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An Intermediate Complexity Approach to the Dynamics of Localized Extreme Heatwaves in the Mid-Latitude Atmosphere for moist-convective environments using Aeolus 2.0

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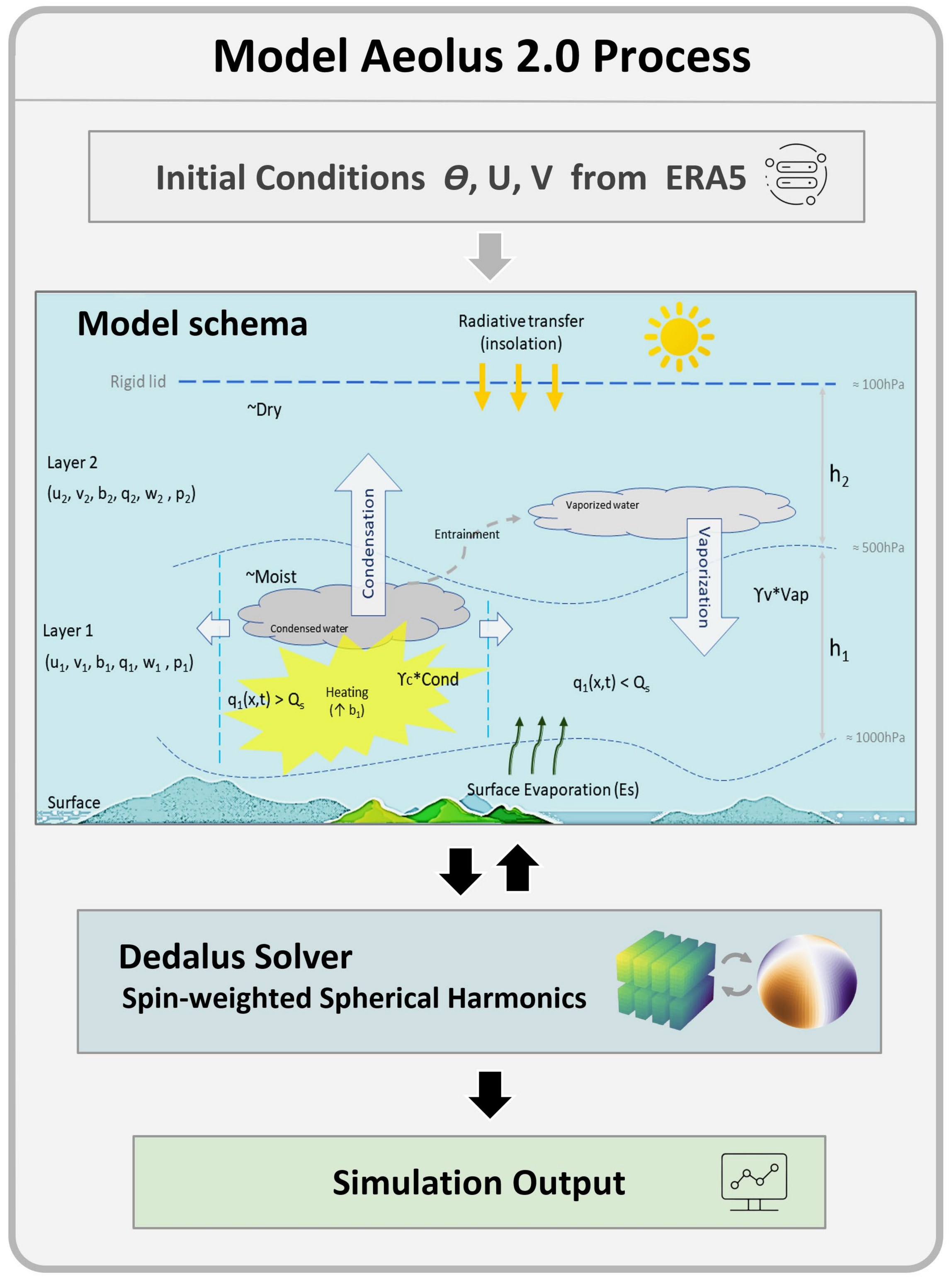
BACKGROUND AND CONCEPTS

For global dynamical simulations, the two-layer **Moist-Convective Thermal Rotating Shallow Water (mcTRSW)** model **Aeolus 2.0** with intermediate complexity was employed. The concept of two interacting layers enabled the study of the dynamics of **localized extreme heatwaves** in **baroclinic** and **barotropic** situations. The model initialization comprises daily averaged velocity and potential temperature variables from **ERA5** data.

Fig. 1 – Model schematic representation



RESEARCH GOALS

- Examine the **evolution** of the **large-scale** localized **buoyancy anomalies** in mid-latitude regions.
- Investigate the adjustments in the atmosphere for **moist-convective** environments, comparing with the dry case.

RESULTS AND CONCLUSIONS

The condensed liquid water content (**CLWC**) anomaly evolution shows that **baroclinic** localized buoyancy perturbation should play an important role for **increased cloud formation and condensation**, as a result of the **heatwave propagation** in the atmosphere for those extreme forcings.

Presence of a **circular positive** buoyancy anomaly in the **lower layer**, while the **upper layer** shows **opposite** circular rotation wind movement for some of the cases analyzed.

Comparing the **strong** and **weak** buoyancy anomalies results, we can notice the **prolonged effects** of **baroclinic** initial condition over the **barotropic** case.

Fig. 2 – Anomaly of Divergence in Layer 2

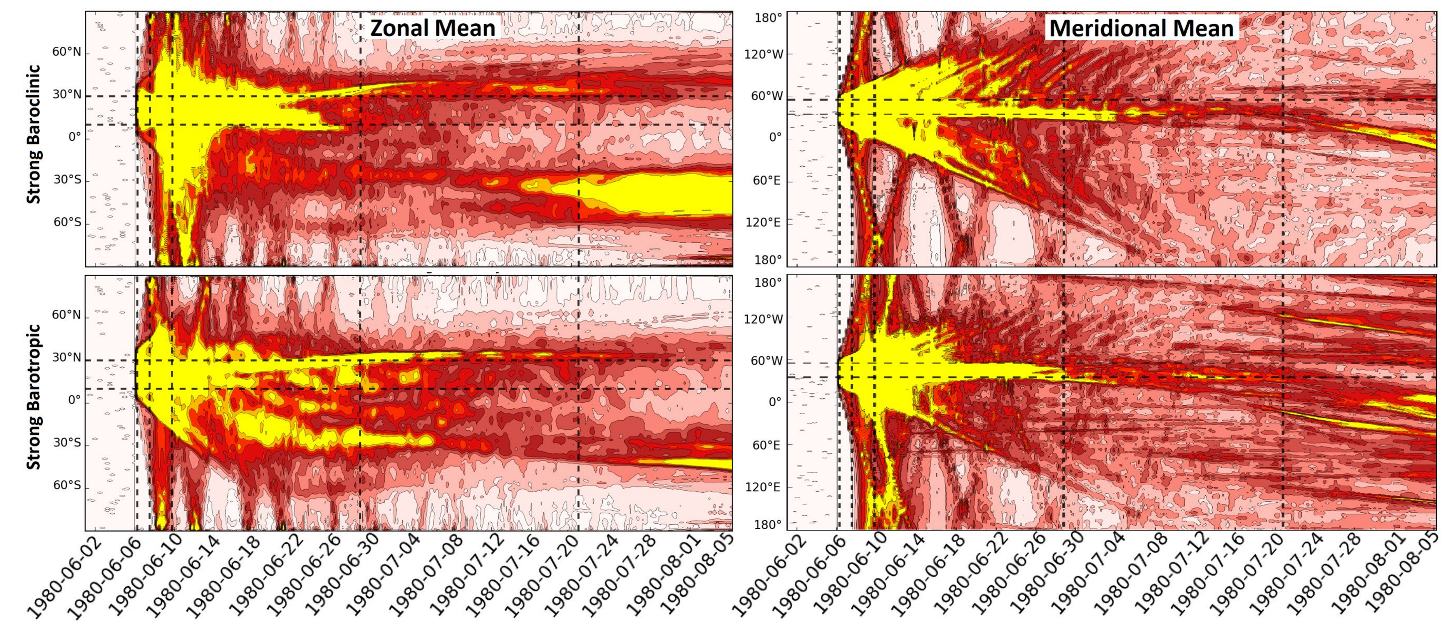


Fig. 4 – Anomaly of Total Energy

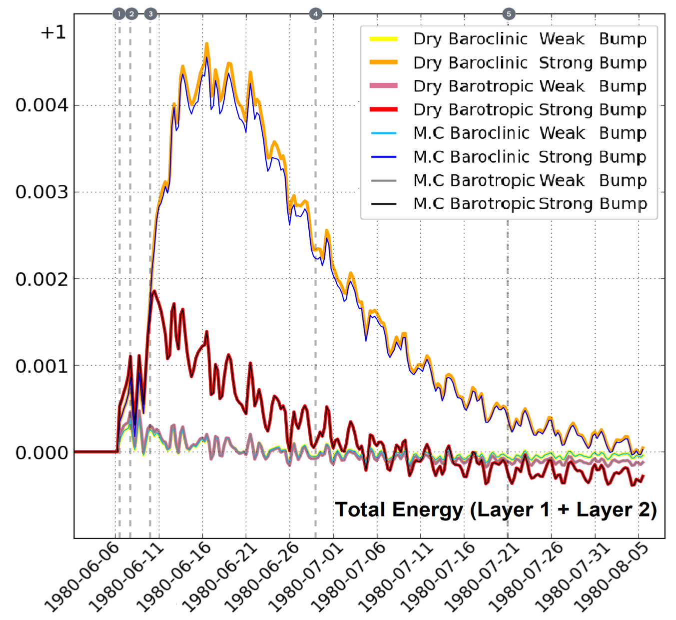


Fig. 6 – Anomaly of Wave Activity

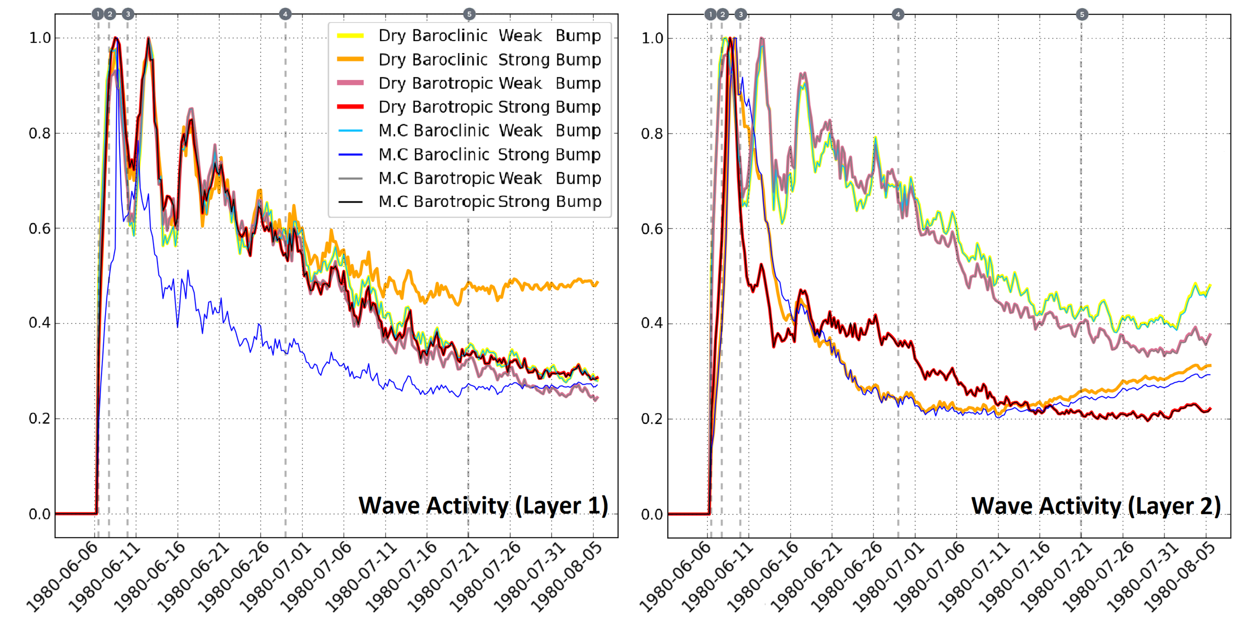


Fig. 3 – Anomaly evolution of buoyancy perturbation

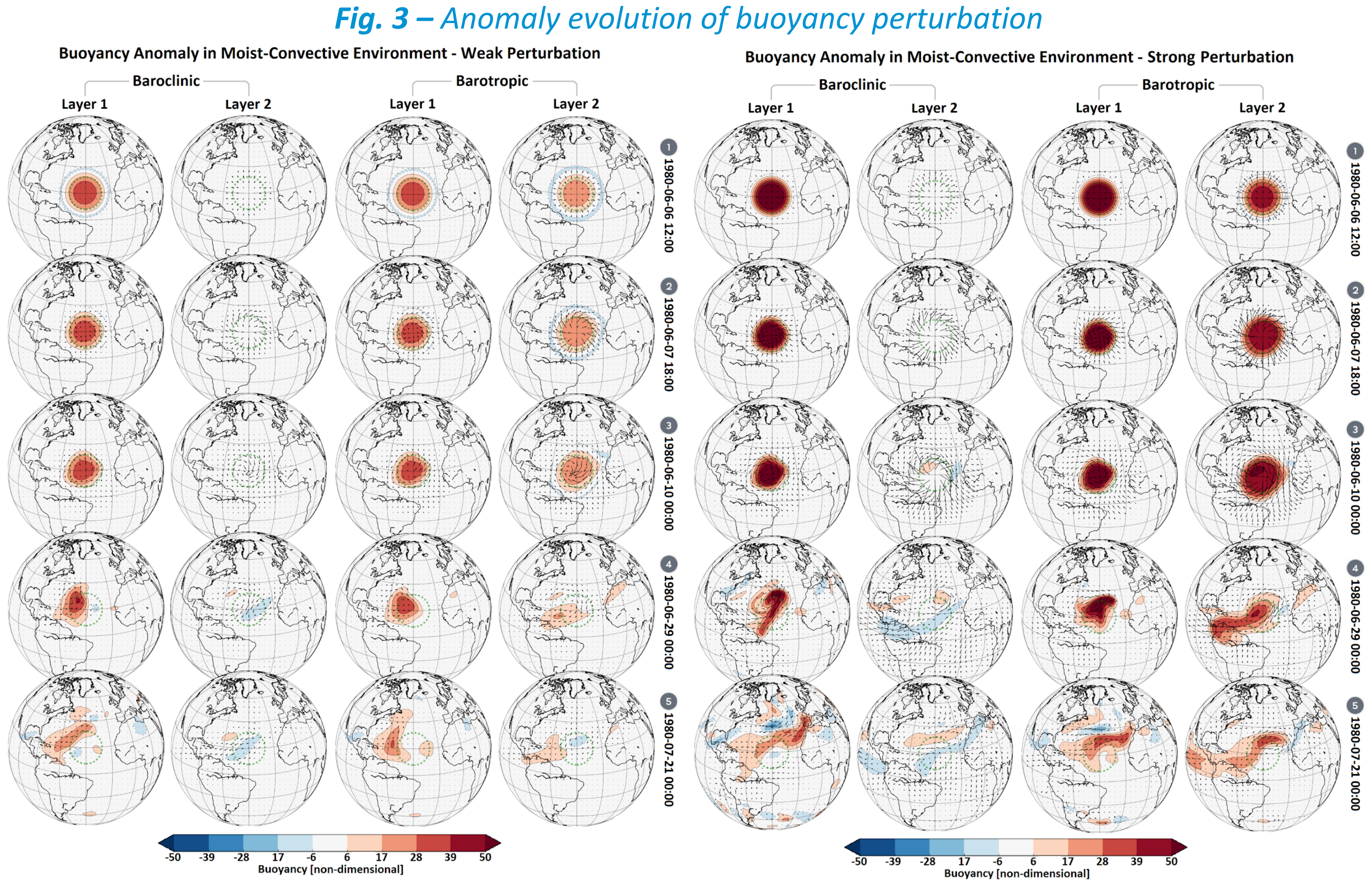
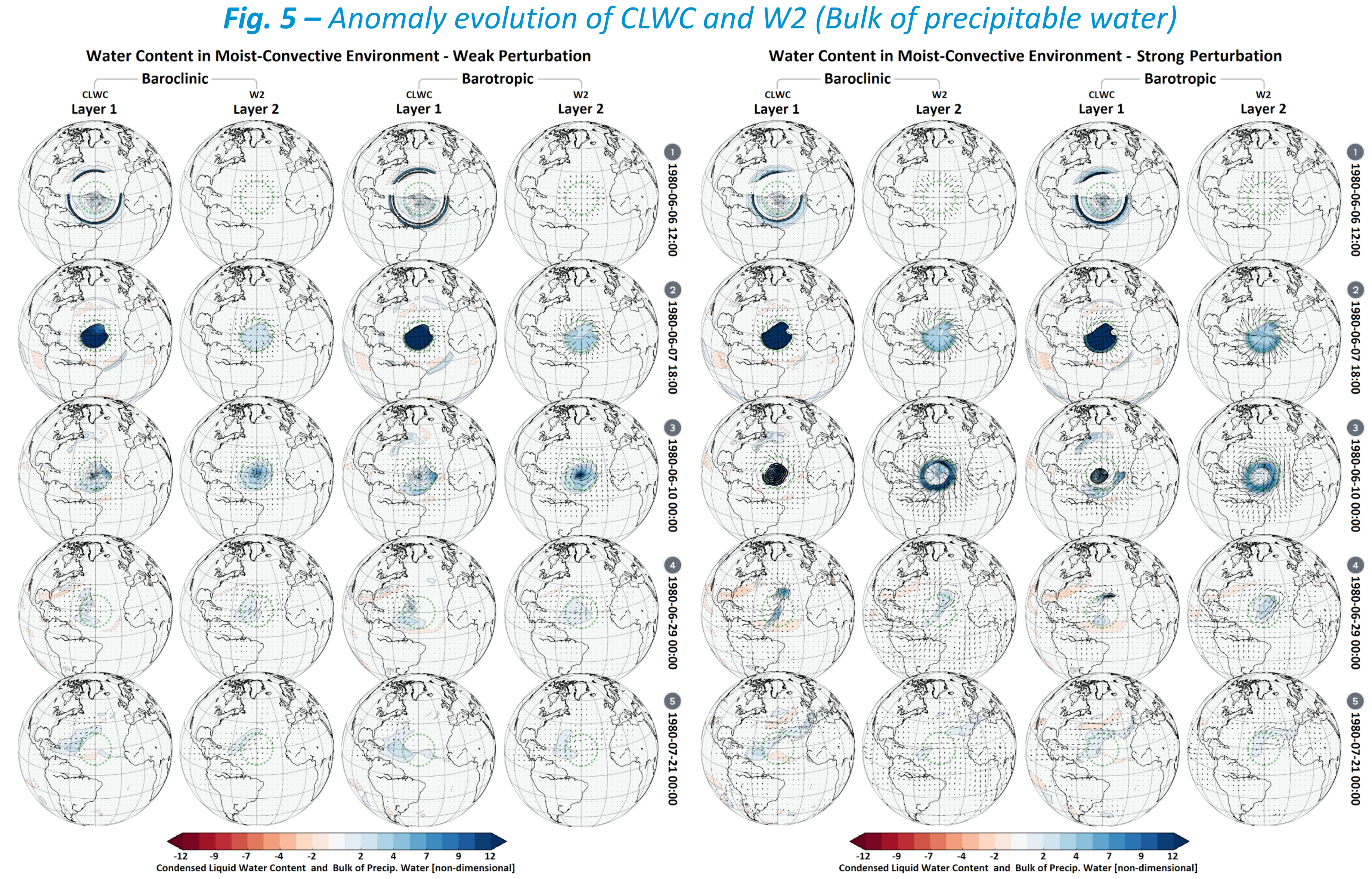


Fig. 5 – Anomaly evolution of CLWC and W2 (Bulk of precipitable water)



ACKNOWLEDGMENTS AND REFERENCES

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Aeolus 2.0 ATMOSPHERE MODEL

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Thermal Rotating Shallow Water (TRSW) Models

An extension of the classical shallow water equations, incorporating **rotation (via Coriolis forces)** and **thermodynamics** (typically via buoyancy or temperature/density variations). It captures the dynamics of a thin layer of fluid where horizontal scales are much larger than the vertical scale, and where **thermal effects drive motion** in addition to mechanical forces.

Key Features:

- **Thermal Forcing:** Allows **buoyancy-driven flows** (e.g., convection, density fronts) by linking the fluid layer thickness or internal energy to temperature/density fields.
- **Wave Dynamics:** Supports both **barotropic** (depth-independent) and **baroclinic** (depth-dependent, thermally influenced) modes.
- **Conservation Laws:** Satisfies energy, momentum, and potential vorticity conservation, critical for realistic long-term behavior.

Typical Applications:

- Modeling **ocean thermocline** dynamics.
- Studying **weather system formation** like cyclones and anticyclones.
- Investigating **equatorial superrotation** in planetary atmospheres.
- Designing **reduced-order models** for climate prediction and large-scale flow.

What It Is Good For:

- **Atmospheric and Oceanic Dynamics:** Models key features of weather systems, ocean fronts, equatorial waves, and large-scale circulations.
- **Instability and Turbulence Studies:** Analyzes **baroclinic instability**, an essential process for mid-latitude weather and ocean eddies.
- **Exoplanet and Planetary Atmospheres:** Simulates rotating, stratified atmospheres with differential heating, relevant for Earth, Jupiter, and exoplanets.
- **Simplified Testing Ground:** Acts as a computationally affordable "laboratory" to develop and test theories before moving to full 3D Navier-Stokes simulations.
- **Understanding Energy Transfer:** Provides insights into how thermal energy converts into kinetic energy and vice versa in rotating systems.

Aeolus 2.0

Equations with Moist-Convection

$$(\boldsymbol{v}_1)_t + \boldsymbol{v}_1 \cdot \nabla \boldsymbol{v}_1 + f\hat{\mathbf{z}} \wedge \boldsymbol{v}_1 = -\left(b_1 \nabla (h_1 + Z) + b_2 \nabla h_2 + \frac{h_1}{2} \nabla b_1 + h_2 \nabla b_2\right) + \frac{\boldsymbol{v}_2 - \boldsymbol{v}_1}{h_1 b_1} \gamma (C - D), \quad (1)$$

$$(\boldsymbol{v}_2)_t + \boldsymbol{v}_2 \cdot \nabla \boldsymbol{v}_2 + f\hat{\mathbf{z}} \wedge \boldsymbol{v}_2 = -\left(b_2 \nabla h_1 + b_2 \nabla (h_2 + Z) + \frac{h_2}{2} \nabla b_2\right), \quad (2)$$

$$(h_1)_t + \nabla \cdot (h_1 \boldsymbol{v}_1) = \frac{1}{b_1} \gamma (C - D), \quad (3)$$

$$(h_2)_t + \nabla \cdot (h_2 \boldsymbol{v}_2) = \frac{1}{b_2} \gamma (-C + D), \quad (4)$$

$$(b_1)_t + \boldsymbol{v}_1 \cdot \nabla b_1 = \frac{1}{h_1} (-C + D), \quad (5)$$

$$(b_2)_t + \boldsymbol{v}_2 \cdot \nabla b_2 = \frac{1}{h_2} (C - \mu E), \quad (6)$$

$$Q_t + \nabla \cdot (Q \boldsymbol{v}_2) = -C + E, \quad (7)$$

Hamiltonian Structure

$$\partial_t \varphi^a = \{\varphi^a, \mathcal{H}\} = \mathbb{J}^{ab} \frac{\delta \mathcal{H}}{\delta \varphi^b}. \quad (\varphi) = (u_1, v_1, h_1, b_1, u_2, v_2, h_2, b_2)^T \text{ is the phase space.}$$

H represents the Hamiltonian, and J denotes the Poisson tensor.

Hamiltonian = total energy

$$\mathcal{H} = \int_{\mathcal{D}} d^2x \left[h_1 \left(\frac{1}{2} \boldsymbol{v}_1^2 + \tilde{h_1} b_1 \right) + h_2 \left(\frac{1}{2} \boldsymbol{v}_2^2 + \tilde{h_2} b_2 \right) \right].$$

The functional derivatives of the Hamiltonian H are:

$$\frac{\delta \mathcal{H}}{\delta \boldsymbol{v}_k} = h_k \boldsymbol{v}_k, \quad \frac{\delta \mathcal{H}}{\delta h_k} = \zeta_k, \quad \frac{\delta \mathcal{H}}{\delta b_k} = h_k \tilde{h_k}.$$

Equations adding Forcings

$$(\partial_t + \boldsymbol{v}_1 \cdot \nabla) \boldsymbol{v}_1 + f\hat{\boldsymbol{z}} \times \boldsymbol{v}_1 = -\langle \nabla p_1 \rangle, \quad (2.11a)$$

$$(\partial_t + \boldsymbol{v}_2 \cdot \nabla) \boldsymbol{v}_2 + f\hat{\boldsymbol{z}} \times \boldsymbol{v}_2 = -\langle \nabla p_2 \rangle - \frac{1 - \gamma}{b_2 h_2} (\boldsymbol{v}_2 - \boldsymbol{v}_1)\ (\mathscr{C} - \mathscr{D}), \quad (2.11b)$$

$$\partial_t h_1 + \nabla \cdot (h_1 \boldsymbol{v}_1) = \frac{1}{b_1} [(1 - \gamma)(-\mathscr{C} + \mathscr{D}) - (1 - \gamma^{\mathbb{F}})\ \mathbb{F}_1], \quad (2.11c)$$

$$\partial_t h_2 + \nabla \cdot (h_2 \boldsymbol{v}_2) = \frac{1}{b_2} [(1 - \gamma)(+\mathscr{C} - \mathscr{D}) - (1 - \gamma^{\mathbb{F}})\ \mathbb{F}_2], \quad (2.11d)$$

$$\partial_t b_1 + \boldsymbol{v}_1 \cdot \nabla\ b_1 = \frac{1}{h_1} [(+\mathscr{C} - \mu \mathscr{E}) + \mathbb{F}_1], \quad (2.11e)$$

$$\partial_t b_2 + \boldsymbol{v}_2 \cdot \nabla\ b_2 = \frac{1}{h_2} [(-\mathscr{C} + \mathscr{D}) + \mathbb{F}_2], \quad (2.11f)$$

$$\partial_t q_1 + \nabla \cdot (q_1 \boldsymbol{v}_1) = -\mathscr{C} + \mathscr{E}, \quad (2.11g)$$

$$\partial_t q_2 + \nabla \cdot (q_2 \boldsymbol{v}_1) = +\mathscr{C} - \mathscr{D}. \quad (2.11h)$$

Sea surface evaporation scheme

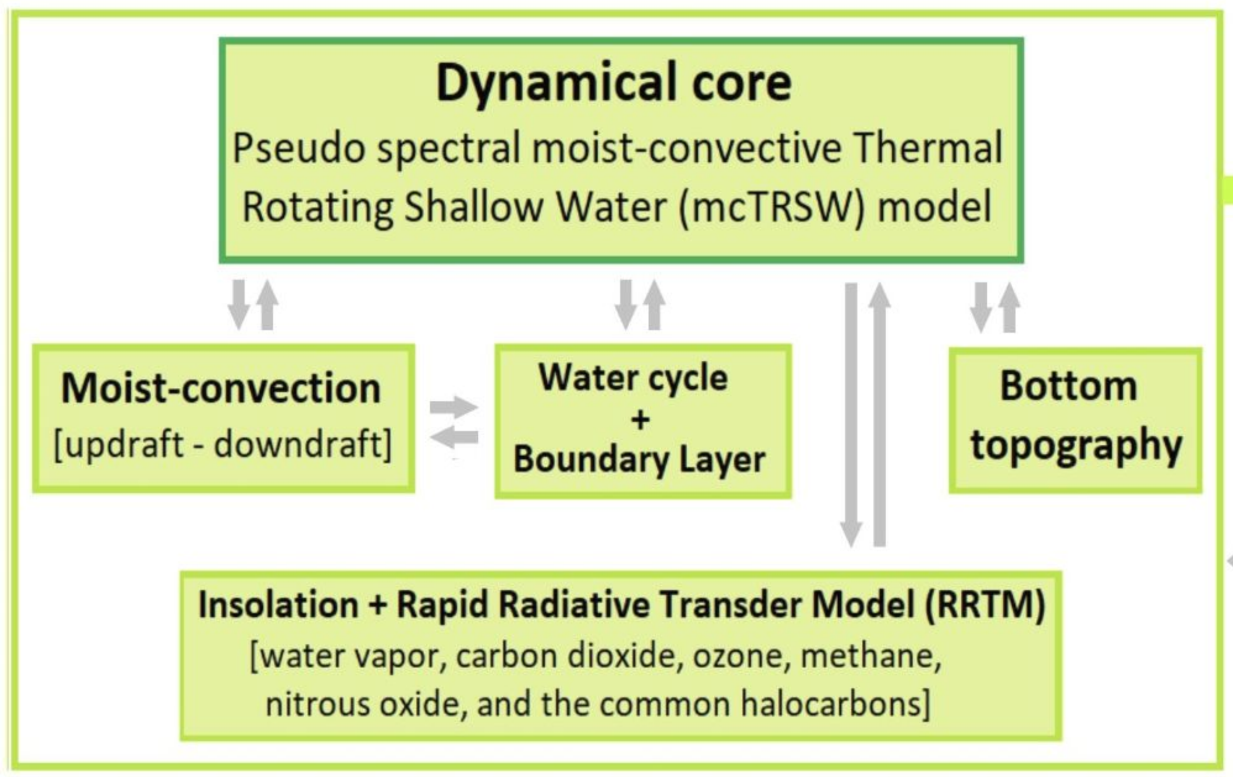
$$\mathcal{E}_{\text{vap}}(T_1) = \mathbb{H}(Q^s - q_1) \exp\left[\frac{-\Delta H_{\text{vap}}}{R_v} \left(\frac{1}{T_1^\alpha} - \frac{1}{T_0^\alpha} \right) \right],$$

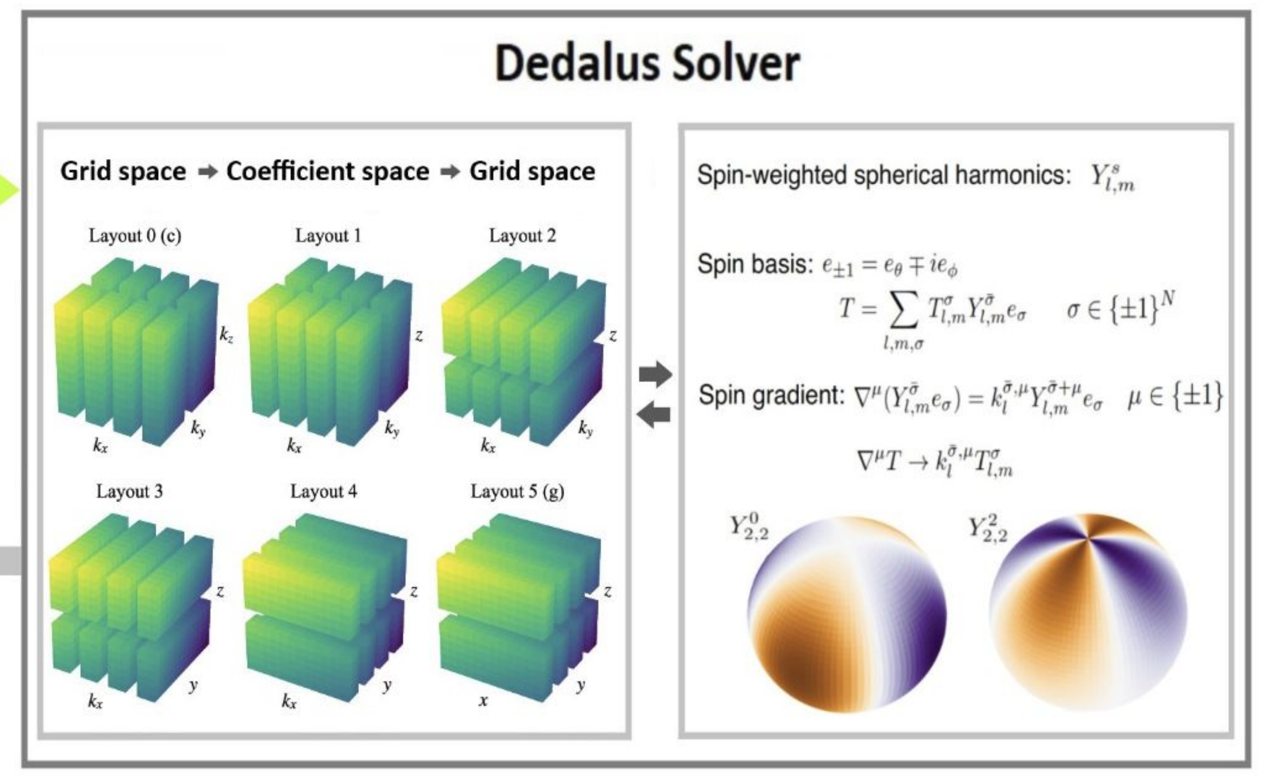
$$\mathcal{E}_{\text{vap}}(|u_1^n|) = \mathbb{H}(Q^s - q_1) \exp\left(\frac{|u_1^n|^{\alpha_{1v}}}{\alpha_{2v}} \right),$$

$$\text{Fr. Conv.} = \mathbb{H}(Q^s - q_1)\, \mathcal{A}_F\, (Q^s - q_1), \quad \text{if } (|u_1^n| \ll 1 \text{ and } b_1 \ll b_1^{\max}),$$

$$\mathcal{E}(T_1, |\boldsymbol{u}_1^n|, q_1) = \mathbb{H}(Q^s - q_1) \left(\mathcal{A}_T\, \hat{\mathcal{E}}_{\text{vap}}(T_1) + \mathcal{A}_u\, \hat{\mathcal{E}}_{\text{vap}}(|u_1^n|) + \text{Fr. Conv.} \right),$$

Aeolus 2.0 ATMOSPHERE MODEL





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