Response to Olivier Pauluis

We thank the reviewer for their careful reading of the manuscript and for their positive assessment of our work. We are pleased that the reviewer finds our results important and worthy of publication. We would like to apologize for missing the very relevant pieces of literature mentioned in the review, and thank the reviewer for pointing them out. We believe these additions have strengthened the manuscript. We are also grateful for the insightful comment on the work done to lift water, which we believe is another important addition to the manuscript. Below we provide detailed responses to each comment, with manuscript changes highlighted in blue.

1 Discussion of the existing literature

1.1 Water vapor and mechanical efficiency

Reviewer's comment

Pauluis (2011) introduces the steam cycle as an analog of the Carnot cycle, in which the energy source is replaced by the injection of water vapor and provides an explicit expression of its mechanical output (see eq. 15 and 25 as well as Figure 3). A central finding in Pauluis (2010) is that the efficiency of atmospheric circulation depends on the relative humidity at which it operates. In particular, shallow convection in a dry environment would be particularly inefficient (see the discussion of Figure 3…).

In Sections 6, 7, and 8 of the manuscripts, the authors present some arguments for why the stratocumulus is inefficient. These arguments, in many ways, repeat parts of the discussion in Pauluis (2010).

Authors' response

We thank the reviewer for pointing out this very relevant reference, and for helping us better understand our results. We have added a discussion of the role of relative humidity in limiting the mechanical efficiency, as described in Pauluis (2011). We refrained from attributing the lower mechanical efficiency of stratocumulus (compared to RCE) to differences in relative humidity as, at least in our simulations, the relative humidity in the stratocumulus mixed layer is actually quite high, with slab-averaged values of $70 - 80\%$ for closed cells, and reaching 95% in some open-cell cases, comparable to those observed in RCE. We have added the following sentences in section 6 (L. 278):

> Furthermore, as argued by Pauluis (2011), the relative humidity at which the system operates also has an impact on the maximum amount of work, with drier systems being less efficient than moister ones. A thermodynamic cycle operating in a partially saturated environment has a maximum efficiency that increases with the degree of saturation, approaching the Carnot limit only in the fully saturated case. The departure from full saturation of the stratocumulus mixed layer therefore provides an additional constraint on the maximum extractable work.

1.2 Moist processes have a much greater impact on shallow convection than deep convection

Reviewer's comment

In Sections 6 and 7, the authors argue that the efficiency of shallow convection is quite small, with a much larger share of the entropy production attributable to moist processes. This is very similar to some of the results presented in Pauluis (2016). This paper introduces a methodology to reconstruct the thermodynamic cycles that underpin an atmospheric flow. It also argues that shallow thermodynamic cycles will be more strongly affected by moist processes (see the discussion after eq. 21):

- "This implies that the relative importance of the Gibbs penalty is inversely proportional to the depth of the cycle, measured here by the temperature difference between the heat source and the heat sink." (p.4417)
- "For shallow convection, the scaling implies that the Gibbs penalty should be on the same order of magnitude as the maximum work." (p.4418)

Authors' response

We agree that our results, particularly from the ensemble analysis in Section 7, are consistent with and support the reviewer's findings on the relative importance of moist processes in shallower cycles. We have added the following sentences at the end of Section 7 to acknowledge this connection (L.353):

> Furthermore, both morphologies show, on average, a higher share of entropy production attributable to moist processes compared to previous RCE results (Pauluis and Held, 2002a, Singh and O'Neill, 2022). This is consistent with previous work of Pauluis (2016), who extracted thermodynamic cycles of different depths from RCE convection and found that shallower cycles show a higher share of moist processes compared to deeper ones. Together with the results presented in this paper, this supports the relative importance of moist processes scaling inversely with the depth of the thermodynamic cycle.

1.3 Mechanical efficiency of atmospheric flows

Reviewer's comment

The fact that moist processes significantly affect the mechanical output of atmospheric flows has been established in numerous studies. Many of these have been ignored by the authors, who mention only a limited number. In addition to the two papers mentioned above, I would point to:

- Several papers have investigated tropical cyclones (Pauluis and Zhang (JAS, 2017), Fang, Pauluis and Zhang (JAS 2017), Regibeau-Rocket, Pauluis and O'Neill (J Climate, 2023).
- Laliberte et al. (Science, 2015) show the impacts of moist processes on the global circulation.

Authors' response

We apologize for the oversight, and we thank the reviewer for the relevant list of references. We have added the references pertaining to the tropical cyclones at L. 55, and the reference to Laliberte et al. (Science, 2015) as L. 49.

2 Water lifting vs. precipitation-induced dissipation

Reviewer's comment

Dissipation of kinetic energy by falling precipitation is a direct result of the fact that the atmosphere continuously lifts water. In RCE, the work done to lift the water exactly balances the precipitation-induced dissipation. This is not the case in the simulations presented here, as a large-scale subsidence continuously "removes" water from the domain. In this context, the work done to lift water exceeds the dissipation by precipitation. This is something that authors should document. In particular, they show that the open-cell convection exhibits a fair amount of dissipation by precipitation in contrast to the closed-cell case. However, it is likely that the work done to lift the water against the large-scale subsidence is quite significant (meaning larger than the precipitation-induced dissipation). While the argument could be made that the lifting does no directly correspond to an entropy source (albeit the water will fall at some point and thus dissipation will occur somewhere else in the atmosphere), it would be useful to document it and discuss it in the context of the efficiency (it is likely that it is larger than the generation of kinetic energy. . .).

Authors' response

Following the reviewer's suggestion, we have computed the work done to lift water in the domain as $\dot{W}_\mathrm{q} = \int \rho g w q_\mathrm{t} \mathrm{d}V$, where q_t is the total water mixing ratio and w is the resolved vertical velocity. We find time-averaged values of 258 $\mathrm{mWm^{-2}}$ for the open-cell case and 486 $\mathrm{mWm^{-2}}$ for the closed-cell case. As the reviewer predicted, these values largely exceed both the kinetic energy generation (20 and 70 $\mathrm{mWm^{-2}}$ for open and closed cells respectively) and the dissipation by falling hydrometeors (183 $\mathrm{mWm^{-2}}$ for open cells and negligible for closed cells). We have added the following paragraph at the end of Section 6 to document and discuss this point (L. 287):

> Beyond the inefficient generation of kinetic energy, stratocumulus perform substantial work in lifting water within the domain against the large-scale subsidence, which we estimate as
>
> $$\langle \dot{W}_q \rangle = \frac{1}{A} \int_\Omega \langle \rho g w q_t \rangle dV, \tag{1}$$
>
> where q_t is the total water mixing ratio and w the resolved vertical velocity. Time-averaged values for $\langle \dot{W}_q \rangle$ are 258 and 486 $\mathrm{mWm^{-2}}$ for the open- and closed-cell cases respectively, largely exceeding $\langle \dot{W}_K \rangle$ (24 and 68 $\mathrm{mWm^{-2}}$). In RCE, at steady-state this work is balanced by the dissipation of kinetic energy by falling hydrometeors within the domain (Pauluis and Held, 2002a). This balance does not hold in our simulations: open cells dissipate only approximately 183 $\mathrm{mWm^{-2}}$ through precipitation, while the non-drizzling closed-cell case has negligible precipitation dissipation. In the real atmosphere, the water removed by subsidence would eventually precipitate in other regions, where the associated dissipation would occur. However, since this process does not happen inside our simulation domain, the associated dissipation is not accounted for in our entropy budget.

Minor comments

- **L. 114:** *"'the frictional effect on falling hydrometeors': please attribute to Pauluis, Balaji and Held (JAS,2000) for the first discussion of rain as a dissipative process and a significant source of entropy."*

  We thank the reviewer for the reference and have added it at L. 121 as suggested. We have also corrected the term from *friction* to *frictional* for consistency.

- **Figure 1:** *"It would be useful to document the water content as well, and possibly where the cloud layer is located in the vertical cross-section. (panels a and d)."*

  We have added the total water mixing ratio q_t profile to panels (a) and (d) of Figure 1 as suggested. Regarding the cloud layer location, we have highlighted it only for the closed-cell case, where it is sufficiently well-defined. For the open-cell case, the cloud layer is unfortunately difficult to identify unambiguously due to the highly heterogeneous nature of the cloud field and the presence of drizzle in the domain and at the surface. This is illustrated in the figure below, showing the vertical profile of cloud water and a cross-section. While the cloud layer starts appearing just below the inversion (above $\sim$ 800 m), the presence of drizzle makes the cloud base hard to cleanly identify. The increased cloud water in the lower part of the domain is due to rain evaporation, which can shift rain back into the cloud-droplet category of the microphysics scheme. This is a known feature related to how the microphysics module classifies rain and cloud water based on their geometric mean radius at the beginning of the bulk scheme.

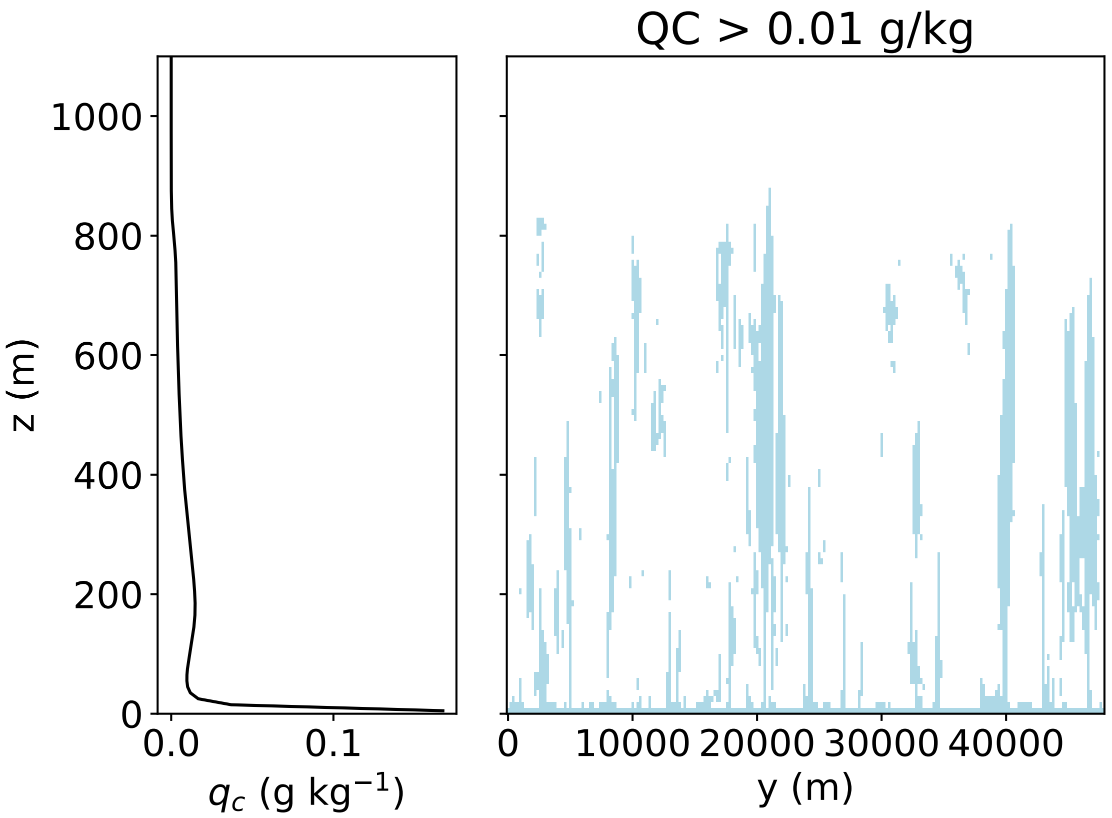

Figure 1: **Open-cell cloud water**. Profile of domain-mean cloud water mixing ratio q_c (averaged over the last hour) on the left, and cross-section of q_c (showing regions where $q_c > 0.01\ \mathrm{g\,kg^{-1}}$) on the right.