Implementing Arakawa's Unified Parameterization in the CAM

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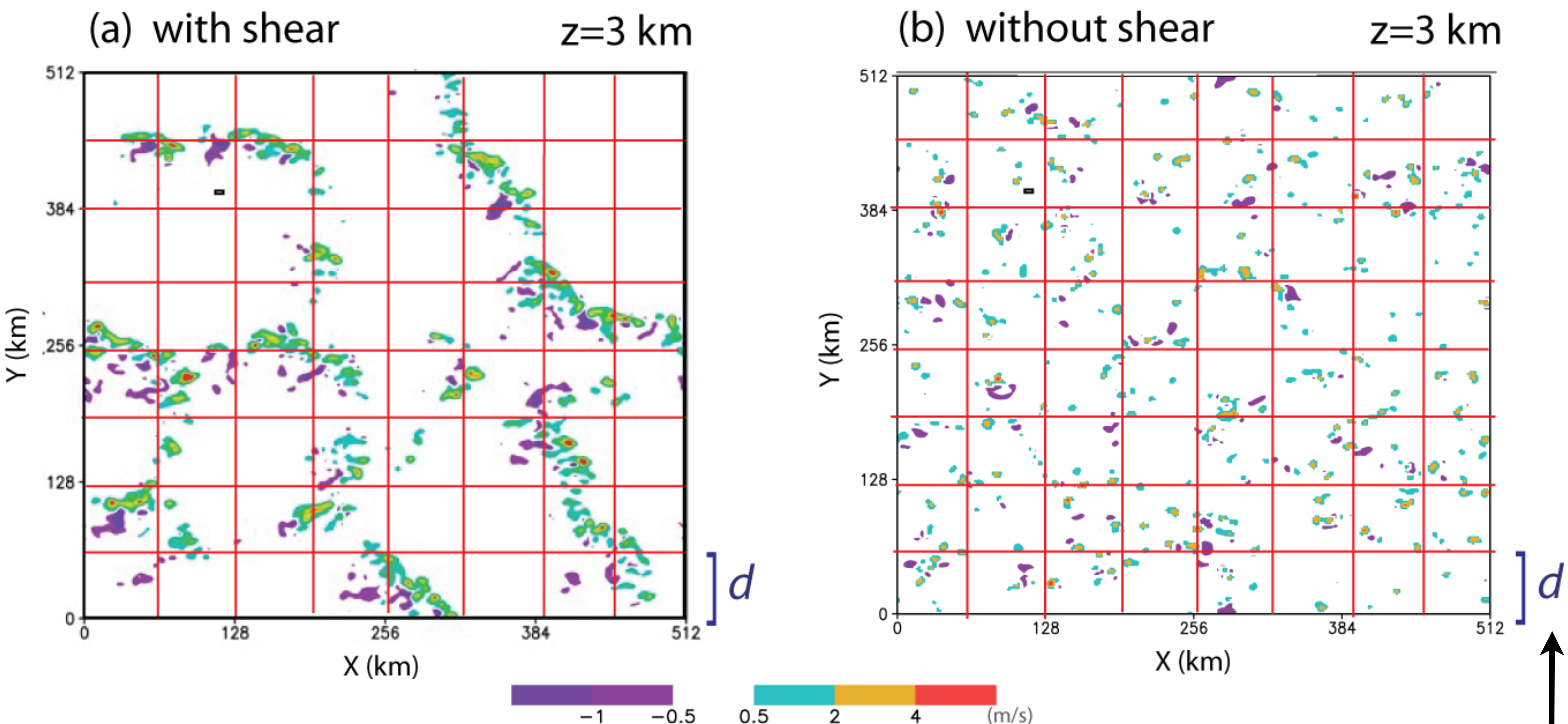
Goal:

- Grow individual clouds when/where the resolution is high.
- Parameterize convection when/where resolution is low.
- Continuous scaling.
- One set of equations, one code.
- Physically based.

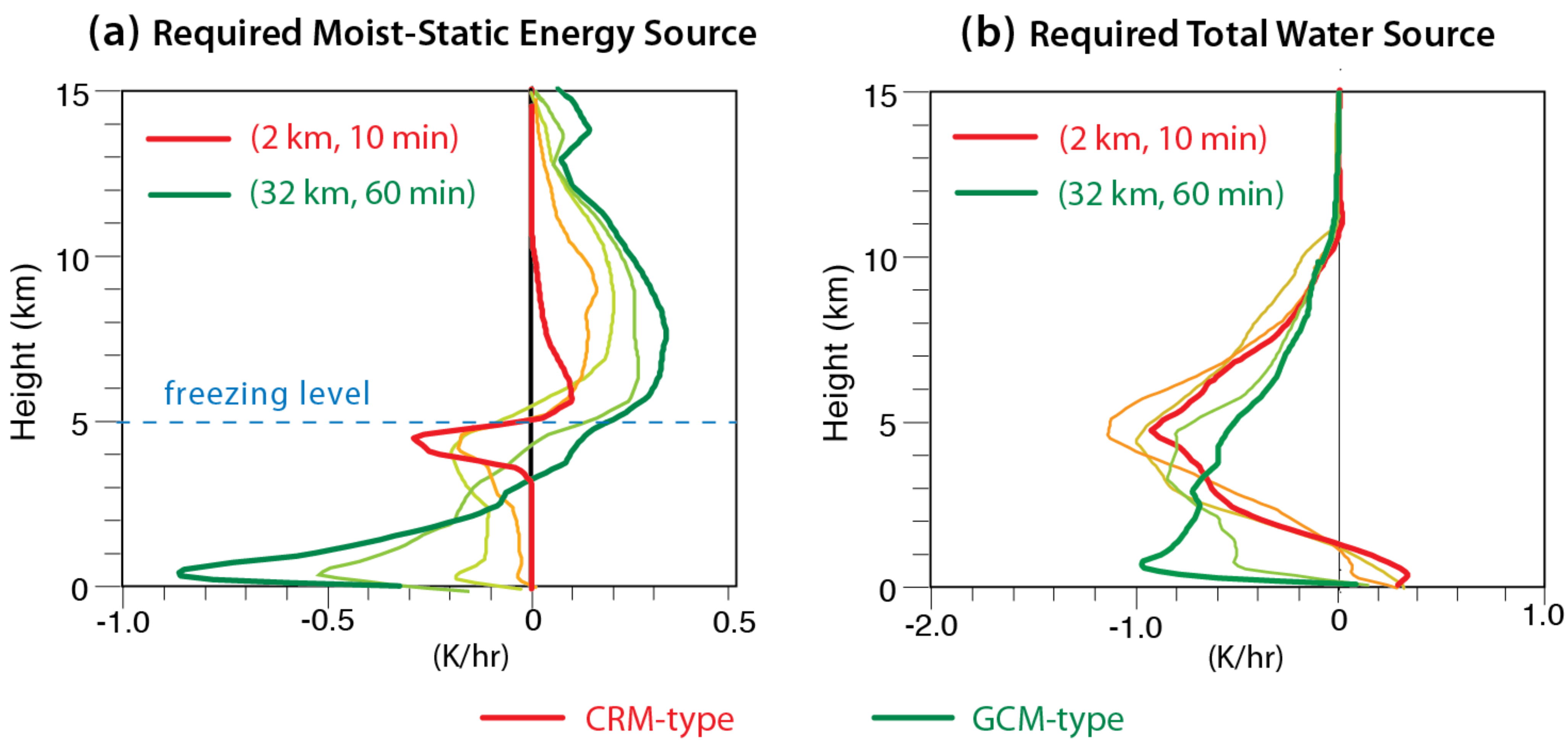
Use a CRM to test ideas.



Vertical velocity 3 km above the surface

Subdomain size, used to analyze dependence on grid spacing

An example of resolution-dependence



Jung, J.-H. and A. Arakawa, 2004.: The resolution dependency of model physics: Illustrations from nonhydrostatic model experiments. *J. Atmos. Sci.*, **61**, 88-102.

Starting point

For the case of a top-hat PDF, we can derive

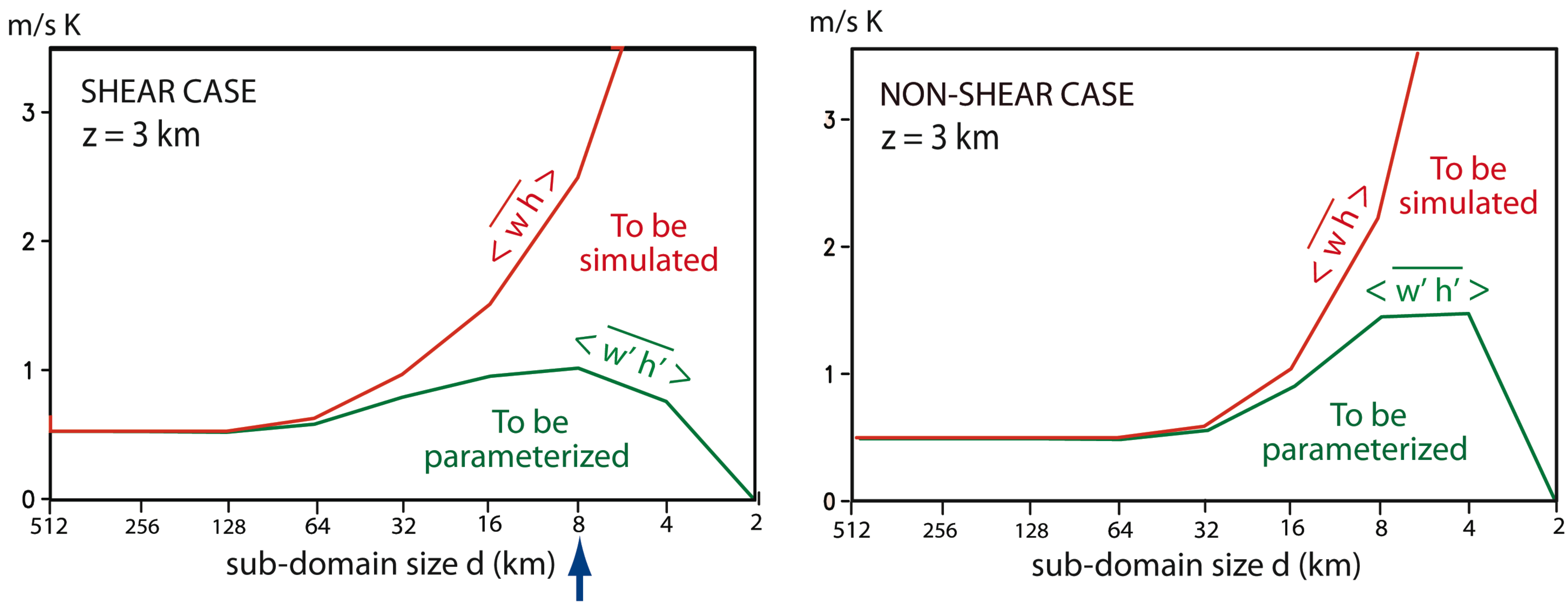
$$\overline{w'\psi'} \equiv \overline{w\psi} - \overline{w}\,\overline{\psi} = \sigma(1-\sigma)\Delta w \Delta\psi \ , \tag{1}$$

where

$$\left(\bar{\ }\right) \equiv \sigma(\ )_c + (1-\sigma)\left(\tilde{\ }\right) \text{ and } \Delta(\ ) \equiv (\ )_c - \left(\tilde{\ }\right), \tag{2}$$

σ is the fractional area covered by the updraft, an overbar denotes a domain mean, the subscript c denotes a cloud value, and a tilde denotes an environmental value. We expect Δw and $\Delta\psi$ to be independent of σ. In that case, (1) implies that $\overline{w'\psi'}$ is a parabolic function of σ.

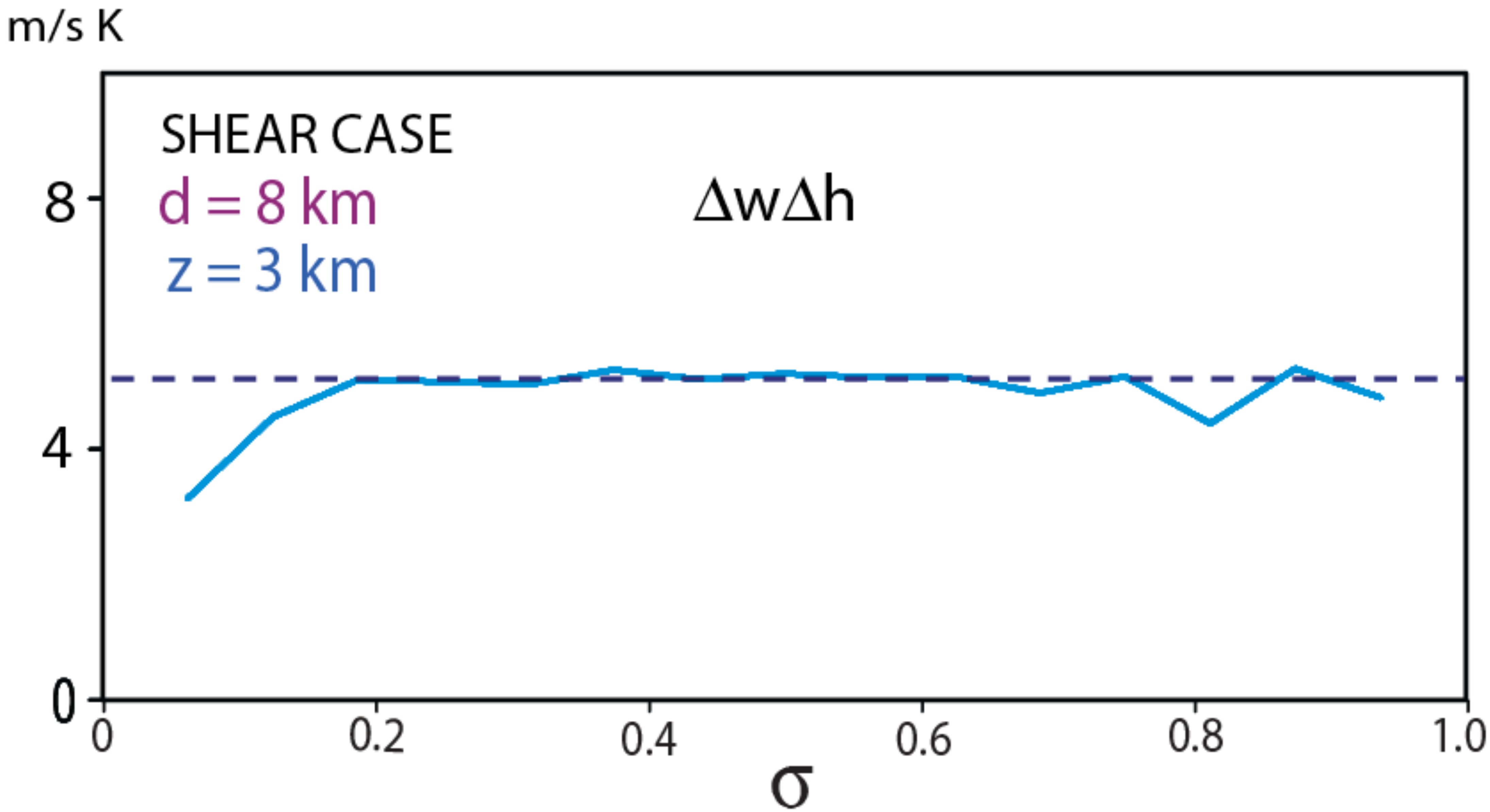
Flux as a function of grid size



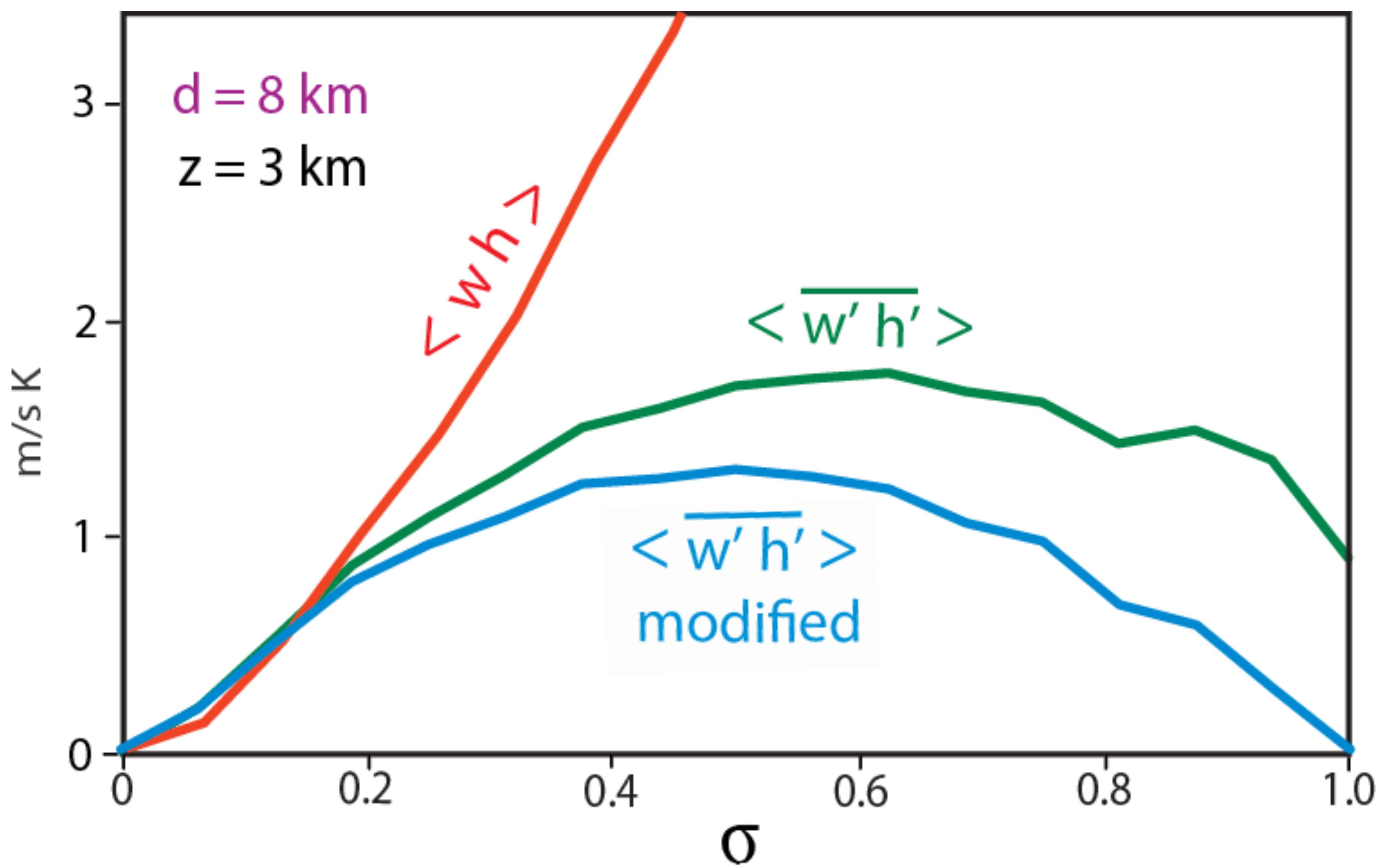
Red curve is total flux.
Green curve is subgrid flux to be parameterized.

The subgrid part is dominant at low resolution, but unimportant at high resolution.

Sigma independence



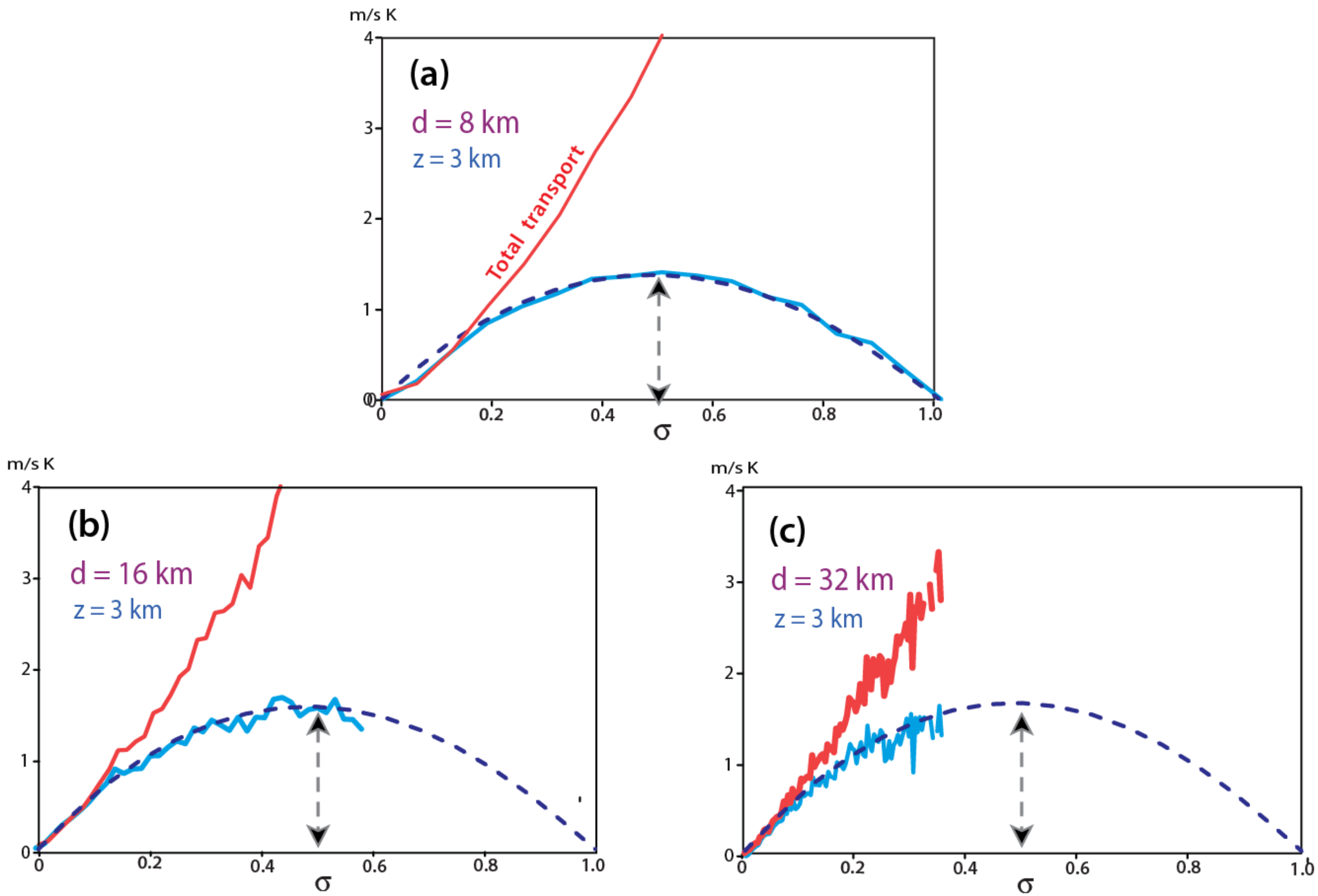
Test of Eq. (1)



$$\overline{w'\psi'} \equiv \overline{w\psi} - \overline{w}\,\overline{\psi} = \sigma(1-\sigma)\Delta w \Delta \psi$$

"Modified" means that the data is averaged over updrafts and environment before computing the flux. In other words, a "top-hat" structure is imposed by averaging.

Other resolutions



These results confirm the quadratic sigma dependence for three different grid spacings. Note that large sigma is only possible when the grid spacing is fine.

Closure assumption

Define $\left(\overline{w'\psi'}\right)_E$ as the flux required to maintain quasi-equilibrium. The closure assumption used to determine σ is

$$\boxed{\sigma = \frac{\left(\overline{w'\psi'}\right)_E}{\Delta w \Delta \psi + \left(\overline{w'\psi'}\right)_E}} \, . \tag{3}$$

The quantities on the right-hand side of (3) are expected to be independent of σ. Eq. (3) is guaranteed to give

$$0 \le \sigma \le 1 \, . \tag{4}$$

By combining (3) and (1), we obtain

$$\boxed{\overline{w'\psi'} = (1-\sigma)^2 \left(\overline{w'\psi'}\right)_E} \, . \tag{5}$$

This shows that the actual flux is typically less than the value required to maintain quasi-equilibrium. In fact, the actual flux goes to zero as $\sigma \to 1$.

A model predicts grid cell means, rather than environmental values, so direct use of (3) is not possible. Define

$$\delta(\ ) \equiv (\ )_c - \left(\overline{\ }\right).$$

(6)

It follows that

$$\delta(\ ) = (1-\sigma)\Delta(\ ).$$

(7)

If $\Delta(\ )$ is independent of σ, then $\delta(\ )$ decreases (in absolute value) as σ increases. We use

$$\Delta w \Delta \psi = \frac{\delta w \delta \psi}{(1-\sigma)^2}$$

(8)

to express the closure assumption, (3), as

$$\sigma = \frac{\left(\overline{w'\psi'}\right)_E}{\dfrac{\delta w \delta \psi}{(1-\sigma)^2} + \left(\overline{w'\psi'}\right)_E}.$$

(9)

Eq. (9) can be rearranged to

$$\sigma = \frac{\lambda(1-\sigma)^2}{1+\lambda(1-\sigma)^2}, \tag{10}$$

where

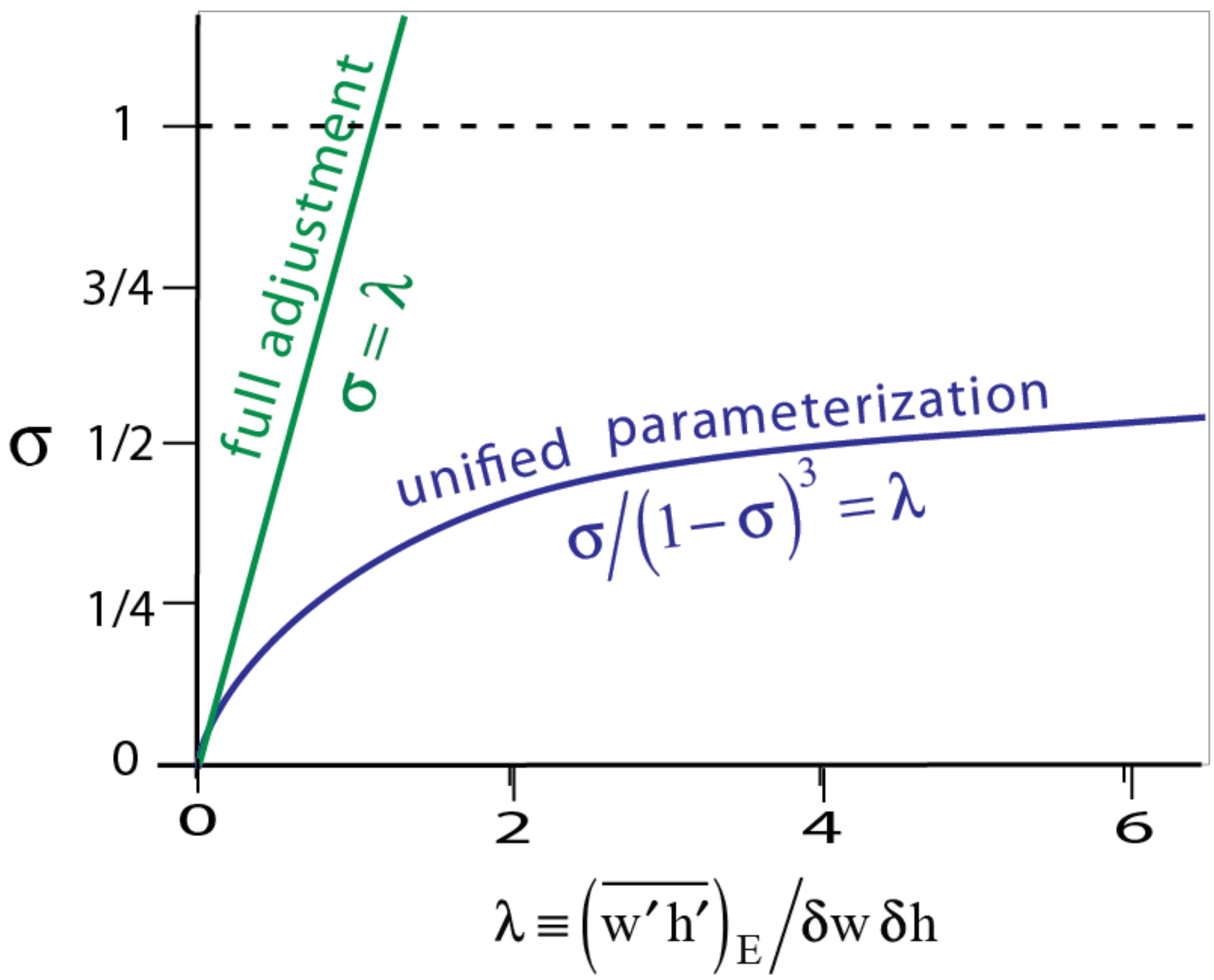
$$\lambda \equiv \frac{\left(\overline{w'\psi'}\right)_E}{\delta w \delta \psi} \tag{11}$$

can be computed using a plume model with quasi-equilibrium closure, provided that the plume model determines the in-cloud vertical velocity, e.g., by solving the equation of vertical motion. In fact, λ is equal to the value that σ would take with quasi-equilibrium closure, although (11) does not guarantee that $\lambda \ll 1$, or even that $\lambda < 1$.

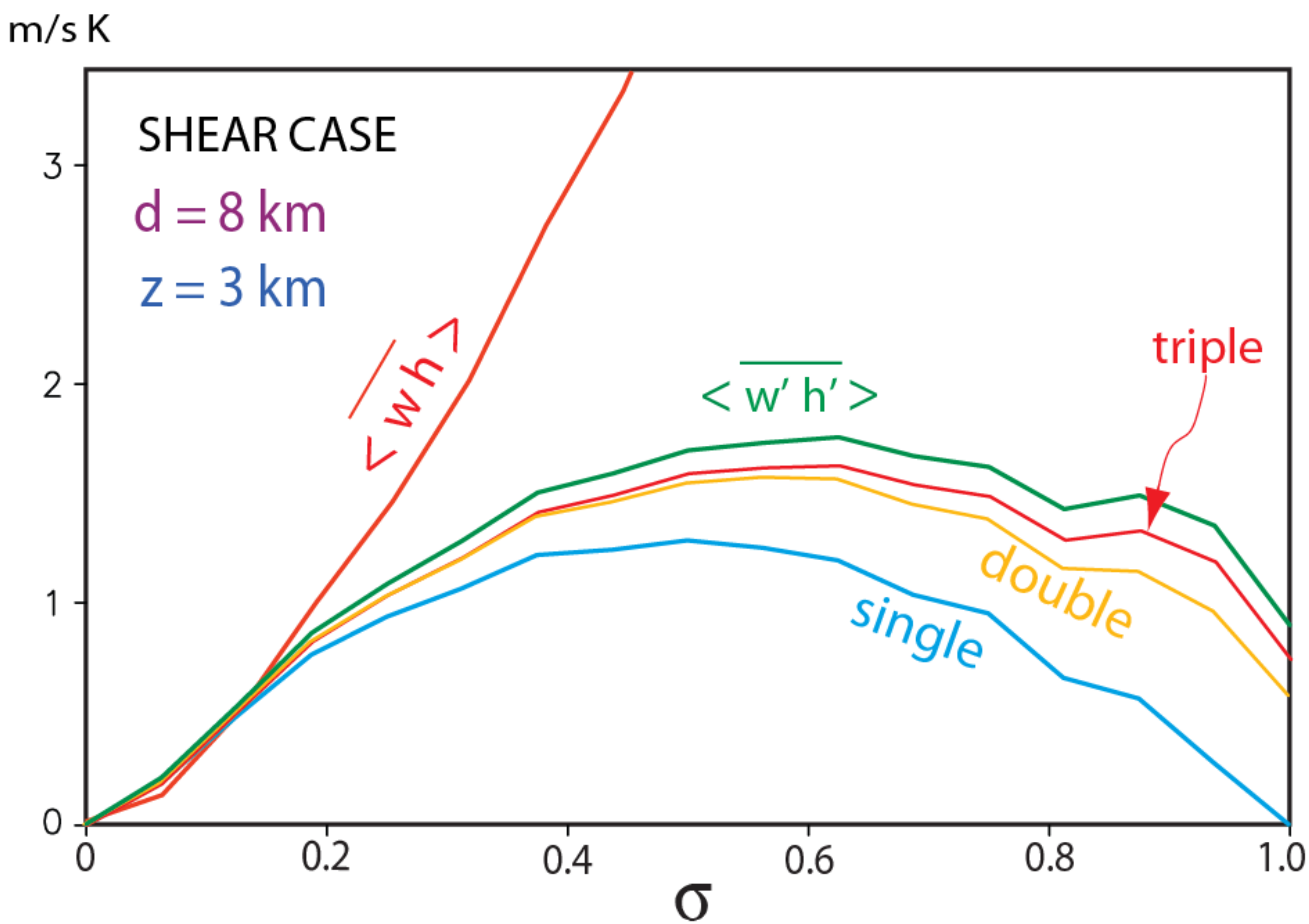
Eq. (10) must be solved as a cubic equation for σ as a function of λ:

$$\boxed{\lambda(1-\sigma)^3 + (1-\sigma) - 1 = 0}. \tag{12}$$

How sigma depends on lamda



Including substructure



Substructures are significant for large sigma, but the eddy flux becomes unimportant for large sigma.

Implementation

1. Choose an existing conventional parameterization that includes the equation of vertical motion for the plumes.

2. Using the plume model, calculate $\left(\overline{w'\psi'}\right)_E$ and δw , and $\delta\psi$. These will be functions of height. To determine δw and $\delta\psi$, we have to choose a particular cloud type.

3. Evaluate λ using (11) and σ using (12). These will be functions of height.

4. Use (5) to “scale back” the convective fluxes.

5. Scale the “non-convective” parts of the tendencies (e.g., the condensation rate) with σ .

References

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AA is currently working on two more papers.