$

The gravitational potential energy that is gained at stage 2 is lost at stage 4:

$$|\Delta U_G^{precip}| + |\delta U_G^{atmlev}| = |\Delta U_G^{wv}| + |\delta U_G^{air}| \,. \tag{A27}$$

Substitute Equation A26 and Equation A27 into Equation A23,

$$-|\Delta U_G^{wv}| - |\delta U_G^{air}| = -|Q_C^{S4}| \,. \tag{A28}$$

The released gravitational potential energy converts to bulk kinetic energy of water and air that completely thermalizes into molecular kinetic energy, ΔKE, and becomes internal energy of the water as it warms up (superscript *wu*),

$$|\Delta U_G^{wv}| + |\delta U_G^{air}| \xrightarrow{molecular\ \Delta KE} |\Delta U_Q^{wu}| \,. \tag{A29}$$

The increase in internal energy dissipates into the environment from the water as warmup heat,

$$|\Delta U_Q^{wu}| \xrightarrow{dissipates\ as\ heat} |Q_C^{wu}| = |Q_C^{S4}| \,. \tag{A30}$$

Substitute Equation A30 into Equation A28 for the energy balance to reveal that heat dissipated into the environment at stage 4 comes from release gravitational potential energy,

$$|Q_C^{wu}| = |\Delta U_G^{wv}| + |\delta U_G^{air}| \,. \tag{A31}$$

Substitute Equation A30 and Equation A31 into Equation A25 to determine heat output of stage 4 (also Equation 23),

$$|Q_{out}^{S4}| = |\Delta U_G^{wv}| + |\delta U_G^{air}| \,. \tag{A32}$$

Appendix A.3. Results of Heat Dissipations of Stages 1 Through 4

The first result is revealed by comparing total heat input to total heat output. Sum Equation A17 and Equation A24 to determine the total heat input for stages 1 through 4:

$$|Q_{in}^{S1\rightarrow 4}| = |\Delta U_Q^{wv}| + |\Delta U_G^{wv}| + |\delta U_G^{air}| \,. \tag{A33}$$

Sum Equation A18 and Equation A32 to determine the total heat output for stages 1 through 4,

$$\left|Q_{out}^{S1\to4}\right| = \left|\Delta U_Q^{wv}\right| + \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|. \tag{A34}$$

Compare Equation A24 and Equation A32,

$$\left|Q_{in}^{S1\to4}\right| = \left|Q_{out}^{S1\to4}\right| = \left|\Delta U_Q^{wv}\right| + \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|, \tag{A35}$$

to reveal that total heat input equals total heat output.

The second result is revealed by comparing the difference of heat input and heat output of stages 1 through 3 to the difference of heat input and heat output of stage 4. The difference for stages 1 through 3 is

$$\left|Q_{in}^{S1\to3}\right| - \left|Q_{out}^{S1\to3}\right| = \left|\Delta U_G^{wv}\right| + \left|\delta U_G^{air}\right|. \tag{A36}$$

This is the amount of energy that is stored during stage 2. The difference for stage 4 is

$$\left|Q_{in}^{S4}\right| - \left|Q_{out}^{S4}\right| = -\left|\Delta U_G^{wv}\right| - \left|\delta U_G^{air}\right|. \tag{A37}$$

This is the amount of stored energy that is released at stage 4. The result is that the stored energy at stage 2 is equal and opposite to the released energy at stage 4,

$$\left|Q_{in}^{S1\to3}\right| - \left|Q_{out}^{S1\to3}\right| = -\left(\left|Q_{in}^{S4}\right| - \left|Q_{out}^{S4}\right|\right). \tag{A38}$$

This reveals that stage 2 and stage 4 of the TWC DS are reversible. The reversibility is a result of conservative forces controlling the storage and release of energy.

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