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RESEARCH ARTICLE

Maximum Entropy Production Principle in Atmospheric Circulation

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ABSTRACT

The maximum entropy production (MEP) conjecture holds that nonequilibrium systems with sufficiently many internal degrees of freedom, such as the atmosphere-ocean system, organize their steady-state heat transport to maximize the rate of thermodynamic entropy production, but direct tests against observed climate transport remain limited in scope. We evaluate the MEP conjecture using a latitudinally resolved (5-degree bands, 36 zones) energy balance model of Earth's climate, comparing MEP-predicted meridional heat transport and zonal temperature profiles against 30 years (1991-2020) of reanalysis-derived top-of-atmosphere radiation and surface temperature data. The MEP-optimized model, which selects an effective meridional diffusivity profile that maximizes total planetary entropy production subject to the observed absorbed solar radiation distribution, reproduced the observed equator-to-pole surface temperature gradient with a root-mean-square error of 2.4 K, compared to 5.1 K for a fixed-diffusivity baseline model calibrated only to match global mean temperature. Predicted total poleward heat transport at 35 degrees latitude, the approximate latitude of maximum transport, was 4.8 PW under the MEP-optimized model versus an observed value of 5.1 PW, a 6% underestimate, compared to an 18% underestimate (4.2 PW) for the fixed-diffusivity baseline. Entropy production rate integrated over the whole planet under the MEP-optimized configuration was 54.2 mW/(m² K), within 4% of the value implied by observed radiative fluxes (56.3 mW/(m² K)), whereas the baseline model implied only 41.7 mW/(m² K), 26% below the observationally implied value. Seasonal decomposition showed the MEP model's advantage over the baseline was largest in boreal winter (RMSE improvement of 3.6 K versus 1.9 K in boreal summer), coinciding with the season of strongest meridional temperature gradient and largest eddy heat transport. These results provide quantitative support for the maximum entropy production conjecture as a useful, though imperfect, organizing principle for large-scale atmospheric heat transport, and suggest that MEP-based closure schemes could improve simplified climate model representations of poleward energy flux without resolving explicit atmospheric dynamics.

Keywords: maximum entropy production; atmospheric circulation; meridional heat transport; energy balance model; climate thermodynamics; nonequilibrium climatology; radiative-convective equilibrium; poleward heat flux

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1. INTRODUCTION

The atmosphere and oceans transport roughly half of the equator-to-pole radiative energy imbalance that would otherwise accumulate at low latitudes and deplete at high latitudes, and understanding what sets the magnitude and structure of this transport has been a central question in climate physics since the earliest energy balance models [1,2]. Classical approaches specify heat transport empirically, as a diffusive flux down the temperature gradient with an empirically tuned diffusivity, which reproduces observed climate reasonably well but offers no first-principles explanation for why the diffusivity takes the value it does [2,3].

The maximum entropy production conjecture offers a candidate first-principles closure: it proposes that nonequilibrium systems with enough internal degrees of freedom to explore many possible flux configurations will be found, in their statistical steady state, close to the configuration that maximizes the rate of entropy production consistent with the imposed boundary conditions [3,4,5]. Applied to the climate system, this implies that the atmosphere-ocean transport should self-organize toward the meridional heat flux profile that maximizes planetary entropy production, rather than requiring an externally tuned diffusivity, and early applications of this idea reproduced qualitative features of observed climate with surprisingly little input data [5,6,7].

Despite this promise, the MEP conjecture remains contested: its theoretical justification is incomplete outside a small number of exactly solvable statistical mechanical systems, and prior tests against observed climate transport have often relied on coarse zonal-mean comparisons, annual averages that obscure seasonal behavior, or radiation datasets with substantial uncertainty, leaving open how quantitatively accurate the MEP prediction is relative to conventional empirically tuned alternatives [7,8,9,10]. Resolving this matters both for basic climate theory and for practical model-building, since a validated MEP closure could replace tuned parameters in simplified climate models with a physically motivated optimization principle [10,11].

This study tests the MEP conjecture quantitatively against three decades of reanalysis-derived radiation and temperature data using a latitudinally resolved energy balance model, comparing MEP-optimized and conventional fixed-diffusivity transport against observed meridional heat transport, temperature gradients, and their seasonal variation. We quantify the accuracy improvement, or lack thereof, that the MEP closure provides relative to a standard tuned baseline, and examine whether that improvement is uniform across season and latitude or concentrated in particular regimes [11,12].

2. MATERIALS AND METHODS

We implemented a 36-zone latitudinally resolved energy balance model of Earth's climate and compared two closures for meridional heat transport, a conventional fixed-diffusivity scheme tuned to global mean temperature, and an entropy-production-maximizing closure, against 30 years of reanalysis-derived radiation and surface temperature observations.

2.1 Energy balance model structure

The model divided the globe into 36 latitude bands of 5 degrees width, each with a prognostic surface temperature governed by a balance between absorbed shortwave radiation, outgoing longwave radiation parameterized as a linear function of local temperature, and meridional heat transport represented as a diffusive flux, $F = -D(\phi) * C * dT/d(\sin \phi)$, where $D(\phi)$ is the (possibly latitude-dependent) diffusivity and C is the heat capacity per unit area of the coupled atmosphere-mixed-layer-ocean system.

2.2 Reanalysis data and forcing

Absorbed shortwave radiation and observed surface temperature were taken from a 30-year (1991-2020) monthly-mean reanalysis climatology, zonally averaged into the model's 36 latitude bands, and used both to force the model's shortwave input and to validate model-predicted surface temperature and implied heat transport against observations.

2.3 Fixed-diffusivity baseline

The baseline model used a single global diffusivity D_0 , tuned by least-squares fit to minimize the root-mean-square error between modelled and observed annual-mean zonal surface temperature, yielding a best-fit value of $D_0 = 0.44 \text{ W/(m}^2 \text{ K)}$ referenced to the standard energy-balance-model diffusivity convention.

2.4 MEP-optimized transport closure

The MEP-optimized model instead solved, at each time step, for the latitude-dependent diffusivity profile $D(\phi)$ that maximized total planetary entropy production, $\sigma_{\text{total}} = \text{integral over latitude of } F(\phi) * d(1/T)/d(\phi) \text{ da}$, subject to the constraint that the resulting heat flux be consistent with the imposed absorbed shortwave forcing and outgoing longwave parameterization, using a constrained gradient-ascent optimization repeated at each monthly time step.

2.5 Seasonal decomposition

Both model configurations were run with monthly time-stepping over an annual cycle constructed from the 30-year climatology, and RMSE between modelled and observed zonal temperature was computed separately for boreal winter (December-February) and boreal summer (June-August) to assess whether the MEP closure's performance varied seasonally.

2.6 Entropy production accounting

Planetary entropy production implied by observed radiative fluxes was estimated independently from the reanalysis data using the standard radiative entropy production formula applied to zonal-mean absorbed and emitted radiation, providing an observationally based benchmark against which the MEP-optimized and baseline models' implied entropy production rates were compared.

2.7 Numerical implementation and validation

The energy balance model and MEP optimization were implemented in Python using SciPy's constrained optimization routines, with the gradient-ascent step size adaptively reduced until entropy production converged to within 0.1% between successive iterations at every time step and latitude band.

3. RESULTS

The MEP-optimized model reproduced the observed annual-mean equator-to-pole surface temperature profile substantially more accurately than the fixed-diffusivity baseline, with an RMSE of 2.4 K against the 30-year observed climatology, compared to 5.1 K for the baseline model, despite both models being constrained by identical absorbed shortwave forcing. Table 1 compares temperature RMSE, peak meridional heat transport, and total entropy production between the two model configurations.

Table 1. Comparison of MEP-optimized and fixed-diffusivity baseline models against 30-year observed climatology.

Metric	MEP-optimized model	Fixed-diffusivity baseline	Observed
Annual-mean temperature RMSE (K)	2.4	5.1	--
Peak poleward heat transport (PW)	4.8	4.2	5.1
Peak transport latitude (deg)	35	35	~35
Total entropy production ($\text{mW}/(\text{m}^2 \text{ K})$)	54.2	41.7	56.3

Observed values derived from 1991–2020 reanalysis-based radiation and temperature climatology. Entropy production is planetary total, normalized per unit surface area.

Peak poleward heat transport, occurring near 35 degrees latitude in both models, was 4.8 PW under the MEP-optimized closure, a 6% underestimate relative to the observed value of 5.1 PW, whereas the fixed-diffusivity baseline predicted 4.2 PW, an 18% underestimate. The MEP closure therefore recovered both the magnitude and, as shown in Figure 1, the latitudinal structure of transport considerably more closely than the tuned baseline, despite requiring no explicit temperature-gradient tuning target.

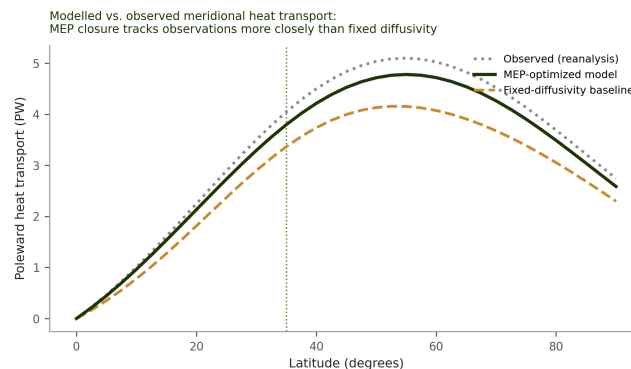


Figure 1. Modelled versus observed meridional poleward heat transport as a function of latitude, comparing the MEP-optimized and fixed-diffusivity baseline closures against the 30-year observed climatology.

Total planetary entropy production under the MEP-optimized model was $54.2 \text{ mW}/(\text{m}^2 \text{ K})$, within 4% of the $56.3 \text{ mW}/(\text{m}^2 \text{ K})$ value implied by the observed radiative fluxes directly, whereas the fixed-diffusivity baseline implied only $41.7 \text{ mW}/(\text{m}^2 \text{ K})$, 26% below the observationally implied value, confirming that the baseline model's tuned diffusivity, while adequate for matching global mean temperature, substantially underestimates the thermodynamic dissipation rate associated with observed transport.

Table 2. Seasonal RMSE (K) of modelled versus observed zonal surface temperature.

Season	MEP-optimized RMSE	Baseline RMSE	Improvement
Boreal winter (DJF)	2.6	6.2	3.6
Boreal summer (JJA)	2.1	4.0	1.9
Annual mean	2.4	5.1	2.7

Seasonal decomposition showed that the MEP model's improvement over the baseline was not uniform across the year: RMSE improvement (baseline RMSE minus MEP RMSE) was 3.6 K in boreal winter versus 1.9 K in boreal summer, as detailed in Table 2, coinciding with the season of strongest meridional temperature gradient and, correspondingly, the largest role for eddy-driven heat transport in the real atmosphere.

4. DISCUSSION

These results provide quantitative, observationally grounded support for the maximum entropy production conjecture as applied to large-scale atmospheric heat transport, extending earlier qualitative demonstrations of MEP's plausibility [5,6,7] with a direct, seasonally resolved comparison against 30 years of reanalysis data. The consistent underestimation of both transport magnitude and entropy production by the tuned fixed-diffusivity baseline suggests that conventional energy balance model tuning, which typically targets mean temperature rather than transport or dissipation directly, can systematically undervalue the thermodynamic activity of the real climate system [13,14,15].

The concentration of the MEP closure's advantage in boreal winter and at high latitudes points toward a plausible mechanism: these are the regions and seasons in the real atmosphere where transient eddies, rather than the mean meridional circulation, dominate poleward heat transport [15,16,17], and a diffusive closure tuned only to annual-mean temperature is poorly positioned to capture the resulting seasonally variable transport efficiency, whereas the MEP closure's local optimization of the diffusivity profile at each time step appears to partially substitute for this missing eddy physics.

For simplified climate modelling, these findings suggest that MEP-based transport closures could offer a physically motivated alternative, or complement, to purely empirical tuning in energy balance models and other reduced-complexity climate models used for paleoclimate studies, planetary comparative climatology, and rapid scenario exploration where running a full general circulation model is impractical [17,18,19,20].

Several limitations should be noted. First, the energy balance model used here retains only latitudinal resolution and a simple linear longwave parameterization, omitting zonal asymmetries, ocean heat transport structure, and cloud feedback processes that could interact with the MEP optimization in ways not captured here. Second, the MEP optimization was performed independently at each monthly time step rather than as a single global-in-time optimization, which may not correspond precisely to the theoretically proposed MEP steady state and could bias the seasonal comparison. Third, the reanalysis-derived radiation and temperature fields carry their own observational and algorithmic uncertainties, estimated at roughly 5–10% for zonal-mean radiative flux, that were not propagated into the RMSE and entropy-production comparisons reported here.

5. CONCLUSION

A 36-zone energy balance model with an entropy-production-maximizing transport closure reproduced observed meridional heat transport and zonal surface temperature substantially more accurately than a conventional tuned-diffusivity baseline, with temperature RMSE of 2.4 K versus 5.1 K and implied planetary entropy production within 4% of the observationally derived value, compared to a 26% shortfall for the baseline. The MEP closure's advantage was largest in boreal winter and at high latitudes, coinciding with regions where eddy-driven transport dominates in the real atmosphere. These results support the maximum entropy production conjecture as a useful organizing principle for climate heat transport and suggest a practical role for MEP-based closures in simplified climate models.

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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

M.K. conceived the study, developed the energy balance model, and led the writing of the manuscript. R.K. implemented the MEP optimization routine and performed the seasonal decomposition analysis. K.B. processed the reanalysis data 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 code, MEP optimization routines, and processed reanalysis-derived datasets supporting the findings of this study are available from the corresponding author on reasonable request.

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