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Modelling the interactions between tropical convection and large scale dynamics

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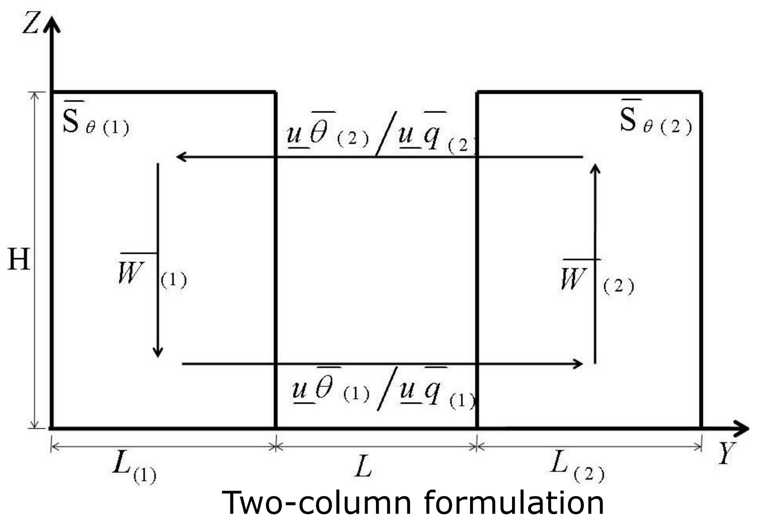
1. Introduction

Radiative-convective equilibrium (RCE) simulations hide information on how large-scale dynamics feedback on convection and vice versa. To allow such feedbacks to occur, the **weak temperature gradient** (WTG) approximation of Sobel and Bretherton (2000) is used to couple a cloud resolving model (CRM) to a reference column (reference column model). In such a model, heat and moisture budgets are not strictly closed. A large-scale circulation develops over a homogeneous environment (results similar to those of Raymond and Zeng (2005) and Perez et al. (2006)). In addition, the model has a **unique final state** no matter how it is initialised.
The WTG approximation is again used to coupled two columns of the CRM (coupled columns model). The budgets are now closed. Such setup is more **realistic** and hasn't been studied before. The two models are compared. A large-scale circulation is not maintained in this model over a homogeneous environment. Hence, the large-scale circulation which develops in the reference column model is **artificial**.

2. WTG calculations



Two-column formulation

Gravity waves time scale. It is related to the length scale of large-scale circulation $\chi = \left(L_{(1)} + L_{(2)}\right)/2 + L$

Large-scale vertical velocities:

$$\bar{\omega}_{(1)} = \frac{\bar{\theta}_{(1)} - \bar{\theta}_{(2)}}{\tau\left(\frac{\partial\bar{\theta}_{(1)}}{\partial z} + \frac{\partial\bar{\theta}_{(2)}}{\partial z}\right)}, \quad \bar{\omega}_{(2)} = -\bar{\omega}_{(1)} \quad \text{with } L_{(1)} = L_{(2)}$$

The tendency of $\bar{\theta}_{(1)}$ due to large-scale circulation.

$$\frac{\partial\bar{\theta}_{(1)}}{\partial t} = \bar{\theta}_{(1)}\frac{\partial\bar{\omega}_{(1)}}{\partial z} - \frac{\partial\bar{\omega}_{(1)}\bar{\theta}_{(1)}}{\partial z}.$$

Similarly for $\bar{q}_{(1)}$, $\bar{\theta}_{(2)}$ and $\bar{q}_{(2)}$.

Heat and moisture budgets:

$$\sum_{i=1,2}\left\{SHF_{(i)} + C_p\int_{surf}^{Z_{top}}\rho\left[\left(\frac{\partial\bar{T}_{(i)}}{\partial t}\right)_{\mu} + \left(\frac{\partial\bar{T}_{(i)}}{\partial t}\right)_{rad} + \left(\frac{\partial\bar{T}_{(i)}}{\partial t}\right)_{WTG}\right]dz\right\} = 0$$

Sensible heat flux; Heating from condensate; Radiative cooling; Heating from the large-scale circulation

and

$$\sum_{i=1,2}\left\{E_{(i)} - P_{(i)} + L_v\int_{surf}^{Z_{top}}\rho\left(\frac{\partial\bar{q}_{(i)}}{\partial t}\right)_{WTG}dz\right\} = 0$$

Evaporation minus precipitation; Moistening from the large-scale circulation

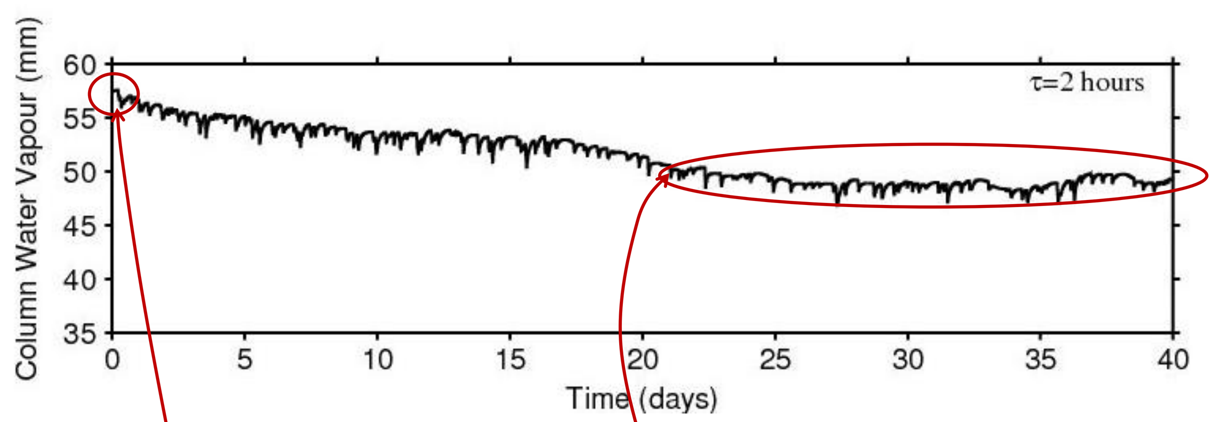
Assumptions:
1- Horizontal flow with no shear, 2-Large-scale circulation doesn't advect condensate, 3- $\partial\bar{\theta}/\partial z \gg 1K/km$

3. Uncoupled model

- The Met Office Large Eddy Model (LEM) at version 2.4 is used.
- The domain size is $Y \times Z = 128 \times 20km$ with horizontal resolution of $0.5km$.
- The lower boundary is a uniform sea surface temperature (SST).
- Radiative cooling is prescribed.
- The model is run for 40 days **with WTG calculations off** and SST of 301.7, 302.7 and $304.7K$.
- The last 20 days profiles are averaged to provide the sounding at RCE. Those obtained at $302.7K$ (**control run**) are used as reference profiles in the reference column model.

4. Reference column model

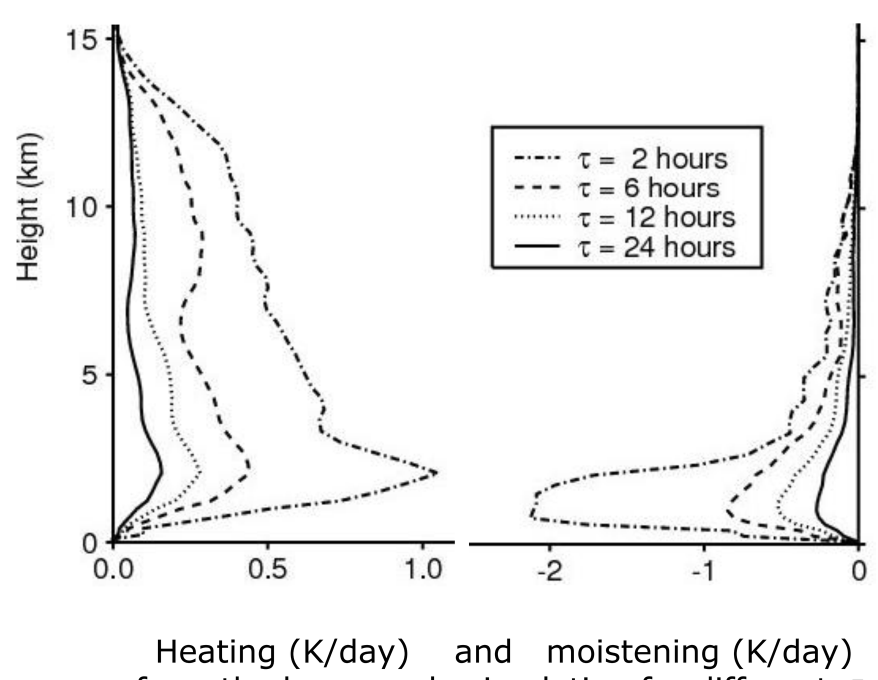
- $\bar{\theta}$ and $\bar{q}$ are specified in one column (reference column).
- Heat and moisture advected out of the other column (test column) is not received by the reference one: **Heat and moisture budgets are not strictly closed.**
- The test column is initialised with profiles of the reference column.
- The SST in both columns is $302.7K$.
- Simulations are performed for $\tau = 2, 6, 12, 24$ and 120 hours. For gravity waves of mean speed $50m/s$, they correspond to large-scale circulation of horizontal length $\chi = 360, 1080, 2160, 4320$ and $21600km$.



Starts from the equilibrium value obtained in the control run

Quasi-steady state **different from the RCE state** obtained in the control run

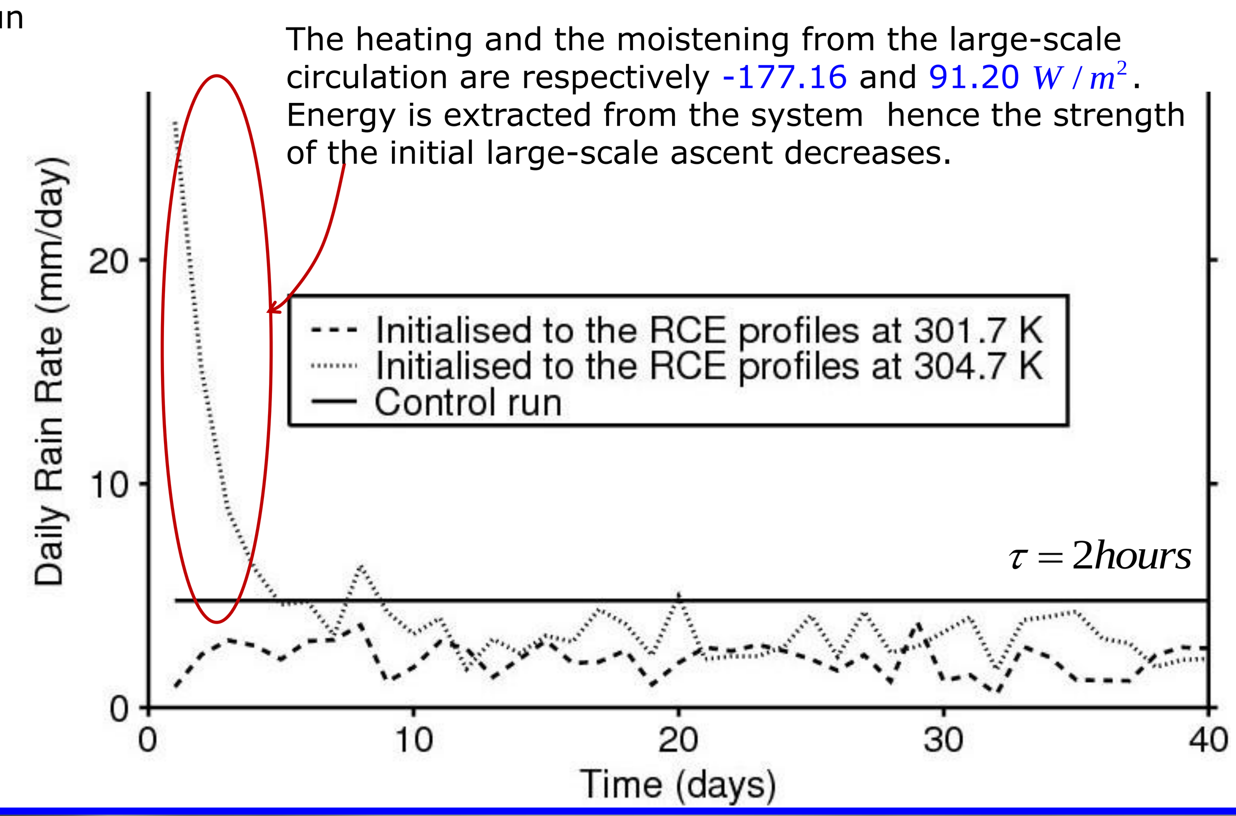
Experiments	Mean rain rate (mm/day)	Evaporation (mm/day)
Control run	4.77	4.80
$\tau = 120$ hours	4.70	4.74
$\tau = 24$ hours	4.40	4.77
$\tau = 12$ hours	4.03	4.78
$\tau = 6$ hours	3.43	4.64
$\tau = 2$ hours	1.99	4.47



Heating (K/day) and moistening (K/day) from the large-scale circulation for different τ

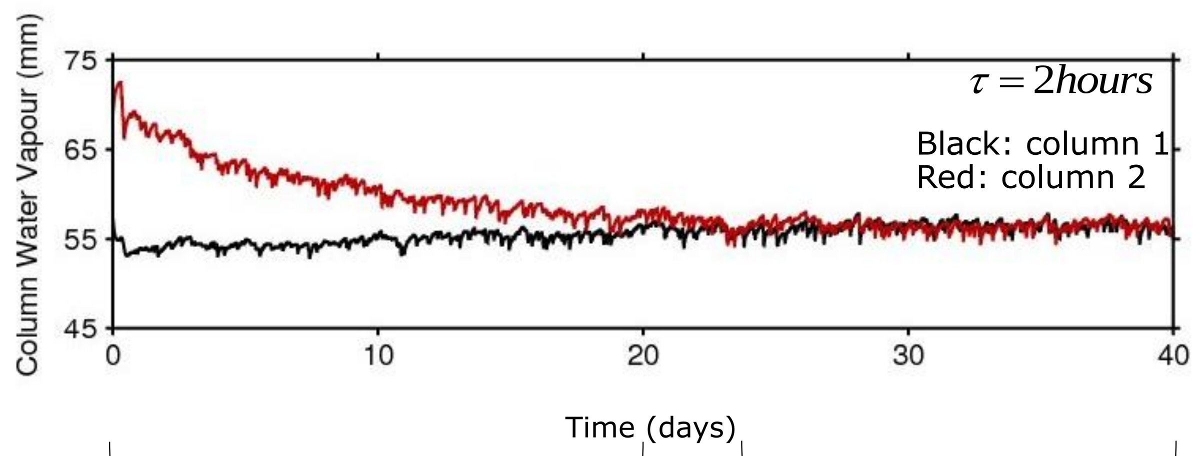
Sensitivity to initial conditions

The heating and the moistening from the large-scale circulation are respectively -177.16 and 91.20 W/m^2. Energy is extracted from the system hence the strength of the initial large-scale ascent decreases.



5-Coupled Columns Model

- The profiles in neither column are specified.
- Heat and moisture advected out of one column is equal to that received by the other column: **Heat and moisture budgets are closed.**
- Column 1 is initialised to the RCE profiles at $302.7K$ and column 2 to that at $304.7K$.



The model tries to maintain the initialised large-scale circulation but this last for 20 days only.

The two columns adjust to almost the same state which is very similar to the **RCE state** obtained in the control run.

	Mean rain rate (mm/day)	Evaporation (mm/day)
Control run	4.77	4.80
Column 1	4.72	4.73
Column 2	4.85	4.77

The adjustment time scale in the coupled columns model decreases with increasing τ.

6-Summaries

Reference column model

- This model has a **unique final state with descent in the test column which does not depend on how it has been initialised.**
- The mean rain rate increases with τ.
- The rate of change of evaporation is negligible hence, precipitation variations are mainly controlled by large-scale horizontal moisture advection.

Coupled columns model

- This new model does not sustain a large-scale circulation no matter the strength of the initial circulation. Hence, **large-scale circulation with descent in the test column is an artefact of the reference column approach.**
- The shorter the value of τ, the longer the time required by the model to adjust to an equilibrium with no large-scale circulation.

Future work

- Examine the equilibrium response of the coupled columns model to inhomogeneous SST.
- Understand how two-way interactions between convection and large-scale circulation influence the transition from shallow to deep convection.

References

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Acknowledgments

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