Unified deep cumulus parameterization for numerical modeling of the atmosphere

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LCDM

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Families of atmospheric models…

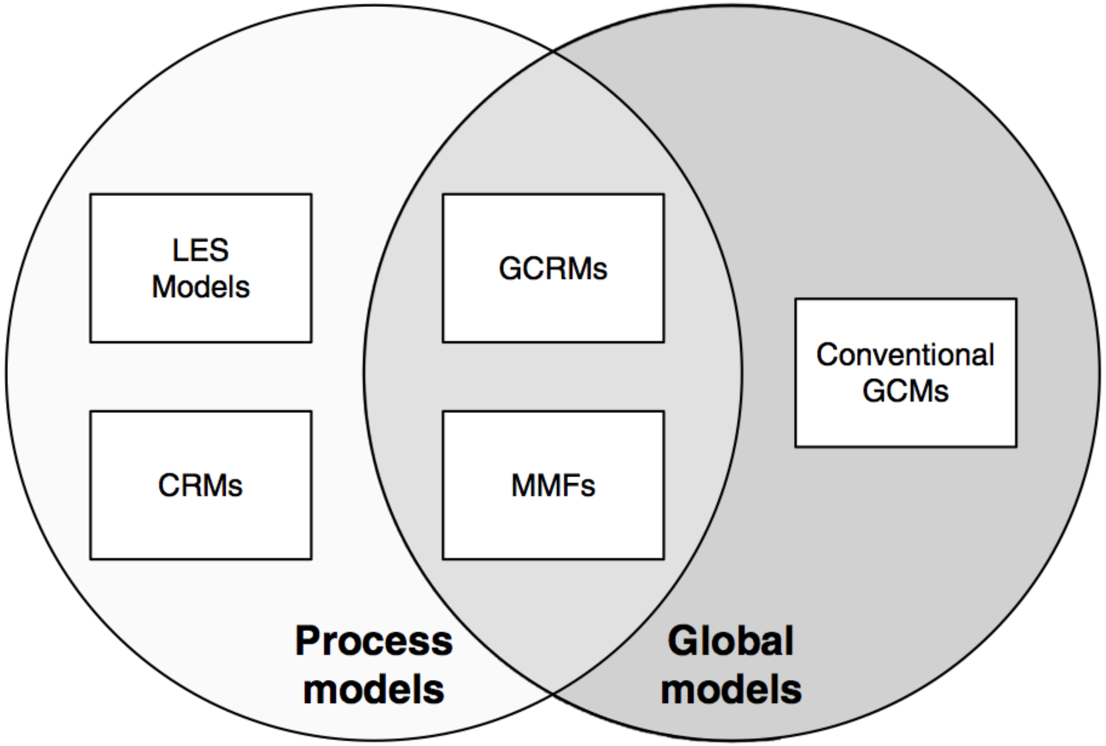


Figure 1. In this Venn diagram, the circle on the left represents process models, including both large-eddy simulation models (LES models) and CRMs. The circle on the right represents global atmospheric models. Until recently, these two classes of models did not overlap. Today, as shown in the figure, there is some intersection in the form of GCRMs and MMFs.

Randall 2013

Moist convection in the general circulation model

The cloud-scale interactions are parameterized using cumulus parameterization

APRIL 1974 AKIO ARAKAWA AND WAYNE HOWARD SCHUBERT

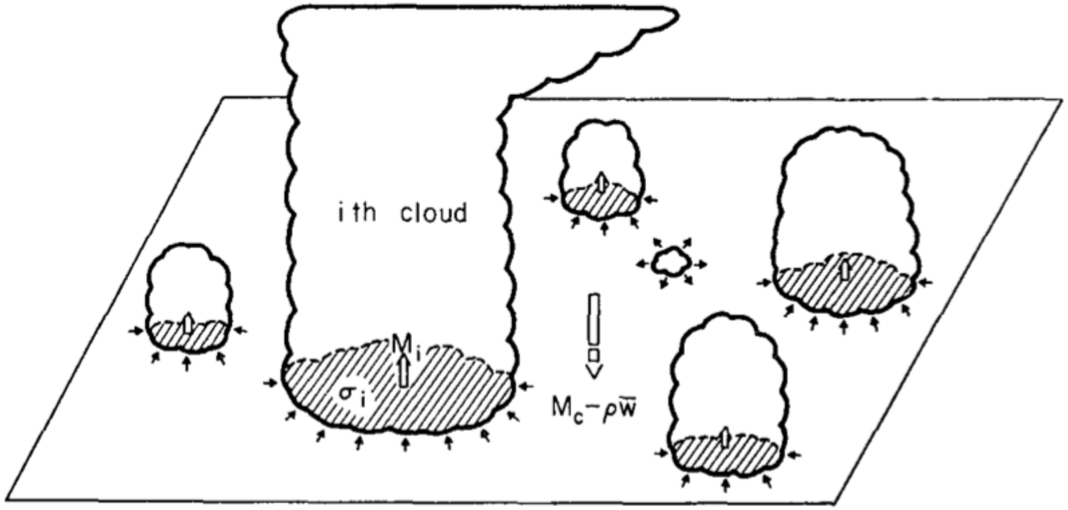
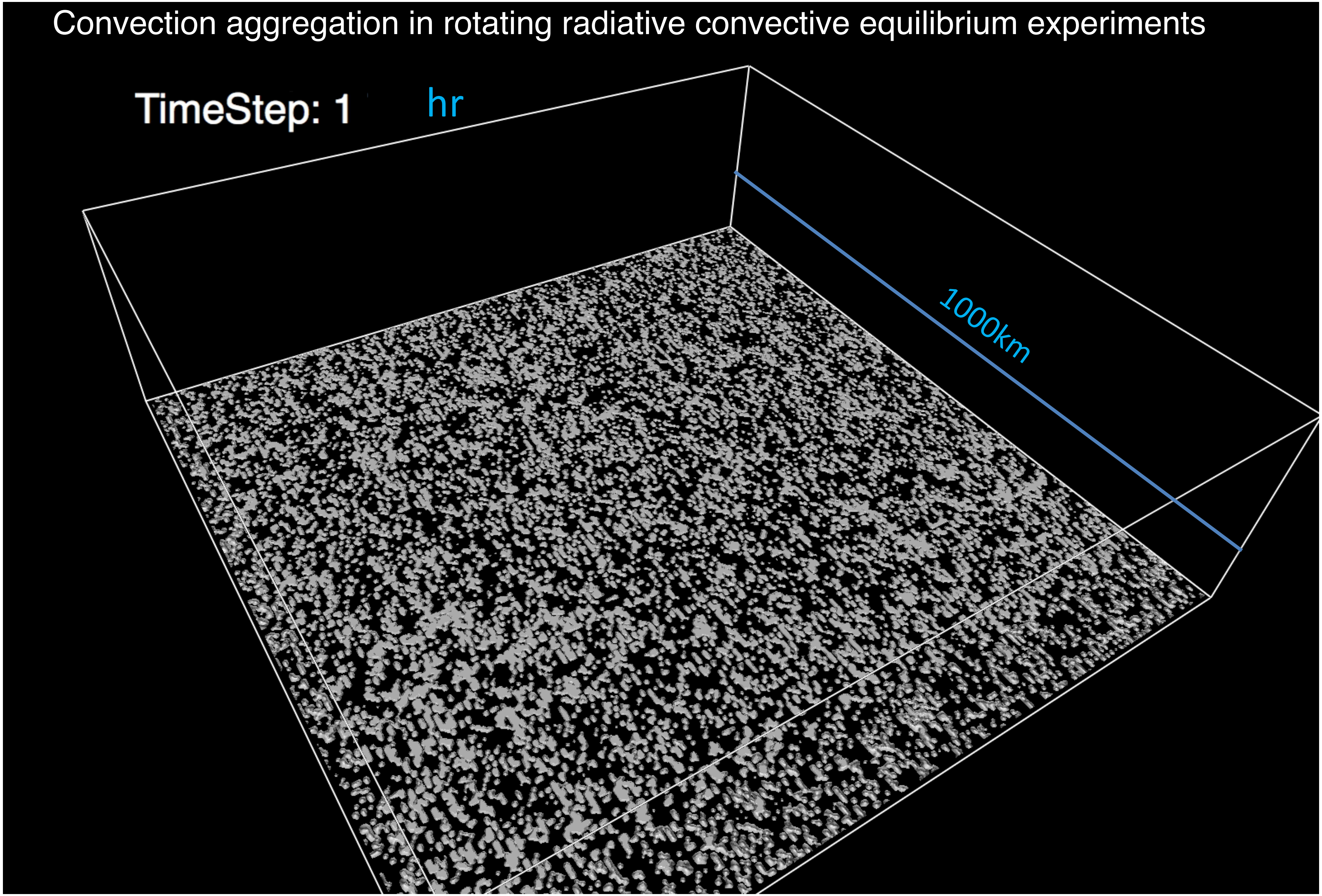


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

The problem of formulating the statistical effects of moist convection to obtain a closed system for predicting weather and climate.

Moist convection in the cloud-resolving model



Cloud resolving models are useful in understanding the ***transitions in convective systems*:**

- **Stratocumulus breakup** (Xiao, Wu et al. 2010, 2012, Tsai and Wu 2016)
- **Aggregated convection** (Tsai and Wu 2016)
- **Diurnal cycle evolution** (Wu et al. 2009, Wu et al 2015, Kuo and Wu 2016)
- **Immersed boundary method** in Vector vorticity equation model. (Wu and Arakawa 2011, Chien and Wu 2016)
- **Unified parameterization** (Arakawa, Jung and Wu 2011, Arakawa and Wu 2013, Wu and Arakawa 2014, Arakawa and Wu 2015, Xiao, Wu et al 2015).

BACKGROUND

As far as representation of deep moist convection is concerned, we have only two kinds of model physics :

highly parameterized,

and

explicitly simulated.

Conventional Parameterizations

Global circulation

Cloud-scale
&mesoscale
processes

Radiation,
Microphysics,
Turbulence

Parameterized

Slide from David Randall

Parameterize less at high resolution.

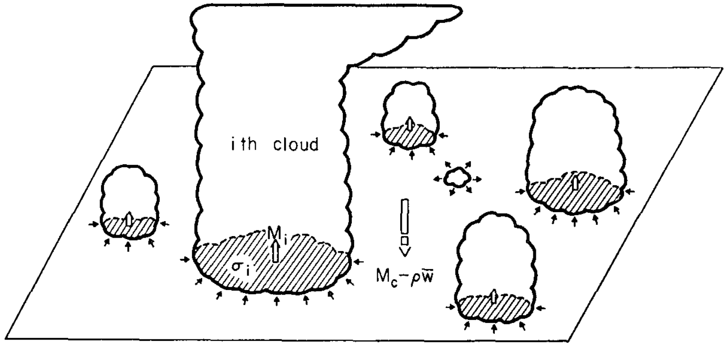
Global circulation

Cloud-scale &mesoscale processes

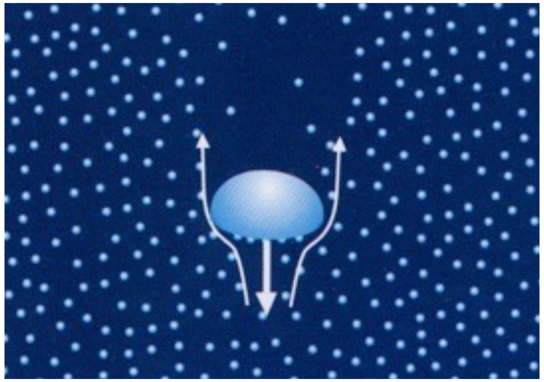
Radiation, Microphysics, Turbulence

Parameterized

Heating and drying on coarse and fine meshes



Increasing resolution



GCM

CRM

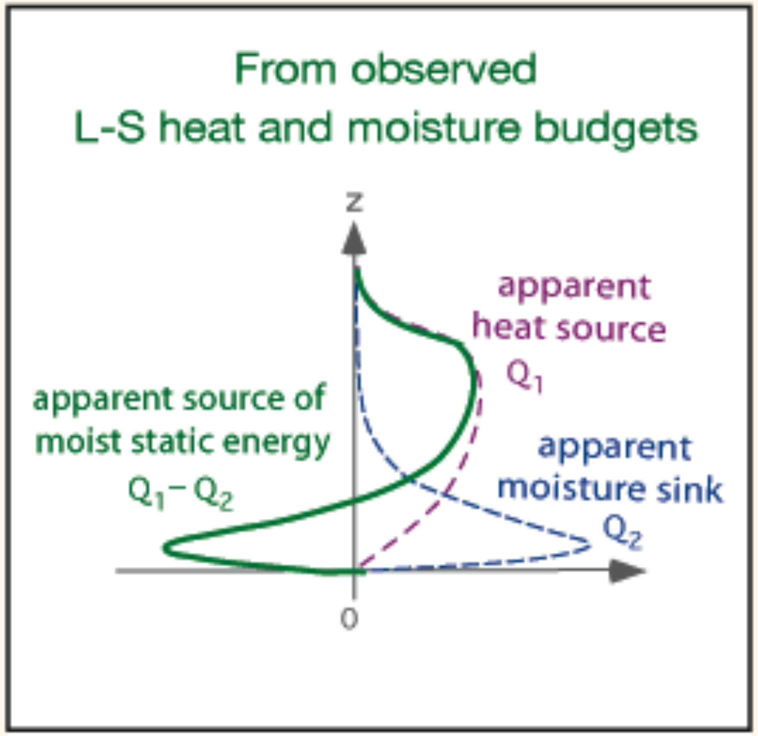
Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

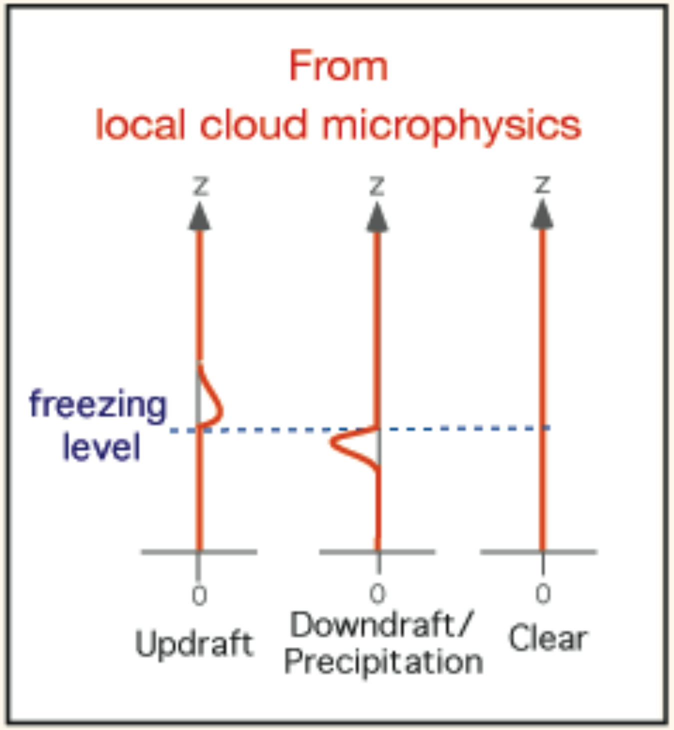
Expected values --> Individual realizations

Slide from David Randall

SCHEMATIC ILLUSTRATION OF MOIST STATIC ENERGY SOURCE UNDER TYPICAL TROPICAL CONDITIONS



From observed
L-S heat and moisture budgets



From
local cloud microphysics

GCM-type profile

CRM-type profile

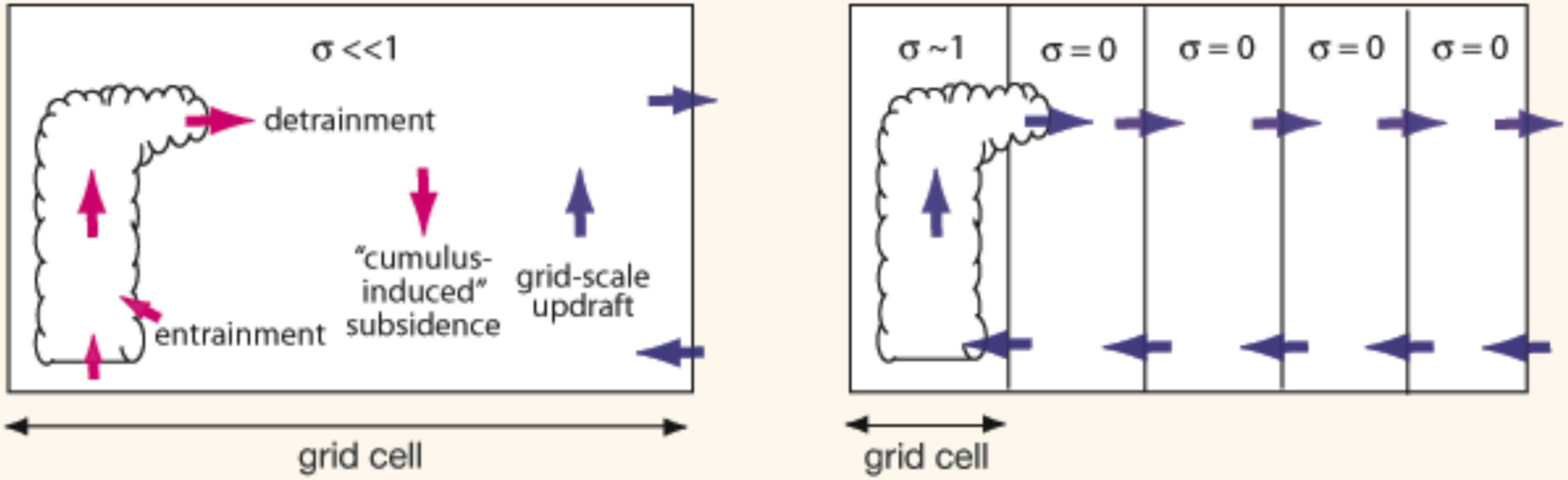
Any space/time/ensemble average of the profiles in the right panel does NOT give the profile in the left panel.

Jung and Arakawa (2005)

OPENING A ROUTE FOR UNIFIED PARAMETERIZATION

σ : the fractional area covered by *all convective clouds in a grid cell.*

- Most parameterization schemes assume σ << 1, either explicitly or implicitly.
- Then the temperature and water vapor to be predicted are essentially those variables for the cloud environment.



- But, if cloud occupies the entire cell, there is no "environment" within the cell.

A key to open this route is eliminating the assumption of σ << 1.

CRM SIMULATIONS USED

Dynamics: VVM (Jung and Arakawa 2008)

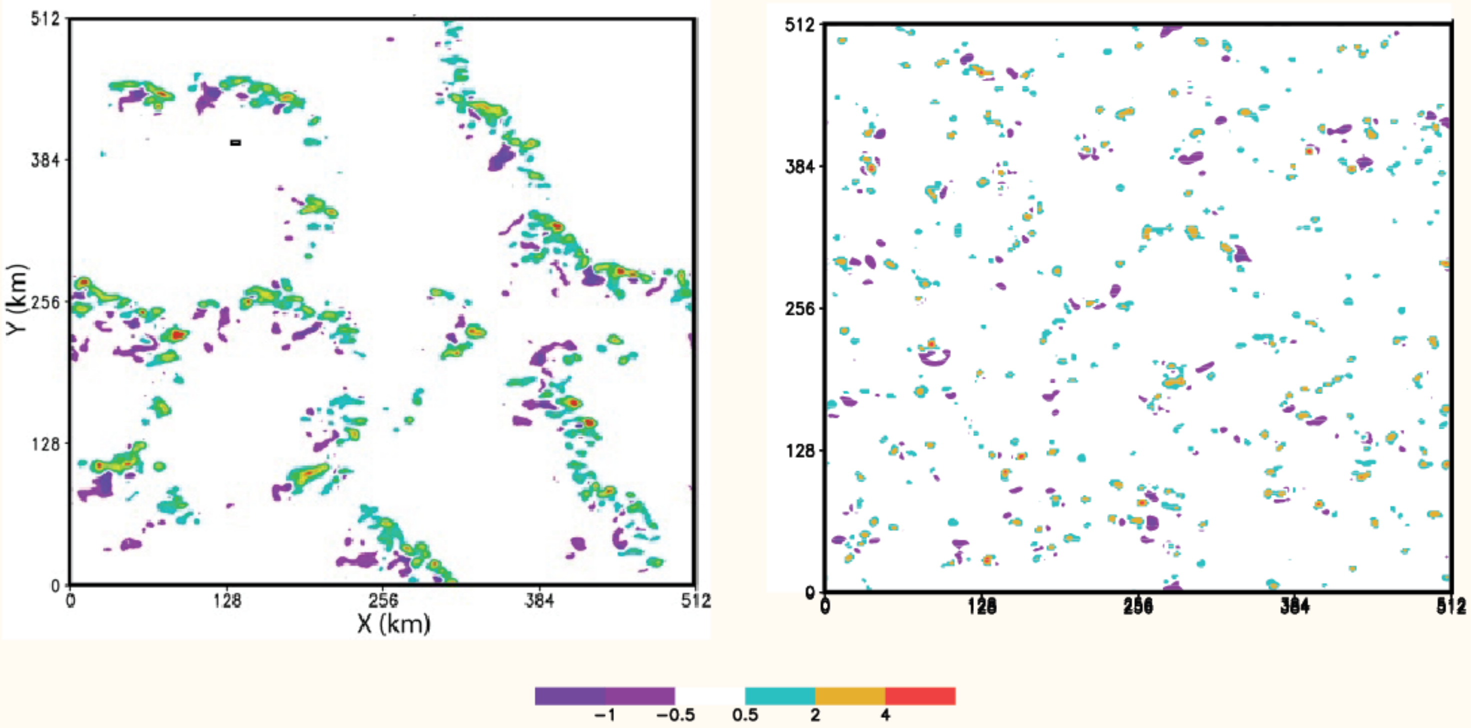
Cloood microphysics: Krueger et al. (1995)

Wu and Arakawa 2011
Chien and Wu 2016

Horizontal domain size : 512 km

Horizontal grid size : 2km

Snapshots of w at z=3 km


with background shear

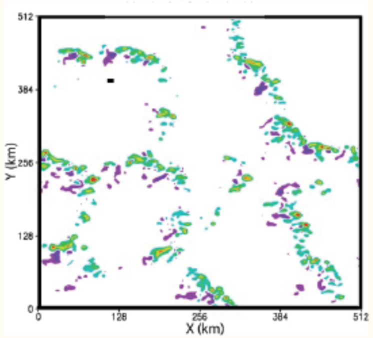
without background shear

ANALYSIS OF THE RESOLUTION-DEPENDENT STATISTICS OF THE CRM–SIMULATED DATA

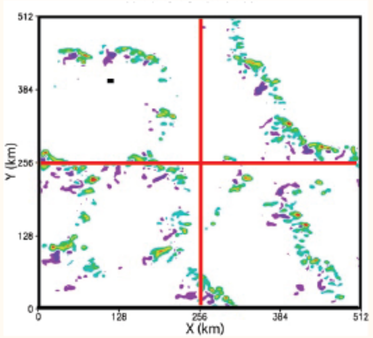
The original domain (512 km) used for CRM simulations is divided into sub-domains of same size.

Examples

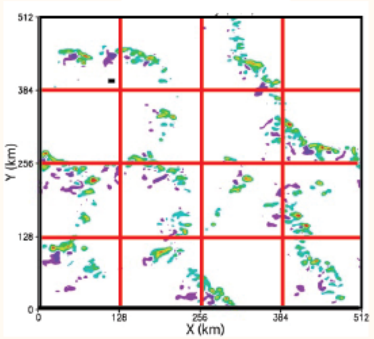
d = 512 km



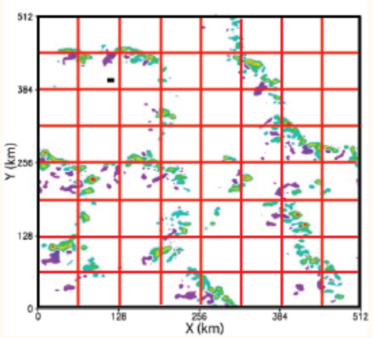
d = 256 km



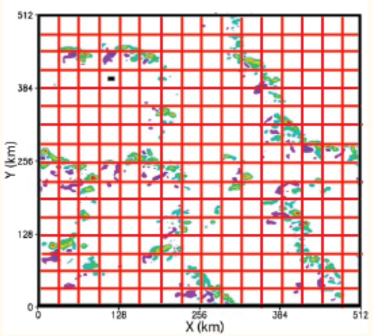
d = 128 km



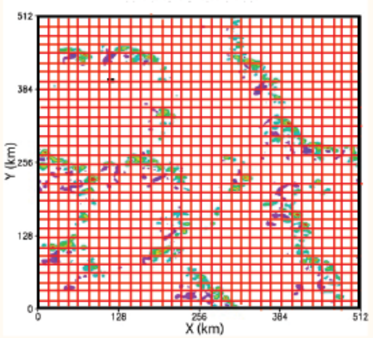
d = 64 km



d = 32 km



d = 16 km



■ ■ ■

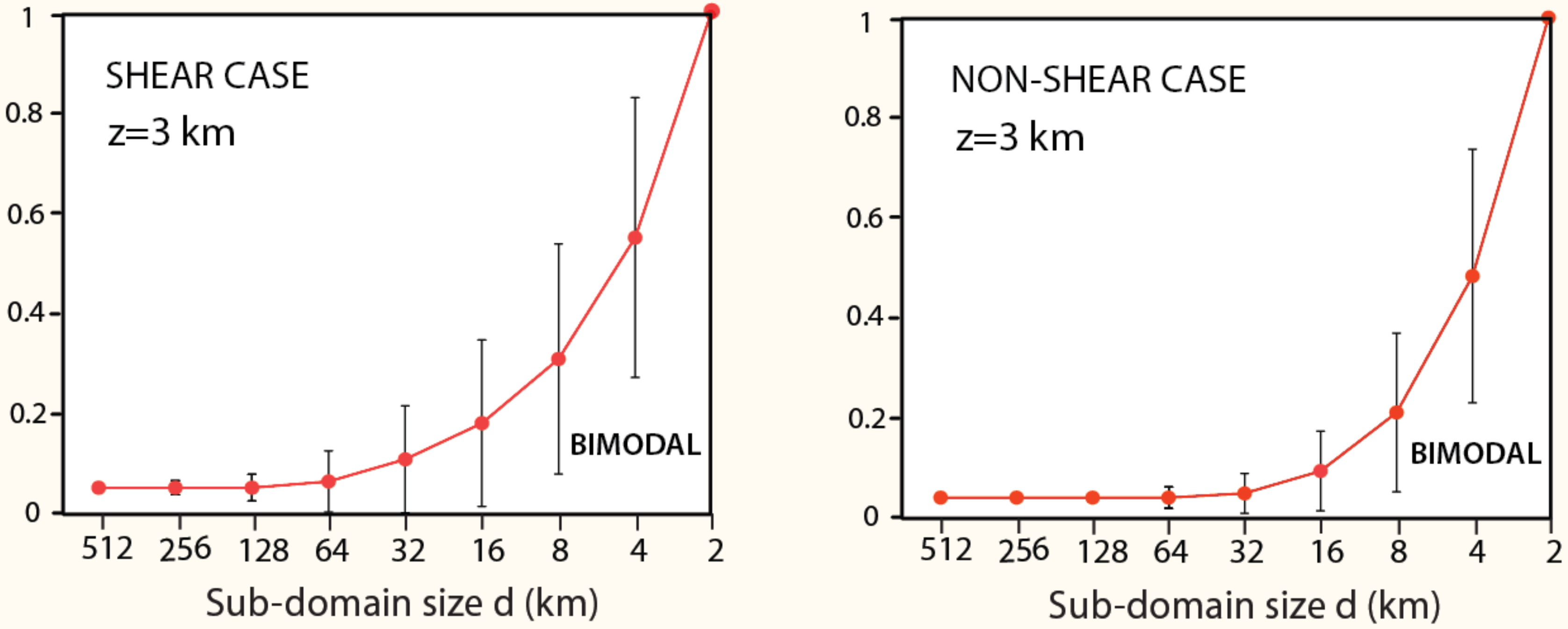
The size of subdomains is interpreted as the GCM grid size.

RESOLUTION DEPENDENCE OF ENSEMBLE-AVERAGE σ

σ: The fractional number of grid points with w>0.5 m/s in a sub-domain

< >: Average over an ensemble of cloud-containing (i.e., $\sigma > 0$) sub-domains

$< \sigma >$



The assumption σ<<*1 is valid only for low resolutions.*

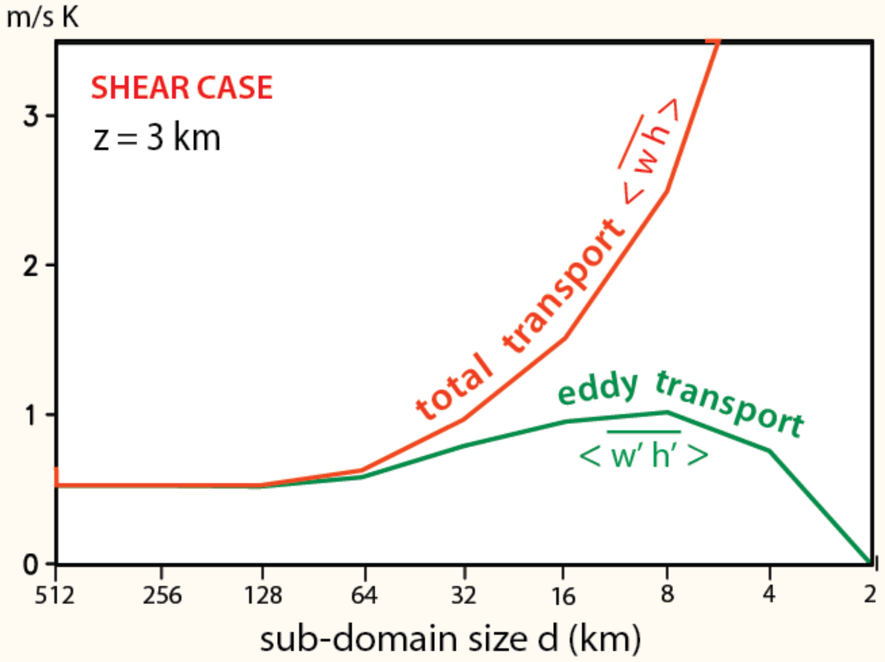
OBJECTIVE OF THE UNIFIED PARAMETERIZATION

Unification of the model physics of GCMs and CRMs

through *generalizing* conventional cumulus parameterizaion

RESOLUTION DEPENDENCE OF

ENSEMBLE-AVERAGE VERTICAL TRANSPORT OF MOIST STATIC ENERGY



h : Deviation of moist static energy from a reference state

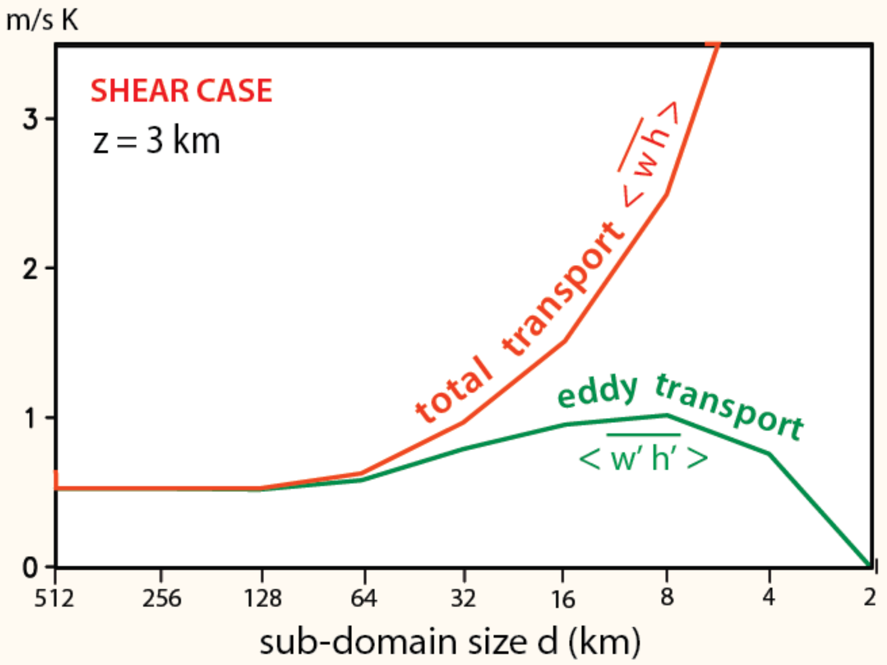
$\overline{(\ )}$: Average over all grid points in the sub-domain

$<\ >$: Ensemble average over all sub-domains with $\sigma > 0$.

$(\ )'$: $(\ ) - \overline{(\ )}$

As the resolution increases, the total transport tends to increase while the eddy transport for small d tends to decreease.

RESOLUTION DEPENDENCE OF ENSEMBLE-AVERAGE VERTICAL TRANSPORT OF MOIST STATIC ENERGY



h : Deviation of moist static energy from a reference state

$\overline{(\ )}$: Average over all grid points in the sub-domain

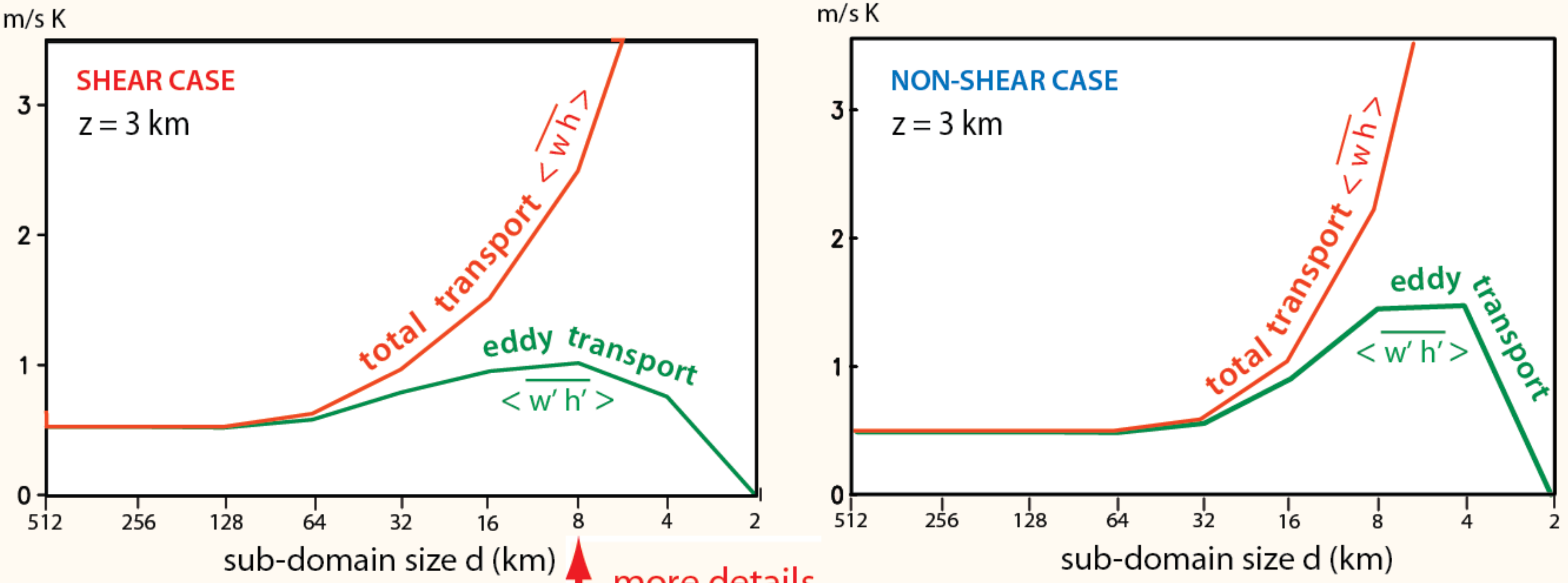
$<\ >$: Ensemble average over all sub-domains with $\sigma > 0$.

$(\ )'$: $(\ ) - \overline{(\ )}$

IMPORTANT !

Parameterization is a formulation of the eddy transport, NOT that of the total transport.

RESOLUTION DEPENDENCE OF
ENSEMBLE-AVERAGE VERTICAL TRANSPORT OF MOIST STATIC ENERGY



more details

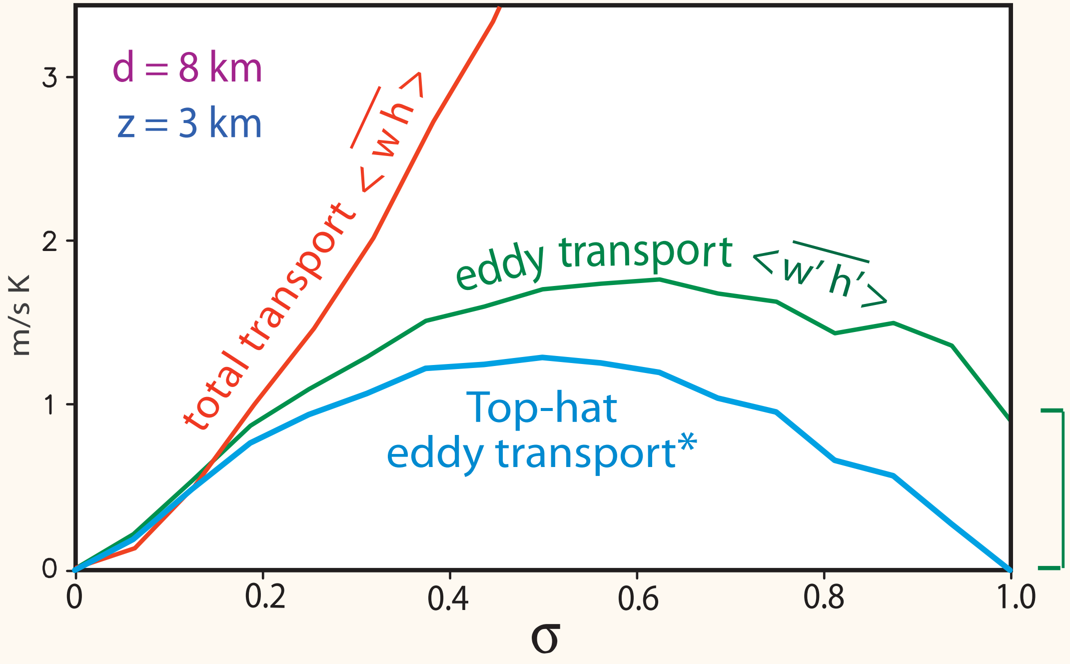
There is no qualitative differene between the shear and non-shear cases.

FIRST STEP TOWARD UNIFIED PARAMETERIZATION

Most conventional parameterizations assume that clouds and the environment are horizontally homogeneous.

–– "top-hat profile" ––

Continue to use this assumption to start.



* Diagnosed from a dataset modified to fit a top-hat profile

Transport due to the internal structure of clouds

EXPRESSIONS WITH TOP–HAT PROFILE

$( )_c$: cloud value $\widetilde{( )}$: environment value $\Delta( ) \equiv ( )_c - \widetilde{( )}$

$$\overline{( )} = \sigma( )_c + (1 - \sigma)\widetilde{( )}$$

$$\overline{w} = \tilde{w} + \sigma \Delta w \qquad \overline{\psi} = \tilde{\psi} + \sigma \Delta\psi$$

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

ψ: a thermodynamic variable

Conventional parameterization

$$\sigma \to 0: \qquad \overline{\psi} \to \tilde{\psi} \qquad \overline{w'\psi'} \to \underbrace{\sigma\, w_c}_{\text{cumulus massflux}} \Delta\psi$$

Unified parameterization

$$\sigma = \sigma: \quad \overline{\psi} = \tilde{\psi} + \sigma\Delta\psi \qquad \overline{w'\psi'} = \sigma(1-\sigma)\Delta w\,\Delta\psi$$

CLOUD PROPERTIES RELATIVE TO THE ENVIRONMENT

Recall

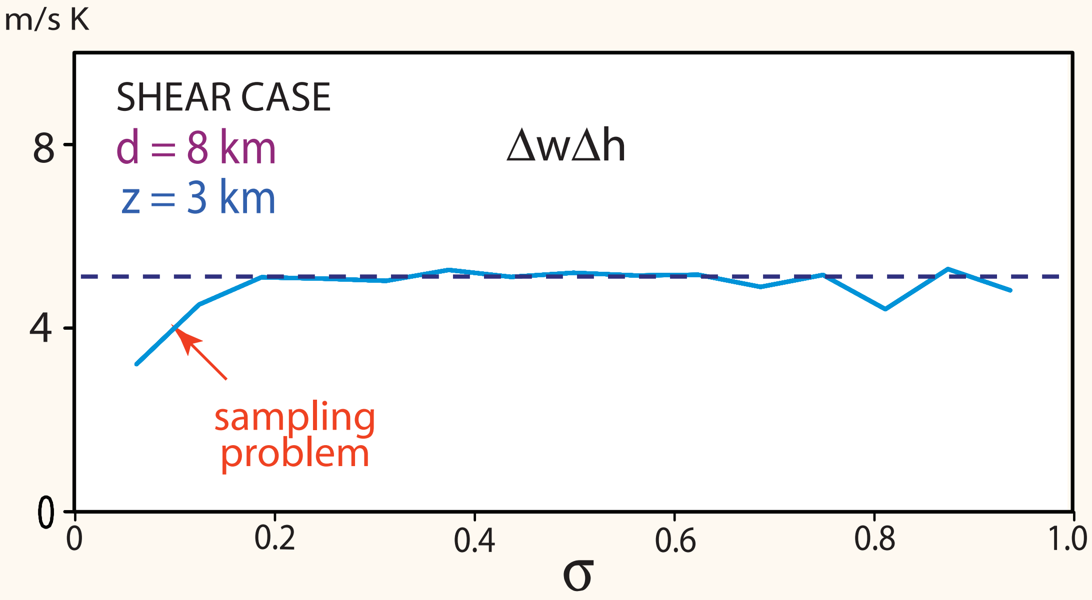
$$\Delta w \equiv w_c - \widetilde{w}$$

$$\Delta \psi \equiv \psi_c - \widetilde{\psi}$$

$\widetilde{(\ )}$: environment value

$\Delta w \Delta \psi$ should be virtually independent of σ,

which is a measure of cloud population in the grid cell.

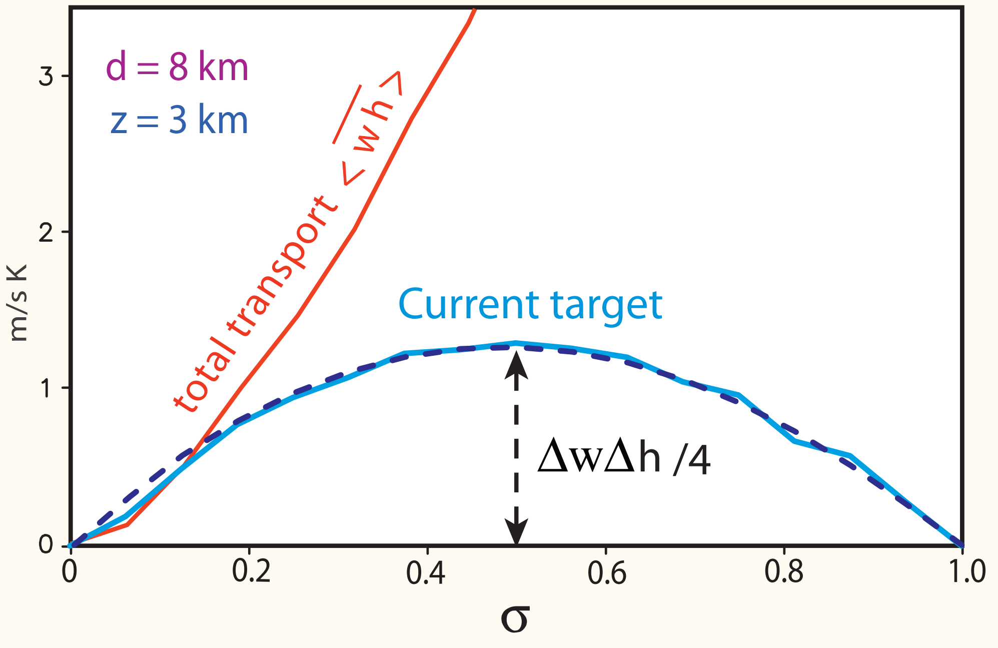


PARAMETERIZATION OF THE σ-DEPENDENCE

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

If $\Delta w \Delta\psi$ is in fact independent of σ,
the eddy transport depends on σ through $\sigma(1-\sigma)$.

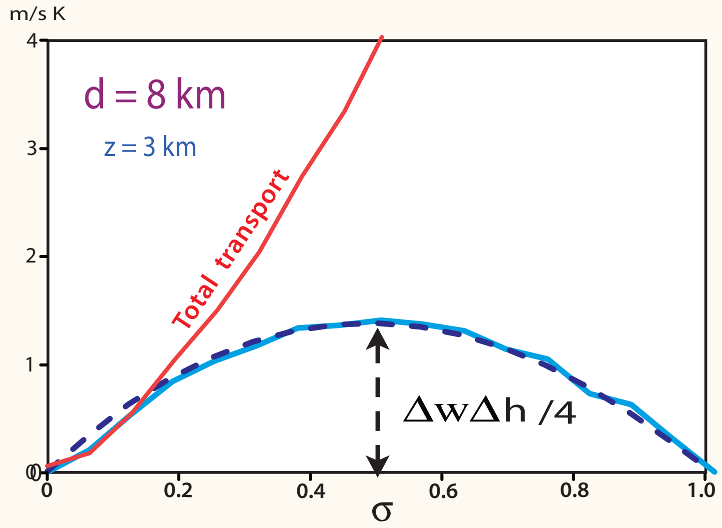
(Earlier, this dependency was introduced as the simplest *choice* for convergence.)



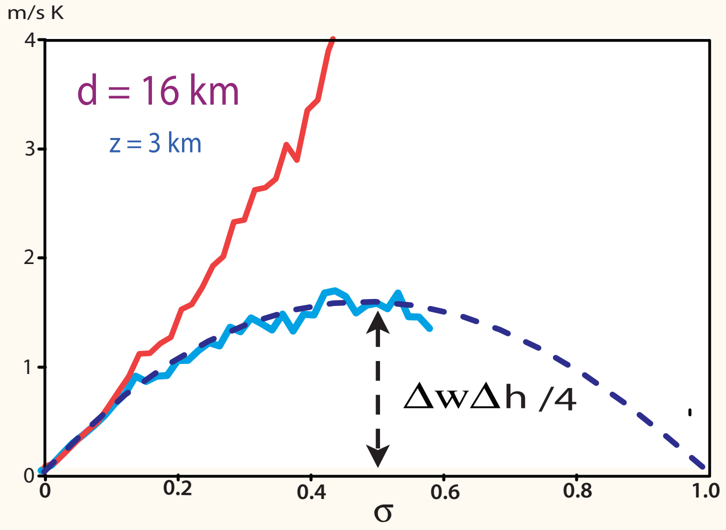
- - -

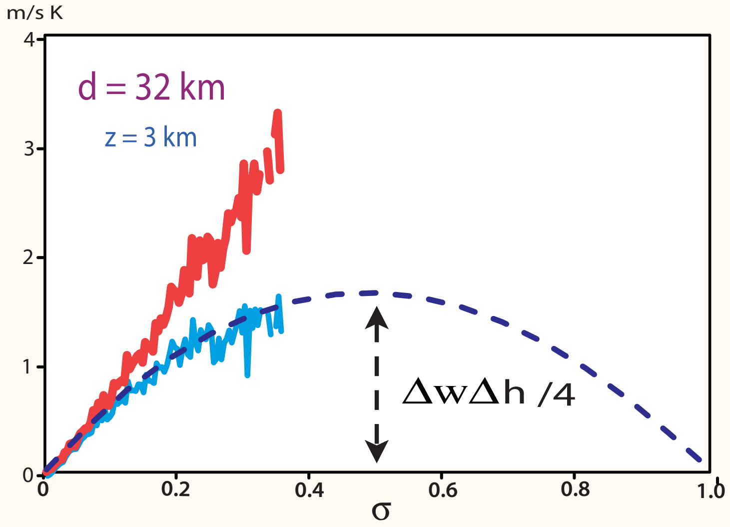
Curve $\sigma(1-\sigma)\Delta w\,\Delta h$
with the “best-fit”
constant $\Delta w \Delta\psi$

SIMILARITY BETWEEN DIFFERENT RESOLUTIONS



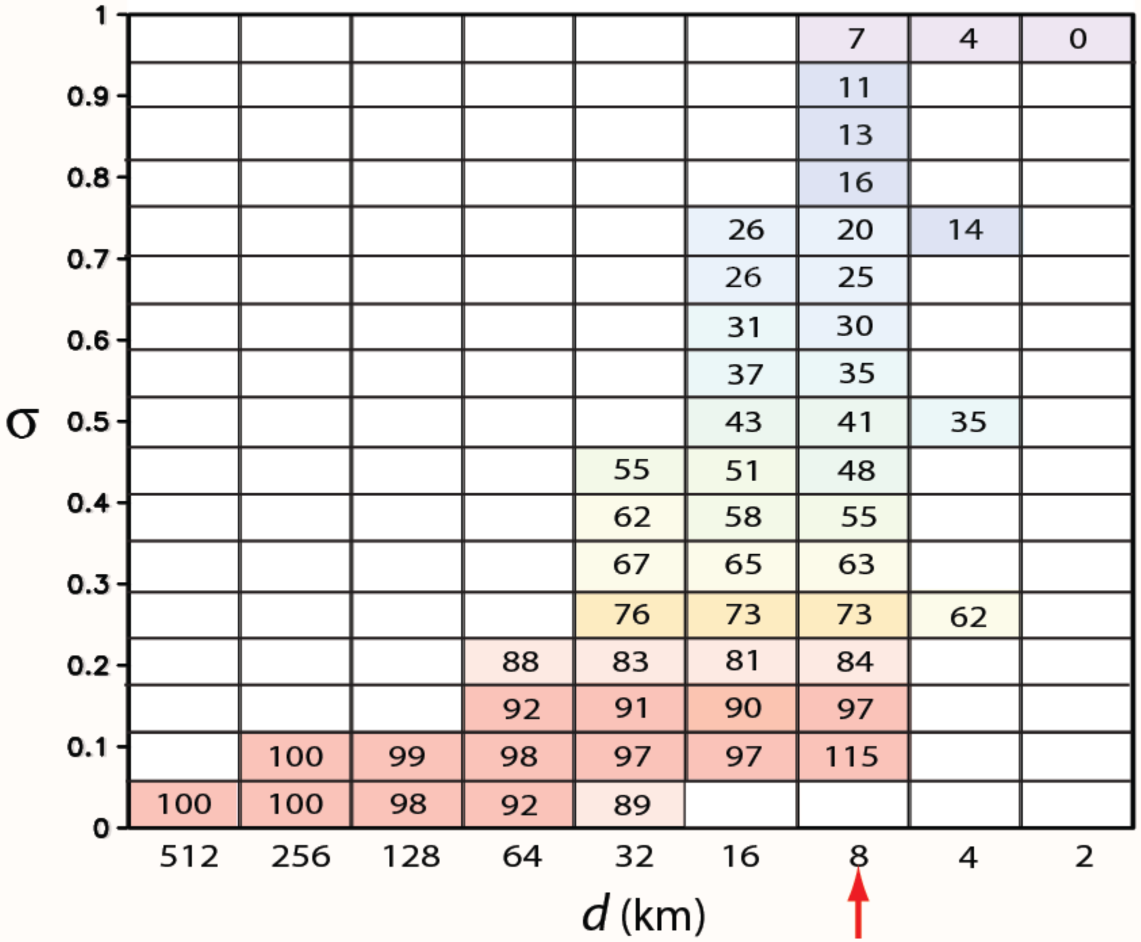
- The σ-dependence of the eddy transport is similar between different resolutions.
- The value of $\Delta w \Delta \psi$ is also similar.





THE RATIO OF THE EDDY- TO TOTAL-TRANSPORT OF OF *h*

$<\overline{w'h'}>/<\overline{wh}>$ SHEAR CASE z=3 km



512	256	128	64	32	16	8	4	2
						7	4	0
						11		
						13		
						16		
					26	20	14	
					26	25		
					31	30		
					37	35		
					43	41	35	
				55	51	48		
				62	58	55		
				67	65	63		
				76	73	73	62	
			88	83	81	84		
			92	91	90	97		
	100	99	98	97	97	115		
100	100	98	92	89				

The ratio depends on σ rather than the resolution,d.

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 $\sigma \to 1$.

DETERMINATION OF σ IN PRACTICAL APPLICATIONS, II

Define $$\boxed{\lambda \equiv \left(\overline{w'h'}\right)_E \Big/ \delta w \, \delta h}$$

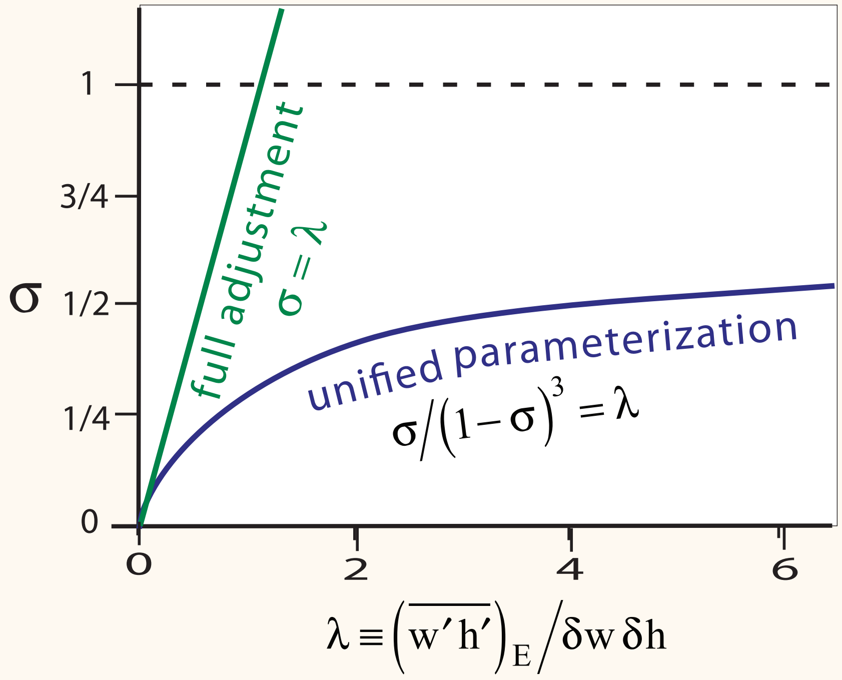
A measure of grid-scale destabilization normalized by eddy transport efficiency

Conventional $\left(\lambda \to 0,\ \sigma \to 0\right)$

$$\sigma \to \lambda$$

Unified $\left(\lambda = \lambda,\ \sigma = \sigma\right)$

$$\sigma / (1-\sigma)^3 = \lambda$$



destabilization

weaker ↔ stronger

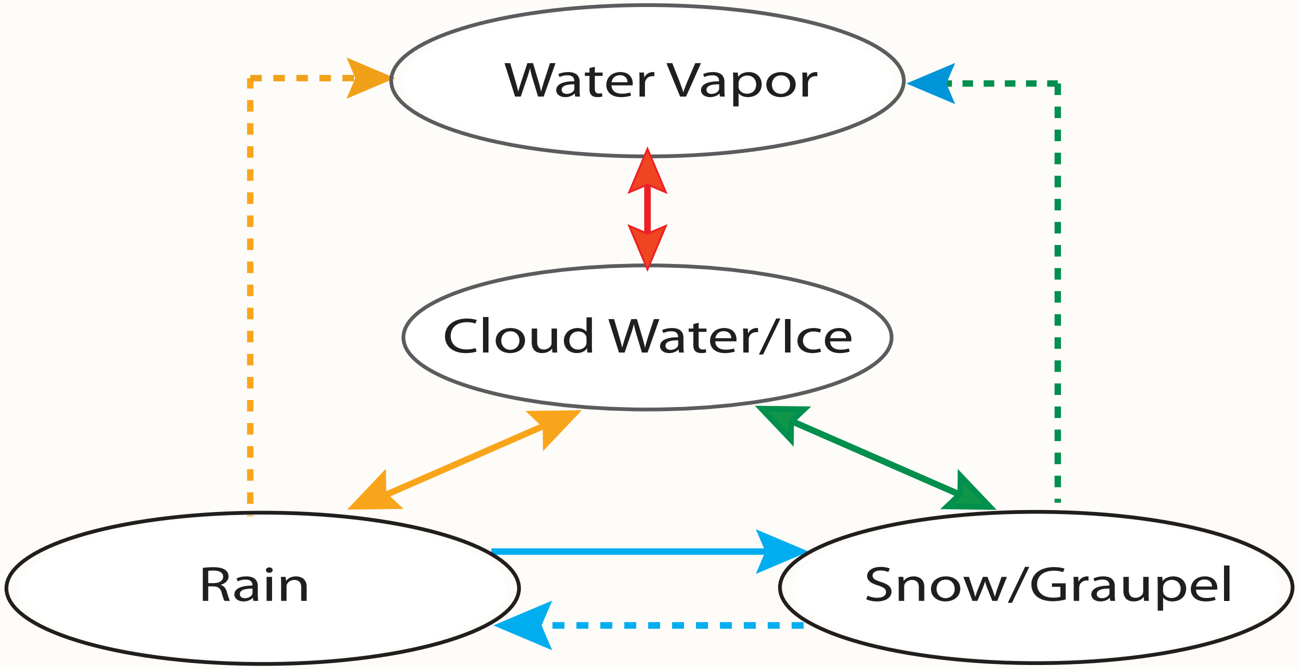
(toward Cu) (toward MCC)

eddy transport efficiency

higher ↔ lower

(toward Cb) (toward Sc)

CLOUD-MICROPHYSICAL CONVERSIONS INCLUDED IN THE MODEL



Solid lines: Conversions taking place primarily within updrafts

Dashed lines: Conversions taking place primarily outside of updrafts

Condensation

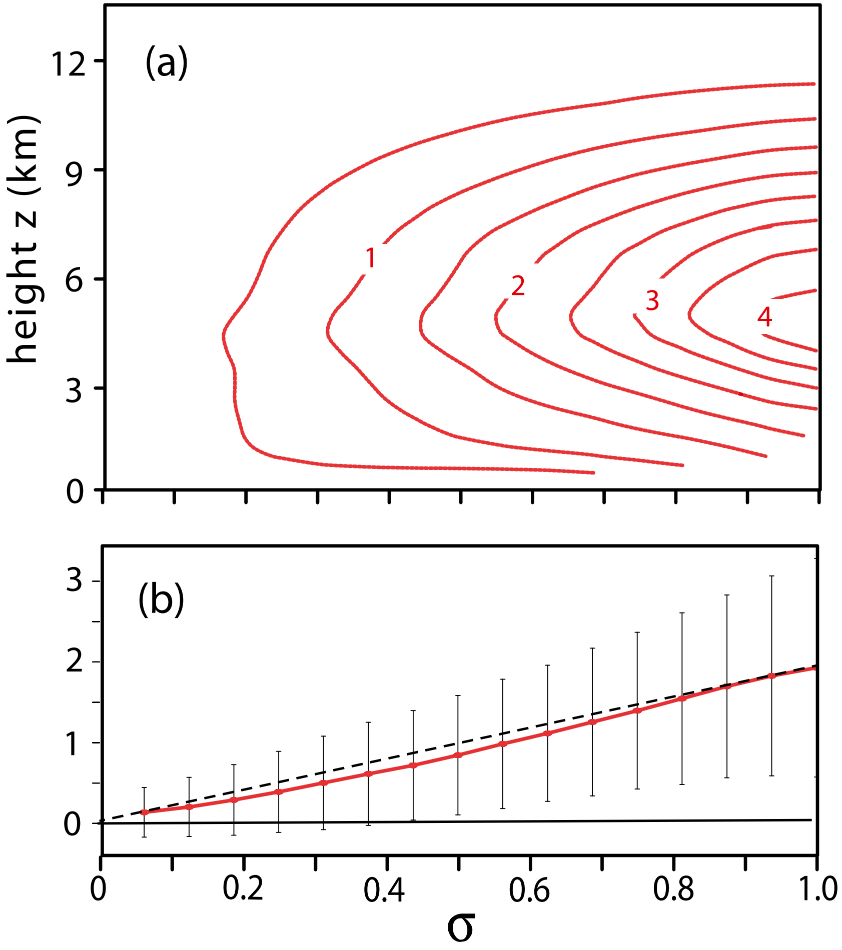


FIG. 11. (a) Ensemble-averaged net conversion from water vapor to cloud water–ice for $d = 8\,\text{km}$ as a function of z and σ. (b) Density-weighted vertical mean of the values shown in (a) with the standard deviation associated with the ensemble average. The dashed straight line connects 0 at $\sigma = 0$ and the diagnosed value at $\sigma = 1$ $(10^{-6}\,\text{kg}\,\text{kg}^{-1}\,\text{s}^{-1})$.

Wu & Arakawa, 2014

Evaporation and sublimation

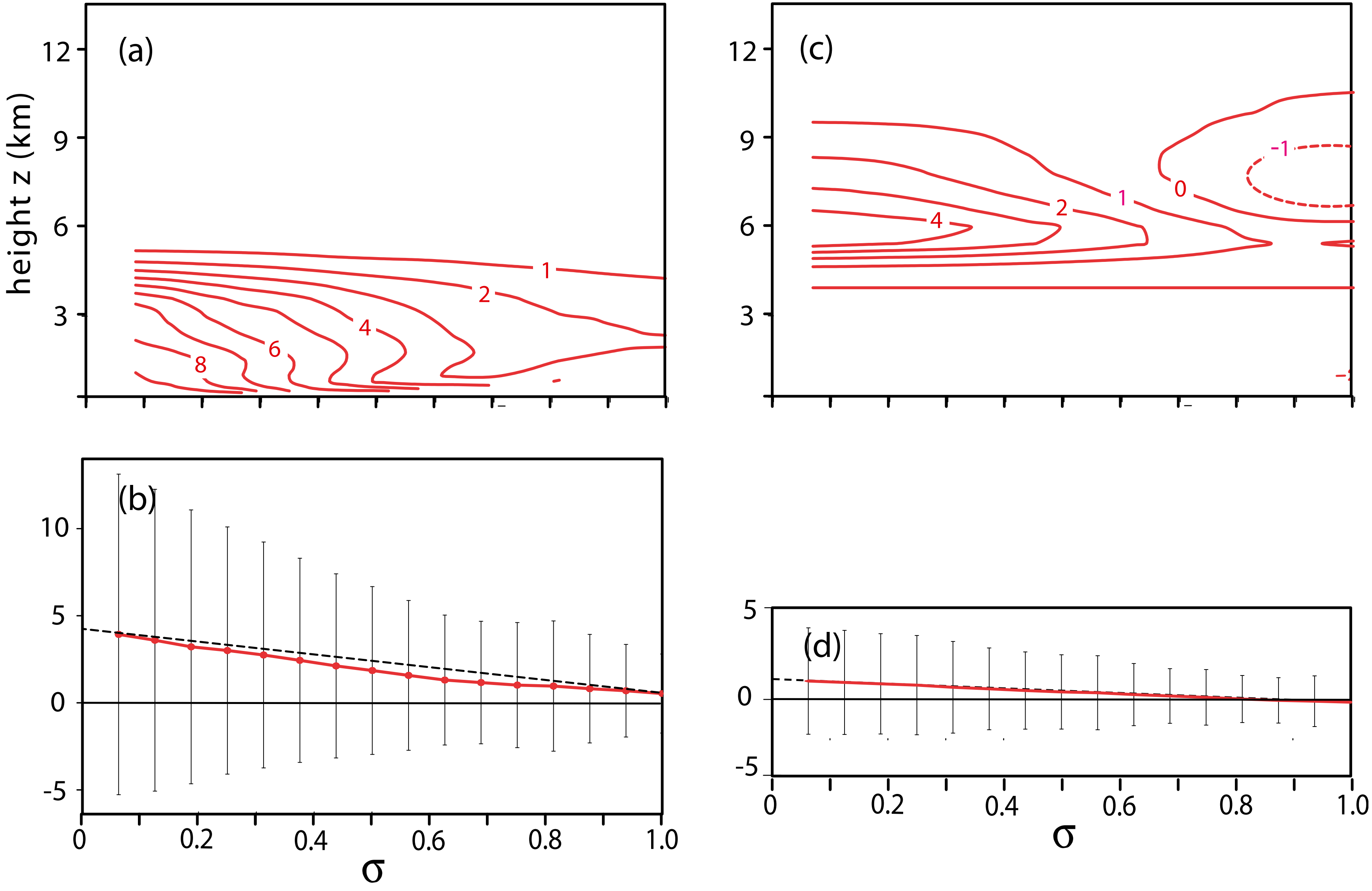


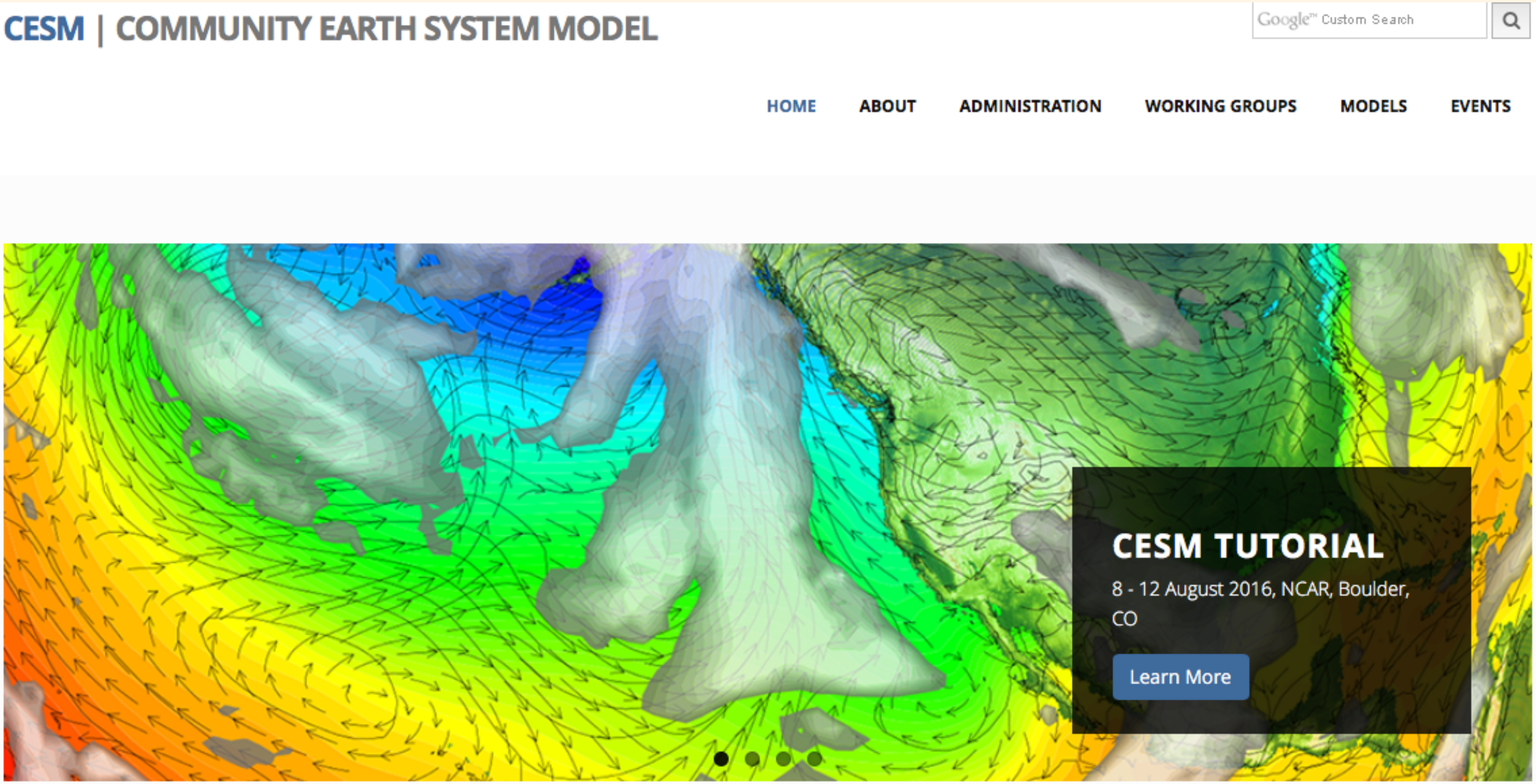
FIG. 14. As in Fig. 11, but for (a),(b) evaporation of rain and (c),(d) sublimation of snow–graupel ($10^{-8}\,\mathrm{kg\,kg^{-1}\,s^{-1}}$; note the difference in units from the previous figures).

Wu & Arakawa, 2014

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-transport" parts of the tendencies (e.g., the condensation rate) with σ for the convective part, and $1-\sigma$ for the environment.

Implementation?



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Practical implementation of Unified Parameterization (I)

The eddy transport in the unified parameterization is relaxed through σ.

$$\overline{w'h'} = (1-\sigma)^2\,\overline{w'h'_E}$$

σ is determined through large-scale destabilization and convective strength

$$\lambda(1-\sigma)^3 - \lambda = 0$$

$$\lambda = \frac{\overline{w'h'_E}}{(w_c - \overline{w})(h_c - \overline{h})}$$

from cumulus parameterization

from plume model

Practical implementation of Unified Parameterization (II)

Zhang and McFarlane scheme (1995), currently CAM5 deep convection scheme

$\overline{w'h_E'}$ is determined through the closure assumption in the cumulus parameterization

$$M_b F = \frac{\max(\mathrm{A} - A_0, \ \ 0)}{\tau}$$

$$M_u = M_b e^{-\Lambda(z)}$$

$$\overline{w'h_E{}'} = M_u(h_u - \bar{h})$$

Practical implementation of Unified Parameterization (III)

deRoode et. al (2012) vertical kinetic energy equation

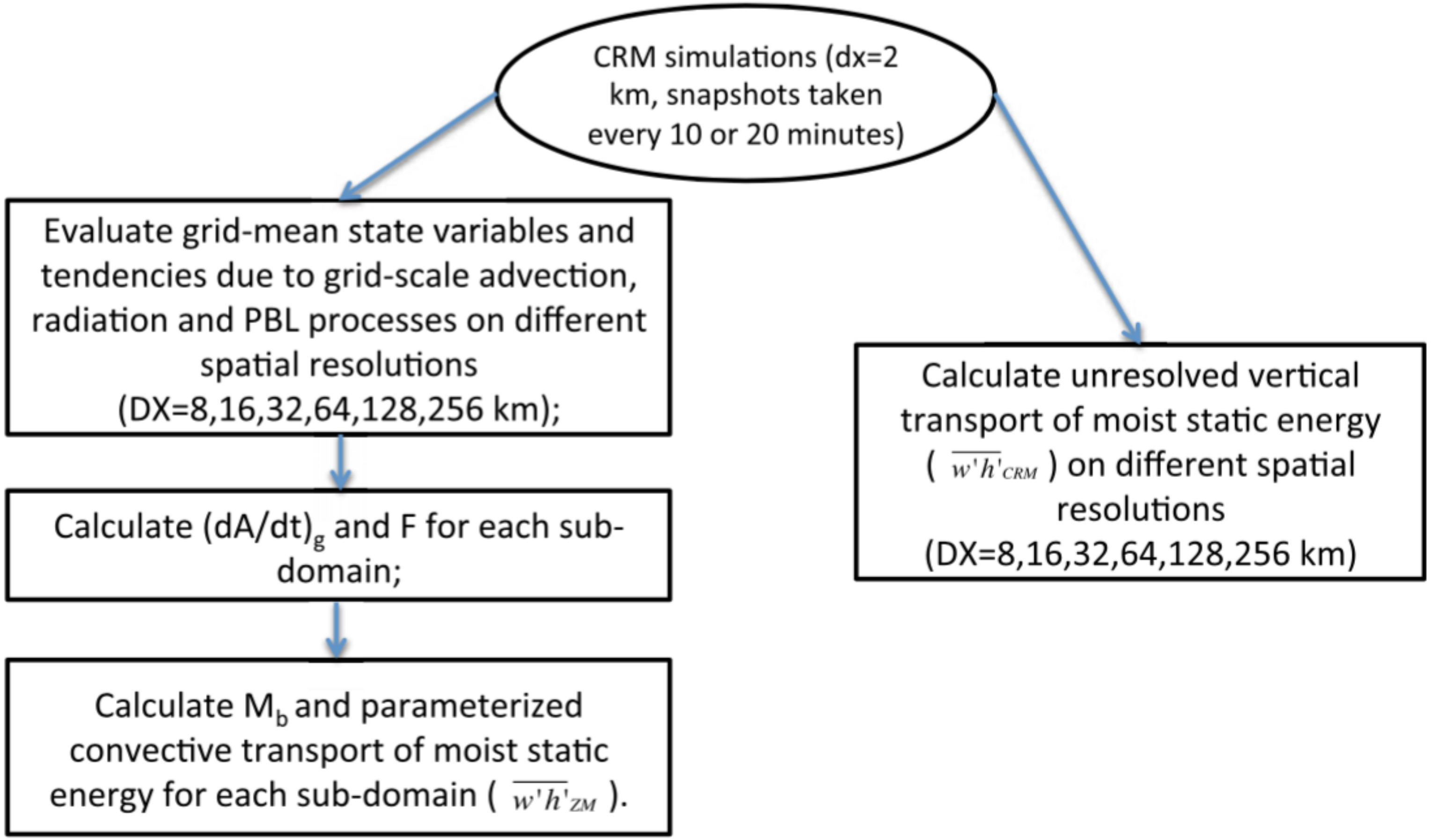
ECMWF(2010)

$$\frac{1}{2}\frac{d{w_c}^2}{dz} = \alpha B - \beta \epsilon w^2$$

Kim and Kang (2011)

$$\frac{1}{2}\frac{d{w_c}^2}{dz} = \alpha(1 - C_\epsilon)B, C_\epsilon = 1/\overline{RH}$$

Preliminary results of ZM diagnoses



CRM simulations (dx=2 km, snapshots taken every 10 or 20 minutes)

Evaluate grid-mean state variables and tendencies due to grid-scale advection, radiation and PBL processes on different spatial resolutions (DX=8,16,32,64,128,256 km);

Calculate $(dA/dt)_g$ and F for each sub-domain;

Calculate M_b and parameterized convective transport of moist static energy for each sub-domain ($\overline{w'h'}_{ZM}$).

Calculate unresolved vertical transport of moist static energy ($\overline{w'h'}_{CRM}$) on different spatial resolutions (DX=8,16,32,64,128,256 km)

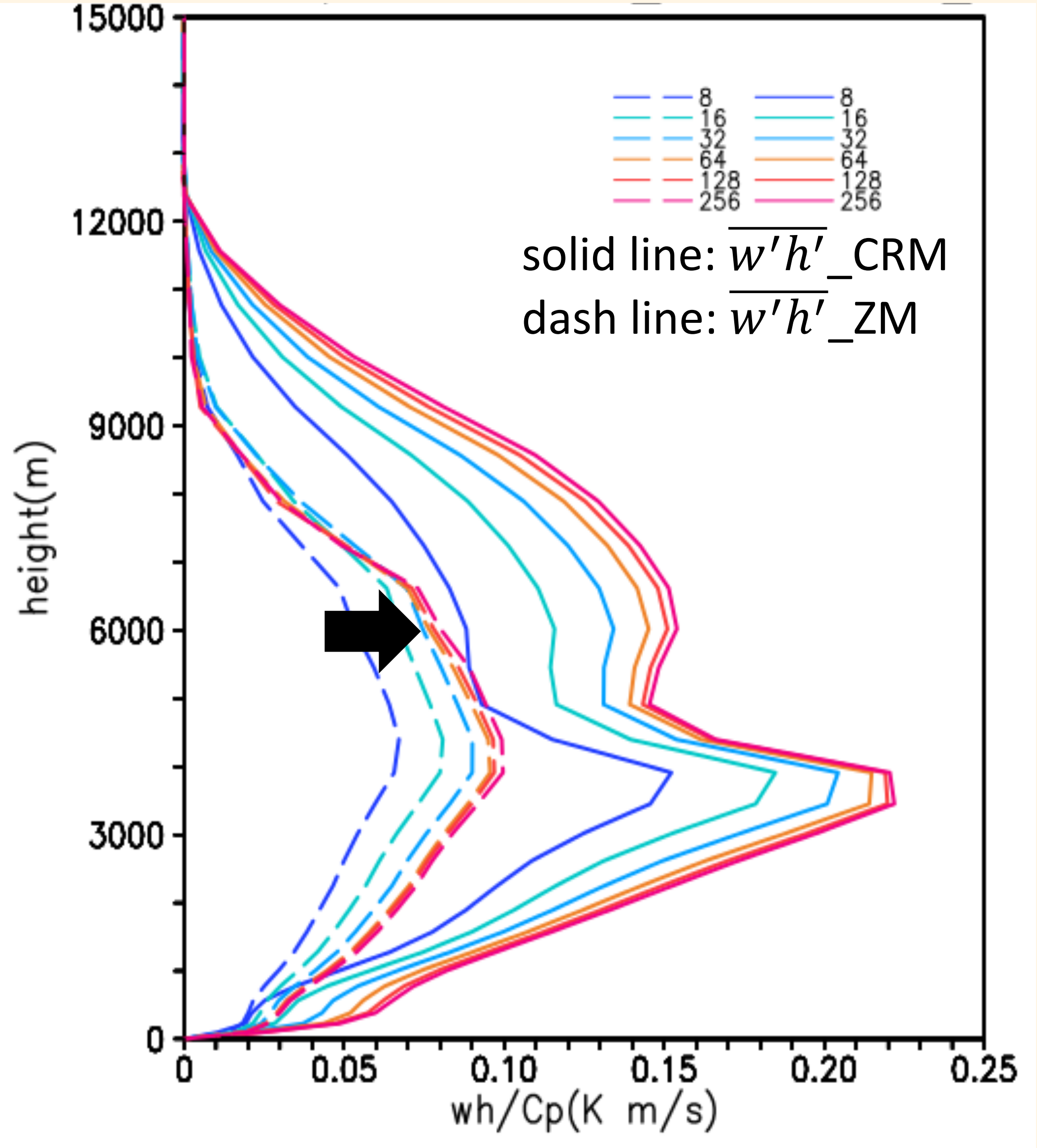
Then we compare $\overline{w'h'}_{CRM}$ and $\overline{w'h'}_{ZM}$.

Figure 2. A schematic showing the procedure we follow to calculate $\overline{w'h'}_{ZM}$ and $\overline{w'h'}_{CRM}$.

Xiao, Wu et al 2015

Eddy transport of moist static energy for ZM scheme

- Whole period of DYNAMO active phase (15 days) simulation instead of idealized forcing.
- Generally weaker eddy transport as well as weaker variability in ZM.



solid line: $\overline{w'h'}$_CRM

dash line: $\overline{w'h'}$_ZM

Eddy transport of moist static energy for ZM scheme

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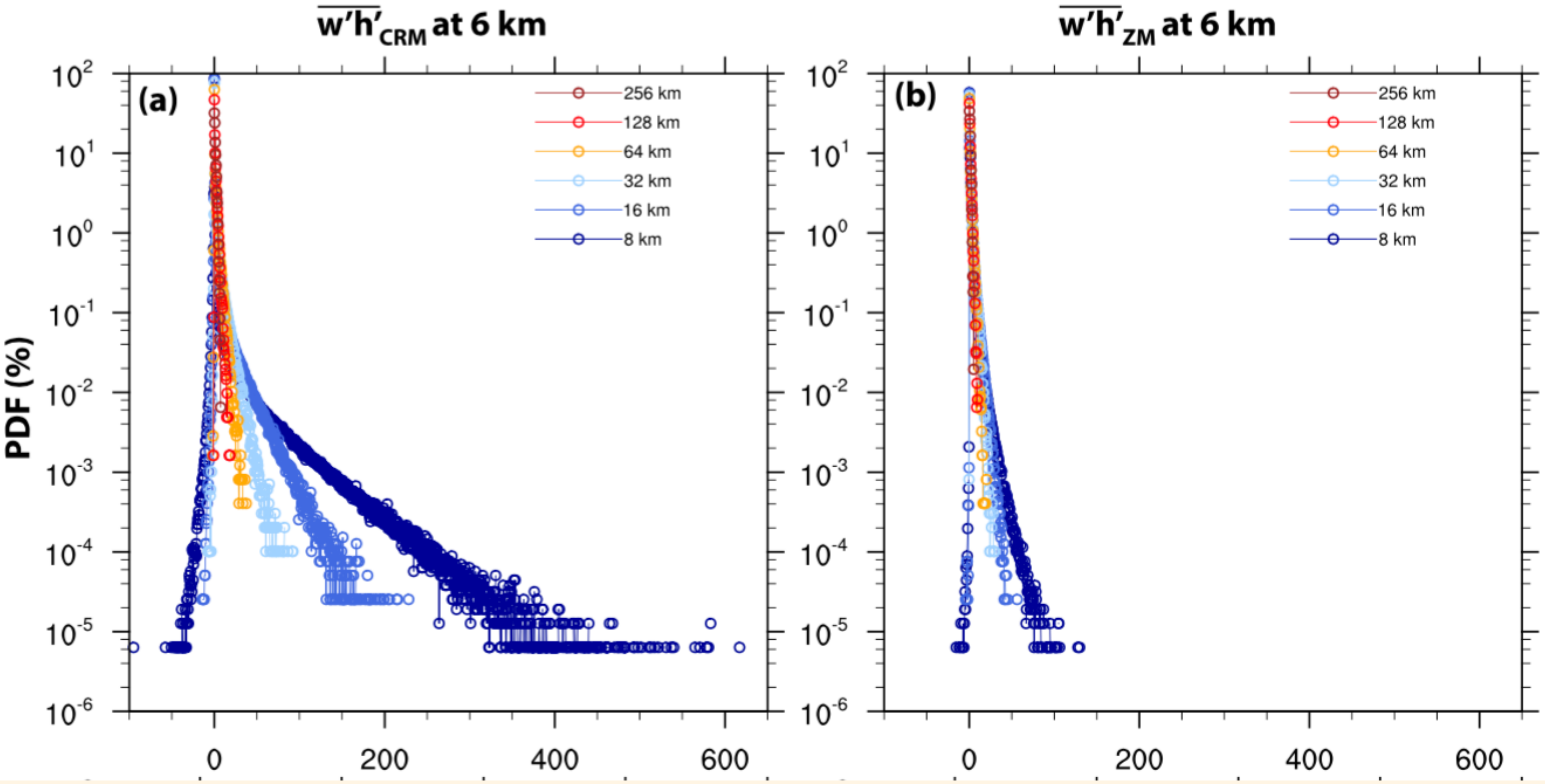
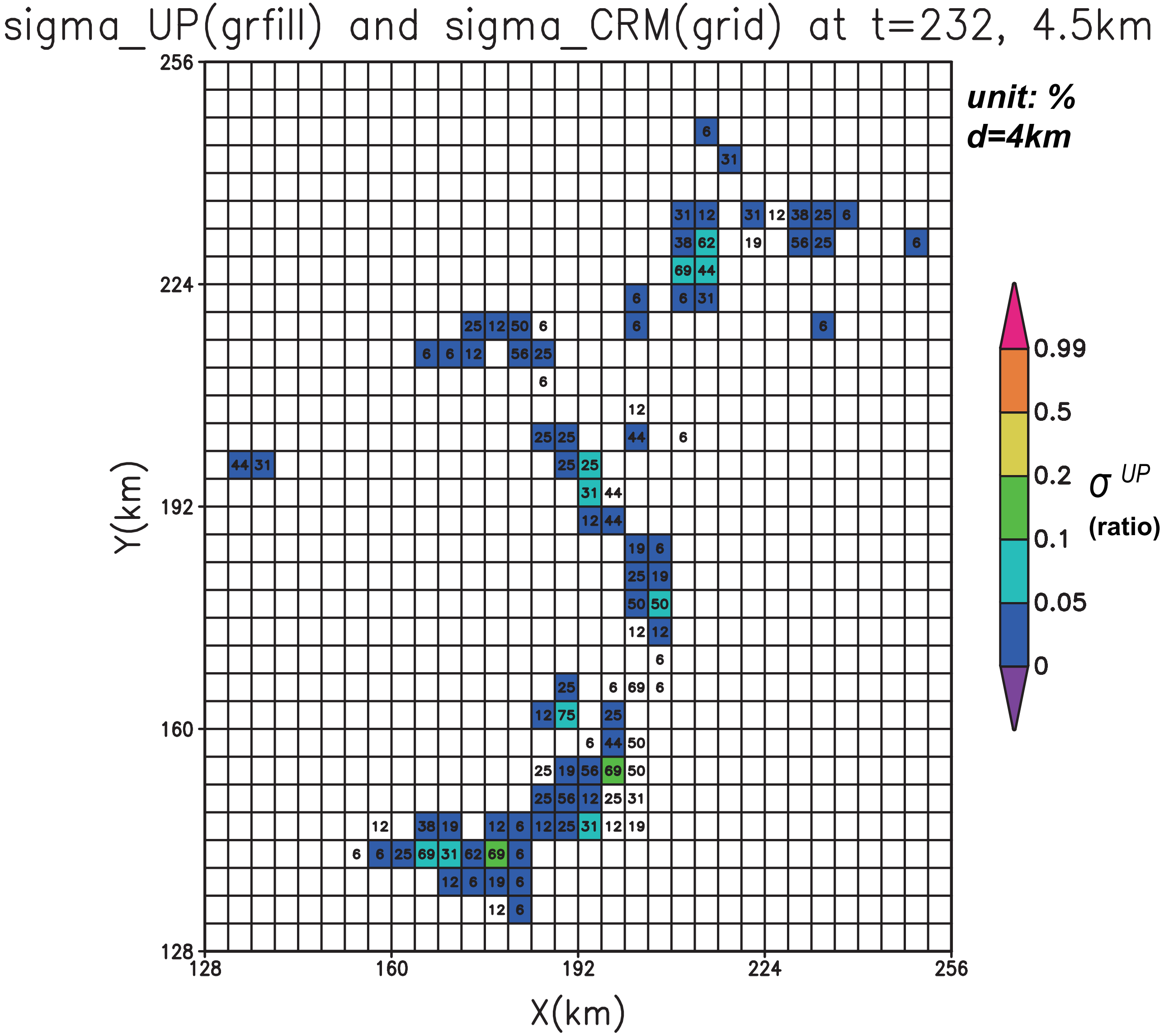


Example of σ distribution in ZM scheme

- Smaller σ in ZM compared to that in the CRM probably due to weaker eddy fluxes in ZM scheme.



Example of σ dependency in ZM scheme

- σ in ZM shows good relationship with that in CRM but with strong variability.