Parameterizing large-scale dynamics: a comparison of WTG and WPG

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March 28, 2012
How to handle the large range of scales?
How to handle the large range of scales?

Approach 1: Parameterize sub-grid-scale (SGS) dynamics

Resolve the large-scale flow, but parameterize the small-scale dynamics within each grid column.

Betts-Miller, RAS, Tiedtke, Zhang-McFarlane, etc.
How to handle the large range of scales?
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Approach 2: Parameterize supra-domain-scale (SDS) dynamics

Resolve the small-scale flow, but parameterize the large-scale dynamics between the column and its environment.
WTG:

\[ \frac{\partial \rho}{\partial t} \delta = p - p_0 \]

Pressure anomaly relative to environment

\[ \rho L_2 - \alpha \delta w = \tau N_2 g (\theta v - \theta v_0) \]

Buoyancy relative to environment

\[ \delta = \frac{\partial}{\partial x} u + \frac{\partial}{\partial y} v \]

WPG:

Rayleigh damping

(Adam, Dave, etc.)

(Kerry, Adam, Dave, Zhiming, Chris, etc.)
Analytical solutions in 3D, WTG, and WPG (using linearized, Rayleigh-damped Boussinesq equations)

Steady heating aloft (e.g., latent heating) generates zero column-integrated buoyancy (i.e., $B \propto -\partial^2_z Q$)

\[ B \propto -\partial^2_z Q \]
Analytical solutions in 3D, WTG, and WPG (using linearized, Rayleigh-damped Boussinesq equations)

Transient patch of buoyancy aloft causes ascent below (i.e., $\partial_t \partial_z B < 0$)

3D: ascent below

WPG: ascent below

WTG: no ascent below
Why should we care about modeling these effects correctly?

Vertical pattern of buoyancy:

Can be $O(1)$ K, which is comparable to that of convection.

Could influence convective mass fluxes.

Ascent/descent below a buoyancy anomaly:

Leads to weakening of convective inhibition.

Could inhibit or excite convection.
Cloud-resolving simulation of an SST hot spot in a bowling-alley domain

Oscillating pattern of buoyancy and monotonic pattern of velocity are incompatible with WTG.

Matching patterns of pressure and divergence support the premise of WPG.
Run 3 simulations and compare
Steady-state vertical velocity

Vertical velocity (m/s)

Height (km)

Bowling alley
Steady-state vertical velocity

WTG is too top-heavy.
Steady-state vertical velocity

WTG is too top-heavy.

WPG does relatively well.
Transient vertical velocity
Transient vertical velocity

Add water vapor

Dry (- - -) & moist (—) simulations

Bowling

WPG

WTG

Distance in x (km)

Height (km)

Vertical displacement (km)

Hour 1

Hour 2

Entire day

Bowling alley

Distance in x (km)

Height (km)

Vertical displacement (km)

Hour 1

Hour 2

Entire day

Bowling alley

Distance in x (km)

Height (km)

Vertical displacement (km)

Hour 1

Hour 2

Entire day

Add water vapor

WPG

WTG
Transient vertical velocity

Dry (–––) & moist (—) simulations

Bowling alley

Add water vapor

WPG

WTG

Horizontal displacement (km)

Height (km)

0

2

4

6

8

10

Vertical displacement (km)

Bowling

Hour 2

Hour 1

Entire day

WPG

Hour 2

Hour 1

Entire day

WTG

Hour 2

Hour 1

Entire day

Distance in x (km)

Vertical displacement (km)
Transient vertical velocity

Bowling alley

Add water vapor

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WTG

Dry (- - -) & moist (——) simulations

Height (km)

Vertical displacement (km)

Hour 2

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Entire day

Distance in x (km)

Bowling

WPG

WTG

Height (km)

Vertical displacement (km)

Hour 2

Hour 1

Entire day

Distance in x (km)

Bowling alley

Add water vapor

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WTG

Height (km)

Vertical displacement (km)

Hour 2

Hour 1

Entire day

Distance in x (km)

Transient vertical velocity
Conclusions

Cold air rises, and WPG captures this

In ascending columns, buoyancy oscillates between positive and negative values, and WPG captures this

Transient patches of buoyancy can cause non-local lifting, potentially triggering convection, and WPG captures this

Vertical velocity over an SST hot spot is replicated well by WPG