MODEL UNIFICATION

— my latest research excitement —

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Wayne Schubert	1973	Cumulus/ L-S interaction
David Randall	1976	PBL/ L-S interaction
Chin-Hoh Moeng	1979	PBL cloud stability
Steven Krueger	1985	Cumulus/ PBL interaction
Kuan-Man Xu	1991	Cumulus/ L-S interaction
Celal Konor	1992	Frontogenesis
Joon-Hee Jung	(1997)	(Stratosphere dynamics)

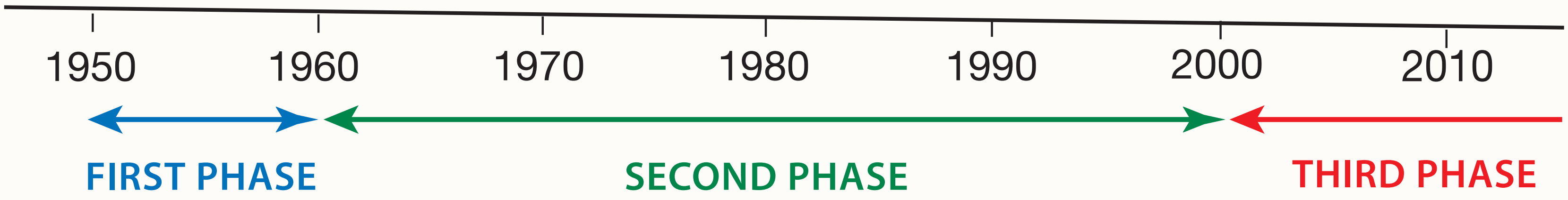
None of these students directly worked on GCM development

because I wanted them to work on scientifically more focused problems.

I am the one who benefitted the most from this policy !

HISTORY OF NUMERICAL MODELING OF THE ATMOSPHERE

I have been fortunate to witness and participate in the entire history of numerical modeling.



FIRST PHASE (1950-1960)

Introdcution of

early NWP models with highly simplified dynamics

ALSO

Recognition of the close relation between

the dynamics of "cyclones" and that of "general circulation"

Highlight: Phillips's (1956) numerical experiment

MY FIRST RESEARCH EXCITEMENT (1961-1963)

Development of a "cyclone-resolving" model

for global circulation

— Opening of the SECOND PHASE —

- The primary interest was still in dynamics.
- The major problem was computational.

  My work on the finite-dIfference Jacobian was almost immediately recognized by the meteorological community, but it took years to convince the applied mathematicians.

SECOND PHASE (1960-2000)

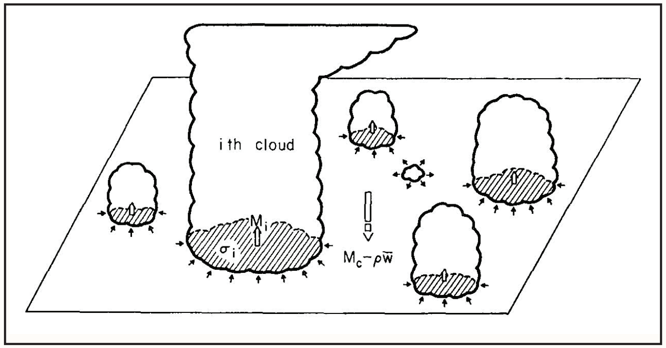
The scope of general circulation modeling magnificently expanded from single-process to multi-process modeling.

- The importance of cumulus convection was recognized almost immediately.
- My major concern was to find the logical basis for parameterizability.

MY SECOND RESEARCH EXCITEMENT (1970-1974)

Arakawa-Schubert (1974):

An attempt to find the logical basis for parameterizability



It took time for this paper to be widely recognized because most people considered parameterization as a simpler engineering problem.

BASIC HYPOTHESES OF ARAKAWA-SCHUBERT

" Consider a horizontal area large enough to contain an ensemble of cumulus clouds but small enough to cover only a fraction of a large-scale disturbance."

The overall intensity of cumulus activity is determined by an approximate balance between destabilization by slow large-scale processes and stabilization by fast cumulus-convective processes.

These are over-simplifications, but I didn't see how cumulus convection can be parameterized without them.

APPROACHING A PLATEAU ?

As the scope of numerical modeling expands,

new modules were kept added, but

there was little effort to improve the scientific basis for modeling.

I was almost ready to fully retire around 2000.

But Dr. Tao asked me to give an invited talk
at the Cumulus Parametrization Workshop
at GSFC on December 3-5, 2001

MAJOR CONCEPTUAL PROBLEMS IN EXISTING PARAMETERIZATIONS OF SUBGRID-SCALE PROCESSES

(An edited version of a slide shown at the Workshop)

1. **Different processes (e.g., radiation, cloud, turbulence, etc.) interact only through grid-scale variables, losing most of their subgrid-scale interactions.**

2. **A single non-physical scale – grid size – separates processes that can be explicitly simulated and those that can only be in quasi-equilibrium.**

3. **The resolution dependence of the required physics is left to blind tuning.**

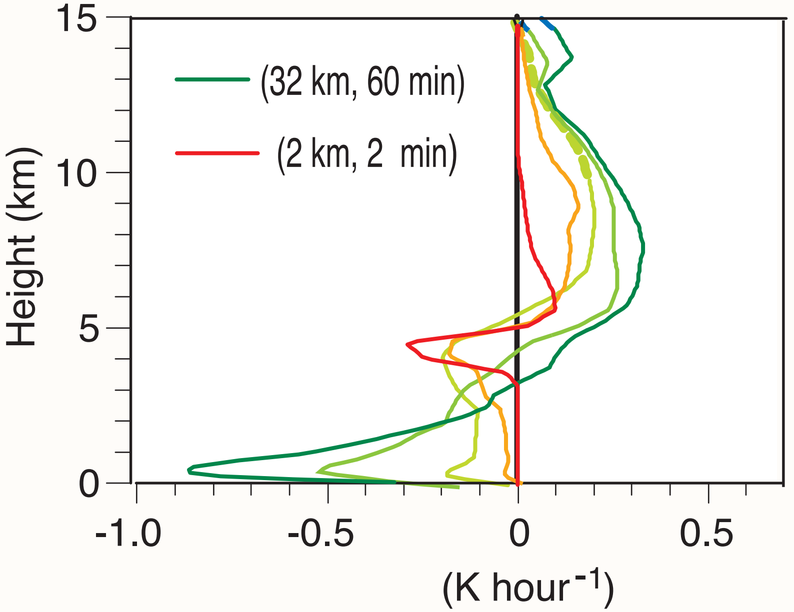
At the same Workshop, David Randall presented early results of Super-Parameterization.

EVIDENCE FOR THE TRANSITION OF MODEL PHYSICS

Jung and Arakawa (2004)

Budget analyses of CRM-simulated data applied to various space/time intervals with and without (a component of) model physics

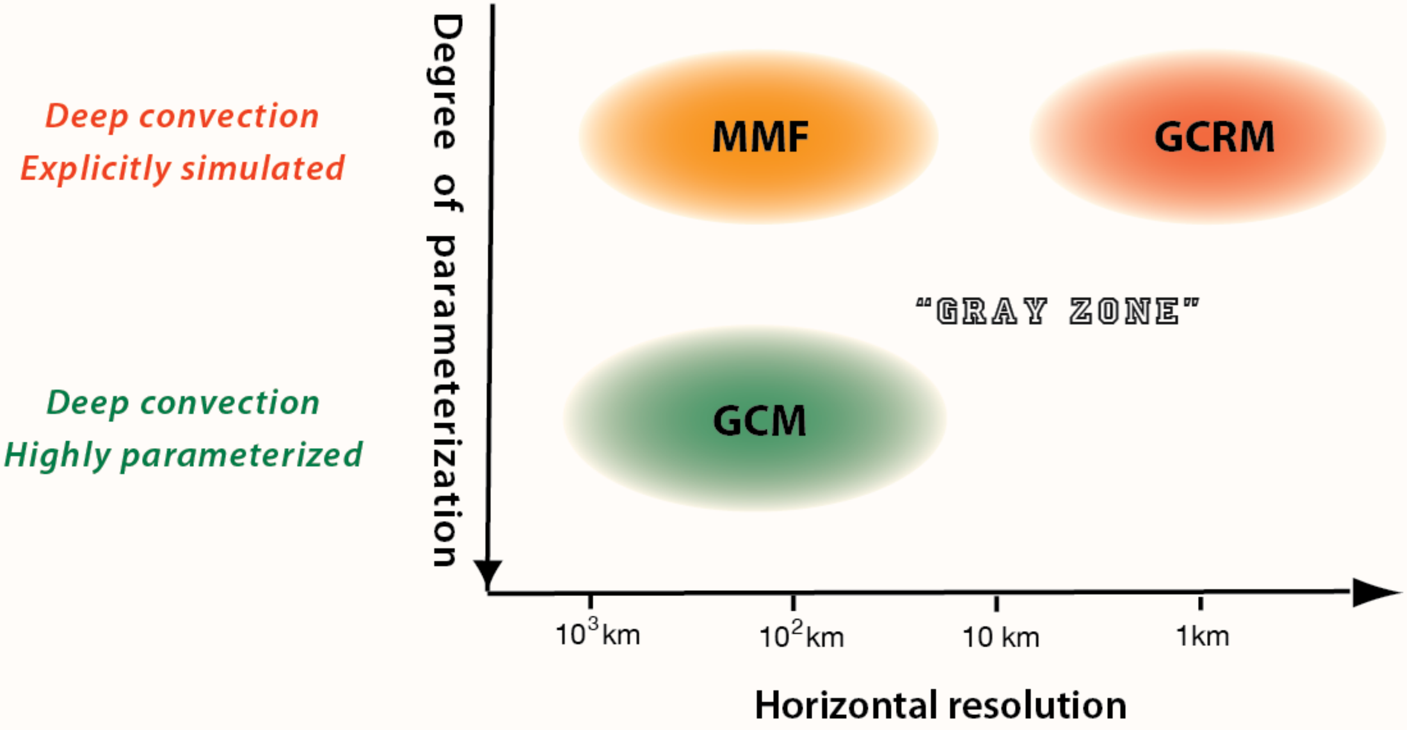
Average Profiles of "REQUIRED" Source for Moist Static Energy



— GCM-type profile

— CRM-type profile

TRI-P0LARIZATION OF GLOBAL MODELS



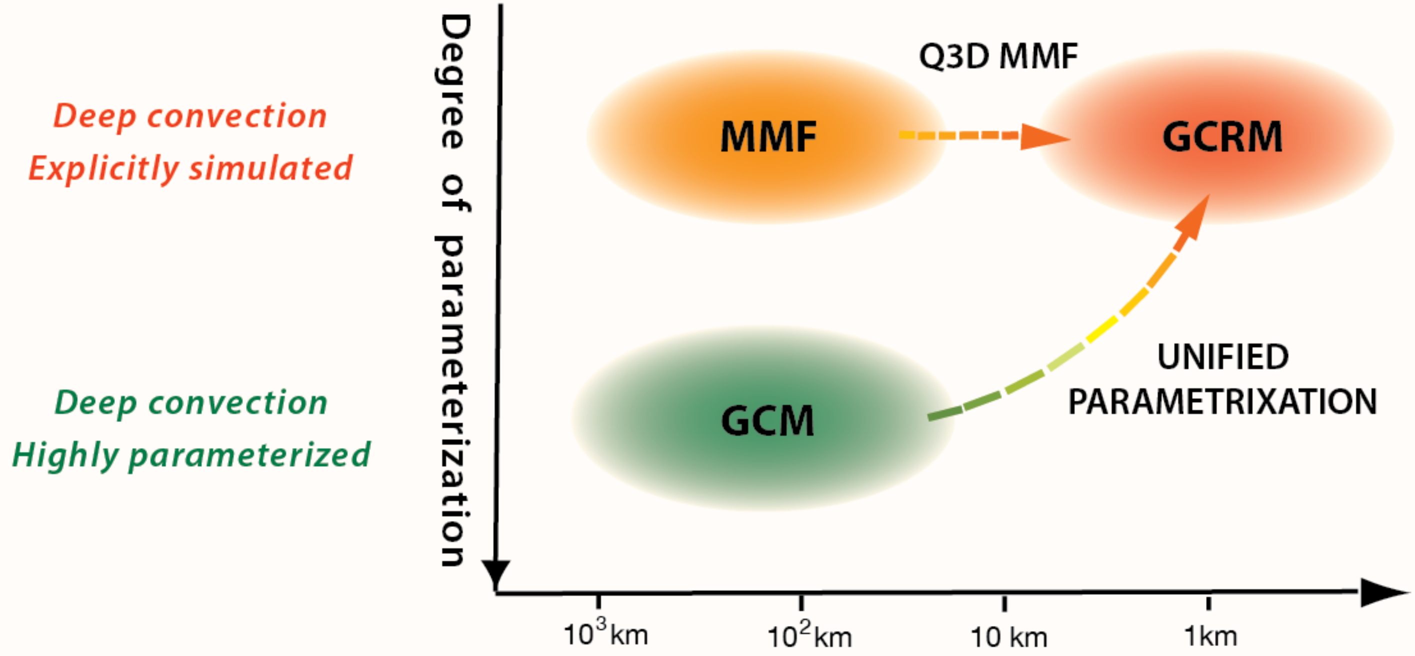
MY LATEST RESEARCH EXCITEMENT (2004-2014)

Working toward unification of these families of models

Thank you, CMMAP, for giving me this excitement !

UNIFICATION OF LOW-RESOLUTION GLOBAL MODELS AND GCRM

Arakawa *et al.*, 2011, *Atmos. Chem. Phys.*



Prerequisite: Regardless of the resolution, the dynamics of the model must be that of GCRM, which is necessarily nonhydrostatic and elastic.

UNIFICATION OF
THE ANELASTIC AND QUASI-HYDROSTATIC SYSTEMS OF EQUATIONS

Arakawa *and Konor*. 2009, *MWR*

Refer to Celal Konor's presentation

These systems are physically quite different.

For example, the physical meaning of pressure is different as :

Quasi-static system: *A measure of the mass above*

Anelastic system: *The potential of a force required to maintain anelasticity*

As in the traditional model, unified models couple the host GCM with an ancillary model that provides collective effects of subgrid-scale processes, either parameterized or simulated.

If the ancillary model represents more than the subgrid-scale processes, double counting of the same process or spurious competition between the grid-scale and subgrid-scale processes may occur.

THE QUASI-3D MULTISCALE MODELING FRAMEWORK

Jung and Arakawa. 2005, *MWR*

Jung and Arakawa. 2010**, 2014,** *JAMES*

Refer to Joon-Hee Jung's presentation

The CRM does not fully represent the cloud-scale 3D processes

but recognizes GCM's 3D structure through the background field.

A product of Joon-Hee's extraordinarily meticulous and patient work

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UNIFIED REPRESENTATION OF DEEP MOIST CONVECTION IN NUMERICAL MODELING OF THE ATMOSPHERE: PART I

Arakawa and Wu, 2013, *JAS*

An attempt to eliminate these assumptions of AS.

" Consider a horizontal area large enough to contain an ensemble of cumulus clouds but small enough to cover only a fraction of a large-scale disturbance."

The overall intensity of cumulus activity is determined by an approximate balance between destabilization by slow large-scale processes and stabilization by fast cumulus-convective processes.

THE KEY PARAMETER IN THE UNIFIED REPRESENTATION

σ : The fractional area in the grid cell covered by convective updrafts

When the area covered by individual updrafts is fixed,

σ is a measure of the fractional population of updrafts.

UNIFIED PARAMETERIZATION

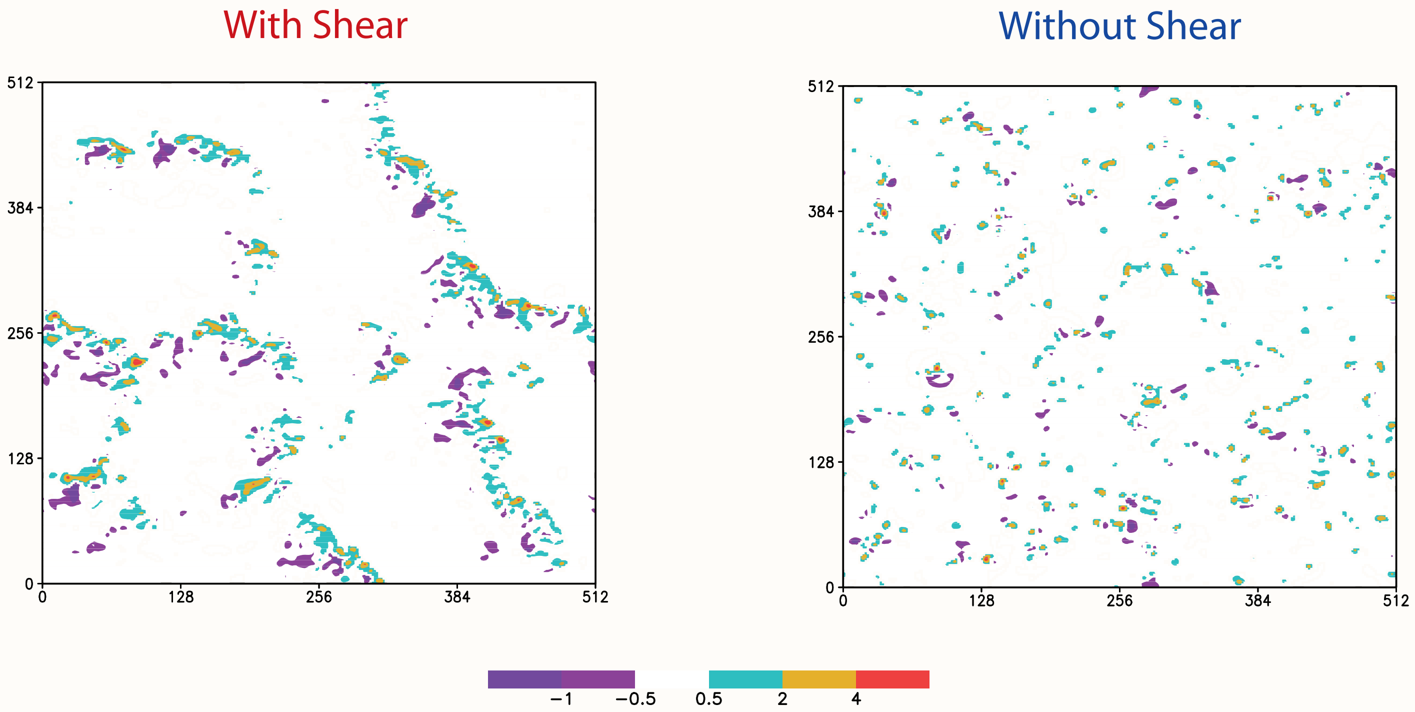
- The assumption of small σ is eliminated.
- In the limit as $\sigma \rightarrow 0$, it reduces to a conventional cumulus parameterization with full adjustment to an equilibrium profile.
- For the transport, it formulates only the eddy transport.
- It includes the reduction of eddy transport as $\sigma \rightarrow 1$ due to filling the grid cell by updrafts.
- σ is determined by the grid-scale destabilization rate normalized by the efficiency of eddy transport.

CRM SIMULATIONS USED FOR STATISTICAL ANALYSIS

Model : The vorticity equation model of Jung and Arakawa (2008)

Horizontal domain size : 512 km   Horizontal grid size : 2km

Snapshots of vertical velocity w at 3 km height

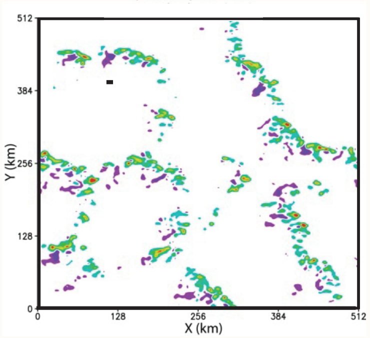


SUB-DOMAINS REPRESENTING DIFFERENT RESOLUTIONS

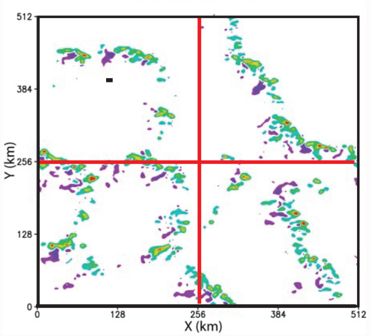
To see the grid-size dependence of the statistics,
the original CRM domain (512 km) is divided into sub-domains of same size.

Examples

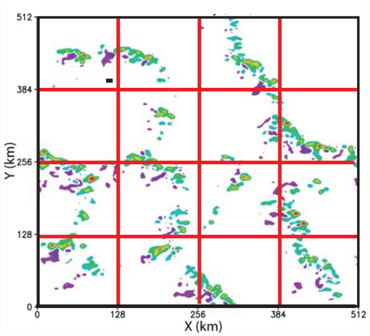
d = 512 km



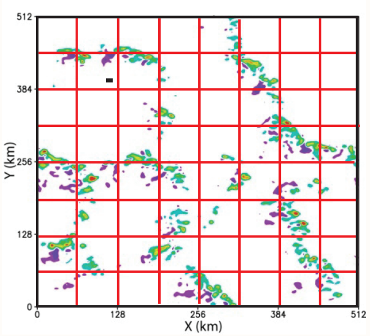
d = 256 km



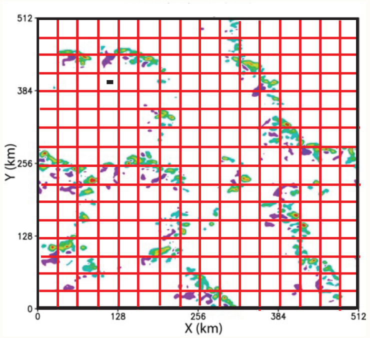
d = 128 km



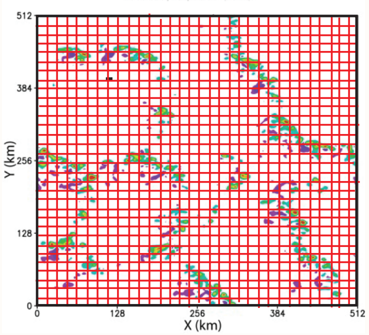
d = 64 km



d = 32 km



d = 16 km



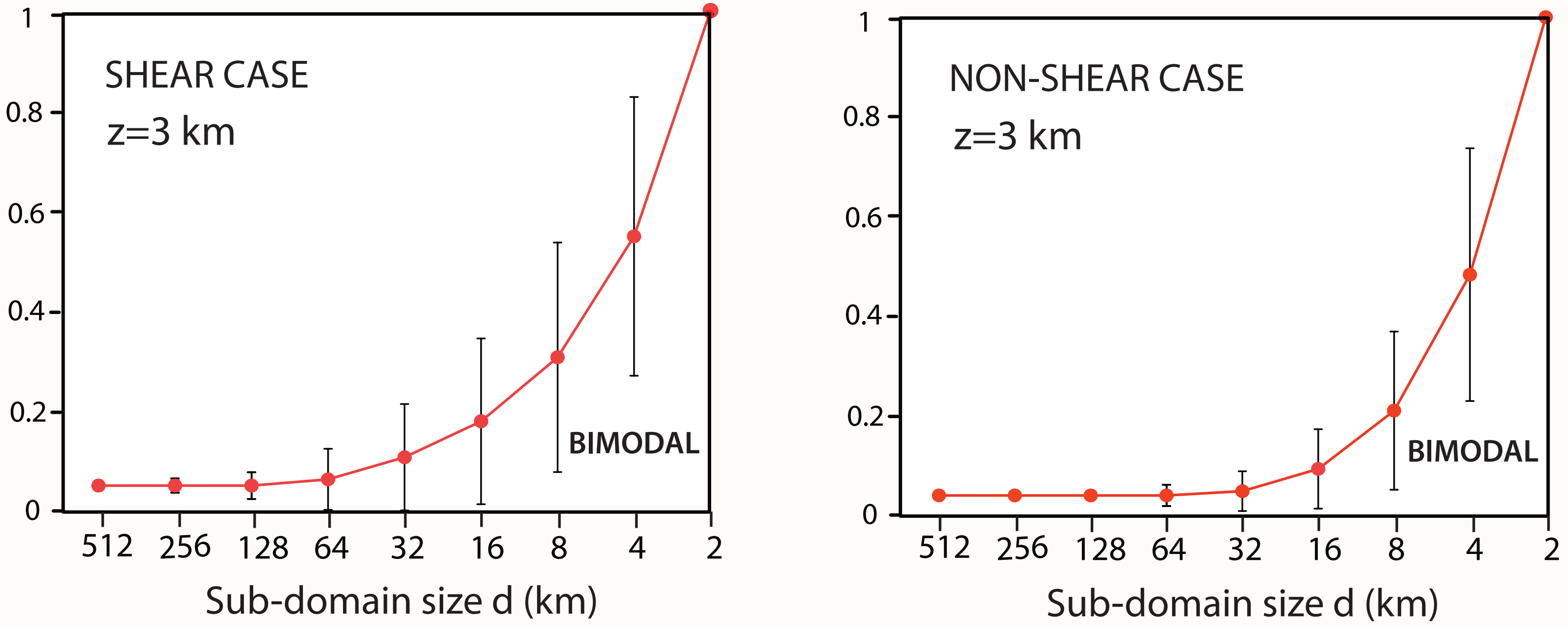
The sub-domain size is interpreted as the GCM grid size.

RESOLUTION DEPENDENCE OF ENSEMBLE-AVERAGE σ

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

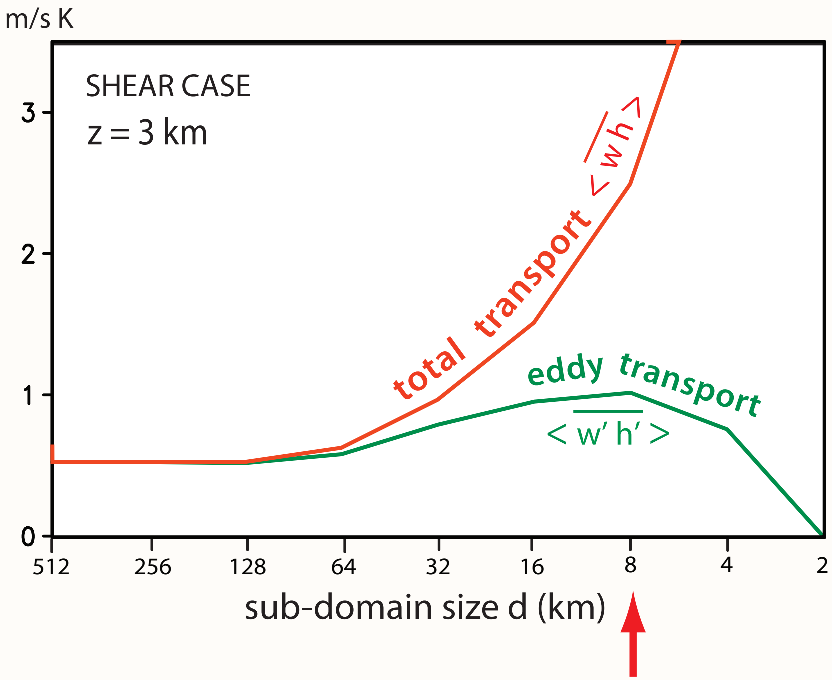
< >: Average over an ensemble of cloud-containing (i.e., σ > 0) sub-domains

$< \sigma >$



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

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



h : Deviation of moist static energy from a reference state

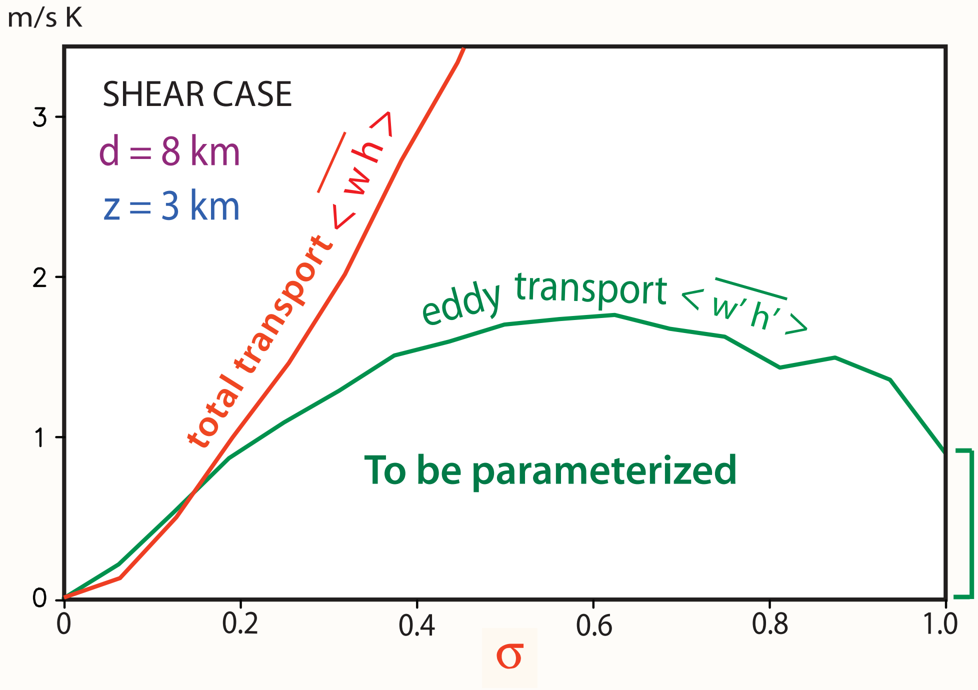
$\overline{(\ )}$: Average over all CRM grid points in the sub-domain

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

Parameterization is supposed to produce the green curve

NOT the red curve.

THE σ–DEPENDENCE OF ENSEMBLE-AVERAGE VERTICAL TRANSPORT OF MOIST STATIC ENERGY

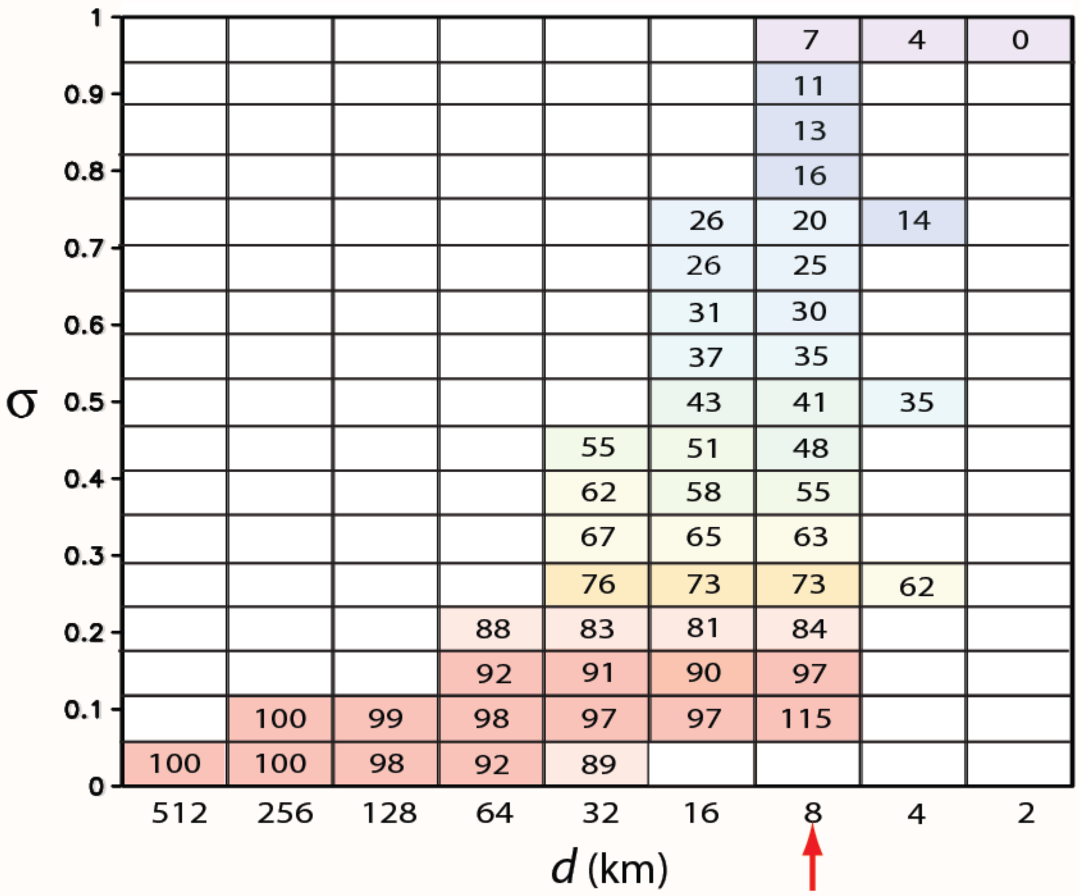


Due to internal structure of updrafts

The relative importance of the component to be parameterized strongly depends on σ.

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.

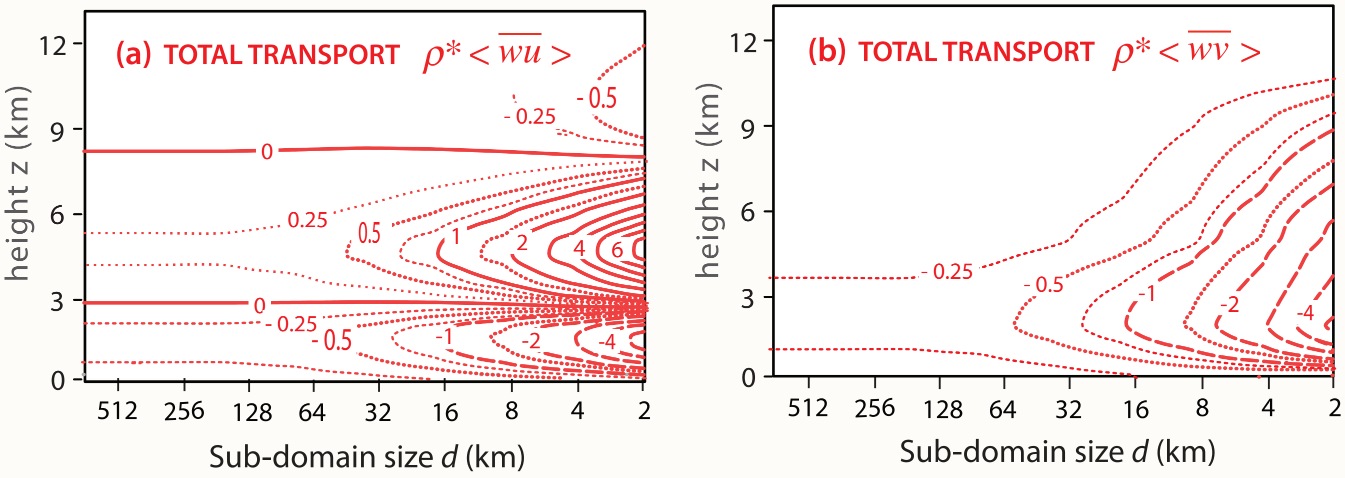
UNIFIED REPRESENTATION OF DEEP MOIST CONVECTION IN NUMERICAL MODELING OF THE ATMOSPHERE: PART II

Wu and Arakawa, 2014, **submitted to** *JAS*

Analyses of the smulated data in view of
the vertical transport of horizontal momentum
and the σ–dependence of physical sources

RESOLUTION DEPENDENCE

VERTICAL TRANSPORT OF HORIZONTAL MOMENTUM

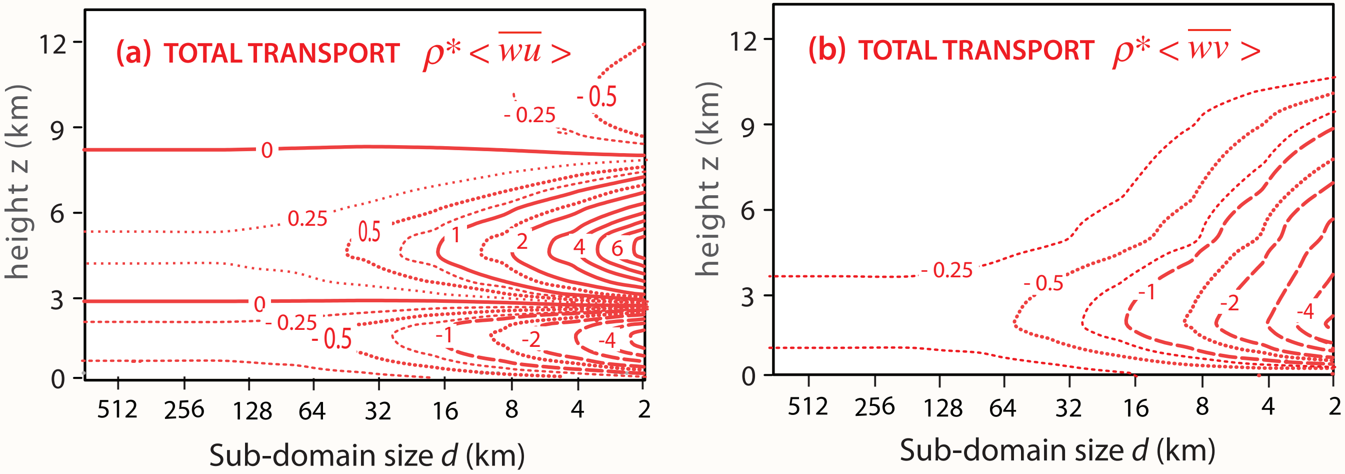


The u-momentum and v-momentum transports have quite different vertical structures (and different dependence on *d*).

RESOLUTION DEPENDENCE

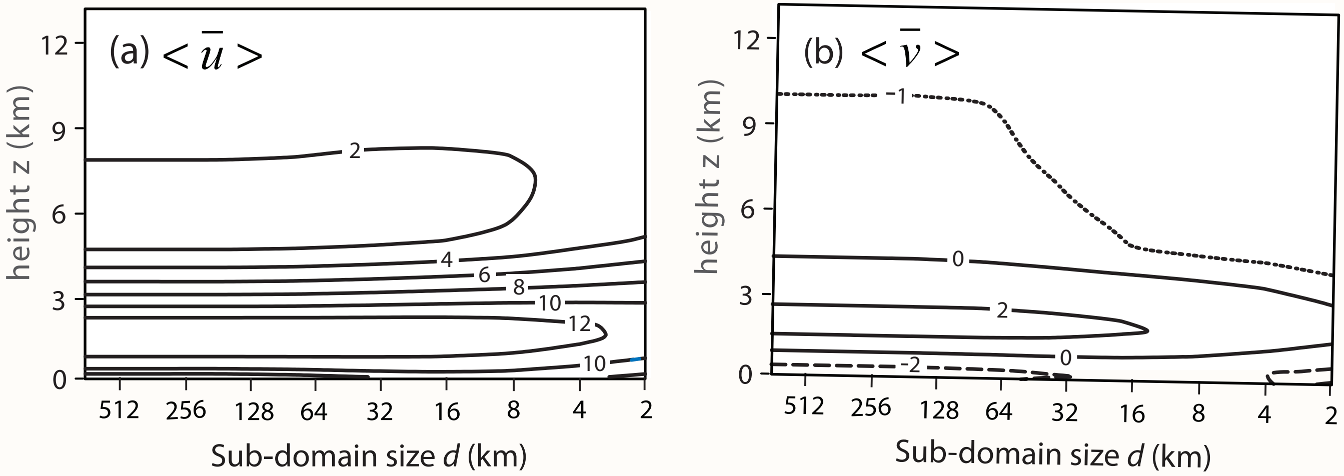
VERTICAL TRANSPORT OF HORIZONTAL MOMENTUM

Mosty
downgradient
of u



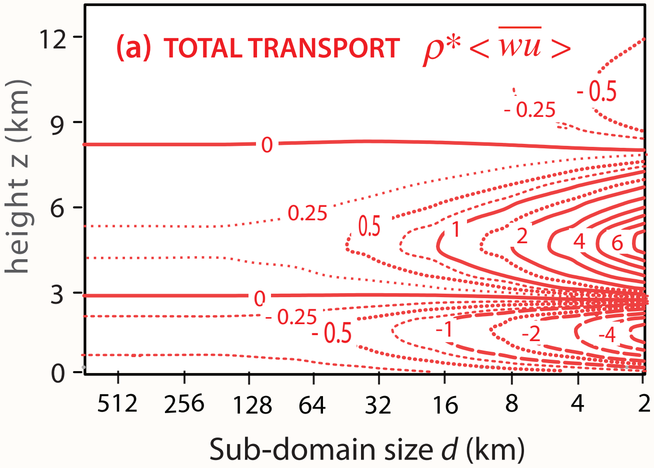
Mosty
upgradient
of v

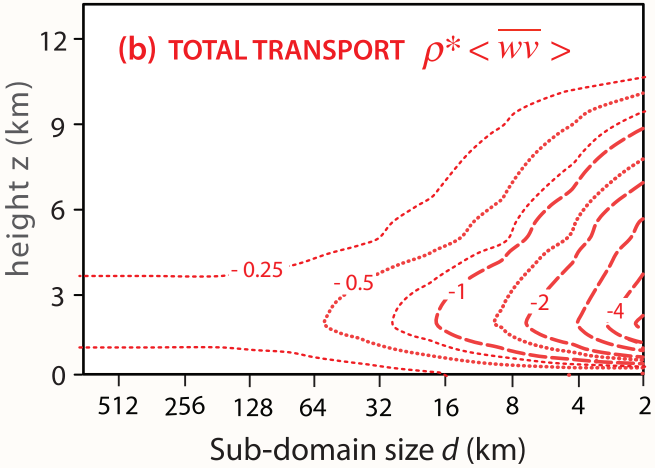
HORIZONTAL VELOCITY



RESOLUTION DEPENDENCE

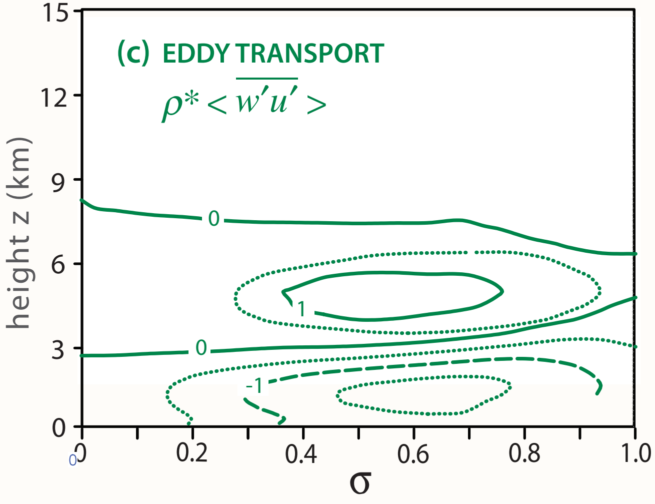
VERTICAL TRANSPORT OF HORIZONTAL MOMENTUM

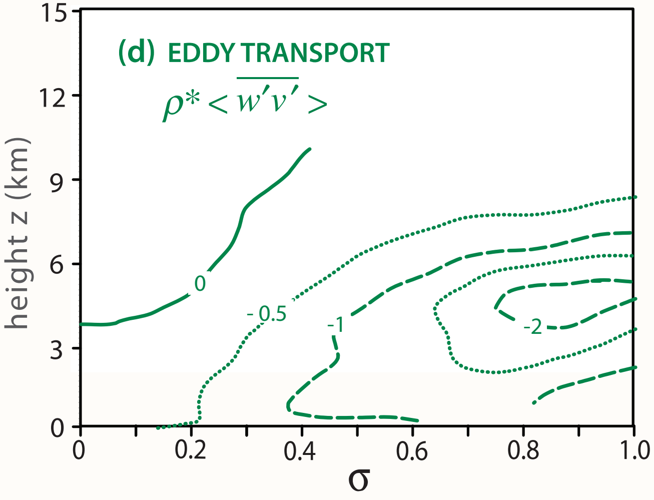




EDDY VERTICAL TRANSPORT OF HORIZONTAL MOMENTUM

Similar to *h*-transport



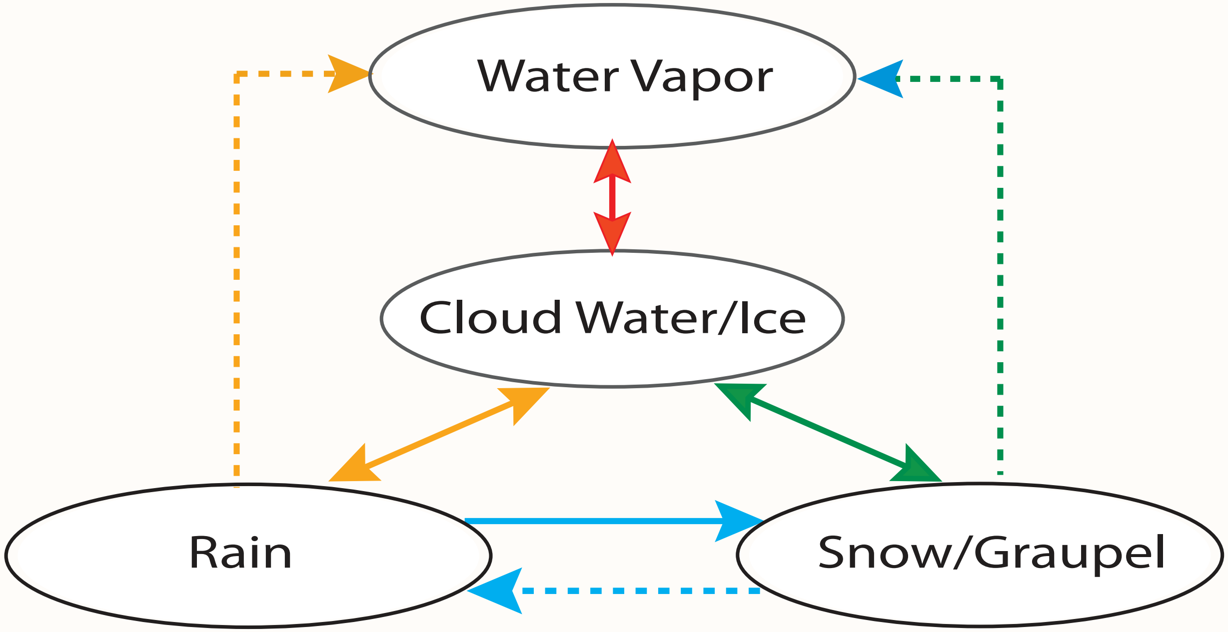


Not similar to *h*-transport

These results seem to be consistent wih

what Mitchell Moncrieff has been emphasizing.

CLOUD-MICROPHYSICAL CONVERSIONS INCLUDED IN THE MODEL



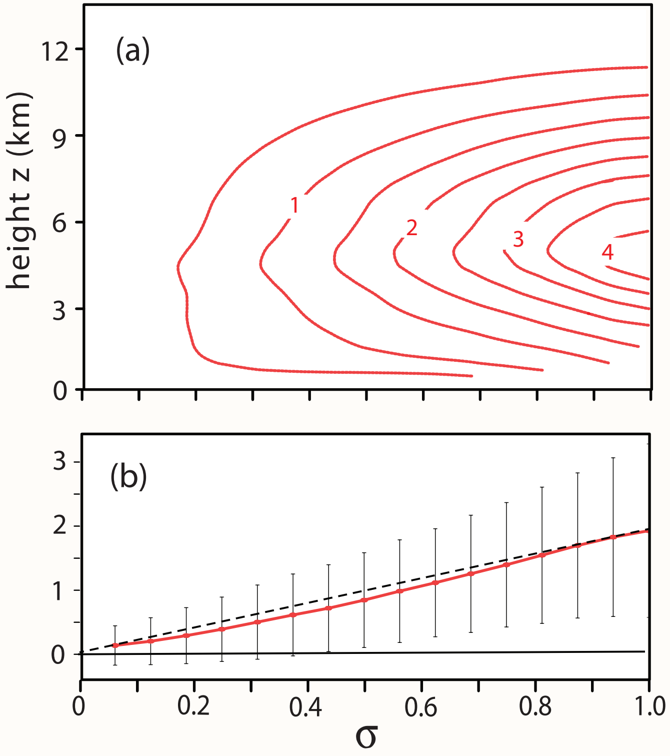
Solid lines: Conversions taking place primarily within updrafts

Dashed lines: Conversions taking place primarily outside of updrafts

THE NET CONVERSION

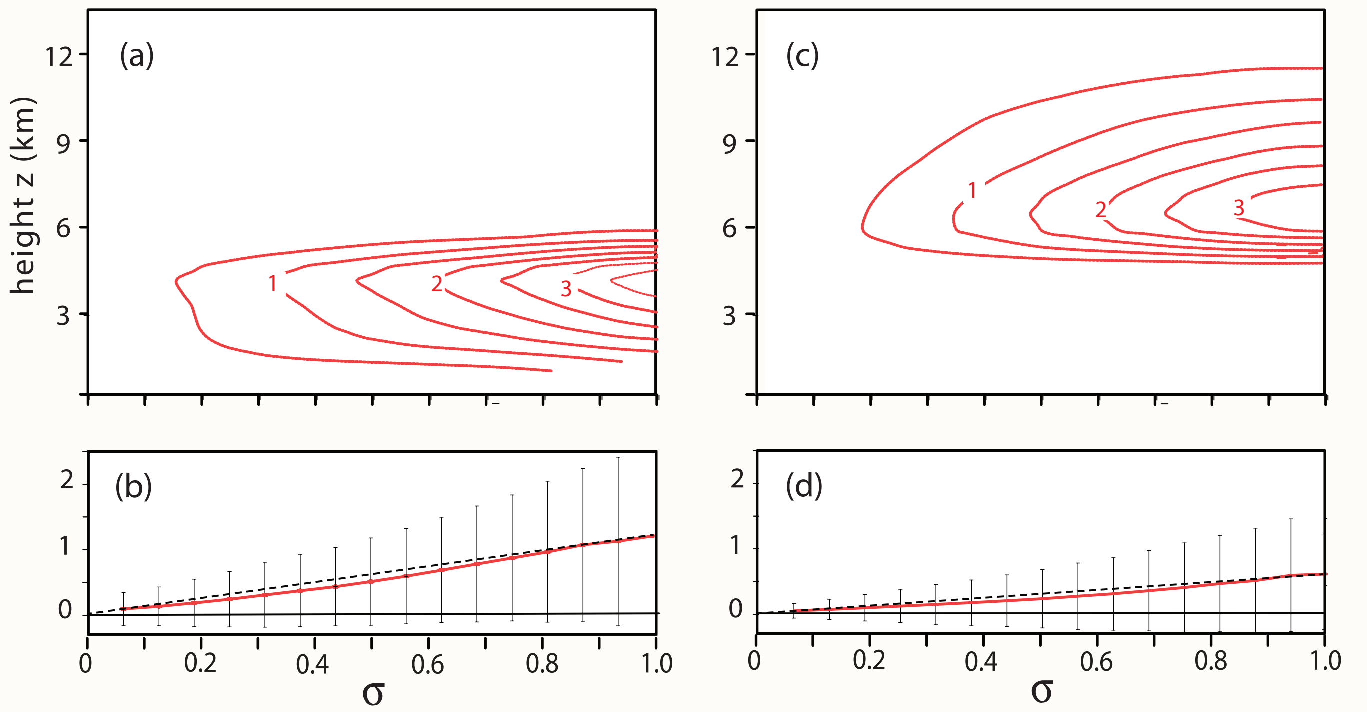
FROM WATER VAPOR TO CLOUD WATER/ICE

d = 8 KM



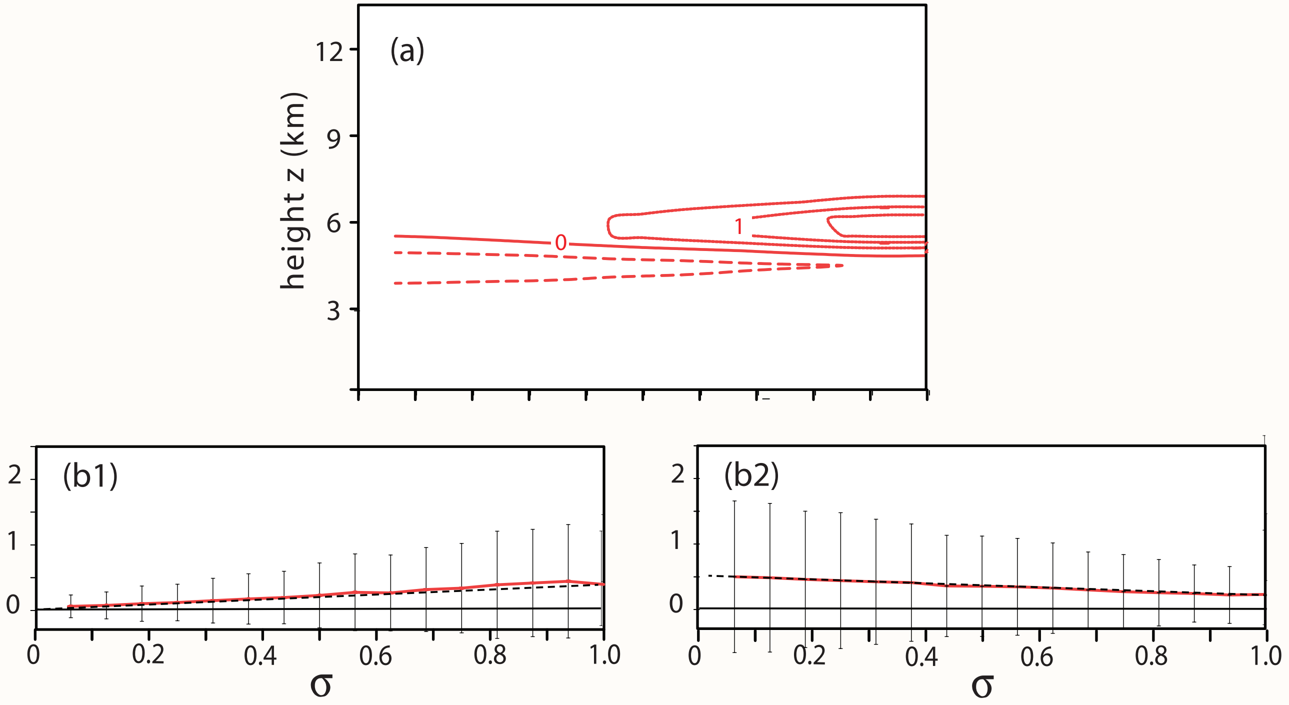
THE NET CONVERSION FROM CLOUD WATER/ICE

TO RAIN d = 8 KM TO SNOW/GRAUPEL



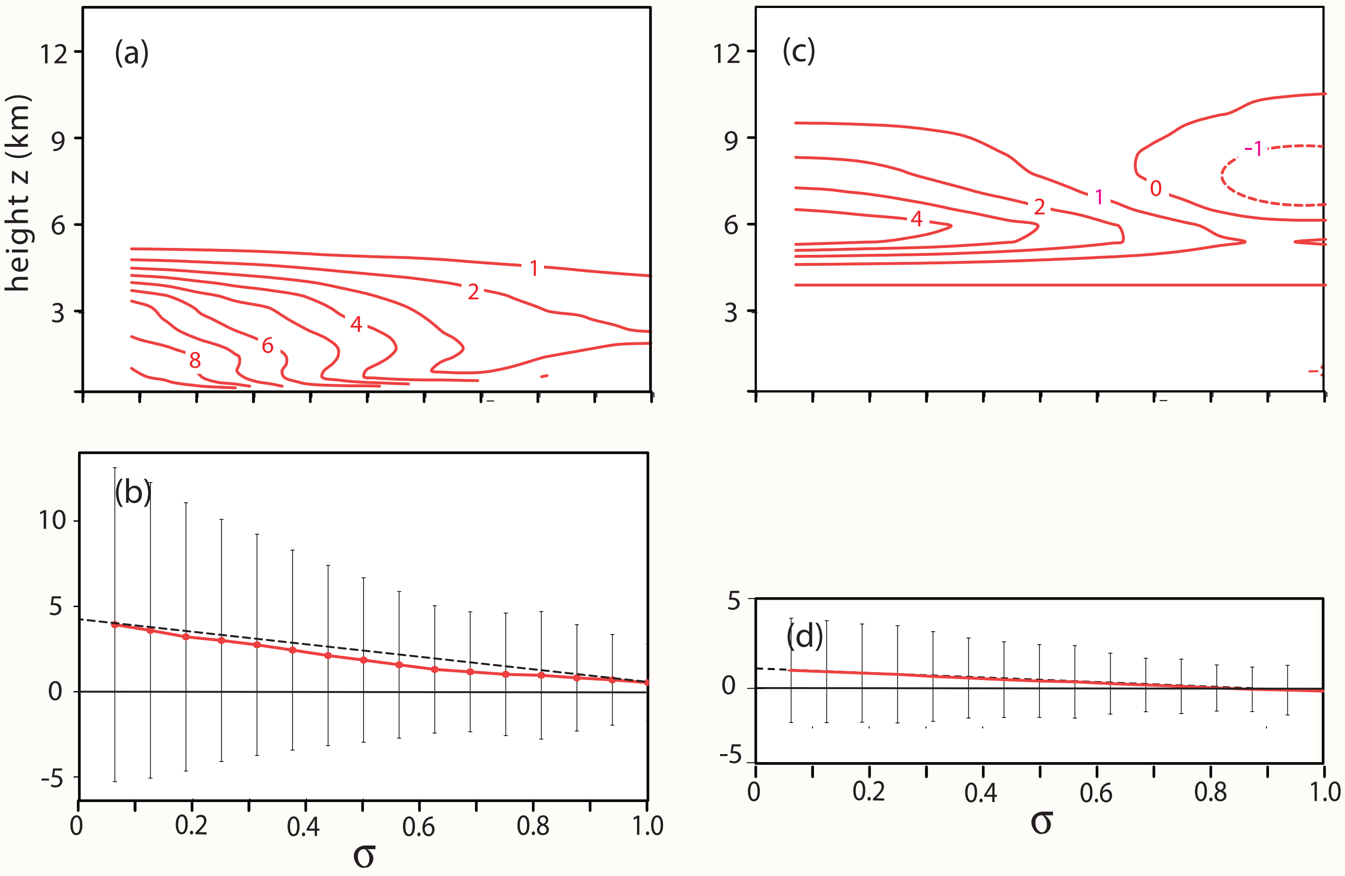
THE NET CONVERSION FROM RAIN TO SNOW/GRAUPEL

d = 8 KM



THE EVAPORATION OF RAIN AND SUBLIMATION OF SNOW/GRAUPEL

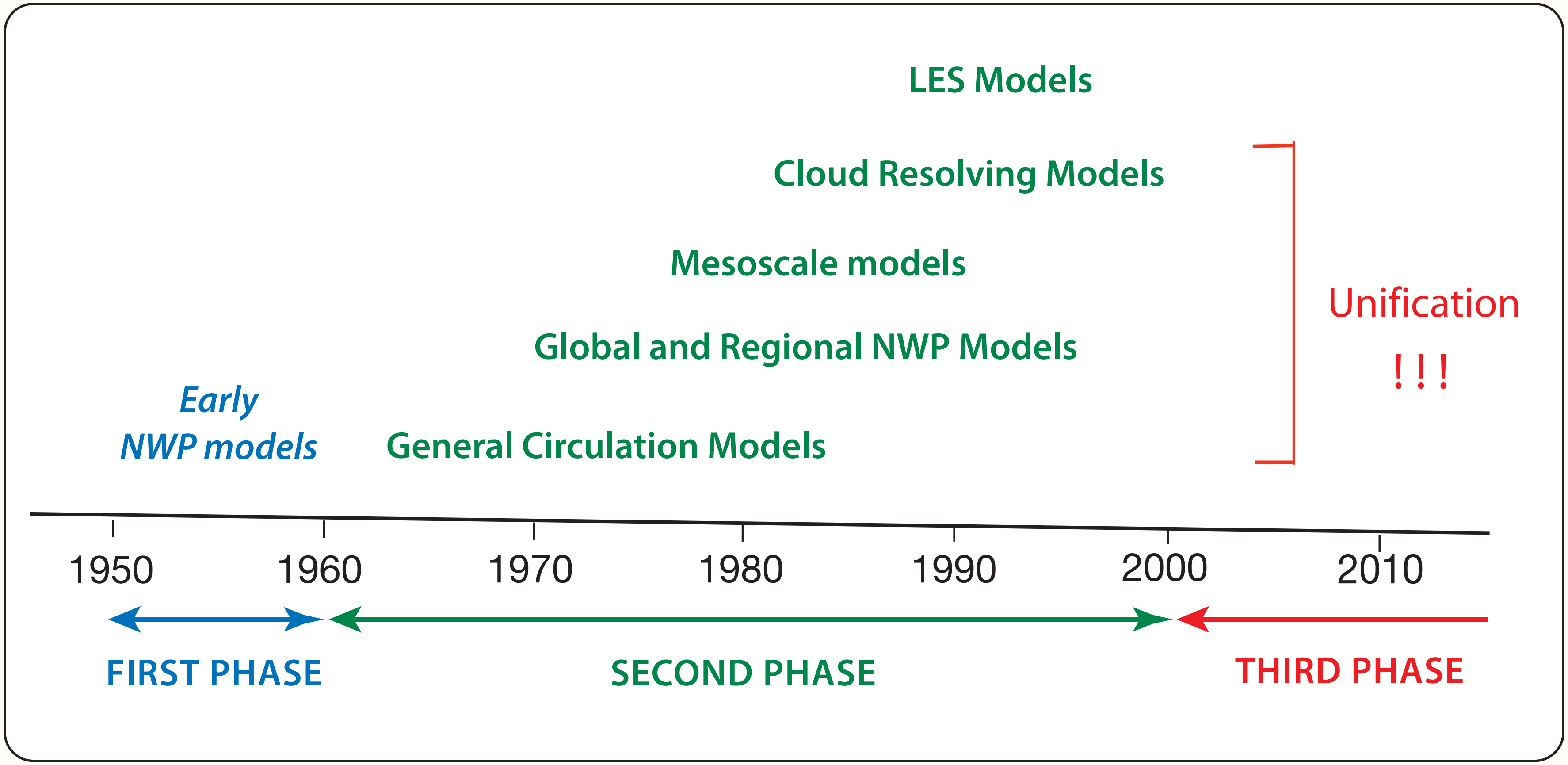
FROM RAIN d = 8 KM **FROM SNOW/GRAUPEL**



SUMMARY

- A generalized modeling framework, called “unified parameterizaion”, is presented.
- The key parameter in the framework is σ determined for each realization of grid-scale process.
- The eddy transport of moist static energy (and other thermodynamic variables) decreases as σ approaches 1.
- The traditional approach of parameterizing the vertical transport of horizontal momentum does not work for the line-normal component. .
- Cioud-microphysical conversions taking place within updrafts is roughly proportional to σ, while those taking place outside of updrafts are roughly proportional to $1 - \sigma$.

HISTORY OF NUMERICAL MODELING OF THE ATMOSPHERE



LES Models

Cloud Resolving Models

Mesoscale models

Global and Regional NWP Models

Early NWP models

General Circulation Models

Unification

! ! !

1950 1960 1970 1980 1990 2000 2010

FIRST PHASE

SECOND PHASE

THIRD PHASE

THANK YOU, DAVE,

AND ALL OF MY EX-STUDENTS AND COLLEAGUES

FOR GIVING ME THIS EXCITEMENT !