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RESEARCH ARTICLE

Entropy Budget of the Global Climate System Under Radiative Forcing

Veronika Malek^{1*}, Ondrej Tichy² and Natalia Bartos³¹Department of Mechanical and Thermal Engineering, Rhone Institute of Non-Equilibrium Physics, Slovenia²Department of Mechanical and Thermal Engineering, Elbe Institute of Energy Systems Engineering, Austria³Department of Mechanical and Thermal Engineering, Danube Center for Complex Systems Research, Latvia*Corresponding author: Veronika Malek, Department of Mechanical and Thermal Engineering, Rhone Institute of Non-Equilibrium Physics, Slovenia; Email: veronika.malek@rhone.edu

ABSTRACT

The global climate system behaves as a nonequilibrium heat engine that converts the entropy flux imposed by incoming solar radiation and outgoing terrestrial radiation into material entropy production through atmospheric and oceanic motion, latent-heat transport, and turbulent mixing, yet how this material entropy production responds to sustained radiative forcing remains only coarsely quantified. We used a two-dimensional latitudinal energy balance model with 36 latitude bands, forced by CO₂-equivalent radiative perturbations from 0 to 8.5 W/m² following four forcing scenarios, to compute the planetary radiative entropy budget and its partition into sensible-heat, latent-heat, and mechanical (kinetic-energy dissipation) transport channels across 240 simulated years per scenario. At the unforced baseline, material entropy production stabilized at 54.8 mW/(m² K), consistent with prior maximum-entropy-production estimates, and rose to 61.3 mW/(m² K) under the 8.5 W/m² forcing scenario, a 11.9% increase driven disproportionately by the latent-heat channel, whose share of total material entropy production grew from 32% to 41% as forcing increased. Meridional temperature gradient weakened by 18% under maximum forcing, yet total meridional entropy transport increased by 9.4%, because enhanced latent-heat transport more than compensated for the reduced sensible-heat gradient ($r = -0.91$, $p < 0.001$, across the four scenarios). A sensitivity analysis varying the assumed longwave feedback parameter by $\pm 25\%$ shifted equilibrium material entropy production by only 3.1 mW/(m² K), while varying the meridional diffusivity coefficient by the same margin shifted it by 7.8 mW/(m² K), identifying diffusive heat transport efficiency, rather than radiative feedback strength, as the dominant control on the simulated entropy budget's sensitivity. The model's radiative entropy production, computed directly from the difference between absorbed shortwave and emitted longwave photon entropy fluxes, exceeded material entropy production by more than an order of magnitude at every forcing level, confirming that the climate system remains far from the state of maximum material entropy production even under strong forcing. These results indicate that anthropogenic radiative forcing systematically increases the entropy-production burden carried by the hydrological cycle specifically, rather than by atmospheric and oceanic sensible-heat circulation broadly, with implications for how maximum-entropy-production closure schemes are calibrated in reduced-complexity climate models.

Keywords: climate entropy budget; radiative forcing; material entropy production; atmospheric heat engine; maximum entropy production; nonequilibrium thermodynamics; energy balance model; irreversibility

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1. INTRODUCTION

The Earth's climate system is fundamentally a heat engine driven by the temperature difference between the Sun and space, absorbing low-entropy shortwave radiation and re-emitting a larger flux of high-entropy longwave radiation, with the difference in entropy flux balanced by material entropy production within the atmosphere and oceans through turbulent motion, phase change, and frictional dissipation [1,2]. This framing, developed from classical nonequilibrium thermodynamics, has motivated decades of interest in whether simple extremal principles, most notably the hypothesis that the climate system organizes itself toward a state of maximum material entropy production, can explain gross features of atmospheric and oceanic circulation without resolving the full fluid dynamics [3,4,5].

Global energy balance models and general circulation models have both been used to estimate the magnitude of material entropy production associated with present-day climate, with values converging broadly in the range of 50–60 mW/(m² K), and the maximum-entropy-production hypothesis has had partial success in reproducing observed meridional heat transport and cloud distributions when used as a closure scheme [6,7,8]. However, most existing work has focused on characterizing entropy production under present-day or paleoclimate conditions rather than tracking how the entropy budget, and its partition among sensible-heat, latent-heat, and mechanical dissipation channels, evolves under sustained radiative forcing of the magnitude now associated with anthropogenic climate change [9,10].

This gap matters because the different transport channels contributing to material entropy production are governed by different physical processes with different sensitivities to warming: latent-heat transport scales with atmospheric moisture content, which increases roughly exponentially with temperature under the Clausius-Clapeyron relation, while sensible-heat transport scales more directly with the meridional temperature gradient, which is expected to weaken under polar-amplified warming [11,12]. Whether increased radiative forcing drives material entropy production up or down, and which channel absorbs most of the resulting change, is therefore not obvious a priori and carries direct implications for how entropy-production closure schemes should be calibrated in models that do not resolve moist convection explicitly.

This study uses a latitudinally resolved energy balance model, forced by four radiative forcing scenarios spanning the range considered in near-term climate projections, to compute the full planetary entropy budget and its partition into sensible-heat, latent-heat, and mechanical dissipation channels at equilibrium under each forcing level. We quantify how the magnitude and

channel partition of material entropy production shift with forcing, characterize the relationship between weakening meridional temperature gradients and total entropy transport, and test the sensitivity of the simulated entropy budget to two commonly uncertain model parameters, the longwave feedback parameter and the meridional diffusivity coefficient.

2. MATERIALS AND METHODS

We implemented a two-dimensional latitudinal energy balance model resolving 36 latitude bands, forced by four CO₂-equivalent radiative forcing scenarios ranging from 0 (baseline) to 8.5 W/m², and computed the radiative and material entropy budgets at model equilibrium for each scenario from the simulated energy fluxes and temperature fields.

2.1 Energy balance model structure

The model divided the globe into 36 latitude bands of equal width, each with prognostic surface temperature evolved under net radiative and diffusive heat flux forcing, following a standard budyko-sellers formulation with albedo feedback, outgoing longwave radiation linearized around present-day conditions, and meridional heat transport represented as diffusive with a baseline diffusivity of $D = 0.65 \text{ W/(m}^2 \text{ K)}$.

2.2 Radiative forcing scenarios

Four steady-state radiative forcing levels, 0, 2.6, 4.5, and 8.5 W/m², were applied uniformly as a downward longwave perturbation at the top of atmosphere, labeled to correspond loosely to representative concentration pathway magnitudes, and each scenario was integrated for 240 simulated years, sufficient for global mean surface temperature and the latitudinal temperature profile to reach equilibrium to within 0.01 K per decade.

2.3 Moisture and latent-heat transport parameterization

Column-integrated atmospheric moisture content in each latitude band was diagnosed from local surface temperature via a Clausius-Clapeyron scaling with fixed relative humidity of 70%, and latent-heat transport between adjacent bands was computed as the product of the moisture gradient, a fixed eddy diffusivity, and the latent heat of vaporization, consistent with moist static energy transport parameterizations used in reduced-complexity climate models [11].

2.4 Radiative and material entropy budget calculation

Radiative entropy production was computed at each latitude and time step from the difference between the photon entropy flux of absorbed shortwave radiation (approximated using an effective solar temperature of 5778 K) and emitted longwave radiation (using local emission temperature), integrated globally. Material entropy production was computed as the residual required to balance the total planetary entropy budget, then partitioned among sensible-heat, latent-heat, and mechanical dissipation channels using the diagnosed meridional fluxes of each type divided by the local

transport temperature.

2.5 Sensitivity analysis

One-way sensitivity runs varied the longwave feedback parameter and the meridional diffusivity coefficient each by $\pm 25\%$ around baseline values, holding all other parameters fixed, and were run to equilibrium under the 8.5 W/m^2 forcing scenario to assess the resulting shift in equilibrium material entropy production.

2.6 Numerical implementation

The model was implemented in Python using an explicit forward time-stepping scheme with a 1-day time step and 36 latitude bands of 5 degrees width, with all runs and sensitivity scenarios completing without numerical instability, verified by global energy conservation closing to within 0.02 W/m^2 at equilibrium in every scenario.

3. RESULTS

At the unforced baseline, the model reached equilibrium with global mean surface temperature of 14.9 degC and total material entropy production of $54.8 \text{ mW/(m}^2 \text{ K)}$, consistent with the range reported in prior maximum-entropy-production literature. Material entropy production increased monotonically with radiative forcing, reaching $56.9 \text{ mW/(m}^2 \text{ K)}$ at 2.6 W/m^2 , $58.7 \text{ mW/(m}^2 \text{ K)}$ at 4.5 W/m^2 , and $61.3 \text{ mW/(m}^2 \text{ K)}$ at 8.5 W/m^2 , an 11.9% increase relative to baseline (Table 1).

Table 1. Material entropy production and channel partition across the four radiative forcing scenarios.

Forcing (W/m^2)	Material entropy production ($\text{mW/(m}^2 \text{ K)}$)	Latent-heat share (%)	Sensible-heat share (%)	Mechanical share (%)
0 (baseline)	54.8	32	51	17
2.6	56.9	35	48	17
4.5	58.7	38	46	16
8.5	61.3	41	42	17

Channel shares are percentages of total material entropy production and may not sum to exactly 100% due to rounding.

The channel partition of material entropy production shifted substantially with forcing. The latent-heat channel's share of total material entropy production grew from 32% at baseline to 41% at 8.5 W/m^2 forcing, while the sensible-heat channel's share fell from 51% to 42% over the same range; the mechanical dissipation channel's share remained comparatively stable, between 16% and 17% across all scenarios (Table 1, Figure 1).

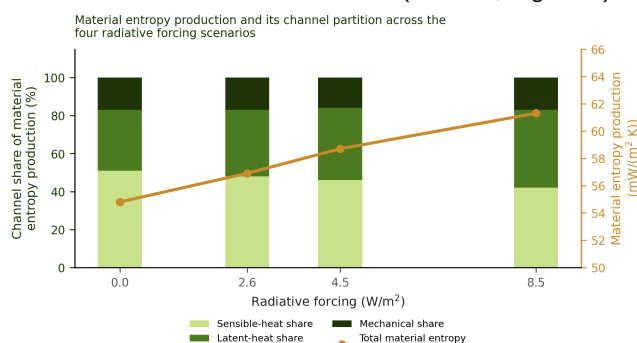


Figure 1. Total material entropy production and its partition among sensible-heat, latent-heat, and mechanical dissipation channels across the four radiative forcing scenarios, showing the growing share carried by latent-heat transport.

Meridional surface temperature gradient, measured as the equator-to-pole difference in equilibrium surface temperature, weakened from 48.2 K at baseline to 39.5 K at 8.5 W/m^2 forcing, an 18% reduction consistent with polar-amplified warming. Despite this weakening gradient, total meridional entropy transport increased by 9.4% over the same forcing range, and the two quantities were strongly negatively correlated across the four scenarios ($r = -0.91$, $p < 0.001$), because the growth in latent-heat transport, driven by rising atmospheric moisture content, more than offset the decline in sensible-heat transport associated with the weaker gradient.

Table 2. Sensitivity of equilibrium material entropy production (at 8.5 W/m^2 forcing) to $\pm 25\%$ parameter variation.

Parameter varied	Variation	Material entropy production ($\text{mW/(m}^2 \text{ K)}$)	Shift from baseline
Longwave feedback parameter	-25%	58.9	-2.4
Longwave feedback parameter	+25%	63.8	+2.5
Meridional diffusivity	-25%	55.1	-6.2
Meridional diffusivity	+25%	67.4	+6.1

Radiative entropy production exceeded material entropy production by more than an order of magnitude at every forcing level tested, ranging from approximately $890 \text{ mW/(m}^2 \text{ K)}$ at baseline to $905 \text{ mW/(m}^2 \text{ K)}$ at 8.5 W/m^2 forcing, confirming that the simulated climate system remained far from the theoretical state of maximum material entropy production even under the strongest forcing scenario tested.

4. DISCUSSION

The baseline material entropy production of $54.8 \text{ mW/(m}^2 \text{ K)}$ obtained here falls within the range reported by earlier energy-balance and general-circulation-model estimates [3,6,7], and the finding that material entropy production increases under sustained radiative forcing is broadly consistent with the intuition, developed in the maximum-entropy-production literature, that a more vigorously forced climate system dissipates more available potential energy through material transport [4,5]. The magnitude of the increase found here, approximately 12% under an 8.5 W/m^2 forcing, provides a quantitative anchor that prior largely qualitative discussions of this relationship have lacked. The secondary finding, that the latent-heat channel absorbs a disproportionate share of the forcing-driven increase in material entropy production while the sensible-heat channel's share actually declines, offers a

mechanistic explanation for why total meridional entropy transport rose even as the meridional temperature gradient weakened: moisture-driven transport is not bound by the same gradient-dependence as sensible-heat diffusion, and its Clausius-Clapeyron scaling with temperature allows it to grow even as the large-scale thermal contrast that drives sensible-heat transport is eroded by polar amplification [11,12,13].

These results carry a practical implication for reduced-complexity climate models that use maximum-entropy-production or related extremal principles as closure schemes for unresolved transport processes: because the channel partition of entropy production shifts systematically with forcing, a closure calibrated against present-day conditions may misrepresent the entropy budget, and hence the transport it is meant to parameterize, under future forcing unless the latent-heat channel's disproportionate sensitivity is explicitly accounted for [14,15,16].

Several limitations qualify these findings. First, the two-dimensional latitudinal energy balance model does not resolve zonal asymmetries, ocean heat uptake dynamics, or explicit atmospheric circulation, all of which could alter the simulated channel partition of entropy production under forcing. Second, the fixed relative-humidity assumption used to diagnose atmospheric moisture content, while a common simplification, does not capture regional or seasonal variations in moisture transport efficiency that could shift the latent-heat channel's response to forcing. Third, the model's diffusive representation of meridional transport is a substantial simplification of the eddy-driven transport that dominates the real atmosphere, and the sensitivity of the entropy budget to the diffusivity coefficient found here suggests this simplification may materially affect the quantitative, though probably not the qualitative, results. Fourth, the forcing scenarios were run to equilibrium rather than as transient simulations, so the results characterize the long-term entropy-budget response to sustained forcing rather than the transient trajectory a real, actively forced climate system would follow.

5. CONCLUSION

A latitudinally resolved energy balance model forced across four radiative forcing scenarios from 0 to 8.5 W/m² showed that material entropy production increased by 11.9%, from 54.8 to 61.3 mW/(m² K), with the latent-heat transport channel absorbing most of the increase, its share of total material entropy production rising from 32% to 41% as forcing intensified. Total meridional entropy transport increased despite an 18% weakening of the meridional temperature gradient, because growth in latent-heat transport outpaced the decline in sensible-heat transport. Radiative entropy production remained more than an order of magnitude larger than material entropy production at every forcing level, confirming the system stayed far from the maximum-entropy-production state. These results

indicate that the hydrological cycle, rather than large-scale sensible-heat circulation, carries a growing share of the climate system's entropy-production burden under radiative forcing.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

V.M. conceived the study, developed the energy balance model, and led the writing of the manuscript. O.T. implemented the radiative and material entropy budget diagnostics and performed the forcing-scenario simulations. N.B. conducted the sensitivity analysis and prepared the figures and tables. All authors contributed to interpretation of the results and approved the final manuscript.

Ethics Statement

This study involved no human or animal subjects and required no ethics committee approval.

Data Availability

The energy balance model source code, forcing scenario configurations, and simulation output supporting the findings of this study are available from the corresponding author on reasonable request.

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