Department of Meteorology

Thermodynamic work done in a WTG-coupled two column model diagnosed using energy cycles

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NERC SCIENCE OF THE ENVIRONMENT

Aims

In order to enhance understanding of the relationship between large-scale circulations and localised convection, we used a CRM model to unpack energetic processes associated with convection within two coupled columns, refining a diagnostic methodology introduced by Pauluis (2016).

The Weak Temperature Gradient (WTG) Approximation

- is a recipe for vertical wind, often used to parametrise large-scale circulations in studies of convection,
- relates vertical wind to temperature anomalies using a relaxation timescale τ:

$$w_{\rm WTG}\frac{\partial \theta}{\partial z} = \frac{\theta'}{\tau}$$

- here it couples two columns, each simulated with a cloud resolving model,
- analytically tractable, e.g. rate of conversion from APE $\bar{A}$ to kinetic energy is $2\bar{A}/\tau$.

Components of work done

Energy throughput by a convective system can be decomposed into:

1. the mechanical work done by the buoyancy,
2. the lifting of precipitable water and
3. the "Gibbs penalty" – the ongoing cost of maintaining a moist atmosphere

$$\oint T dS \approx \oint B dz + g\oint r_t dz - \sum_{w=v,l,i}\oint \mathcal{G}_w dr_w$$

$\mathcal{G}_w$ is the specific Gibbs free energy of water in its 3 states - see Pauluis (2016). We calculate these for trajectories in (θ_e, z) space.

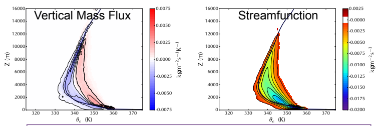
CRM Model setup

We use the Met Office's Large Eddy Model (LEM):

- in a simplified 2-D configuration
- with fixed radiation
- WTG circulation links two equally-sized columns identical except for SSTs of 302.7K and 304.7K. (see Daleu et al 2012.)

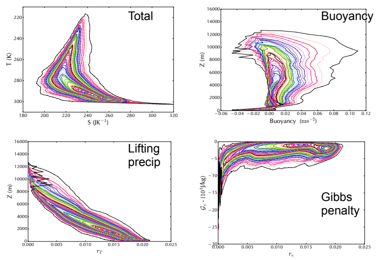
Streamfunction trajectories

These components of work done are calculated using weighted integrals along contours of the streamfunction:



Vertical mass flux in isentropic/height coordinates and associated streamfunction for uncoupled column - SST 302.7K

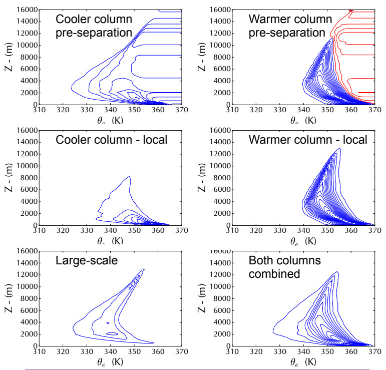
The integrals can be represented graphically:



Thermodynamic diagrams representing components of the work done equation for uncoupled column.

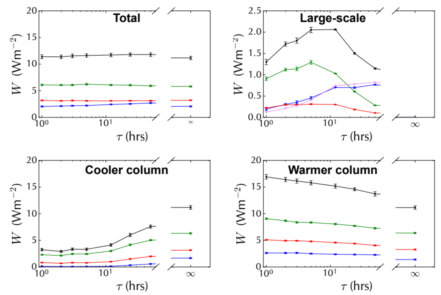
Coupling & streamfunctions

Coupling causes mass transfer between the columns and we need to separate out the large-scale circulation to get closed streamfunctions:



"Streamfunctions" for two coupled columns (τ= 2 hrs) – blue is negative and red positive – showing effect of separating LS

Results – components of work done

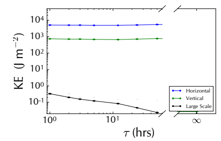


Black line represents **total work** input, blue is **buoyancy work**, red is the **lifting of moisture** and green the **Gibbs penalty.** Where shown violet is the **predicted work done.** τ reduces with stronger coupling. Note that the LS circulation occurs over both columns and hence has a double weighting in the total.

- Coupling has slight effect on total system.
- Even very weak coupling suppresses convection in the cooler column and enhances that in the warmer column; as coupling increases this effect increases.
- Large-scale circulation buoyancy plays a much greater relative role than in the individual columns.
- Gibbs penalty for the large-scale circulation (depends on the log of the relative humidity at which moisture is evaporated into the system) increases as the coupling increases and the cooler column dries out, then reduces as stronger coupling converges the columns.
- Analytical expression for conversion from potential energy to kinetic energy matches the buoyancy work closely.
- With strong coupling the work done components for the large scale circulation are comparable in magnitude for those in the cooler column.

Results - Kinetic Energy

- The large-scale circulation energy is 10^3 times smaller than the vertical & horizontal components in total.



Components of kinetic energy as a function of coupling

Key Points

- Isentropic analysis of the vertical mass flux of a convective system provides insight into the components of work done (namely buoyancy, lifting of moisture and the Gibbs penalty).
- We can partition the work done by a coupled two-column model into localised components and those due to the large-scale circulation.
- Even very weak coupling between the columns has a marked impact on the energetics of the two columns
- Further strengthening of the coupling increases this effect.
- The large scale circulation is more dominated by the buoyancy component than are the local circulations.
- The kinetic energy associated with the large-scale circulation is trivial relative to the rest of the system even though the large-scale that governs the character of the entire system.

References

1. Daleu, C., S. Woolnough, and R. Plant, 2012: Cloud-resolving model simulations with one-and two-way couplings via the weak temperature gradient approximation. *Journal of the Atmospheric Sciences*, 69 (12), 3683–3699.
2. Pauluis, O. M., 2016: The mean air flow as Lagrangian dynamics approximation and its application to moist convection. *Journal of the Atmospheric Sciences*, 73 (4), 1A,1–48.

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