Toward the end of cumulus parameterization?

Sensitivity of radiative-convective equilibrium simulations to horizontal resolution

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Thanks to

S. Garner, C. Kerr, I. Held, L. Donner

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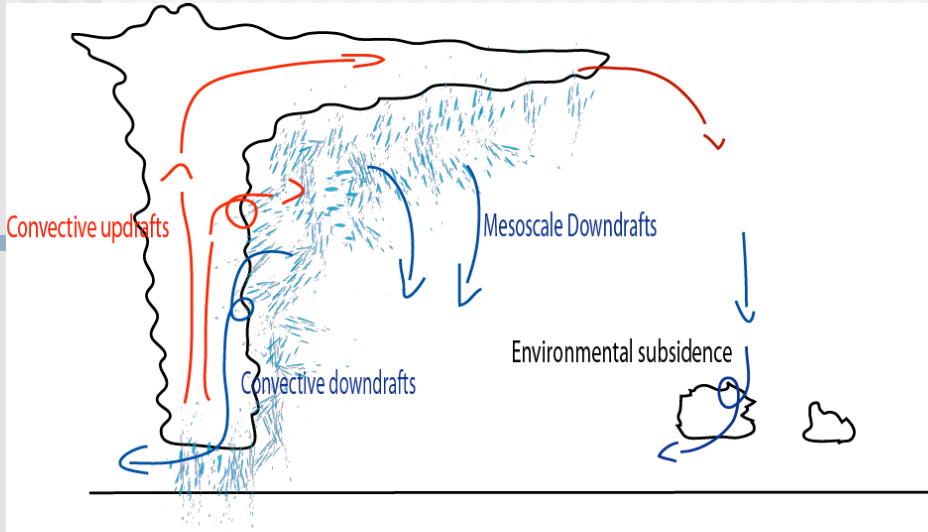
Outline

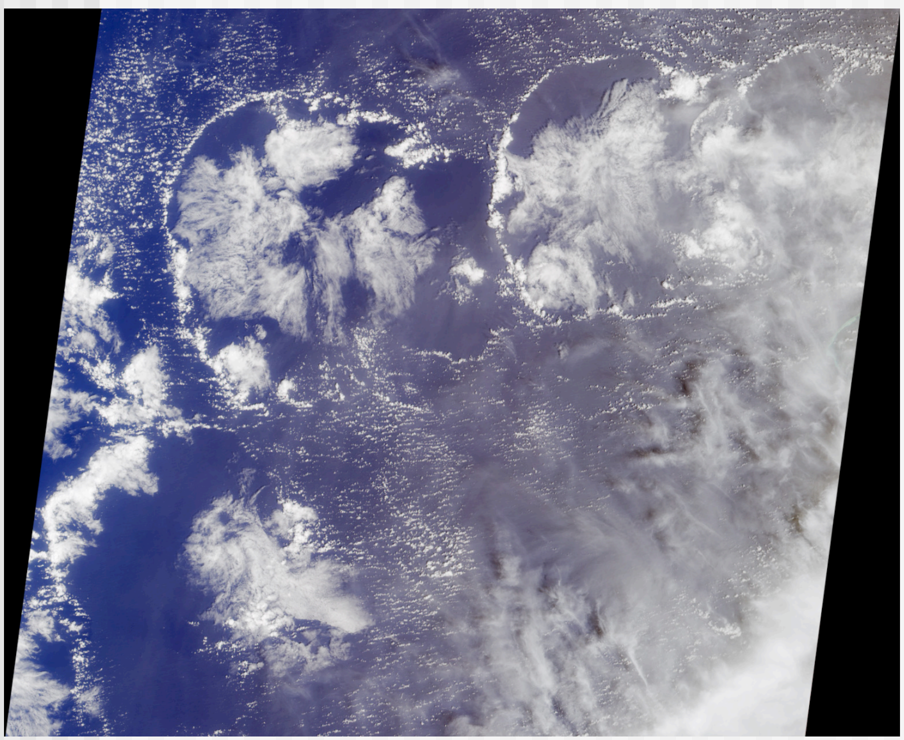
- Introduction: Why do we need a convective parameterization?
- Numerical convergence of cloud resolving simulations of RCE
- Physical interpretation
- Conclusion

Introduction

- Deep convection plays a central role in various aspects of the climate system:
  - Release of latent heat of vaporization.
  - Radiative impacts of clouds and water vapor.
  - Ascending branch of the general circulation.
  - Key role in tropical variability.
- GCM resolution (~100km) is insufficient to resolve deep convection, which then must be parameterized.

The need to parameterize deep convection remains a large source of uncertainty in climate simulations.



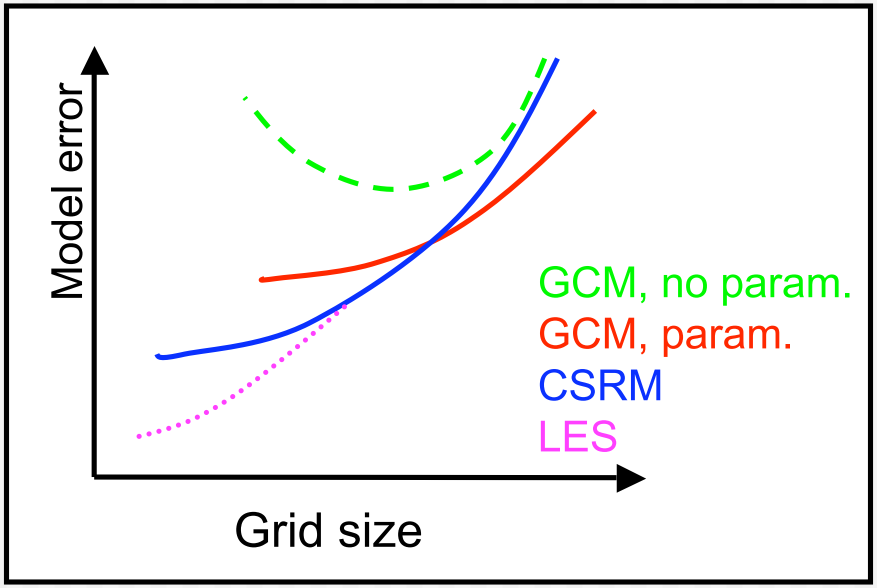


A fundamental difficulty with moist convection lies in the wide range of scale involved:

- Microphysics (few mm)
- Internal turbulence (~100m)
- Convective tower (~1km)
- Anvil cloud (~10 km)
- Meso-scale organization (100km)
- Strongly affected by synoptic and planetary motions

How much detail is required to capture the statistical behavior of moist convection?

- This is a problem of numerical convergence:
  - In theory, numerical solutions converges toward analytic solution at high resolution
  - In practice, one must settle for a satisfactory solution.



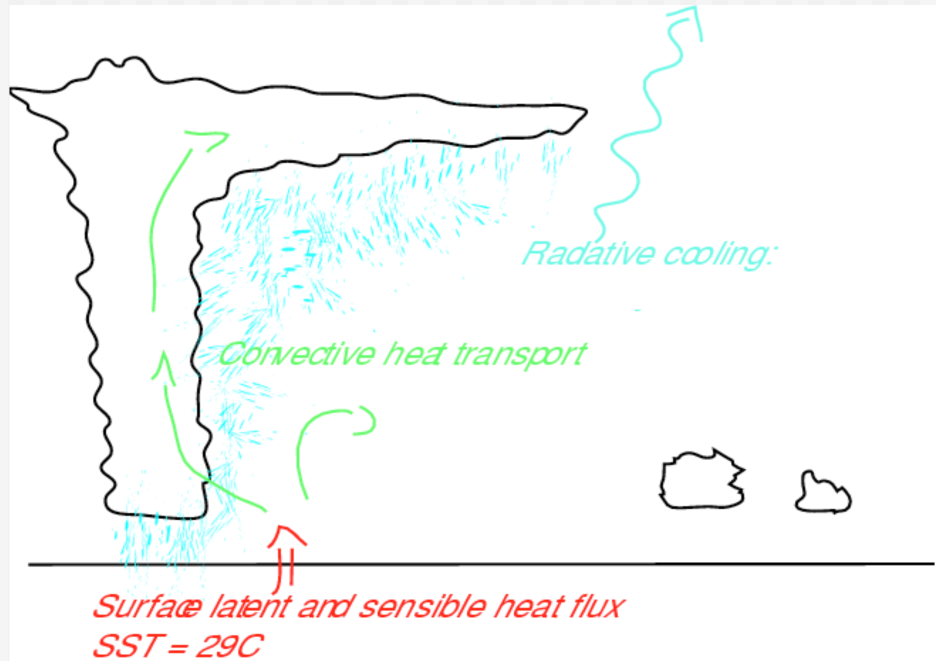
The use of a parameterization is justified if it improves the model convergence.

Zetac: a non-hydrostatic multi-scale model:

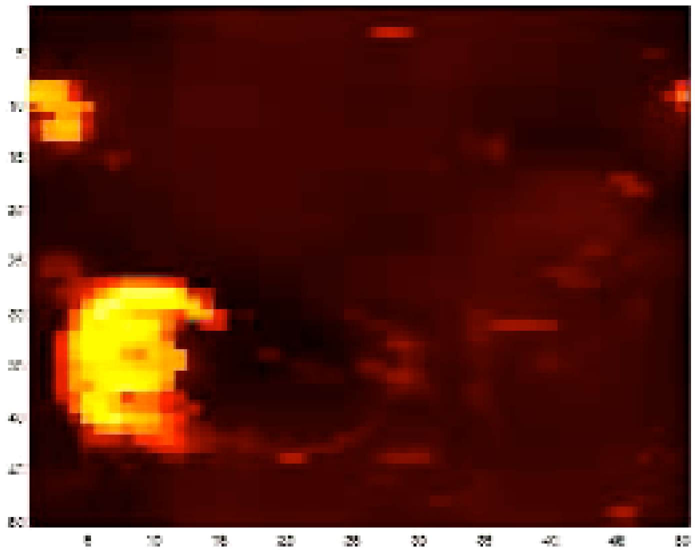
- Fully compressible dynamical core can be used for global simulations as well as LES.
- Monotonic advection scheme (Piecewise Parabolic Method). The model does not require any additional numerical diffusion.
- 5 species microphysics (LFO 1984).
- Parameterization for isotropic turbulence.
- Compatible with GFDL Flexible Modeling System: Zetac has access to all physical parameterizations developed for GFDL AM2 model.

Radiative-convective equilibrium

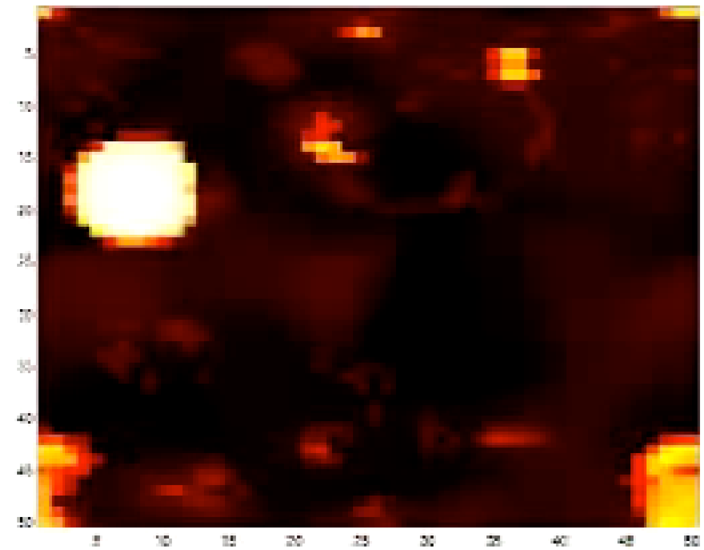
- Long integration (~16 days)
- Constant SST (302.15 K)
- Interactive radiation.
- Weak and strong wind shear cases.
- Compare simulations with 2, 4, 8, 16 and 32km resolutions. (Vertical resolution is unchanged.)
- Domain size is 50x50x60 grid points



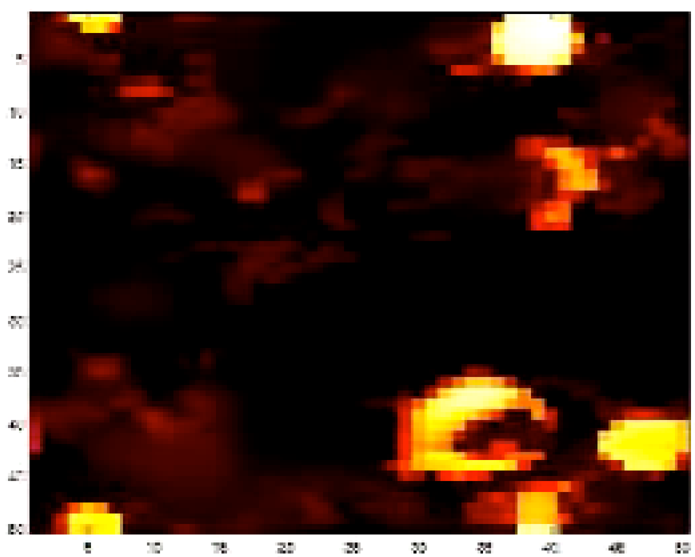
2 km



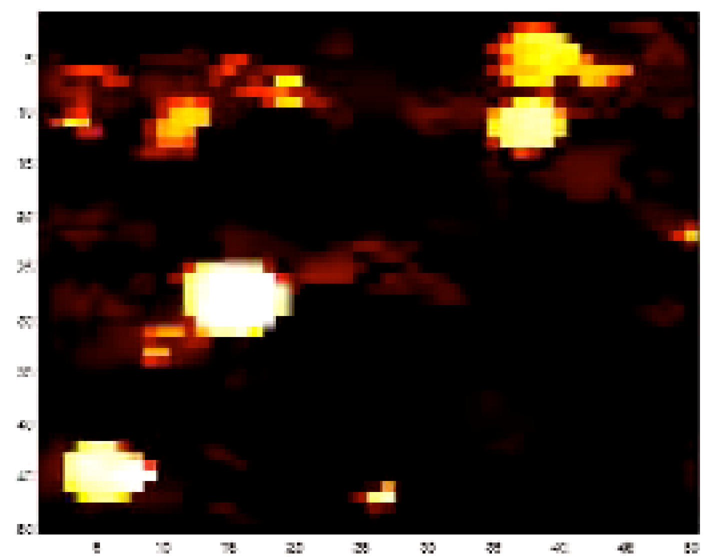
4 km



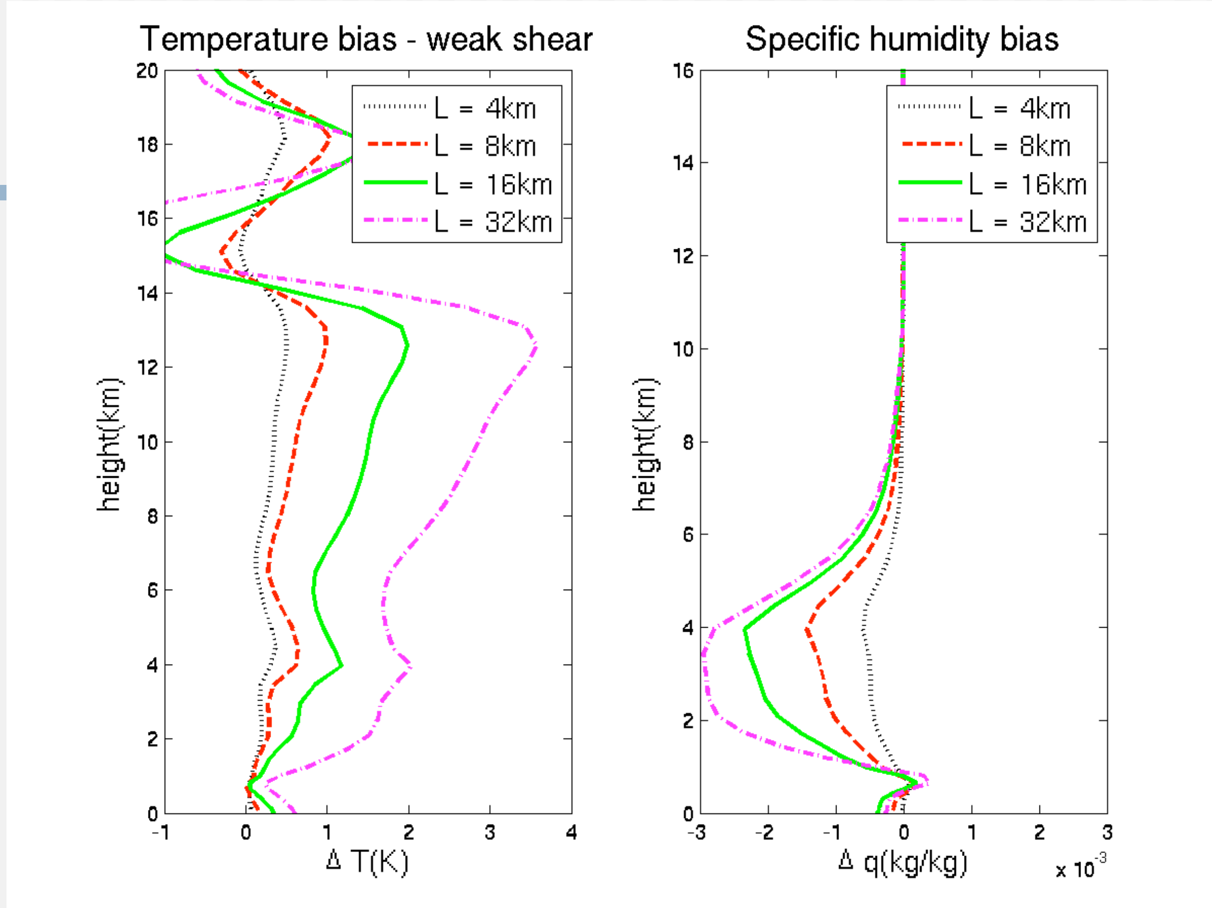
8 km



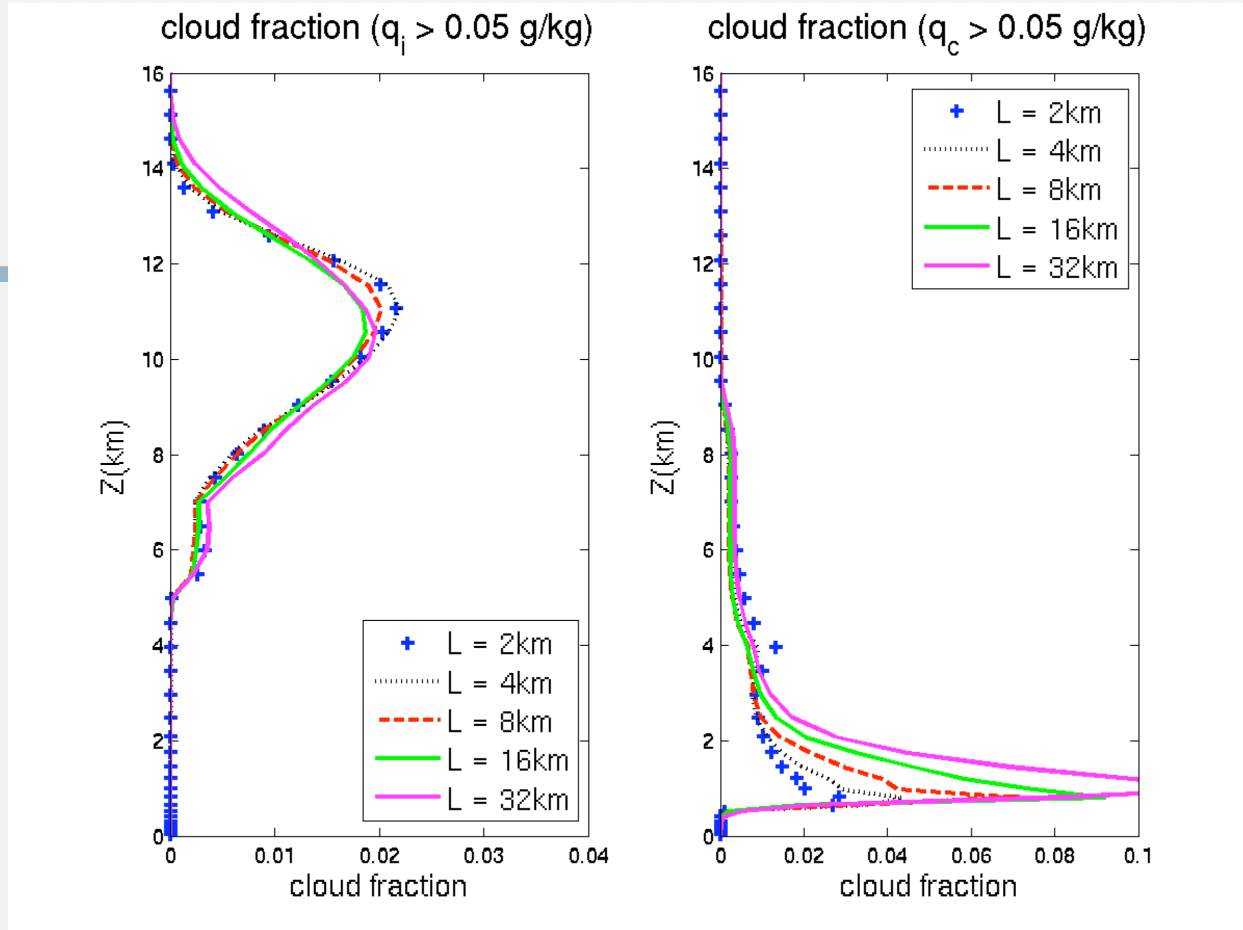
16 km



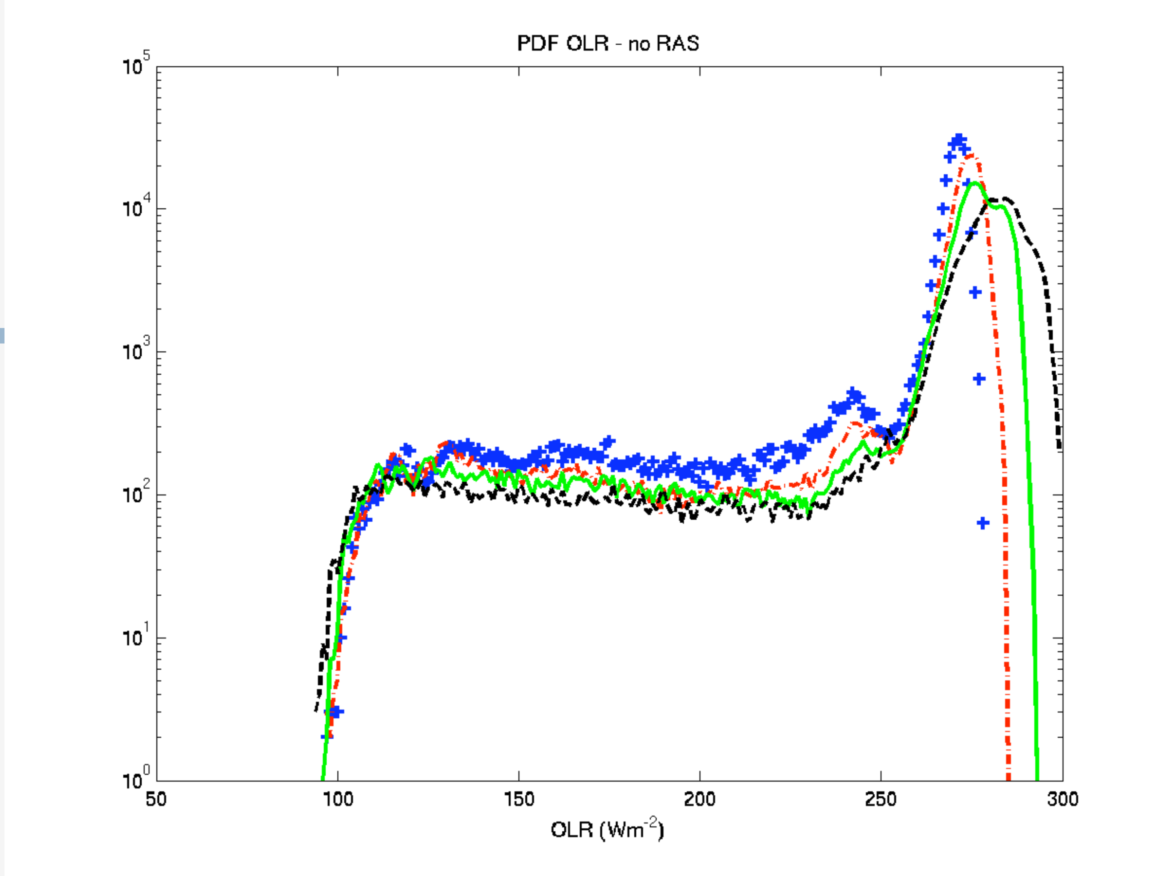
Numerical results



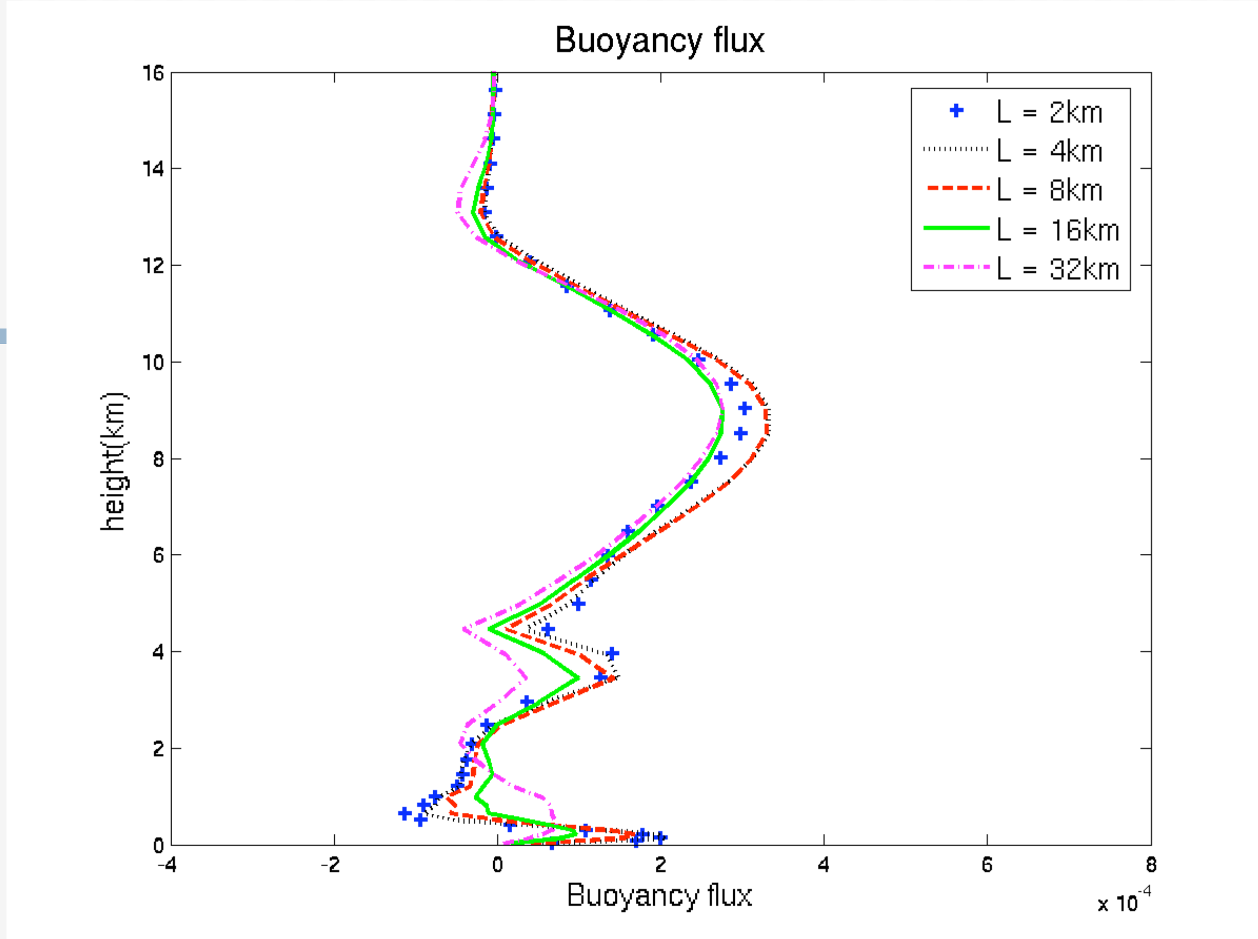
- Temperature and humidity bias (difference with reference 2km simulation) as function of horizontal resolution



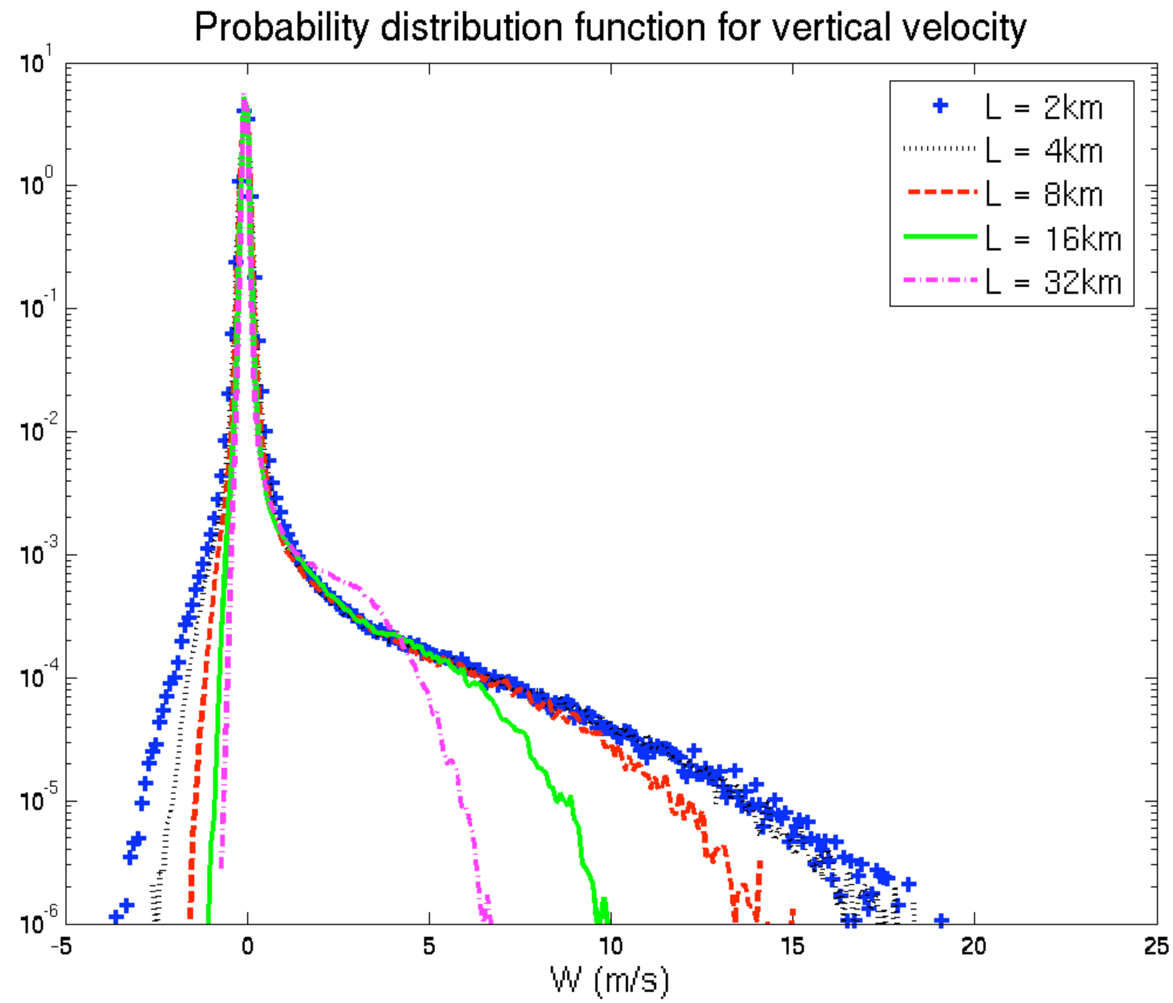
- Cloud ice and water fraction as function of model resolution



- Due primarily to the humidity bias, OLR increases at coarse resolution (error~10-15Wm^{-2})

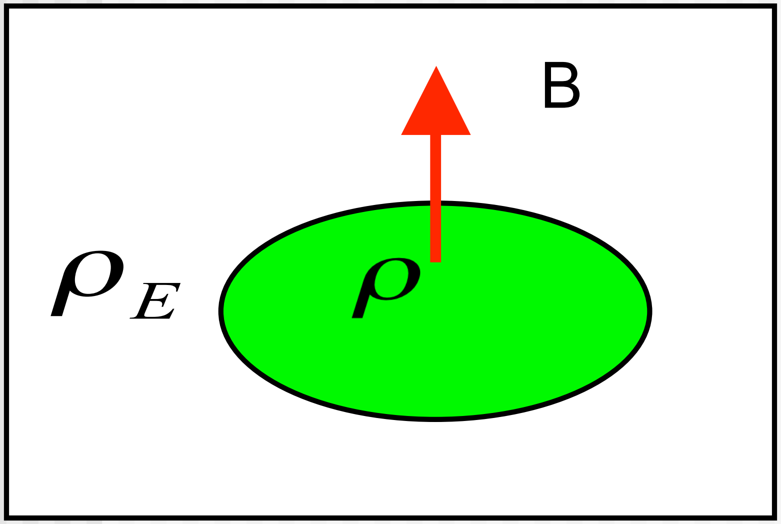


- Buoyancy Flux as function of model resolution



- Probability Distribution of Vertical Velocity as function of Model resolution

Buoyancy and vertical acceleration



Archimedes' principle: a static fluid exerts a pressure force on any immersed body equal to the weight of the displaced fluid:

$$B = \int_V g(\rho_E - \rho)$$

However, the pressure within a moving fluid is not the same as the hydrostatic pressure for a fluid at rest.

$$\overline{\rho}\partial_t V + \overline{\rho} V \bullet \nabla V = -\nabla p - \rho g \hat{k}$$
$$\nabla \bullet (\overline{\rho} V) = 0$$
$$\partial_t \overline{\rho}(z) = 0$$

- The pressure *p* can be decomposed into an hydrostatic and non-hydrostatic filed:

$$p = p_h + p_{nh} \quad \text{with} \quad p_h(x, y, z) = \int_z^\infty \rho g dz$$

- In this case, the vertical momentum equation is

$$\overline{\rho}\partial_t w + \overline{\rho} V \bullet \nabla w = -\partial_z p_{nh}$$

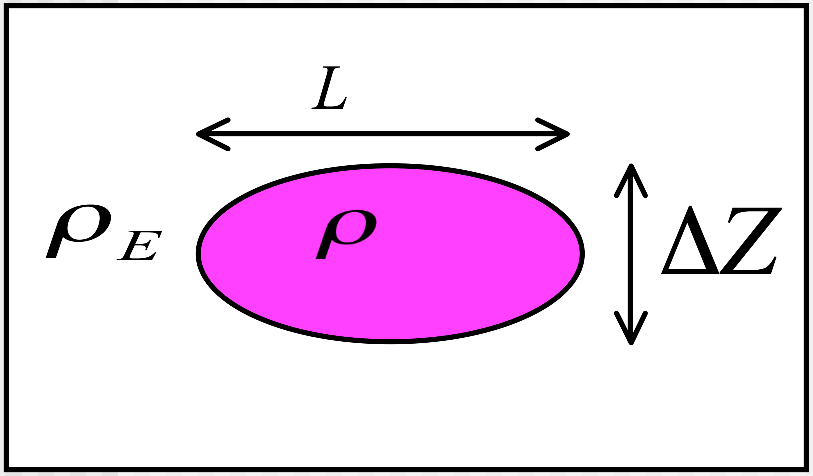
- The non-hydrostatic pressure field can be obtained from the continuity equation:

$$\boxed{\nabla^2(\partial_z p_{nh}) = g\nabla_H^2 \rho + NL}$$

After Davies-Jones (2003)

Isolated Bubble

$$\frac{\partial^2}{\partial z^2}(\partial_z p_{nh}) - \frac{4}{L^2}\partial_z p_{nh} = \frac{4}{L^2} g(\rho_E - \rho)$$



$$\partial_z p_{nh} = \int_0^\infty G(z,z')\frac{4g}{L^2}(\rho_E(z') - \rho(z'))dz'$$

$$G(z,z') = \frac{L}{2}\sinh\left(\frac{2z'}{L}\right)\exp\left(-\frac{2z}{L}\right) \text{ for } z > z'$$
$$= \frac{L}{2}\sinh\left(\frac{2z}{L}\right)\exp\left(-\frac{2z'}{L}\right) \text{ for } z' > z$$

Faraway from the lower boundary, this yields

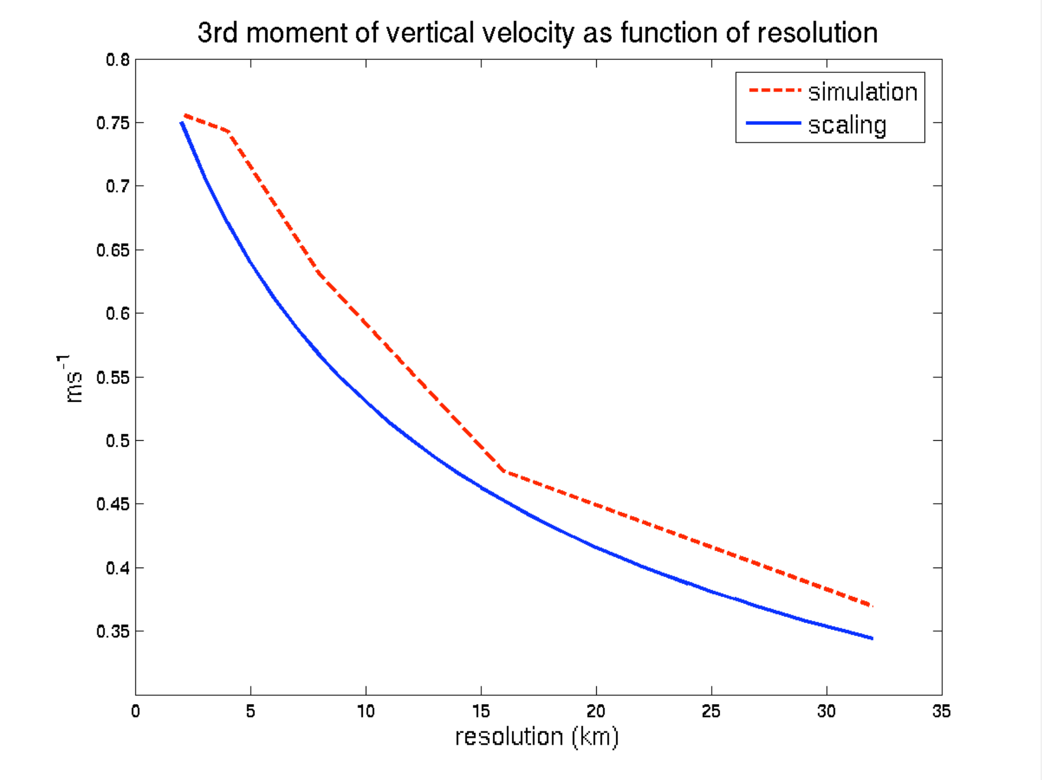
$$-\frac{1}{\overline{\rho}}\partial_z p_{nh} \approx g\frac{\rho_E - \rho}{\overline{\rho}}\left(1 + \frac{L}{\Delta Z}\right)^{-1} = \frac{b}{1 + \frac{L}{\Delta Z}}$$

Vertical Velocity scaling

$$\frac{1}{2}w^2 \approx \int_0^Z \frac{1}{\bar{\rho}}\partial_z p_{nh}$$

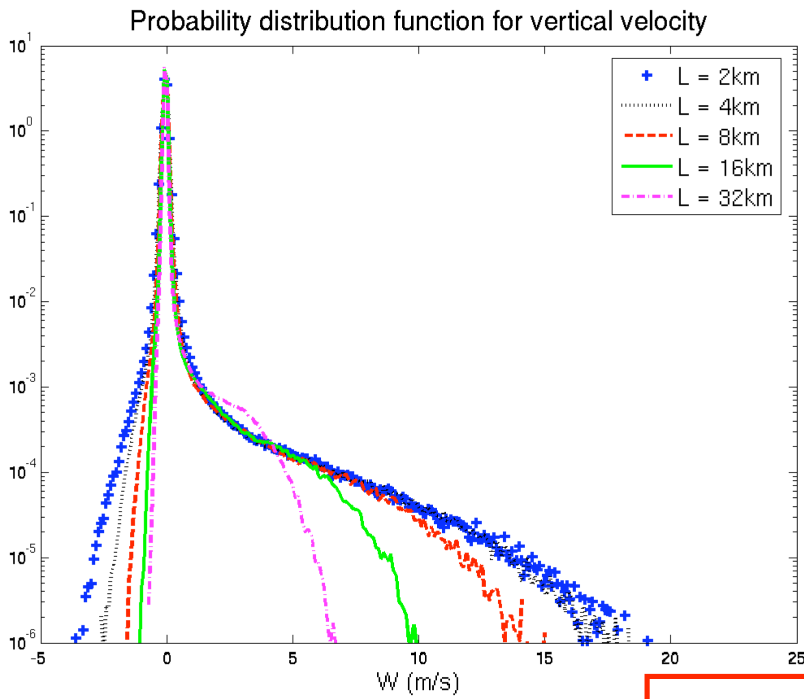
$$w \approx \frac{w_0}{(1+\frac{L}{\Delta Z})^{\frac{1}{2}}}$$

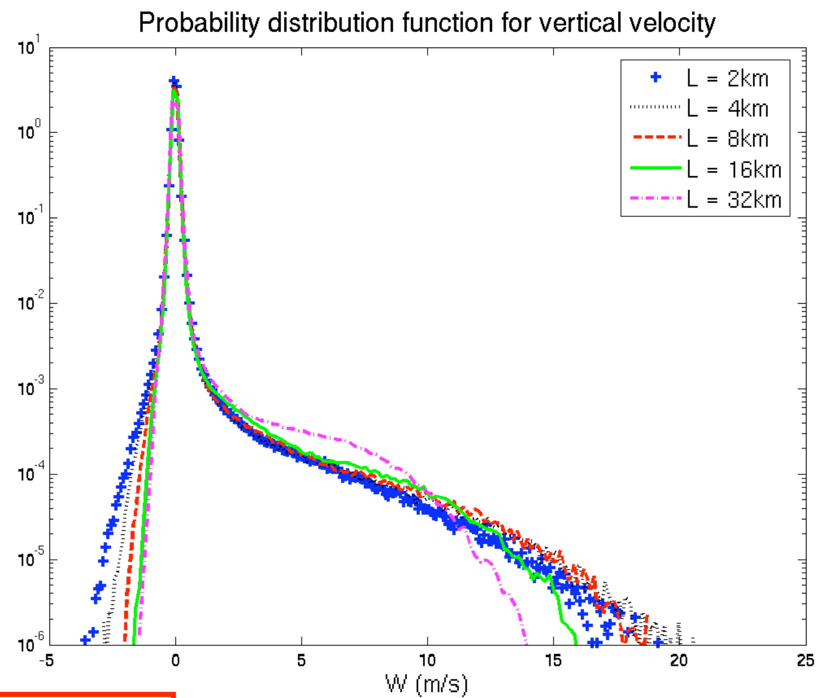
Scaling for vertical velocity is much less sensitive than traditional hydrostatic scaling W~1/L .



Dashed Line: Vertical velocity in simulations
Solid Line: theoretical scaling

Rescaling the vertical velocity



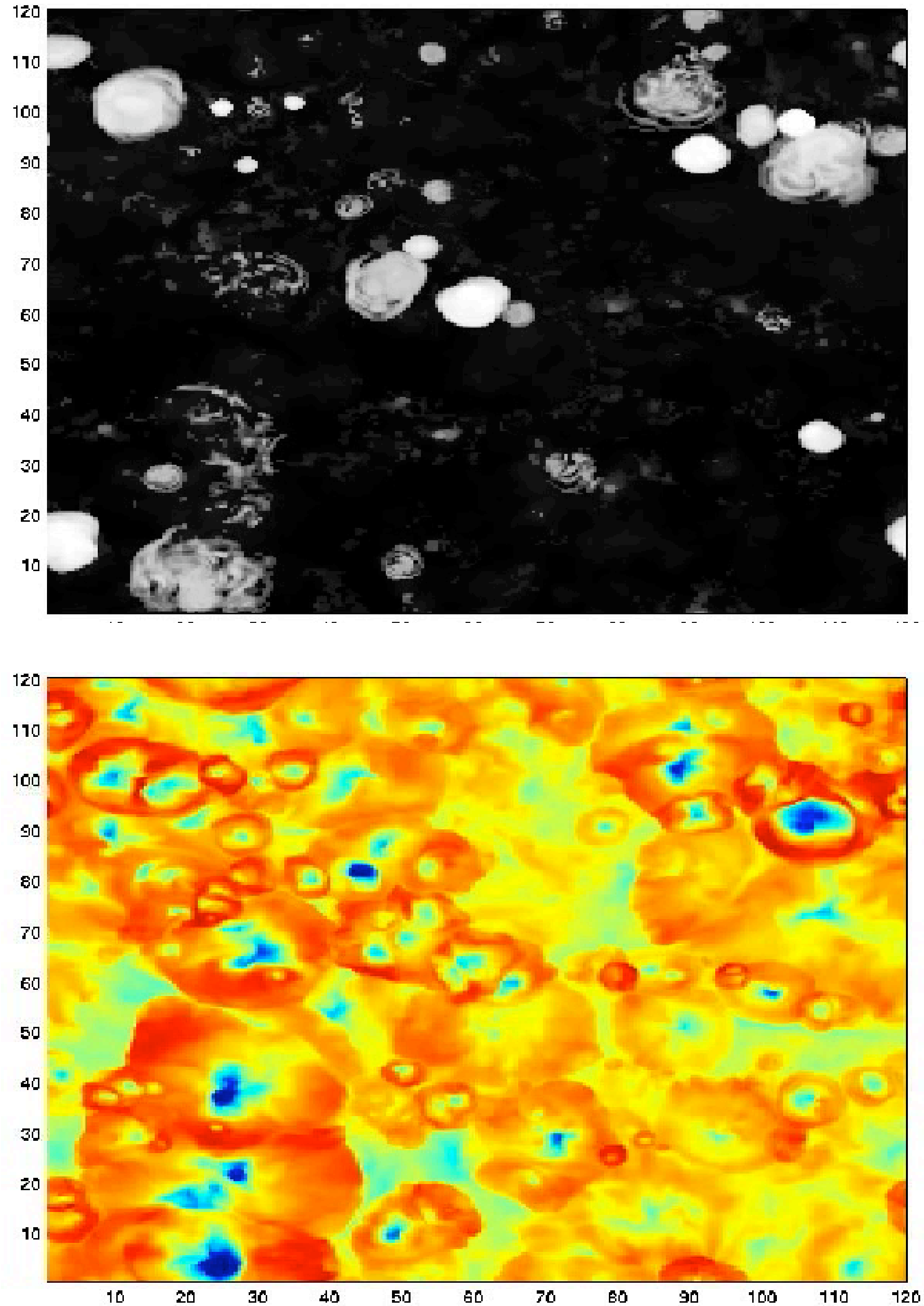


$$w_{rs} \approx \frac{(1+\frac{L}{\Delta Z})^{\frac{1}{2}}}{(1+\frac{2km}{\Delta Z})^{\frac{1}{2}}} w$$

- Very close match after rescaling of the vertical velocity PDFs.
- Breakdown at larger scales, which should follow a different scaling law.

Why does the rescaling work?

- Dominant dynamic is non-hydrostatic ascent of buoyant air parcel.
- Buoyancy distribution in convective updraft is not affected by model resolution.
- Thermodynamic properties of the updrafts unaffected by model resolution.
- Minor impact of isotropic turbulence scheme on updraft velocity and thermodynamics.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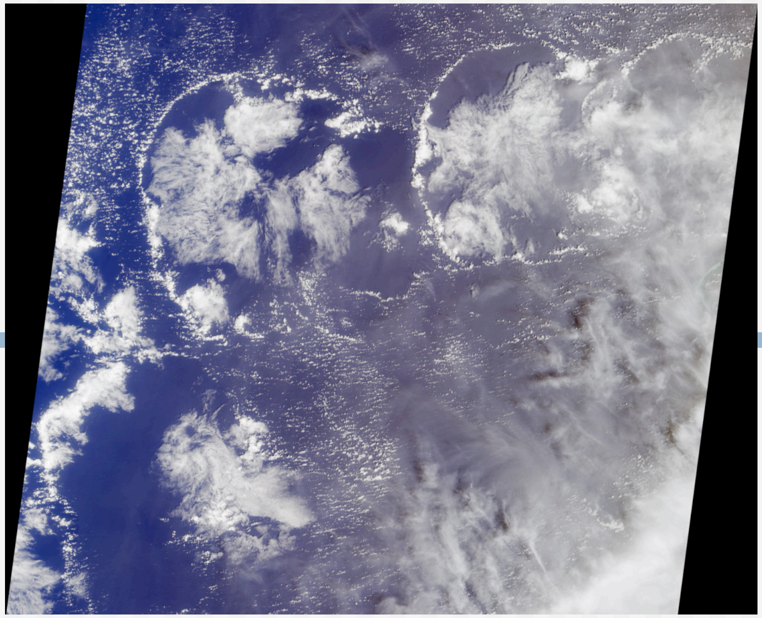
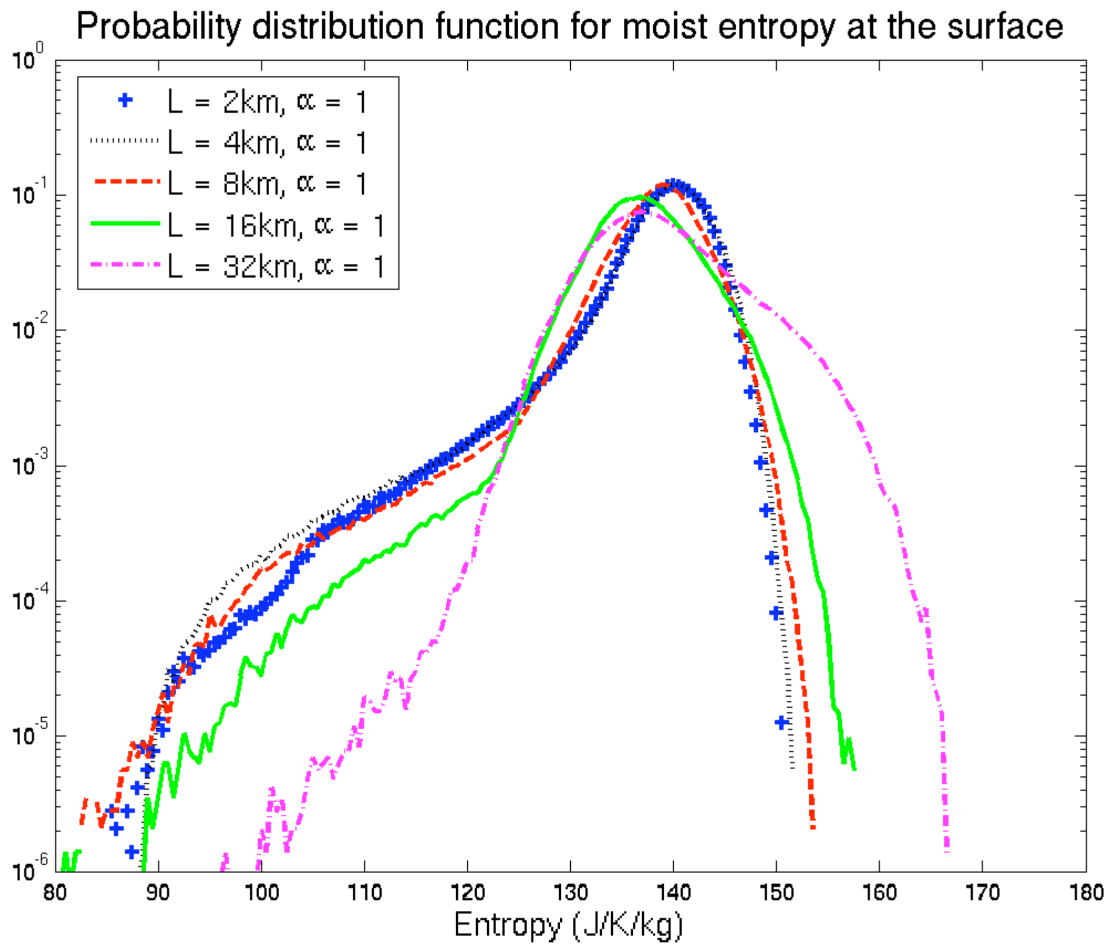


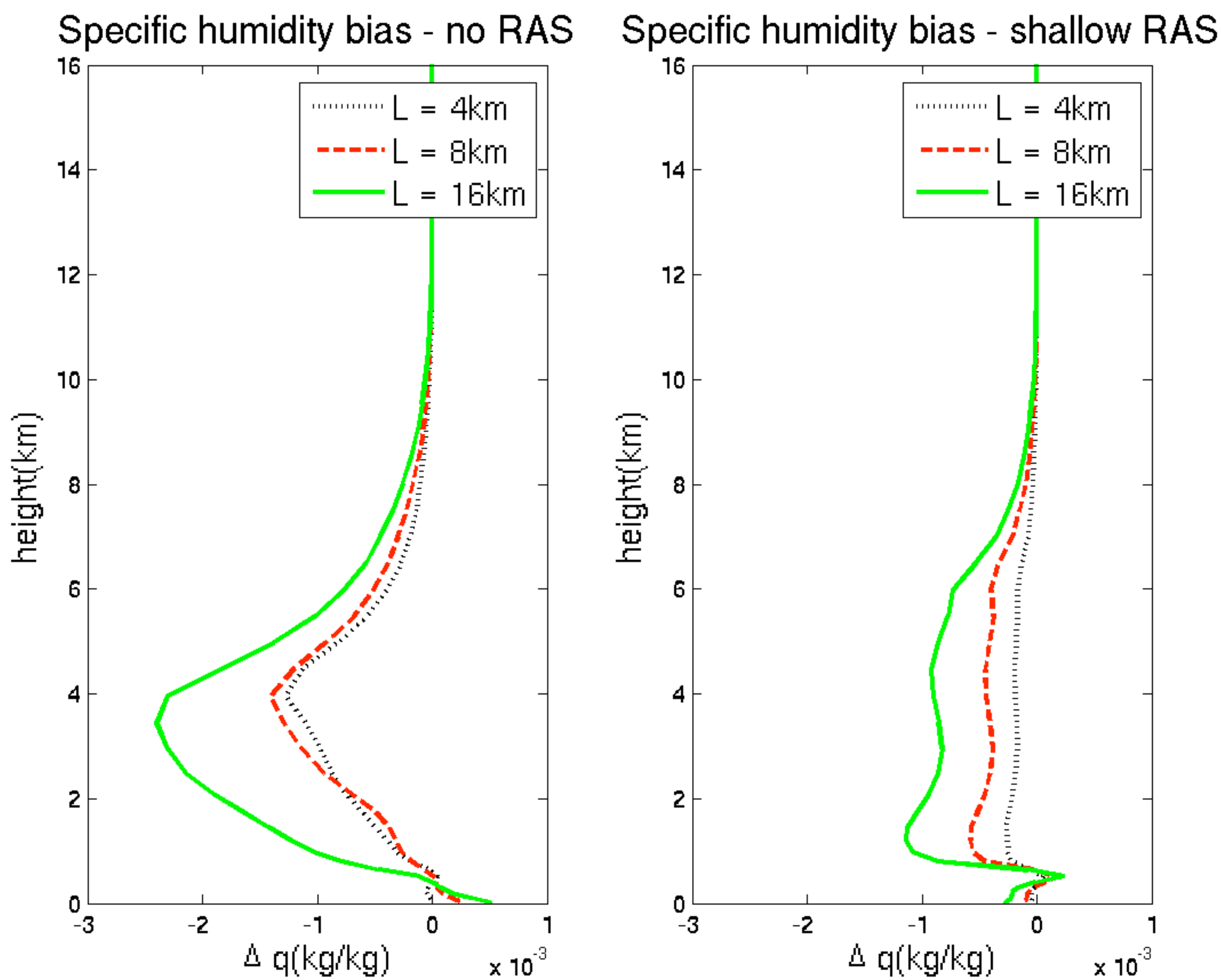
- Cold pool dynamics takes place at scale much larger than the updrafts.
- Tompkins (2001) argues that the cold pool dynamics plays a fundamental role in regenerating the unstable air masses



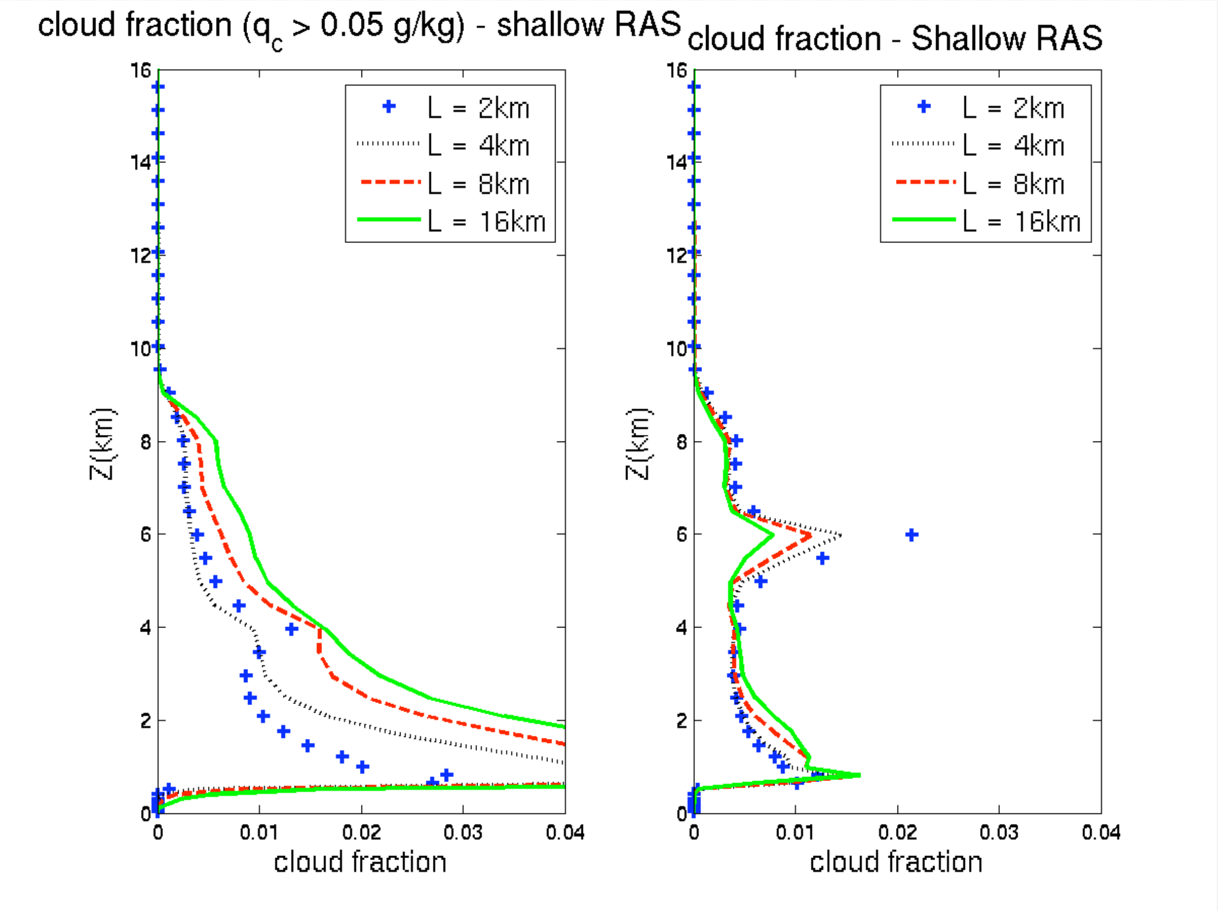
$$\delta \mathrm{CAPE} \approx (T_{surf} - T_{LNB})\delta S$$

$$\approx \frac{T_{surf} - T_{LNB}}{T_{surf}} L_v \delta q \approx 800 J kg^{-1} \delta q$$

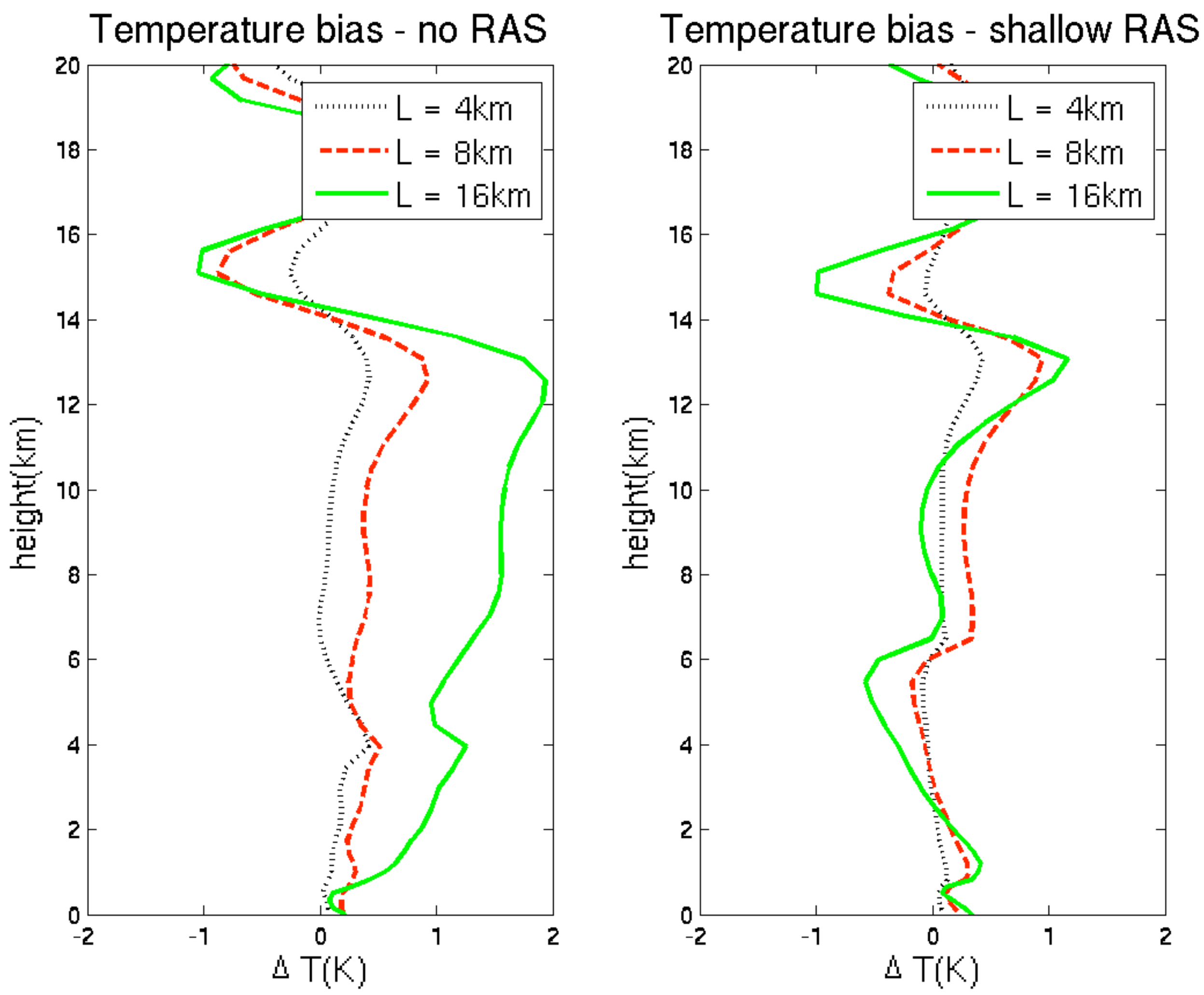
- Deep convection well behaved for resolution up to ~16km.
- Confirmed by scaling law which indicates only a weak reduction in vertical velocity at coarse resolution.
- But significant bias for temperature, humidity and low level cloudiness, related to a poor representation of shallow convection.
- Re-do the sensitivity studies, but using a strip down Relaxed Arakawa Schubert (RAS) as a poor man shallow convection scheme with:
  - No precipitation from RAS.
  - RAS is not allowed to go above 500mb.



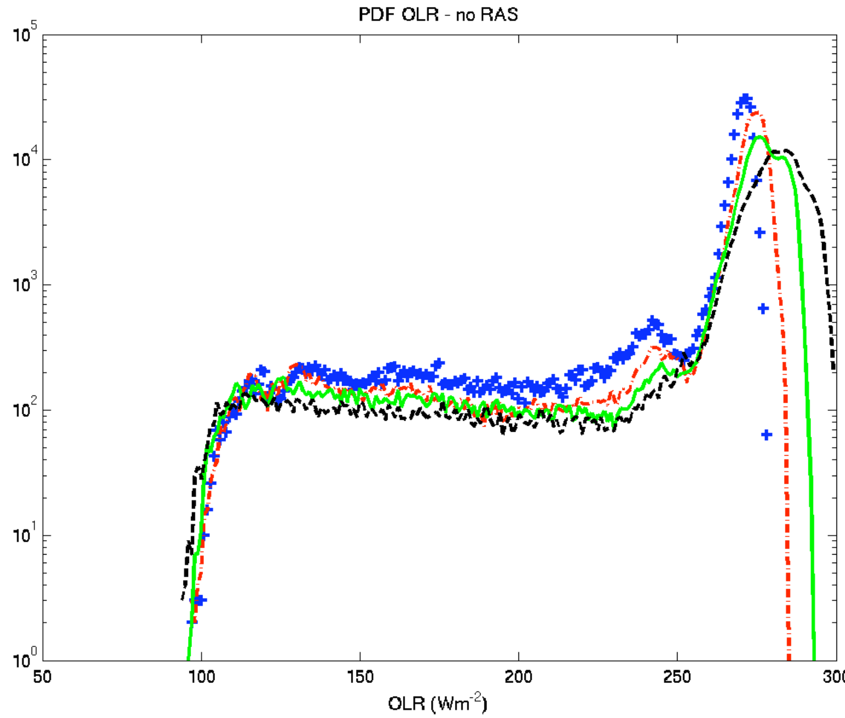
Specific humidity bias - no RAS
Specific humidity bias - shallow RAS
L = 4km
L = 8km
L = 16km
height(km)
Δ q(kg/kg)
x 10^-3

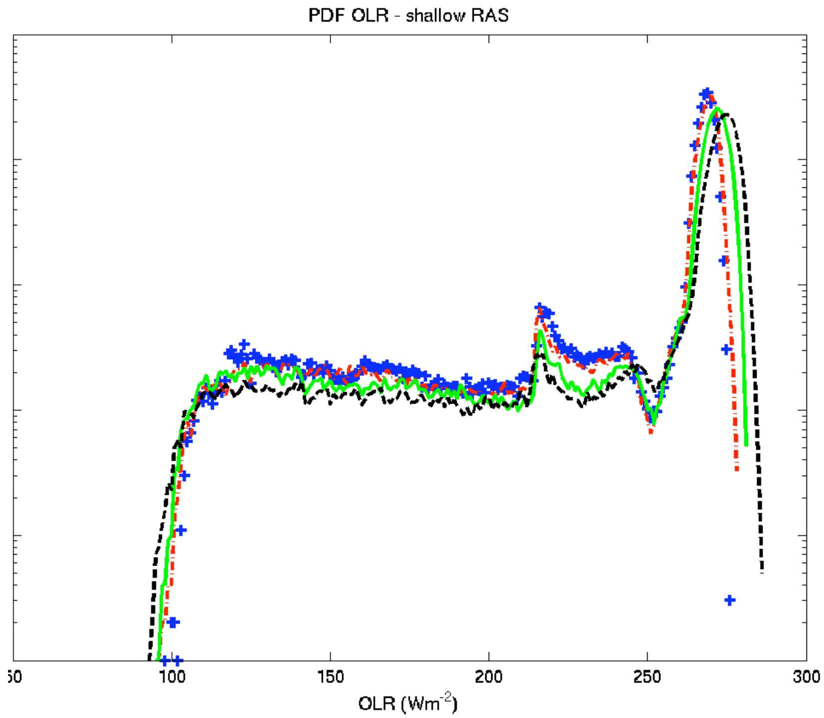


- Reduction in the bias for low level cloudiness
- The peak at 6km corresponds to the 500 mb level and is most likely related to the use of RAS for shallow convection.



- The temperature bias has also decreased.

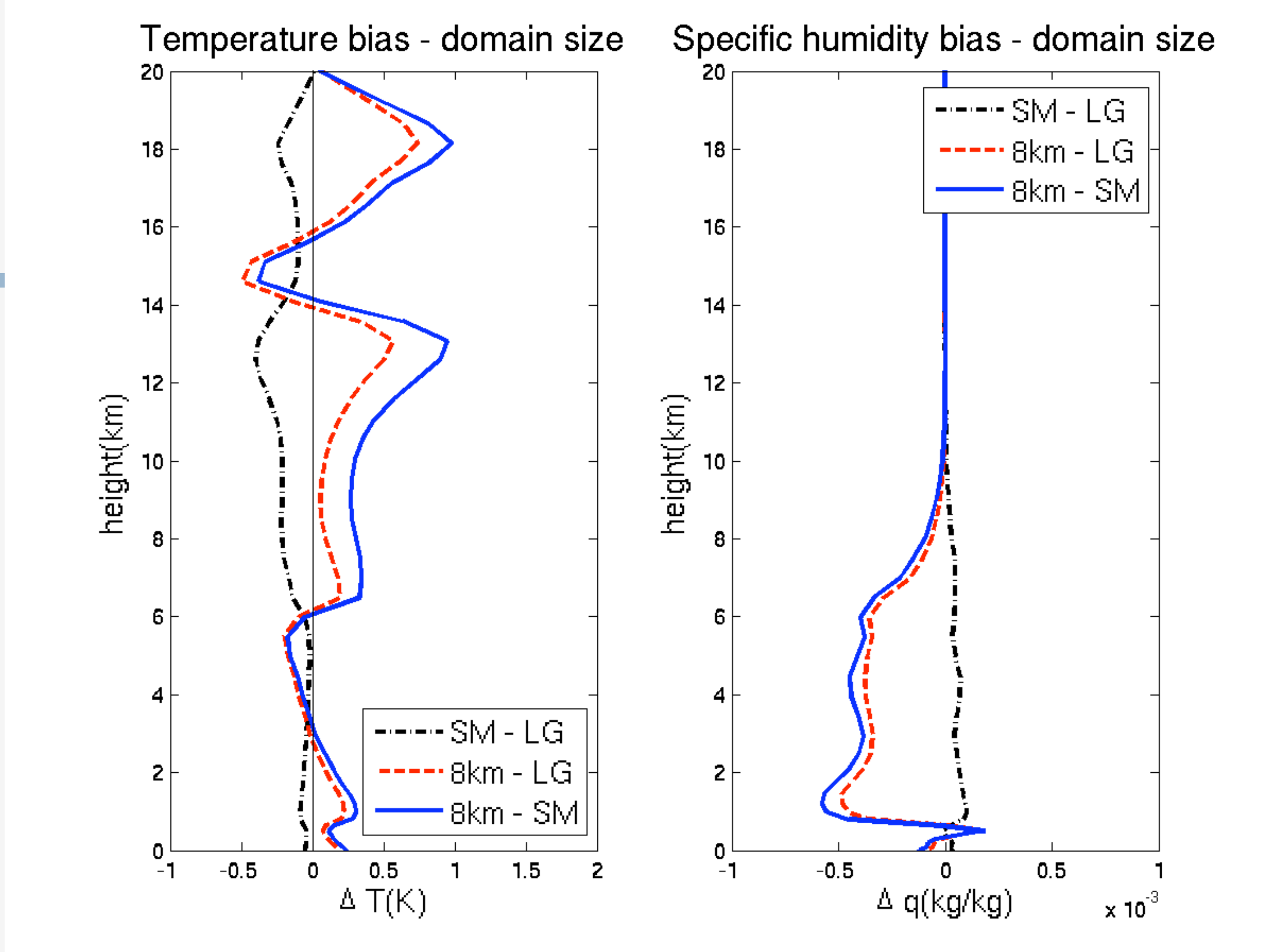




No shallow RAS

With shallow RAS

- Reduction of the humidity bias also reduces the OLR error (error~5-10Wm^{-2})



The temperature bias is partially caused by the difference in domain size

Conclusion

- The vertical velocity of deep convection to horizontal resolution is only weakly sensitive to horizontal resolution.
- Scaling law is confirmed by numerical simulations

$$w \approx \frac{w_0}{(1 + \frac{L}{\Delta Z})^{\frac{1}{2}}}$$

- Coarse resolution simulations are however marked by warm and dry bias.
- Inclusion of a (crude) representation for shallow convection does improve the convergence.
- Domain size has an impact on the temperature bias.
- It should possible to reproduce the behavior of a 2km resolution model with a 10-15km resolution.

TO-DO List

- Better shallow convection scheme.
- Study the sensitivity
  - of the horizontal velocity transport and spectrum.
  - of the onset of convection.
- Rescaling approach to improve the model behavior (e.g. hyper-hydrostatic scaling)