Parameterizing large-scale circulations based on the weak temperature gradient approximation

Bob Plant, Chimene Daleu, Steve Woolnough
and thanks to GASS WTG project participants

Department of Meteorology, University of Reading

GAFD Seminar,
Department of Mathematics, University of Exeter
13 March 2017
Overview

- Weak temperature gradient parameterization: how it works
- Circulations in a homogeneous environment
- Circulations in an inhomogeneous environment
- Transitional cases and parameterization testing
Weak temperature gradient parameterization: how it works
Scale difference problem

- Difficult to parameterize the sub-grid convective activity in a GCM
Simulations which well resolve the convective activity typically neglect, or prescribe, motions on scales larger than the domain.
Modelling approaches

- Large-domain and high-resolution simulations
- GCM: simulate the large-scale circulation but parameterize the convection
- CRM: impose the large-scale circulation and simulate the convection
- SCM: impose the large-scale circulation and test parameterization of the convection (too easy?)
- Today: parameterize the large-scale circulation and simulate the convection
- Also: parameterize the large-scale circulation and parameterize the convection
Little variation in free troposphere over the tropics
Basic ideas

- Gravity waves are effective in redistributing density anomalies so as to maintain near uniform density on isobaric surfaces.
- This leads to large-scale circulations which act to balance local anomalies of heating so as to produce quasi-uniform potential temperature.
- The boundary layer is different because conditions there are tied to the local underlying surface temperature.
Diagnosing circulations

\[ \frac{\partial \theta}{\partial t} + \mathbf{v} \nabla_h \theta + w \frac{\partial \theta}{\partial z} = S \]  \hspace{1cm} (1)

On the large scale, simplify to:

\[ \bar{w} \frac{\partial}{\partial z} \bar{\theta} \approx \bar{S} = Q_R + Q_c \]  \hspace{1cm} (2)

- Based on \( \bar{S} \), can evaluate the \( \bar{w} \) required for the WTG balance.
- Can enforce Eq. 2 by resetting \( \theta(t, z) = \theta(z) \), and allow the diagnosed \( \bar{w} \) to produce a source/sink term in moisture equation (Sobel and Bretherton, 2000).
- \( \theta(z) \) typically taken from RCE.
Relaxation form

A weaker version envisages gravity waves reducing temperature difference over a finite timescale $\tau$,

$$\bar{w} \frac{\partial \bar{\theta}}{\partial z} = \frac{1}{\tau} (\bar{\theta} - \bar{\theta}_{\text{ref}})$$  \hspace{1cm} (3)

(Raymond and Zeng, 2005)

- $\tau$ is of order a few hours, corresponding to lengthscales of order 1000 km for gravity waves of order 50 ms$^{-1}$
- Reference state typically taken from RCE
- The RCE surroundings do not vary in response to the WTG-derived circulation
Generalize to two regions

- Reference state imagines open system with coupling to infinite reservoir
- Consider two regions with a diagnosed circulation affecting both
- Allows study of influence of remote changes on local convection
Generalization to two regions

\[ w_2 \frac{\partial}{\partial z} \bar{\theta}_2 - w_1 \frac{\partial}{\partial z} \bar{\theta}_1 = \frac{1}{\tau} (\bar{\theta}_2 - \bar{\theta}_1) \] (4)

For continuity

\[(1 - \epsilon)w_1 + \epsilon w_2 = 0 \] (5)

leading to

\[ \bar{w}_1 = \frac{1}{\tau} \left[ \frac{\bar{\theta}_1 - \bar{\theta}_2}{\frac{\partial \bar{\theta}_1}{\partial z} + \left( \frac{1-\epsilon}{\epsilon} \right) \frac{\partial \bar{\theta}_2}{\partial z}} \right] \] (6)

Recovers reservoir formula for relative area \( \epsilon \rightarrow 0 \) or 1.
We also associate a horizontal WTG velocity with $\bar{w}_{\text{wtg}}$ in order to close the circulation.

This gives a closed two-region approach constrained by energy and moisture conservation.
Treatment of boundary layer

- Boundary layer conditions tied to the local SST
- Treatment is to calculate $w_{WTG}$ for heights above some nominal BL top, say 1.5km, and linearly interpolate between $w_{WTG}(z_{BL})$ and $w_{WTG}(z = 0) = 0$
- We will return to this...
Circulations in a homogeneous environment
Models used

- Run to equilibrium with prescribed radiative cooling
- Typically for 40 days, with first 20 discarded as spin-up
- Using LEM, 2D with $\Delta x = 500\, \text{m}$
- Also use some GASS WTG intercomparison results for reference-state cases
Reference state, same SST

- Generate RCE reference state
- Make a WTG coupling to this state with simulated region initialized to the RCE state
- Use identical forcing and surface conditions to the RCE configuration
- What happens?
Reference state, same SST

**Descent in simulated region** with associated heating and drying tendencies

<table>
<thead>
<tr>
<th>mm/d</th>
<th>Rain</th>
<th>Evap</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCE</td>
<td>4.77</td>
<td>4.80</td>
</tr>
<tr>
<td>( \tau = 120 , \text{h} )</td>
<td>4.70</td>
<td>4.74</td>
</tr>
<tr>
<td>( \tau = 24 , \text{h} )</td>
<td>4.40</td>
<td>4.77</td>
</tr>
<tr>
<td>( \tau = 12 , \text{h} )</td>
<td>4.03</td>
<td>4.78</td>
</tr>
<tr>
<td>( \tau = 6 , \text{h} )</td>
<td>3.43</td>
<td>4.64</td>
</tr>
<tr>
<td>( \tau = 2 , \text{h} )</td>
<td>1.99</td>
<td>4.47</td>
</tr>
</tbody>
</table>
Some develop large-scale circulations within a homogeneous environment.

Some support multiple equilibria.
Two region configuration

- Produces no time-mean WTG circulation irrespective of $\varepsilon$
- Adjustment to equilibrium much slower for small $\varepsilon$
- **But** note small $\varepsilon$ qualitatively different from reference configuration
Role of Boundary Layer Top

- Consider $w_{WTG}$ profiles in cases of dry equilibria
- Change of sign can occur close to BL top
- Sign may differ from that which would have been expected without the linear interpolation prescription

![Graphs showing $w_{WTG}$ profiles and Omega vs Pressure](image)
Varying the Boundary Layer Top

- Critical BL depth to get the dry state: equilibrium state can be made precipitating by setting a lower depth (but still above mixed layer)

- Some dependence of multiple states on SST (more likely if higher) and $\tau$ (more likely if shorter)
Circulations in an inhomogeneous environment
Precipitation variations

- Vary surface wind speed with $\tau = 2$ h for reference column case and for $\varepsilon = 0.5$
- Two region case less sensitive due to constraints from closed budgets
Precip variations for small $\varepsilon$

- Comparison against $\varepsilon = 0.1$ and $\tau = 4$ h
- Similar to reference approach at $\tau = 2$ h for large changes in surface changes
- But differences remain for small changes
Comparison of models

Varying SST in reference-state approach

(a) CRM with WTG
- WRF
- MesoNH
- LaRC-CRM
- NMTCMv3
- LEMv2.4

(b) SCM with WTG
- LMDzA
- LMDzB
- GISS-SCM
- ARPv6
- UMv7.8
- EC-Earthv1
- EC-Earthv3
Precip and column relative humidity

Comparison with observational fit from satellite data over tropical oceans

(a) CRMs with WTG

(b) SCMs with WTG

\[ P \text{ (mm d}^{-1}\text{)} \]

\[ \text{CRH} \]

- 302 K
- 301.5 K
- 301 K
- 300.5 K
- 300 K
- 299.5 K
- 298 K
Precip and column relative humidity

Some collapse if scaled by reference RCE values
Transitional cases and parameterization testing
Transition, suppressed → active

- Start from equilibrium state of two-region configuration with SST difference of 2K
- Rain rates are 0.98 and 8.47 mm/d in cold and warm regions
- Now transition to state of equal SST, no circulation, by
  1. local transition: increase cold SST by 2K
  2. remote transition: decrease warm SST by 2K
  3. mixed transition: increase cold and decrease warm SST by 1K
Local transition

The need to remove the WTG circulation slows the transition

Dashed line, set circulation to zero at transition time
Remote transition

- Reduce evaporation in active region
- Leads to reduced convection there
- Reduces circulation
- Ultimately enough to allow convection in suppressed region
Transition times

<table>
<thead>
<tr>
<th>Type</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>5.4 days</td>
</tr>
<tr>
<td>Remote</td>
<td>10.9 days</td>
</tr>
<tr>
<td>Mixed</td>
<td>8.7 days</td>
</tr>
</tbody>
</table>

Transition time: that required for rain rate to increase by half the amount needed to reach new equilibrium
## Comparison with SCM

<table>
<thead>
<tr>
<th>Type</th>
<th>CRM</th>
<th>SCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>5.4</td>
<td>3.9</td>
</tr>
<tr>
<td>Remote</td>
<td>10.9</td>
<td>5.9</td>
</tr>
<tr>
<td>Mixed</td>
<td>8.7</td>
<td>4.8</td>
</tr>
</tbody>
</table>

- Repeat same transition experiments with the UMSCM (v7.8)
- All of the transitions are faster
- In the CRM, heating and moistening effects of large-scale circulation are about equally divided
- In the SCM, heating effects more important than moistening
Simple parameterization tests

- Vary closure timescale of UM convection parameterization
  - very little effect: only alters high-frequency variability

- Vary entrainment and detrainment rates of UM convection parameterization
  - This is a key source of uncertainty in GCMs for both mean state and some modes of variability
  - We increase the entrainment and detrainment rates by 25% and 50%
Changes to entrainment

Feedback effects of entrainment rate on large-scale circulation do matter, rather than any more direct effect.
Effects on Transition Times

A non-trivial test of parameterization interactions with large-scale circulations

The University of Reading
Summary

- WTG approach allows coupling between convection and large-scale tropical circulations
- Normally coupling is to a reference RCE state and system is open
- This can produce ascent/descent/no circulation for uniform SST depending on the convection model
  - Caution: this does not happen in a closed two-region approach for any $\varepsilon$
- And can have multiple equilibrium with a non-precipitating state
  - Caution: this is very sensitive to the rather arbitrary treatment of the boundary layer circulation
Summary

- For distinct surface conditions, can produce good precip vs $w_{LS}$ and precip vs CRH relationships.
- CRH relation under WTG may provide a good test for SCM parameterizations.
- The two region approach allows simulation of new idealized problems: e.g., effects of remote changes on suppressed $\rightarrow$ active transitions.
- Transitions under WTG may provide a difficult test for SCM parameterizations.
References


Daleu, Plant and Woolnough (2017), Using the weak temperature gradient approximation to evaluate parameterizations: An example of the transition from suppressed to active convection. *Submitted to JAMES*.
Thermodynamic Analysis

\[ \int TdS \approx \int Bdz + g \int r_Tdz - \sum_{w=v,l,i} \int G_w dr_w \]

With Kamieniecki, Ambaum