Review for GMD (Geoscientific Model Development)

Manuscript: *Subtropical Extreme Heatwave Dynamics in the Intermediate-Complexity Atmospheric Model Aeolus 2.0*
Recommendation: Major Revisions

General assessment

This manuscript presents numerical experiments with the intermediate-complexity moist-convective Thermal Rotating Shallow Water (mcTRSW) model Aeolus 2.0 to investigate the evolution of imposed subtropical buoyancy anomalies under dry and moist-convective conditions. The study explores the emergence of cyclonic/anticyclonic structures, wave adjustment, rainband-like features, and barotropic/baroclinic differences. The topic is relevant to the GMD community because it concerns the development and application of an idealized atmospheric model framework designed to bridge conceptual theory and more comprehensive climate models. The manuscript also provides open code/data access and builds upon earlier Aeolus/mcTRSW developments.

The manuscript contains potentially interesting dynamical results, especially regarding moist-convective adjustment and the role of imposed buoyancy anomalies. However, in its current form, it does not yet meet the standards expected for publication in GMD. The main issue is that the paper reads primarily as a physical interpretation study rather than a rigorous model-development paper. Critical methodological details, validation procedures, numerical configuration information, reproducibility elements, and quantitative diagnostics are insufficiently documented. Furthermore, the manuscript contains substantial language issues, conceptual ambiguities, notation inconsistencies, and several claims that are overstated relative to the evidence presented.

I therefore recommend **major revisions** before the manuscript can be considered further.

Major comments

1. Insufficient focus on model development for GMD

GMD papers require strong emphasis on:

- model formulation,
- numerical implementation,
- evaluation/verification,
- reproducibility,
- limitations,
- technical innovation.

At present, the manuscript is dominated by qualitative interpretation of atmospheric phenomena, while the actual advances in Aeolus 2.0 are not sufficiently demonstrated.

For example, the manuscript states that:

“Including background effects in addition to the anomaly forcing is a new development relative to Rostami et al. (2023)”

However, this innovation is not rigorously documented. The manuscript does not clearly explain:

- what exact equations were modified,
- how ERA5 forcing/background fields are incorporated,
- whether initialization is balanced,
- how topography is numerically represented,
- whether conservation properties are preserved,
- how stability constraints are handled,
- whether the implementation changes numerical behavior.

A GMD paper requires a dedicated section clearly distinguishing:

1. inherited mcTRSW equations,
2. new Aeolus 2.0 developments,
3. new additions introduced specifically in this paper.

At present these distinctions are blurred.

2. Lack of numerical configuration details

The manuscript lacks critical numerical information required for reproducibility. Missing details include:

- horizontal resolution,
- spectral truncation,
- timestep,
- diffusion/hyperdiffusion,
- filters,
- boundary treatment,
- conservation properties,
- CFL conditions,
- runtime performance,
- sensitivity to resolution,
- initialization procedure,
- spin-up rationale,
- convergence tests.

The paper mentions Dedalus usage but provides no implementation details sufficient for reproducibility.

A dedicated subsection on numerical implementation is required.

3. Validation is inadequate

The manuscript repeatedly claims realism and consistency with observations:

- comma-cloud structures,
- mesoscale vortices,
- ridge-trough coupling,
- heatwave persistence,
- Rossby-wave behavior.

However, validation is qualitative and mostly anecdotal.

For example:

“The success in reproducing phenomena observed in nature like rainbands, comma-cloud patterns, ridged trough coupling validates the approach…”

This statement is too strong given the evidence shown.

The manuscript needs:

- quantitative diagnostics,
- comparison with theory,
- comparison with reanalysis metrics,
- scaling arguments,
- spectral characteristics,
- phase speeds,
- energy budgets,
- Rossby radius consistency,
- growth rates,
- conservation diagnostics.

Without these, many conclusions remain speculative.

4. Heatwave terminology is conceptually problematic

The manuscript defines “heatwaves” as buoyancy anomalies:

“the term heatwaves is used in a connotation to describe the phenomenon involving the gradual formation and sustained presence of large-scale, localized regions of positive buoyancy”

This is problematic because:

- real heatwaves involve land-atmosphere coupling,
- radiative processes,
- boundary layer physics,
- surface energy balance,
- persistence metrics,
- temperature thresholds.

The experiments instead impose idealized buoyancy perturbations in a reduced-order dynamical system.

The manuscript should substantially soften claims about “heatwaves” and instead frame the study as:

idealized buoyancy-anomaly dynamics relevant to subtropical blocking and heatwave-like circulation responses.

Currently the title and framing overstate applicability.

5. Excessive qualitative interpretation

Many results sections contain speculative meteorological interpretation unsupported by diagnostics.

Examples:

- “mesoscale convective systems,”
- “frontal boundaries,”
- “rainfall organization,”
- “heatwave environment,”
- “persistent and stable weather conditions,”
- “ridge-trough coupling.”

These claims require diagnostics that are absent.

The figures mainly show anomaly fields and vectors, but not:

- PV evolution,
- vorticity,

- geopotential,
- precipitation,
- wave decomposition,
- energetics,
- instability diagnostics.

The discussion should be substantially tightened and better linked to what the model can actually resolve.

6. Mathematical notation and presentation require major revision

Several equations contain formatting or notation problems.

Examples:

- Eq. (4b) appears incorrect/repeated.
- Some symbols are undefined or inconsistently rendered.
- Several equations appear corrupted during typesetting.
- Variables switch notation between sections.
- Equation references are sometimes unclear.

The manuscript needs careful proofreading of all mathematical expressions.

7. Figures require improvement

The figures are difficult to interpret because:

- color bars are not described sufficiently in captions,
- units are unclear,
- anomaly normalization is unclear,
- vector scaling is not explained,
- timestamps are difficult to follow,
- panel labeling is insufficient,
- quantitative interpretation is impossible.

For GMD, figures should better support:

- model evaluation,
- numerical behavior,

- process interpretation.

Specific comments

Abstract

The abstract is too broad and overstates conclusions. Statements such as:

“provides new insight into the dynamics that sustain extreme heatwaves in a warming world”

are not demonstrated by the idealized experiments.

Please moderate such claims.

Introduction

The introduction mixes:

- heatwaves,
- blocking,
- subtropical vortices,
- Rossby waves,
- moist convection,
- shallow-water theory,

without clearly defining the precise scientific question.

The scientific objectives should be reformulated more explicitly.

Section 2.1

The model description is currently too compressed for GMD standards.

Please provide:

- a table of prognostic variables,
- parameter values,
- dimensional scales,
- nondimensionalization summary,
- conservation properties,
- solver details,

- computational cost,
- numerical scheme description.

Equation system

The equations are central to the paper, yet several terms are insufficiently explained.

For example:

- entrainment,
- condensation closure,
- Newtonian relaxation,
- external forcing,
- evaporation parameterization.

A table summarizing all symbols and parameters is needed.

Section 2.2

The anomaly forcing definition is difficult to follow.

Equation (5) is not clearly typeset.

Please rewrite carefully and define:

- α-Gaussian,
- normalization,
- dimensional amplitude,
- physical interpretation,
- relation to temperature perturbation.

Results

The results rely too heavily on visual inspection.

Please add:

- quantitative diagnostics,
- timescale analysis,
- spectral decomposition,

- wave propagation speeds,
- energy partitioning,
- sensitivity experiments.

Conclusions

The conclusions again overstate realism.

For example:

“validates the approach”

should be softened unless quantitative validation is added.

Language and style

The manuscript requires substantial English editing.

Examples:

- grammatical inconsistencies,
- awkward phrasing,
- repetition,
- excessively long sentences,
- unclear terminology.

Examples include:

- “heatwaves is used in a connotation”
- “hold over multiple consecutive days”
- “performed the highest peak”
- “simulate an equal aspect”

A professional language revision is strongly recommended.

Recommendation

The manuscript contains potentially valuable work on idealized moist-convective atmospheric dynamics using Aeolus 2.0, but major improvements are required before it is suitable for publication in GMD.

The most important revisions are:

1. strengthen the model-development focus,

2. provide full numerical implementation details,
3. add quantitative validation and diagnostics,
4. reduce speculative interpretation,
5. clarify mathematical notation,
6. substantially improve language quality,
7. moderate claims about real-world heatwaves.