# Super-parameterization: what it is and what is "super" about it?


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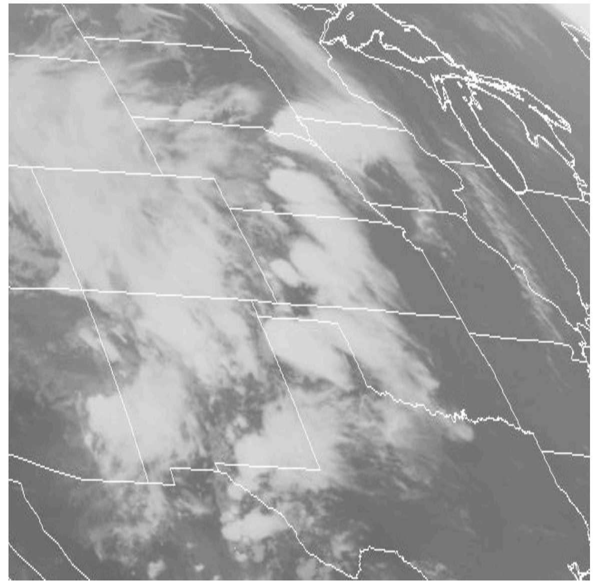
- Introduction: the concept of super-parameterization (SP)
- Examples of initial applications
- Further developments and applications
- Towards global LES: can we get there faster?

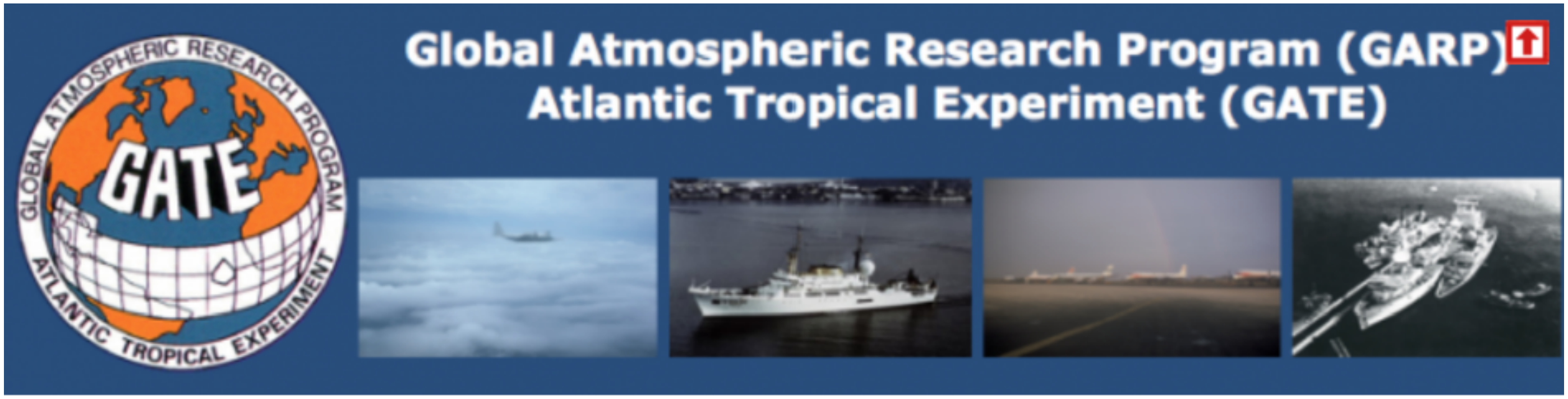
Mesoscale convective
systems over US



*Clouds and climate:*
*the range of scales...*

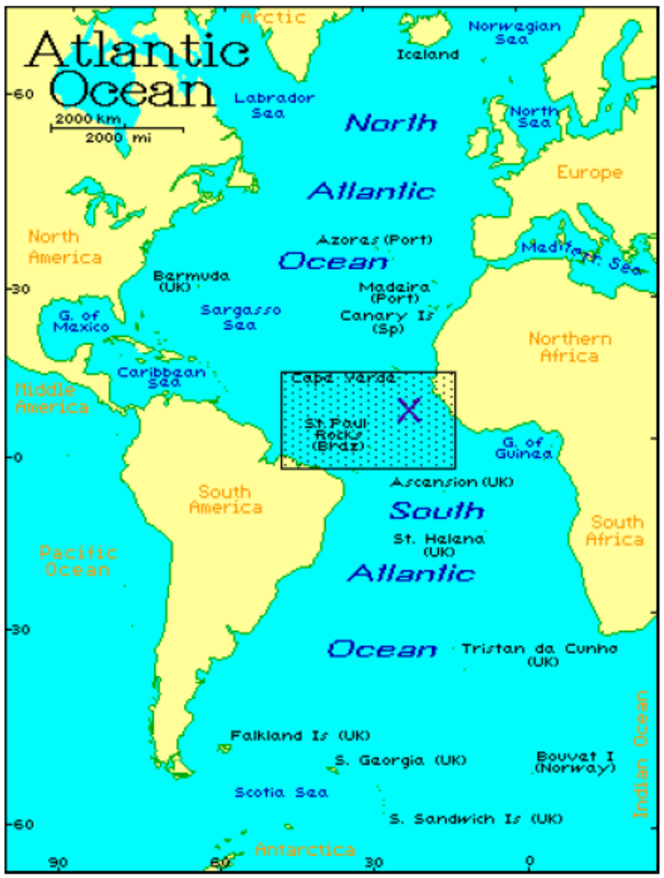
Small cumulus
clouds

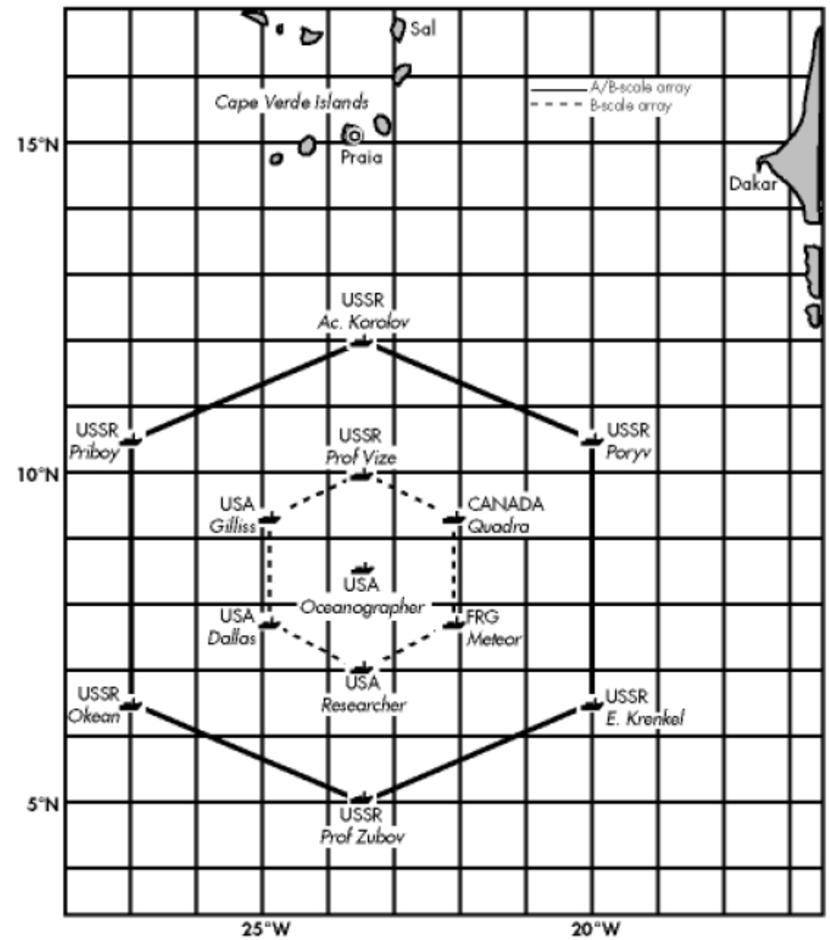
Mixing in laboratory
cloud chamber

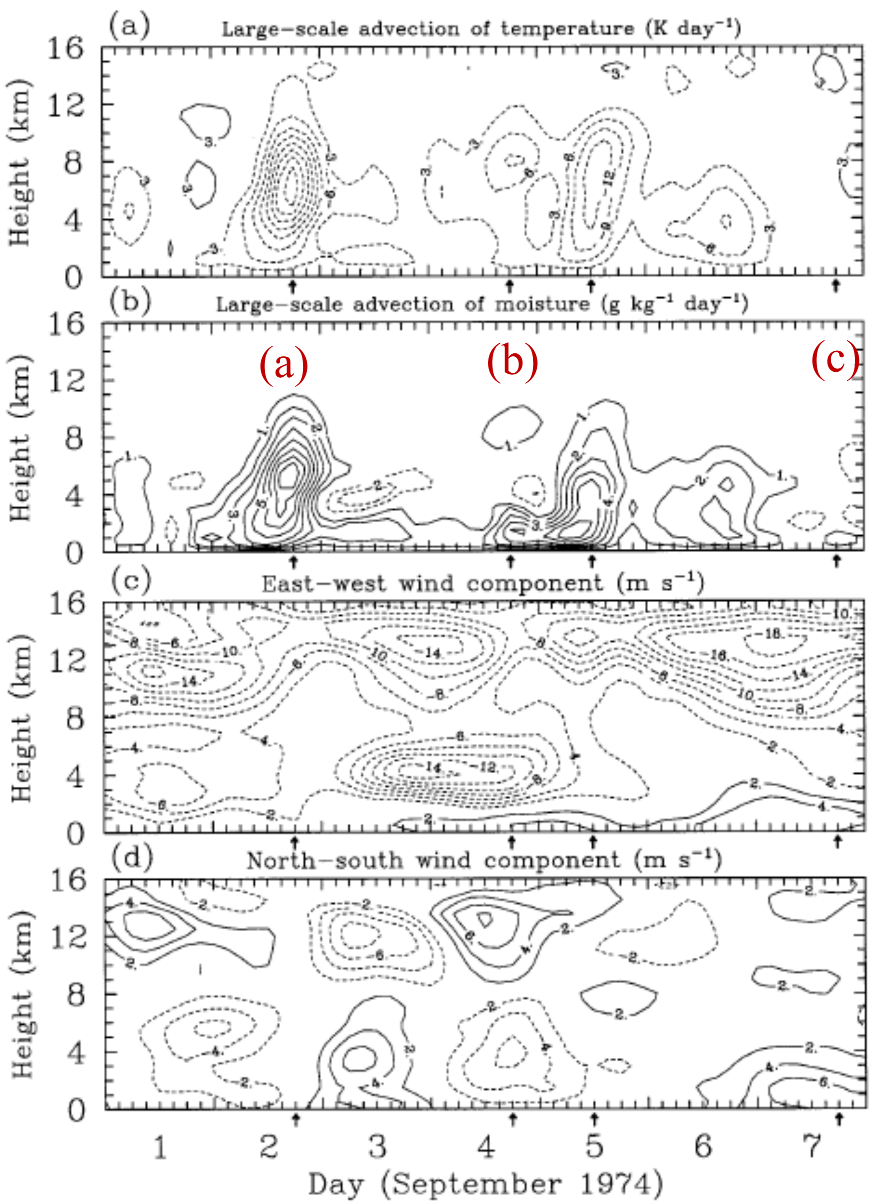


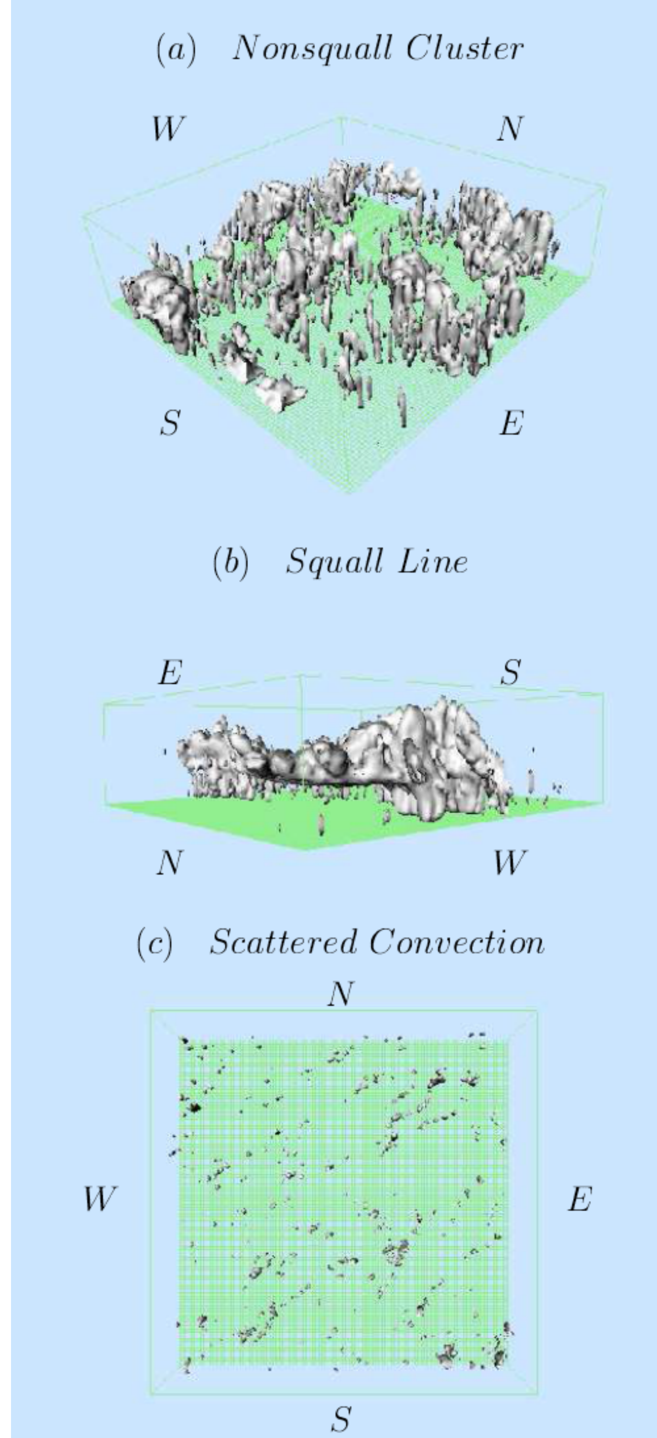

June 15, 1974 to September 23, 1974

**Project Location:** Atlantic Ocean






Grabowski et al. *JAS* 1996, 1998a,b

# Cloud-resolving modeling of GATE cloud systems
(Grabowski et al. JAS 1996, 1998)

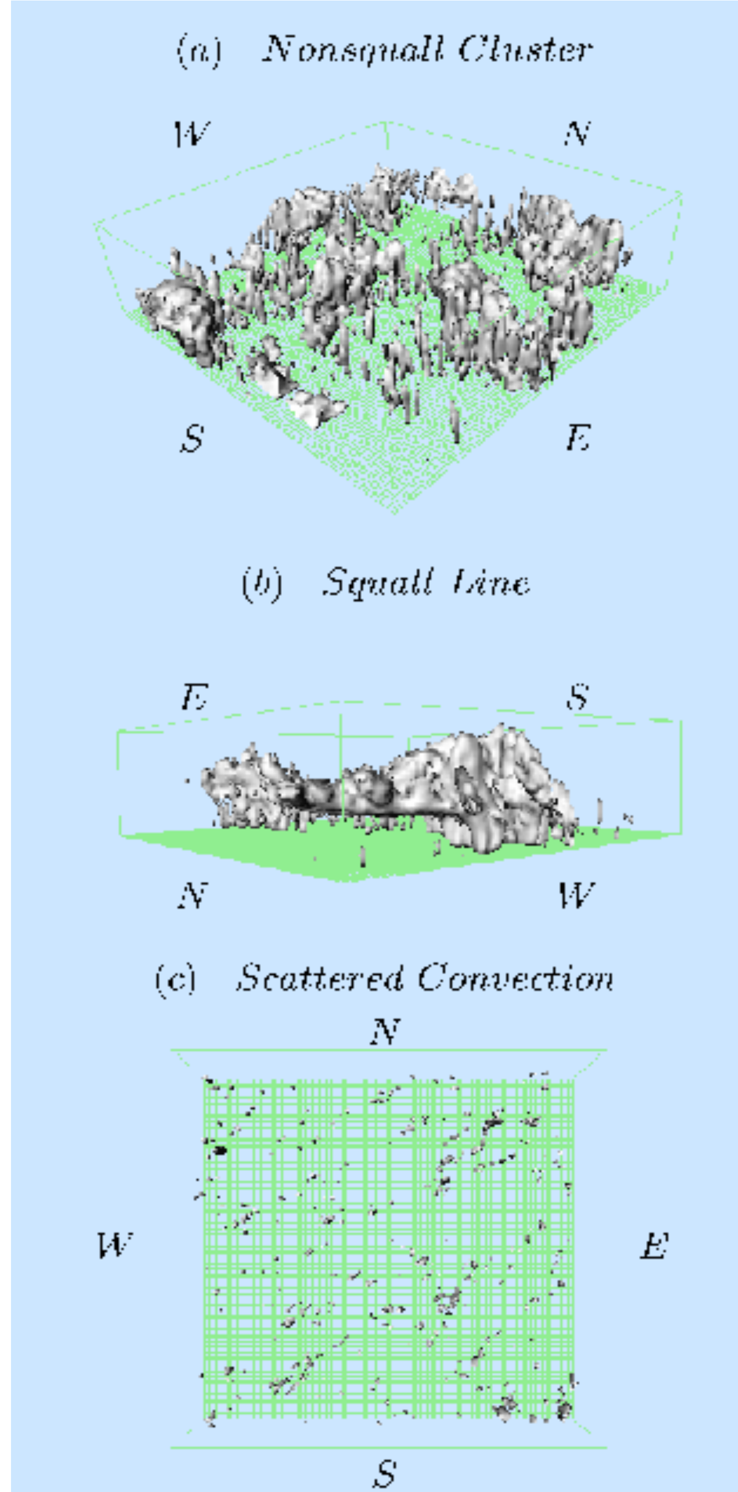
2 Sept, 1800 Z

400 x 400 km horizontal domain,
doubly-periodic,
2 km horizontal grid length

Driven by observed large-scale conditions

4 Sept, 1800 Z

7 Sept, 1800 Z



Grabowski et al. JAS 1998:

"…low resolution two-dimensional simulations can be used as realizations of tropical cloud systems in the climate problem and for improving and/or testing cloud parameterizations for large-scale models…"

- *Can we use 2D cloud-resolving model (CRM) in all columns of a climate model to represent deep convection?*

- *Can we move other parameterizations (radiative transfer, land surface model, etc) into 2D CRM?*

# Cloud-Resolving Convection Parameterization (CRCP)

## (super-parameterization, SP)

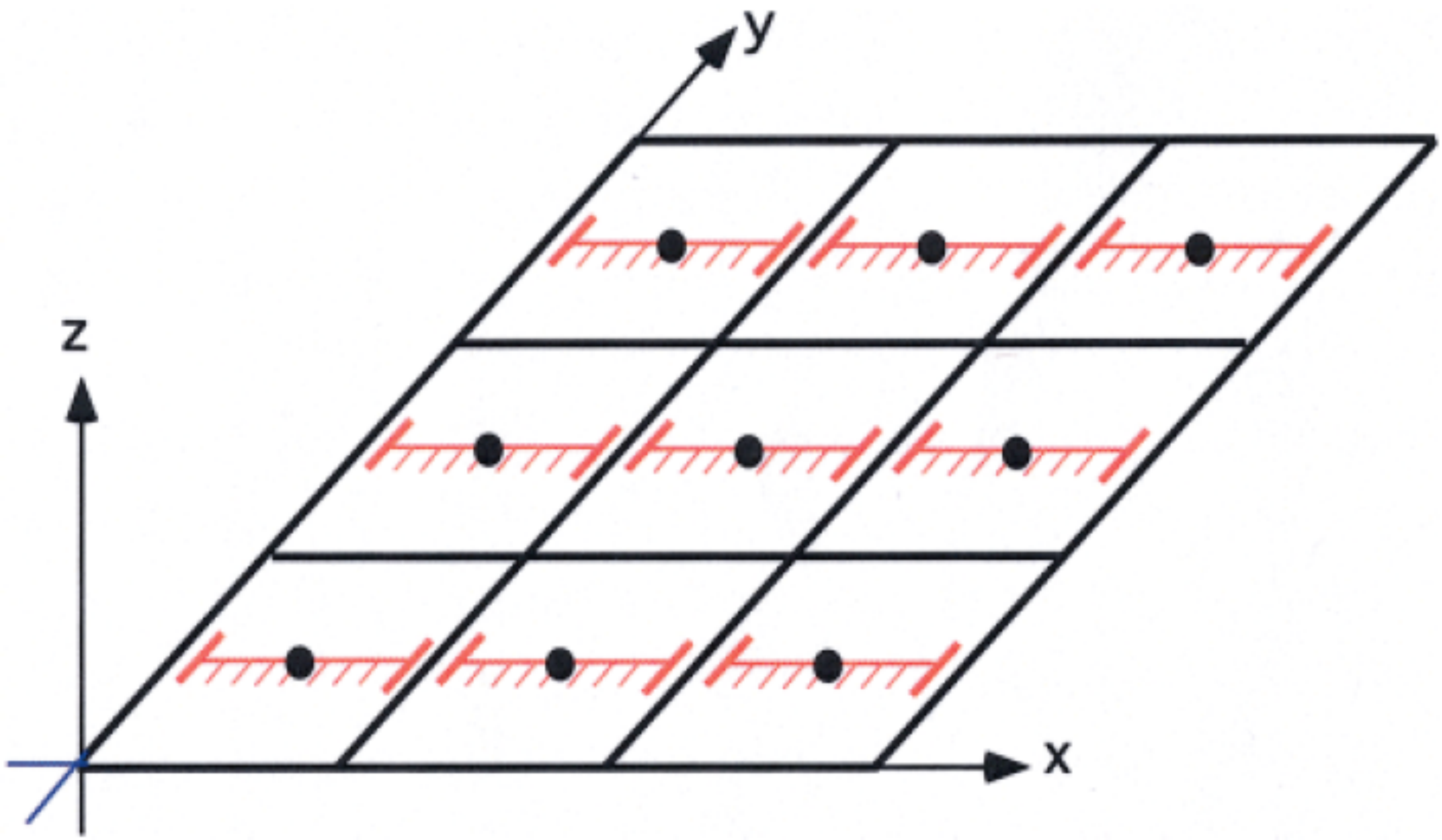
Grabowski and Smolarkiewicz, Physica D 1999

Grabowski, JAS 2001

The idea is to represent subgrid scales of the 3D large-scale model (horizontal resolution of 100s km) by embedding periodic-domain 2D CRM (horizontal resolution around 1 km) in each column of the large-scale model

*Another (better?) way to think about CRCP: CRCP involves hundreds or thousands of 2D CRMs interacting in a manner dictated by the large-scale dynamics*

# Original SP proposal:




Randall et al. *BAMS* 2003

- CRCP is a “parameterization” because scale separation between large-scale dynamics and cloud-scale processes is assumed; cloud models have periodic horizontal domains and they communicate only through large scales

- CRCP is “embarrassingly parallel”: a climate model with CRCP can run efficiently on 1000s of processors

- CRCP is a physics coupler: most (if not all) of physical (and chemical, biological, etc.) processes that are parameterized in the climate model can be included into CRCP framework

# “A day, a year, a millennium” paradigm

With the same amount of computer time, one can perform:

- about a day-long simulation using cloud-resolving AGCM
- about a year-long climate simulation using AGCM with super-parameterization
- about a millennium-long climate simulation using a traditional AGCM with parameterized convection

# CRCP (SP, MMF) was making a steady progress…

- **Grabowski (NCAR): idealized simulations of large-scale tropical dynamics (MJO; Grabowski JAS 2003, 2006; Grabowski and Moncrieff QJ 2004)**

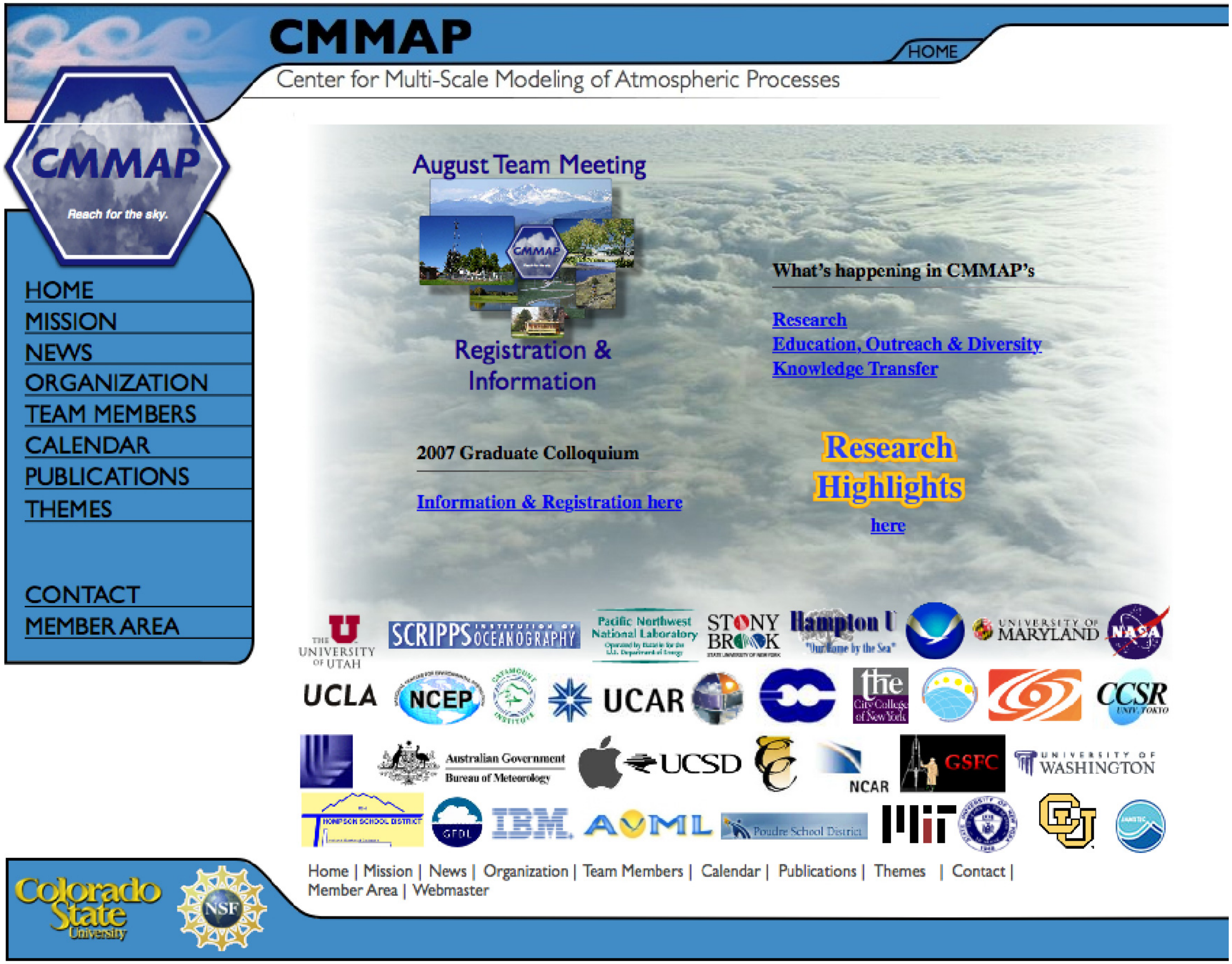
- **Khairoutdinov/Randall (CSU): realistic climate simulations using CAM (atmospheric part of NCAR's CCSM; Khairoutdinov et al. JAS 2005, 2007)**

- **Arakawa: proposal to extend original formulation to remove some of the limitations (see Randall et al. BAMS 2003, Jung and Arakawa MWR 2005)**

- **Effort within ARM Program to compare SP AGCM simulations with ARM observations (CSU model in DOE Labs, e.g., Ovtchinnikov et al. JCli 2006)**

- **Efforts within NASA (Goddard, Langley) to run SP GCMs (Tao, Xu)**

- **NSF Science and Technology Center at CSU: Center for Multiscale Modeling of Atmospheric Processes, CMMAP**




7 6 8 2

http://saddleback.atmos.colostate.edu/cmmap/

# A Multiscale Model Is A Scientific Water Hole.

(Dave Randall, 2007)

# Examples of initial applications:

- Simulations of the Madden-Julian Oscillation (MJO)-like coherences on a constant-SST aquaplanet (Grabowski JAS 2001, 2006)

- AGCM simulations using CAM (Colorado State University: Khairoutdinov et al. JAS 2005; JCli 2007)

**Madden and Julian, JAS 1972**

34 days

0 days, 45 days

12 days

22 days

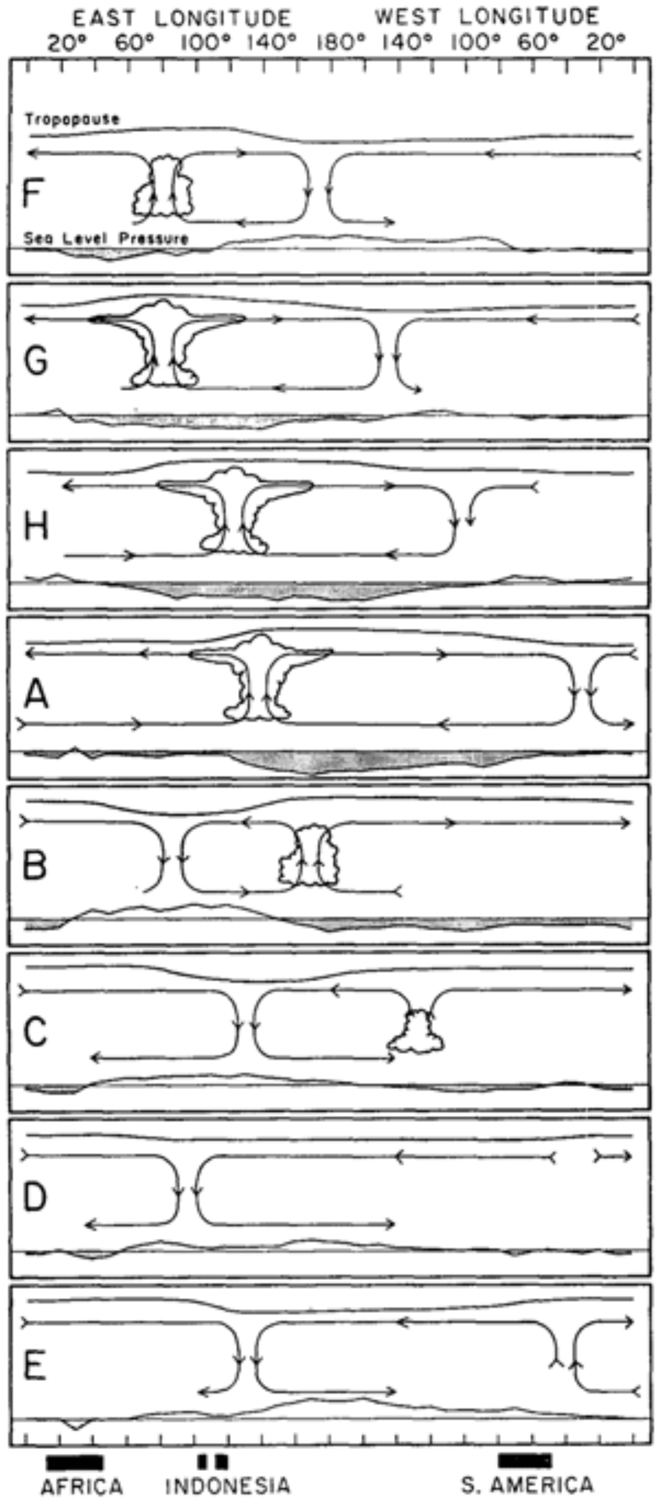
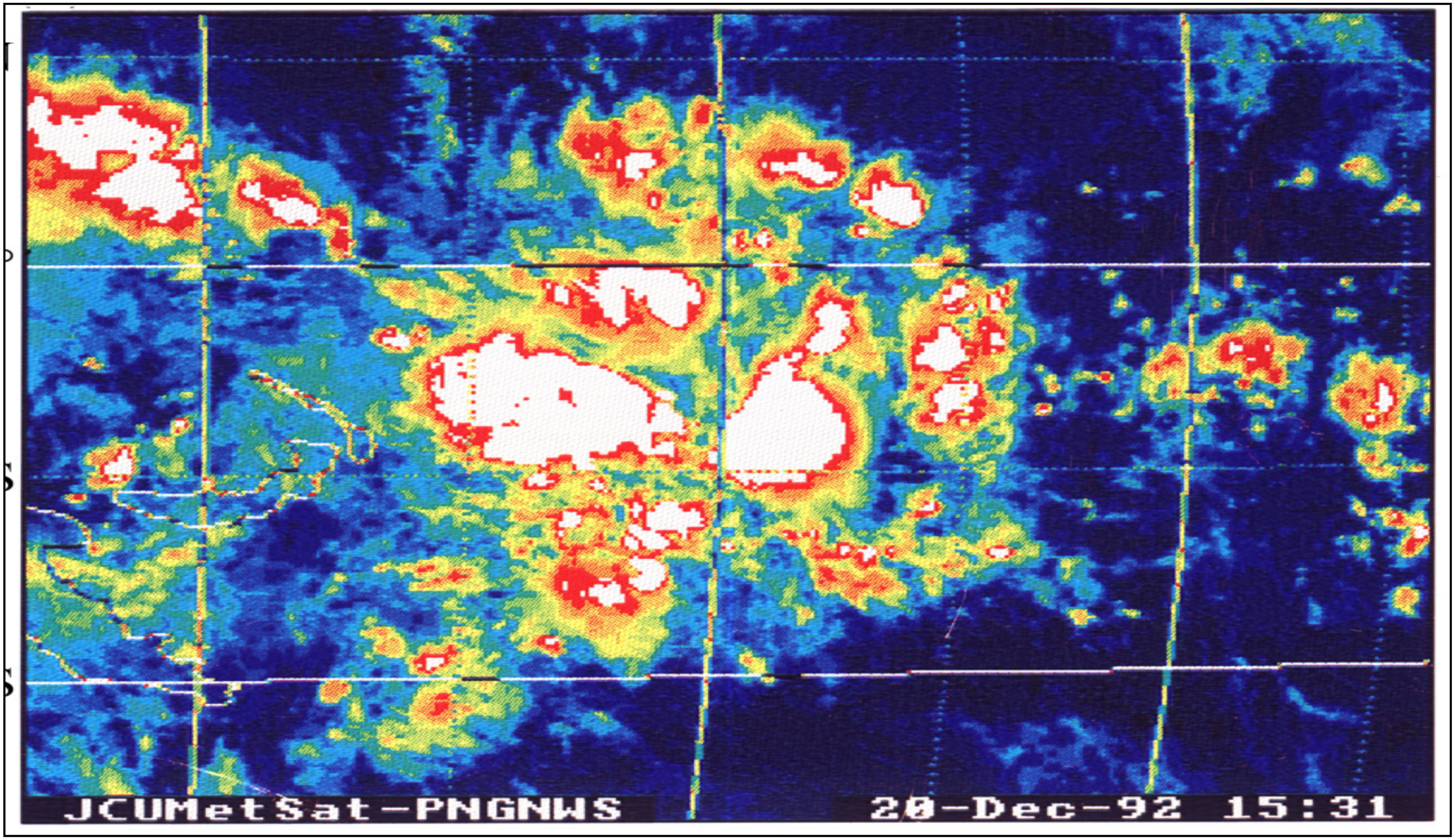
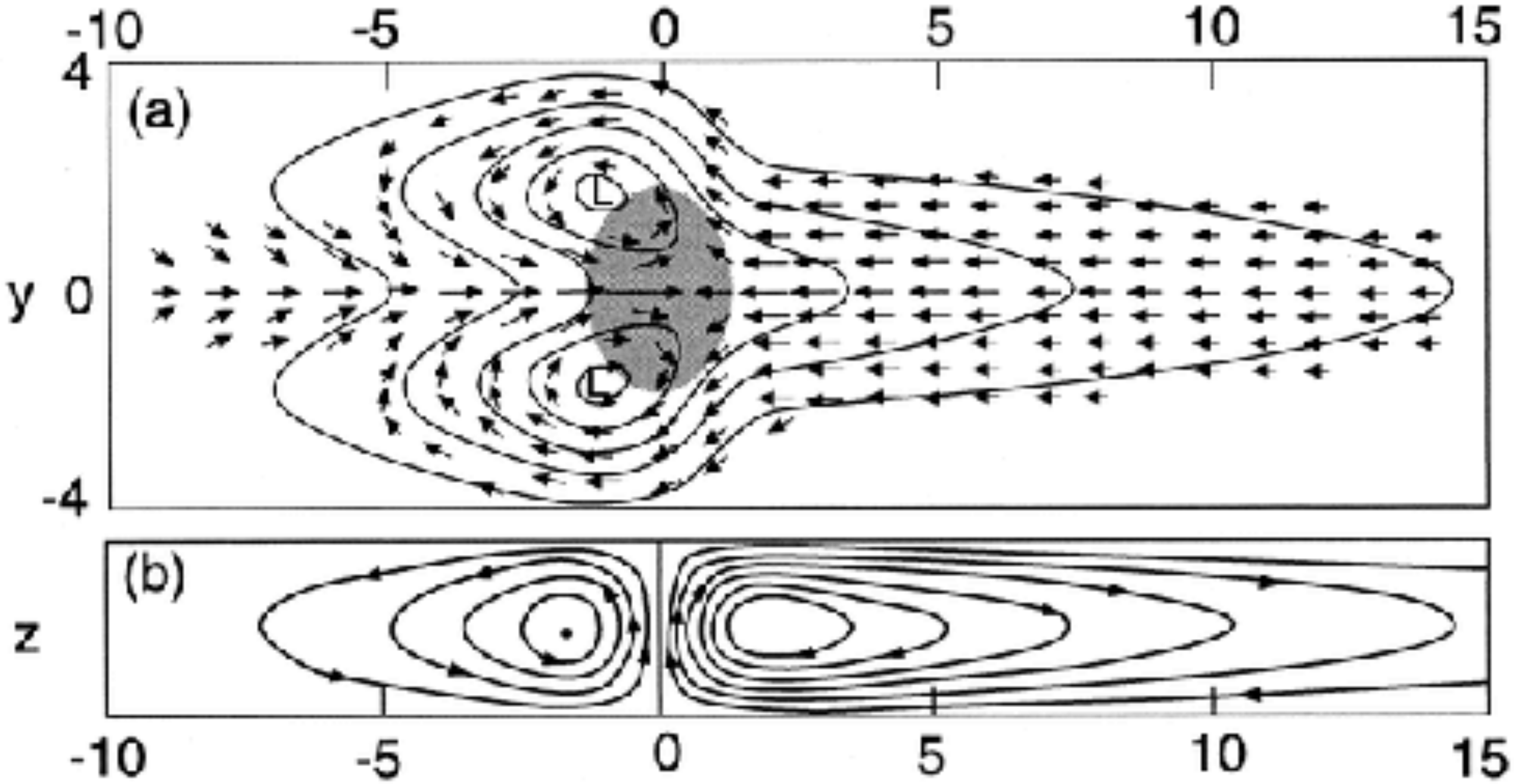



FIG. 16. Schematic depiction of the time and space (zonal plane) variations of the disturbance associated with the 40–50 day oscillation. Dates are indicated symbolically by the letters at the left of each chart and correspond to dates associated with the oscillation in Canton's station pressure indicated in Fig. 11. The mean pressure disturbance taken from Fig. 12 is plotted at the bottom of each chart with negative anomalies shaded. The circulation cells are based on the mean zonal wind disturbance presented in Fig. 13. Regions of enhanced large-scale convection are indicated schematically by the cumulus and cumulonimbus clouds. The relative tropopause height is indicated at the top of each chart.

Satellite picture of a super-cluster during TOGA COARE






Flow at the surface

Streamlines at the equatorial plane

Circulation produced by deep heating anomaly over the equator (stripped), with Kelvin-wave response to the east and Rossby-wave response to the west, the Kelvin-Rossby wave (Gill 1980, as shown by Salby 1996).

Plethora of theories trying to explain the large-scale organization of tropical convection:

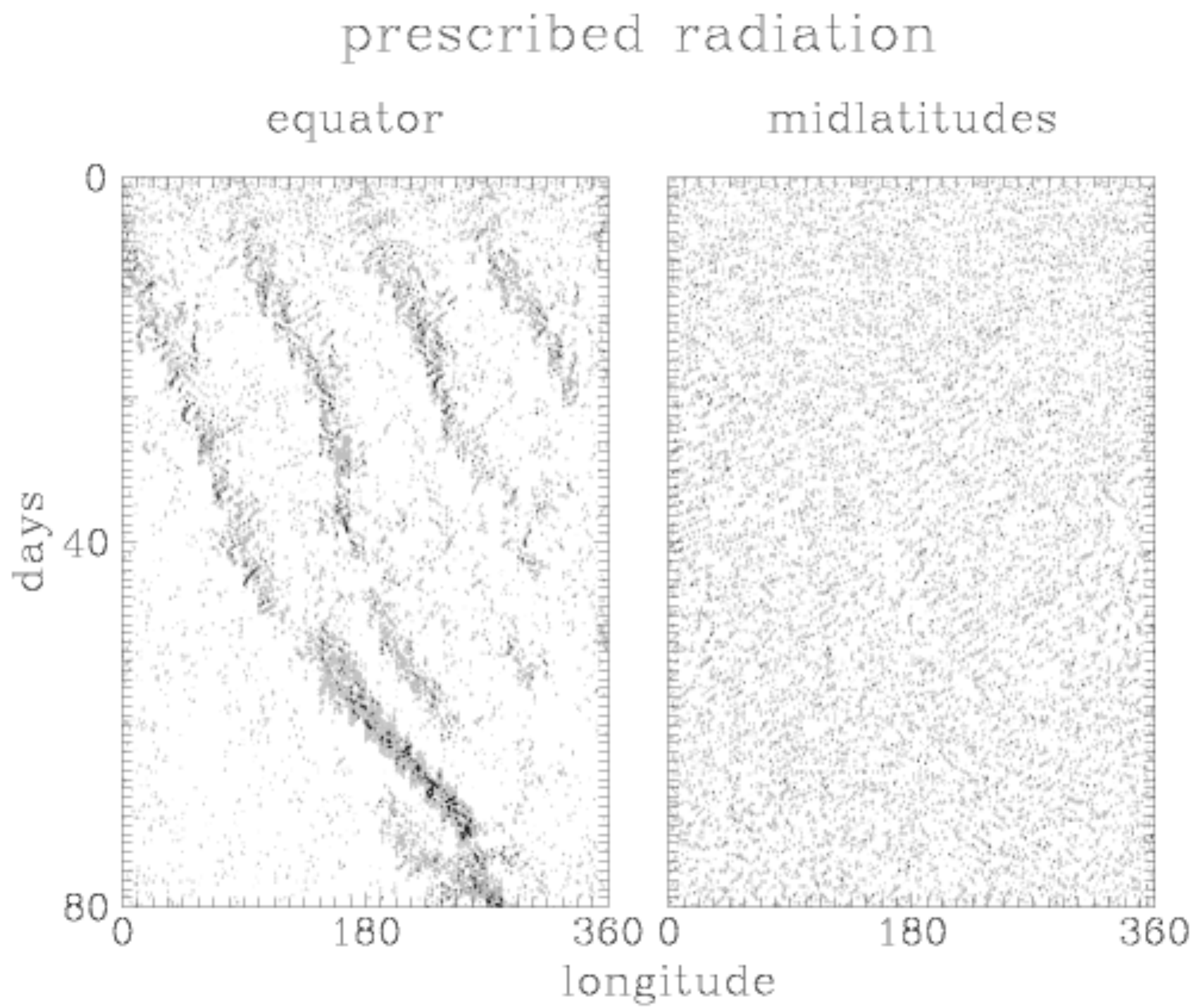
- Coupling between convection and large-scale equatorial perturbations (wave-CISK, etc; e.g., Lindzen 1974; Lau et al. 1989; Wang and Rui 1880; Majda and Shefter 2001…)
- Impact of moisture/clouds on radiative transfer (e.g., Pierrehumbert 1995; Raymond 2000, 2001…)
- Impact of free-troposheric humidity on convection (e.g., Raymond 2000; Tompkins 2001a,b; Grabowski 2003; Grabowski and Moncrieff 2004; Bony and Emanuel 2005)
- Impact of gravity waves on subsequent convective development (e.g., Mapes 1993, 1998; Ouchi 1999)
- Up-scale effects of organized convection (Moncrieff 2004) and synoptic-scale waves (Biello and Majda 2005)
- Atmosphere-ocean interaction:
  - WISHE (Emanuel 1997; Neelin et al. 1997)
  - coupled atmosphere-ocean dynamics (e.g., Flatau et al. 1997)

# MJO-like coherent structures on a constant-SST ("tropics everywhere") aquaplanet

- Size and rotation as Earth
- SST=30 degC
- Prescribed radiative cooling or interactive radiation transfer model (within CRCP domains; sun overhead over entire aquaplanet, no diurnal cycle)
- Atmosphere at rest (at large scales) at t=0
- Low horizontal resolution global model (32 x 16), small cloud models (100 x 50; dx=2 km, dz=0.5 km)

Grabowski *JAS* 2001

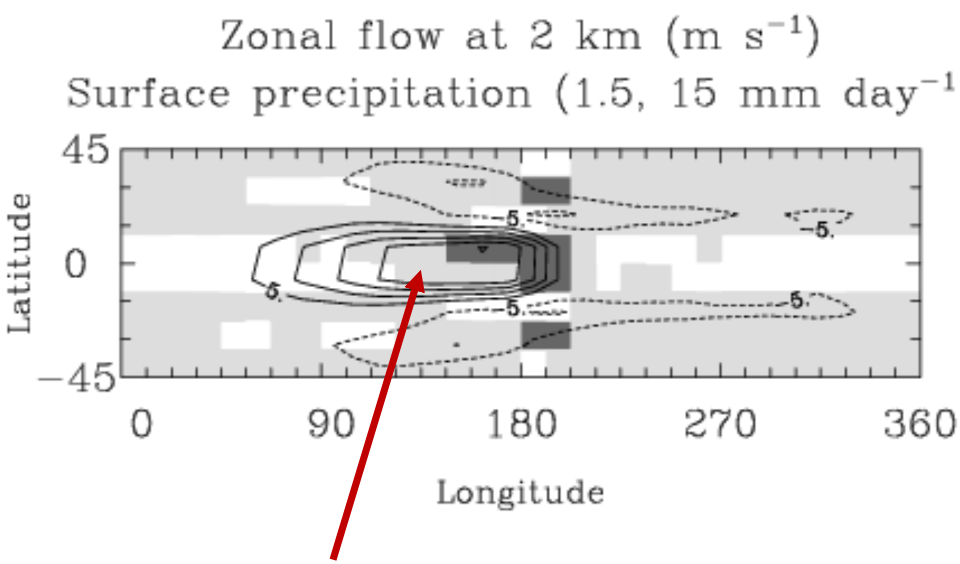
CRCP aligned EW,
free-slip surface,
prescribed radiation

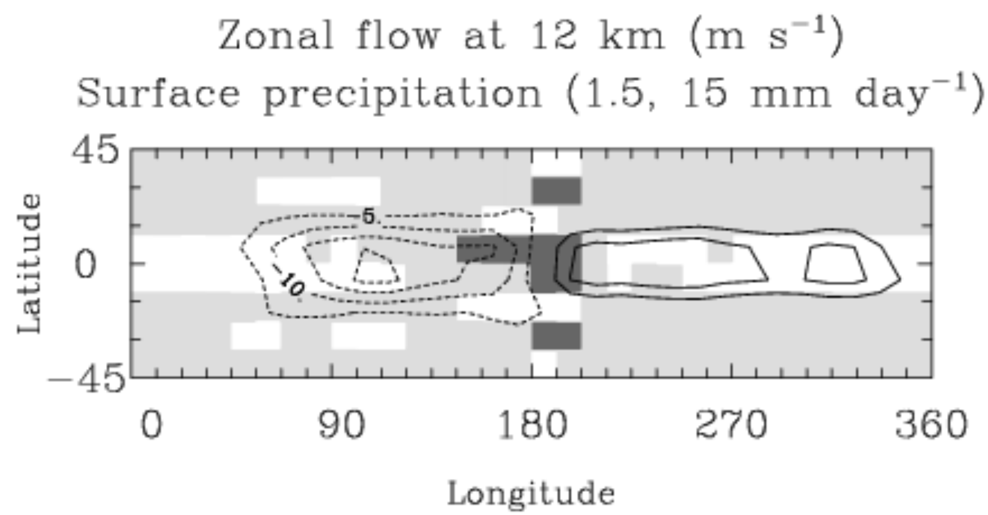



Surface
precipitation

Zonal flow (ground-relative) and surface precipitation,
20-day average in the reference frame moving with
MJO-like coherence

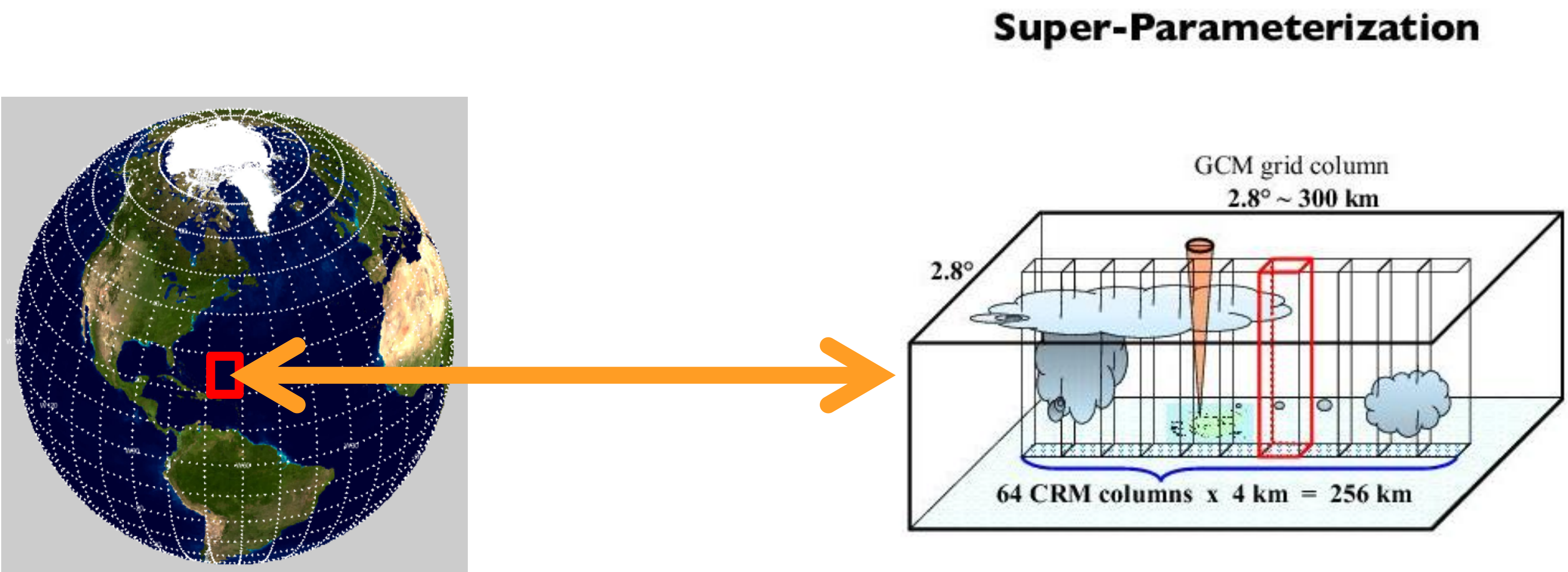
Kelvin/Rossby wave response to east/west



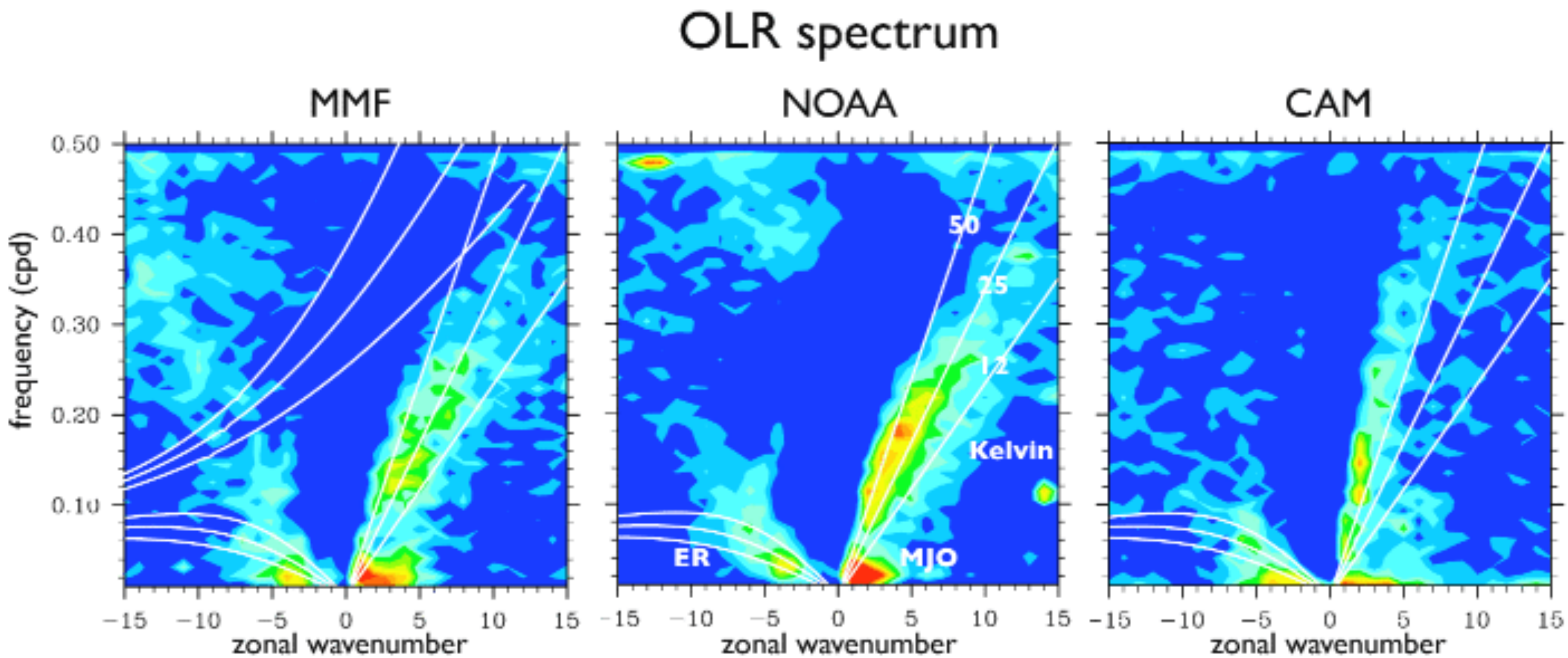

“westerly wind burst”

Multiscale Modeling Framework (MMF): SP (Super-Parameterized) CAM (Community Atmospheric Model, part of NCAR's Community Climate System Model (CCSM)




**(Khairoutdinov and Randall, 2001; Khairoutdinov et al. 2005, 2007; Wyant et al. 2006… and many many more, including coupled atmosphere-ocean simulations and land-surface model moved into SP, see an impressive list of publications at http://www.cmmap.org/research/pubs-ref.html**

# Tropical disturbances in MMF and standard CAM compared to observations on the Wheeler-Kiladis diagram



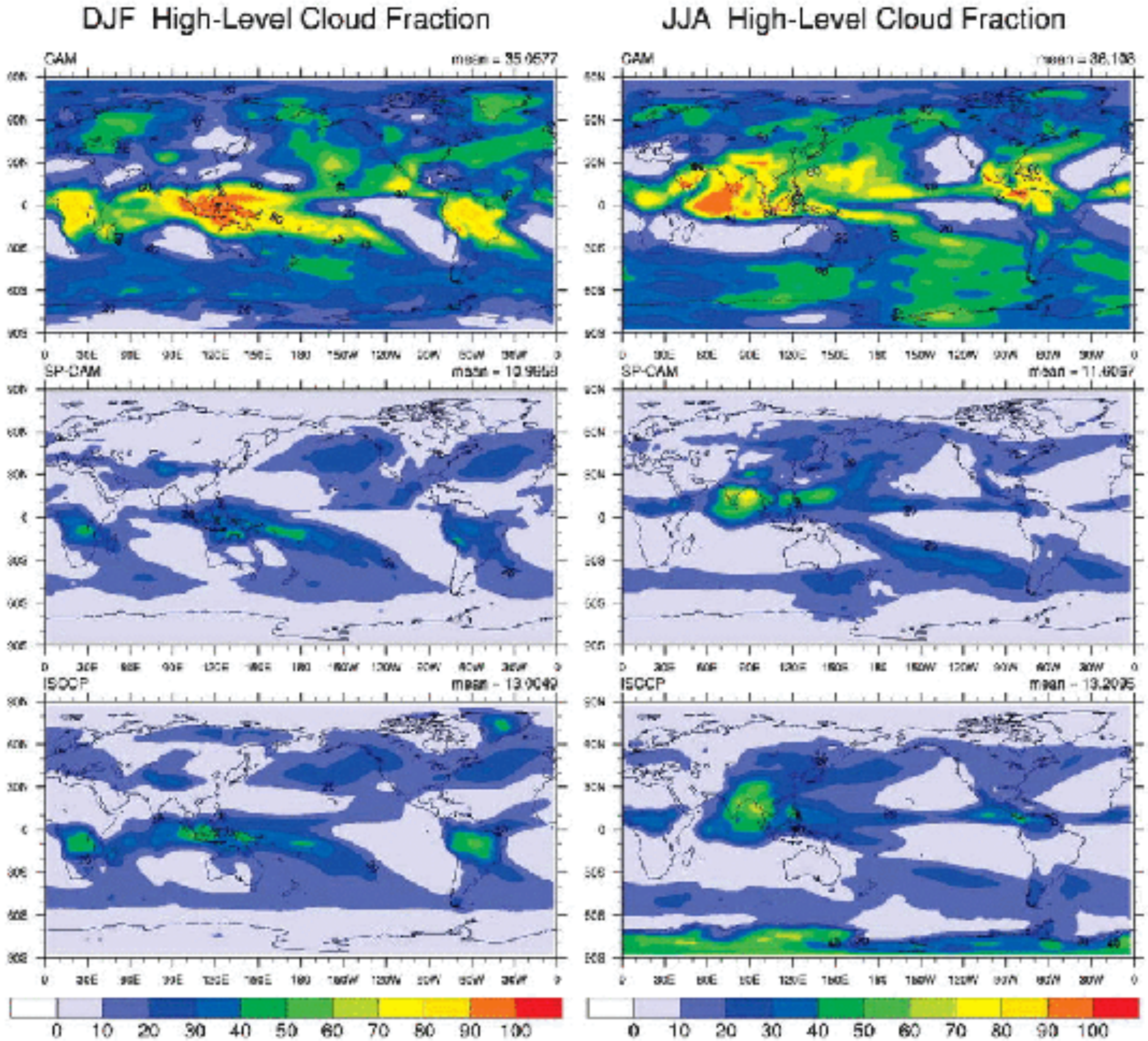

(Khairoutdinov et al. JAS (2007)

# Results from a traditional climate model versus MMF

**Traditional**

**MMF**

**Observations**




Khairoutdinov et al. JAS 2005

The works of CMMAP (2006-2016):

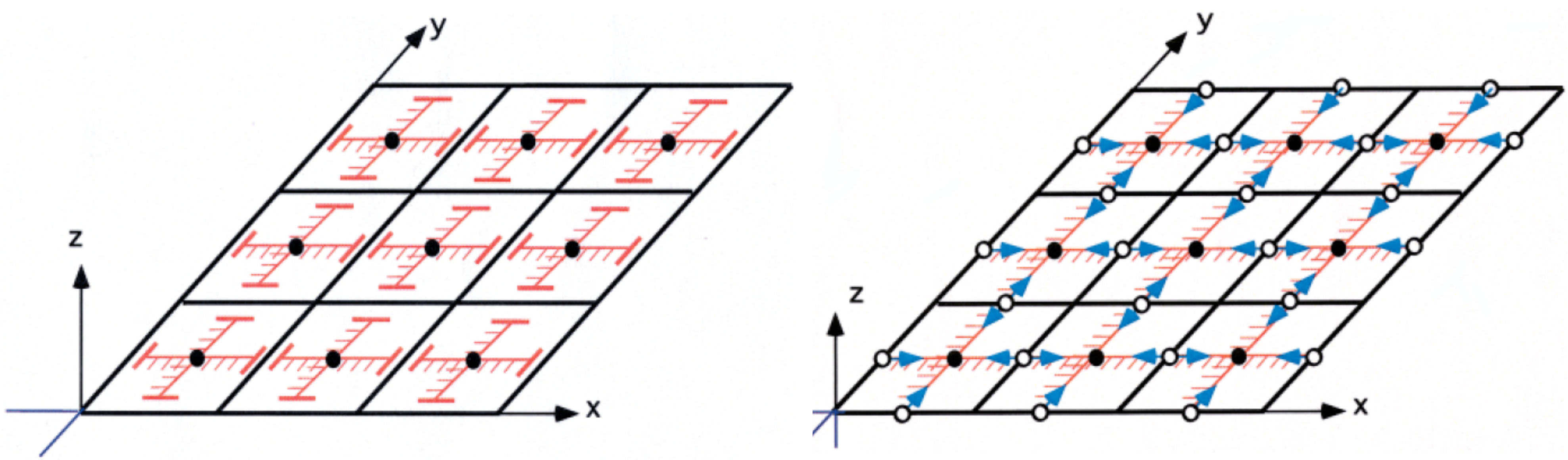
- studies of various aspects of intraseasonal variability and MJO;
- including HOC turbulence scheme into embedded CRM;
- development of global CRM;
- expanding atmosphere-only (SP-CAM) simulations to simulations with coupled ocean (ENSO etc.);
- simulations with land-surface model embedded within CRM;
- development of a next-generation of SP model.

about 400 peer-reviewed publications
http://saddleback.atmos.colostate.edu/cmmap/research/pubs-ref.html
a brief review (and more!) in Grabowski (JMSJ 2016)

# BREAKING THE CLOUD PARAMETERIZATION DEADLOCK

BAMS 2003

BY DAVID RANDALL, MARAT KHAIROUTDINOV, AKIO ARAKAWA, AND WOJCIECH GRABOWSKI

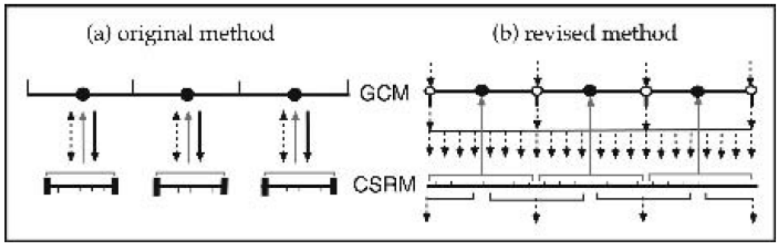


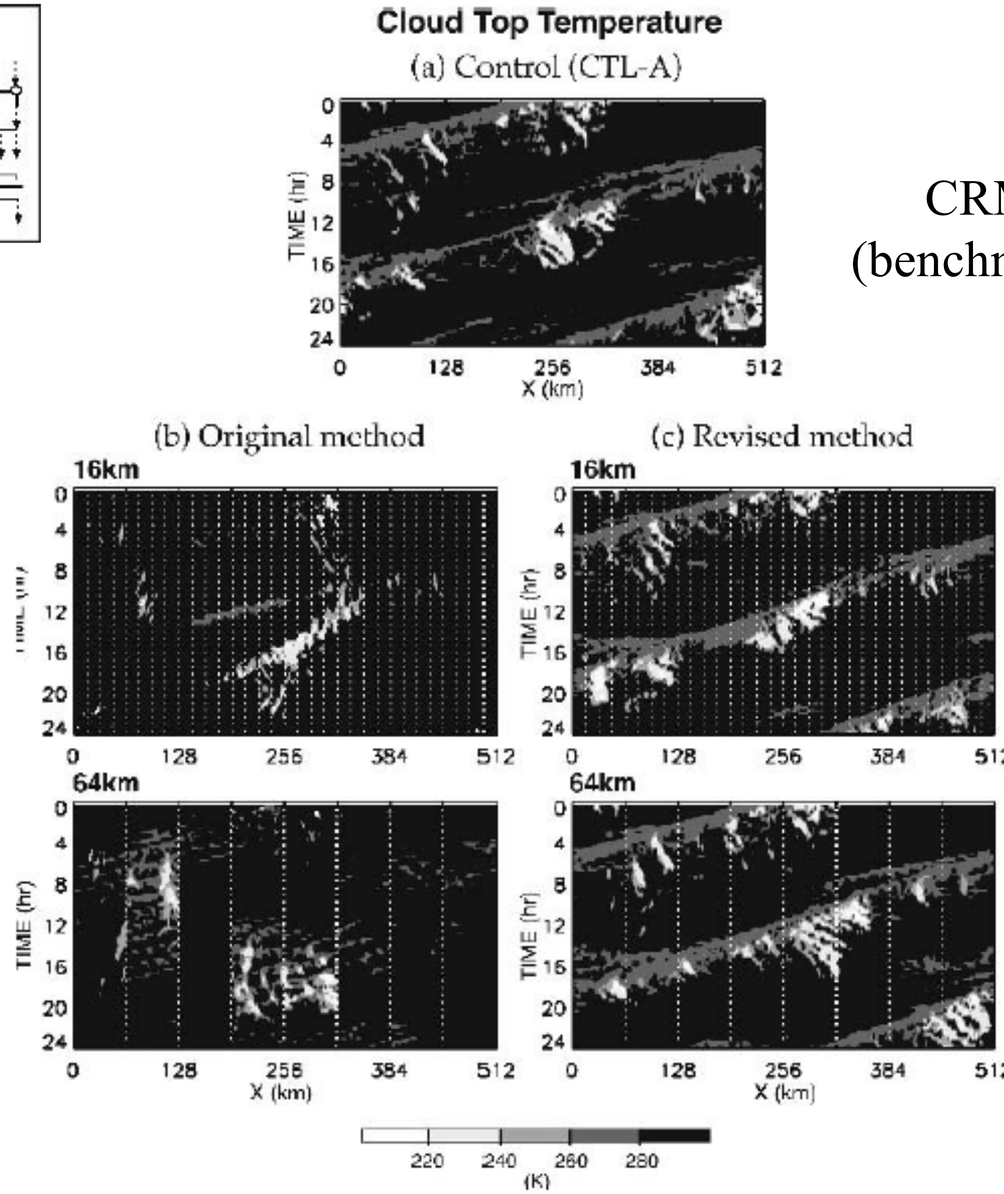
## Preliminary Tests of Multiscale Modeling with a Two-Dimensional Framework: Sensitivity to Coupling Methods

MWR 2003

JOON-HEE JUNG* AND AKIO ARAKAWA

*Department of Atmospheric Sciences, University of California, Los Angeles, Los Angeles, California*

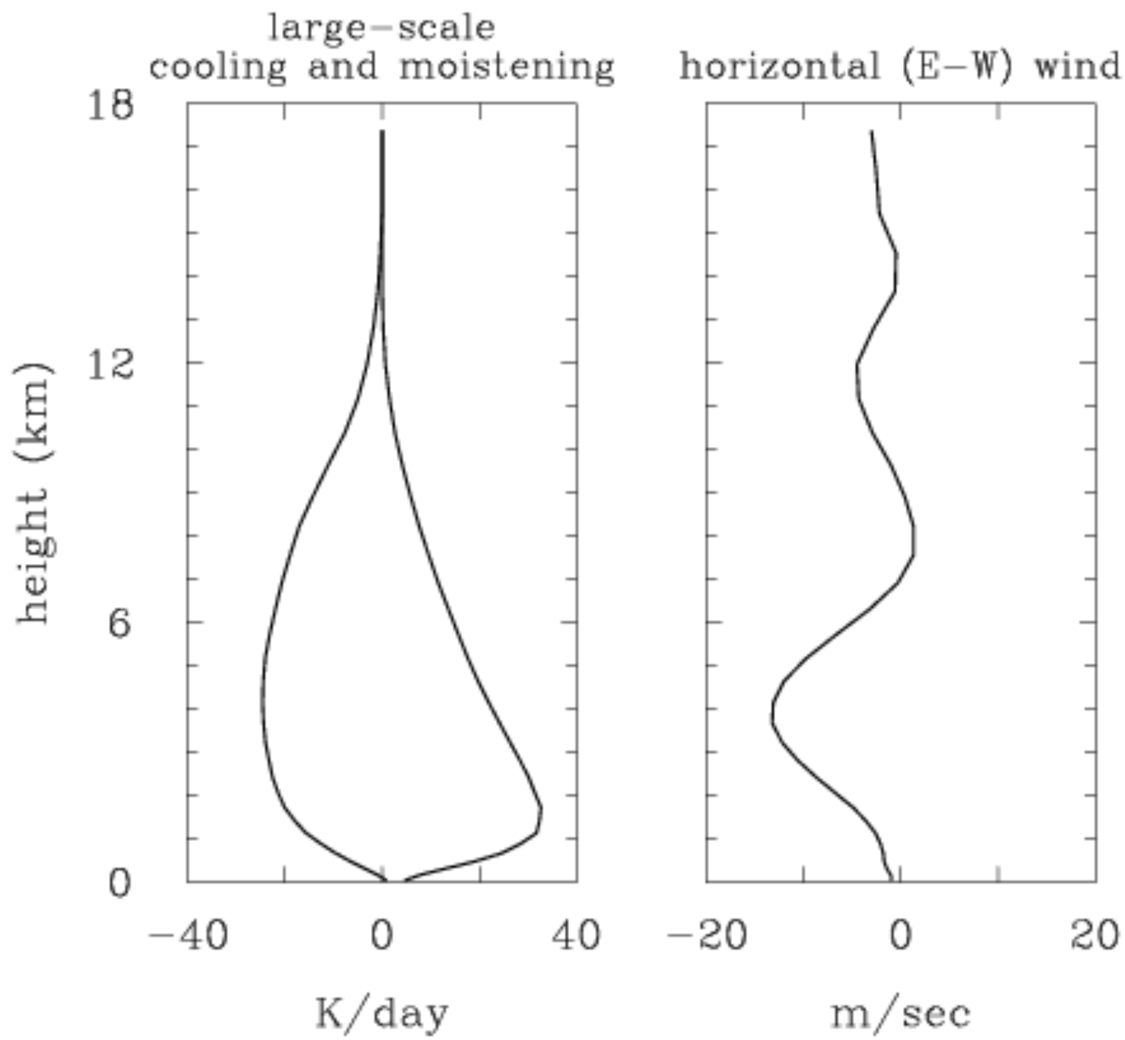


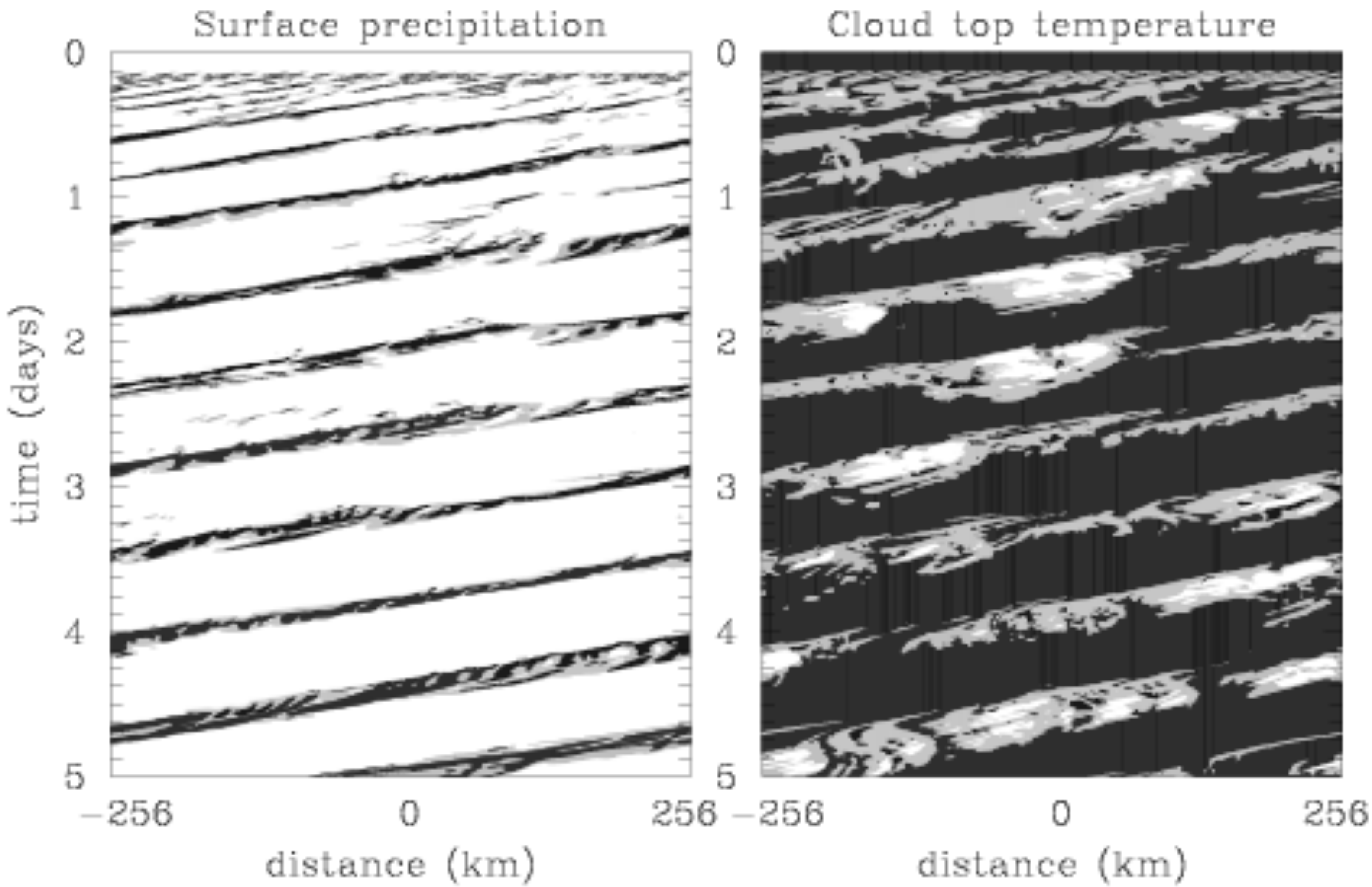

CRM (benchmark)

Tests with a strongly sheared environment

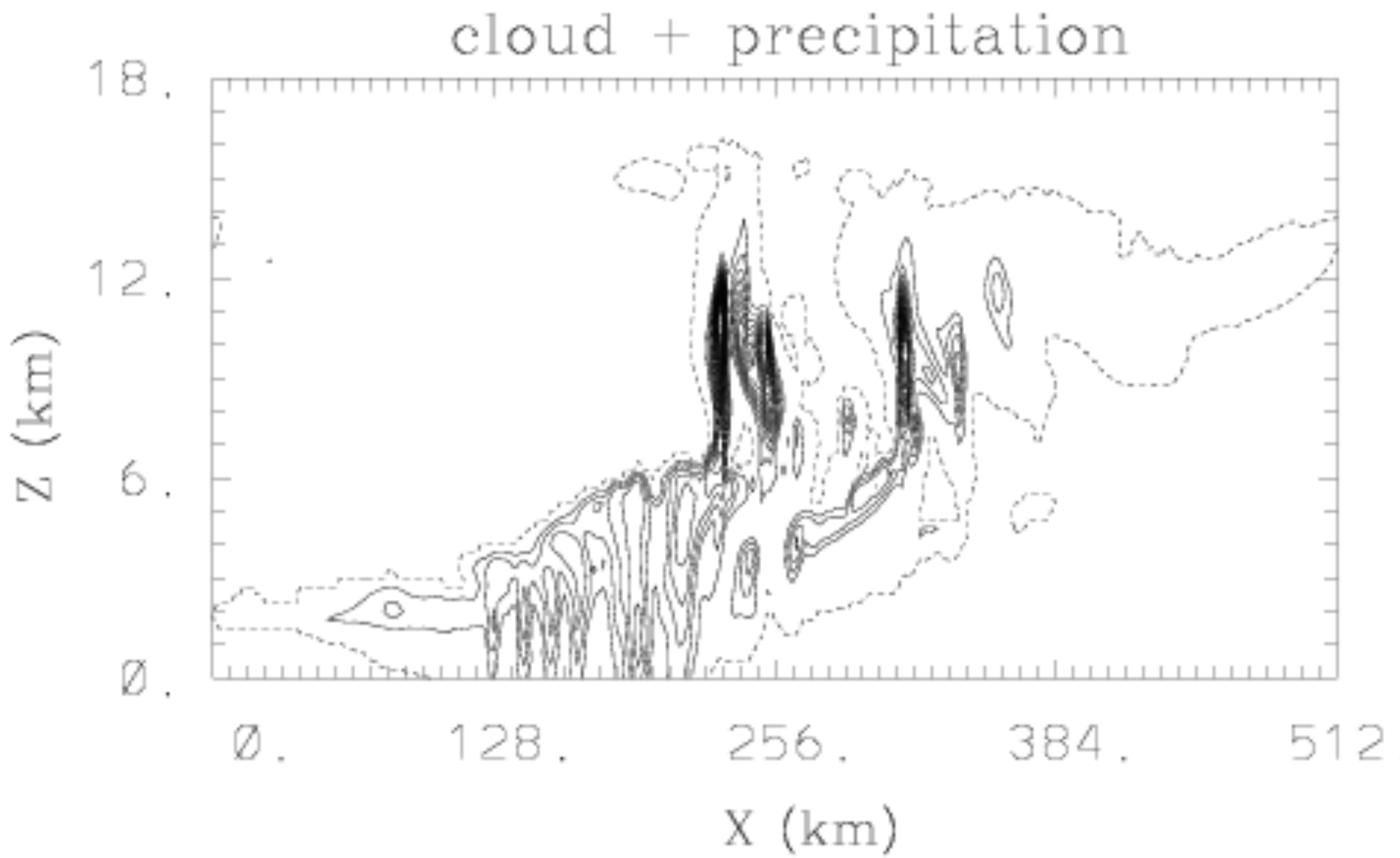
SP


large-scale
cooling and moistening
horizontal (E-W) wind
height (km)
18
12
6
0
−40
0
40
K/day
−20
0
20
m/sec

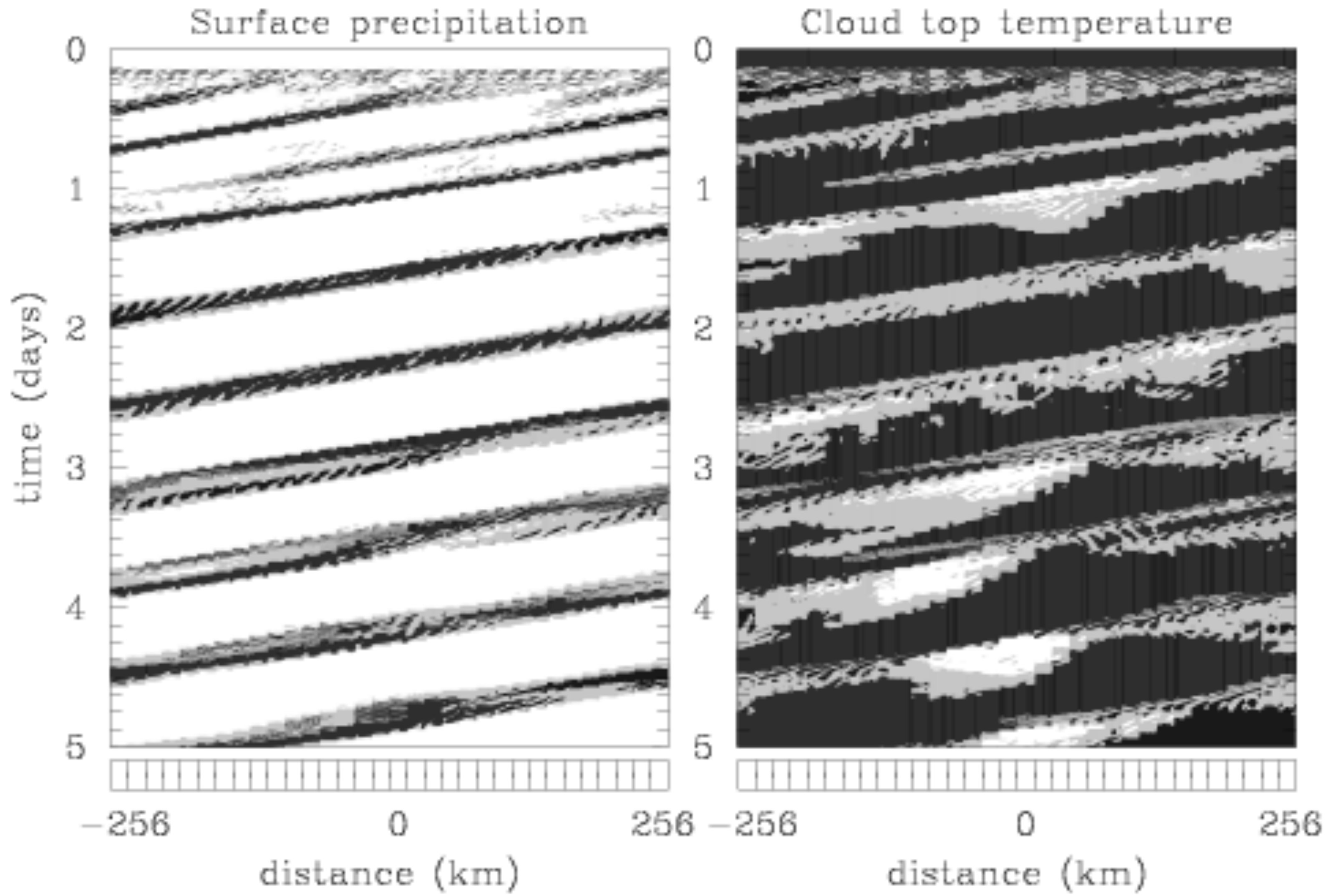
# Cloud-resolving simulation (benchmark): $\Delta x$=2km



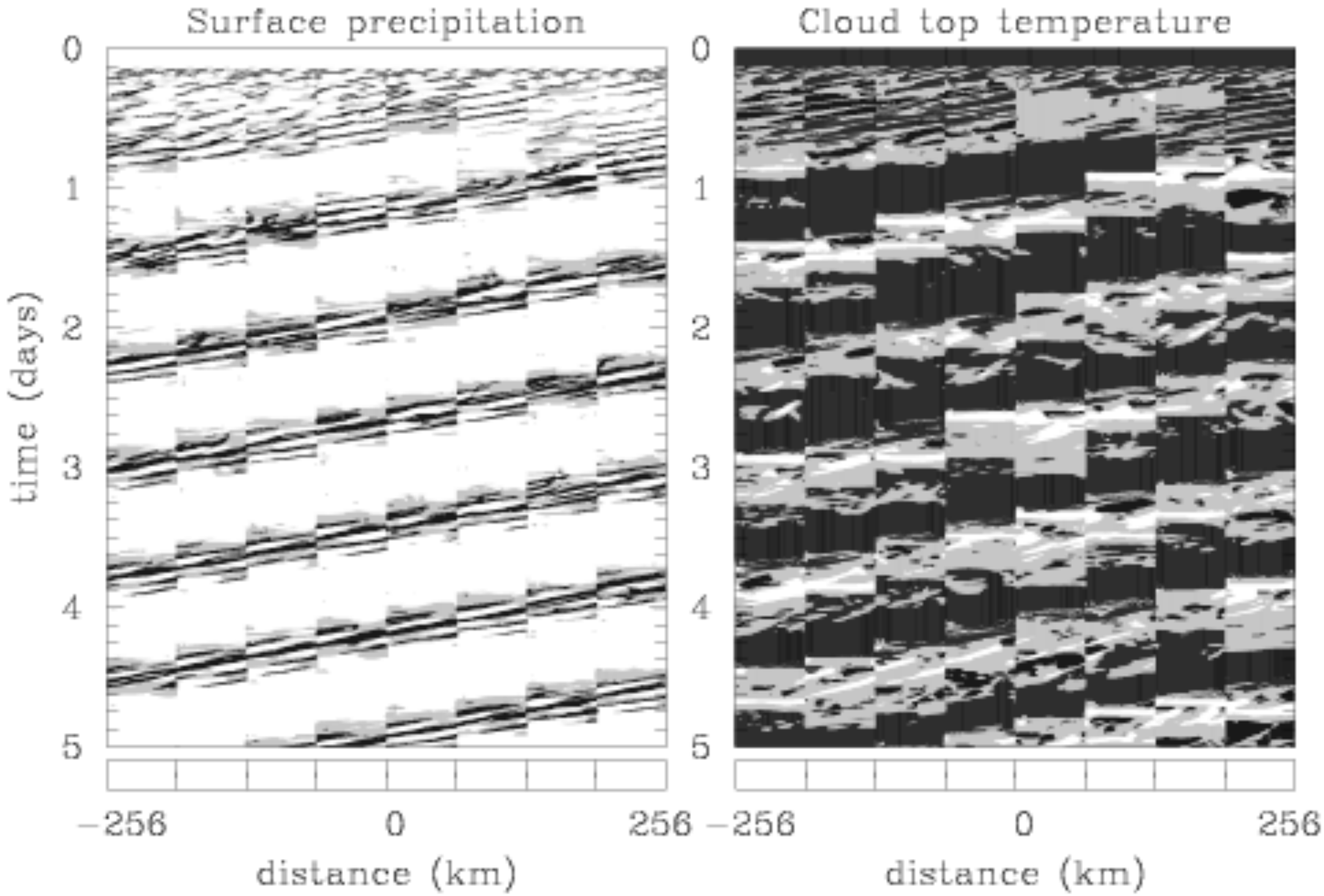
# Cloud-resolving simulation (benchmark): $\Delta x$=2km



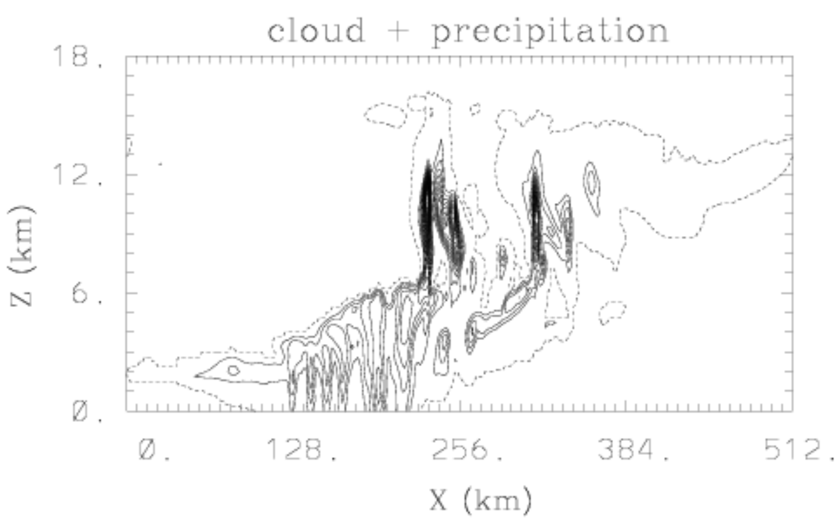
SP simulation: 32 columns with 16-km periodic small-scale models



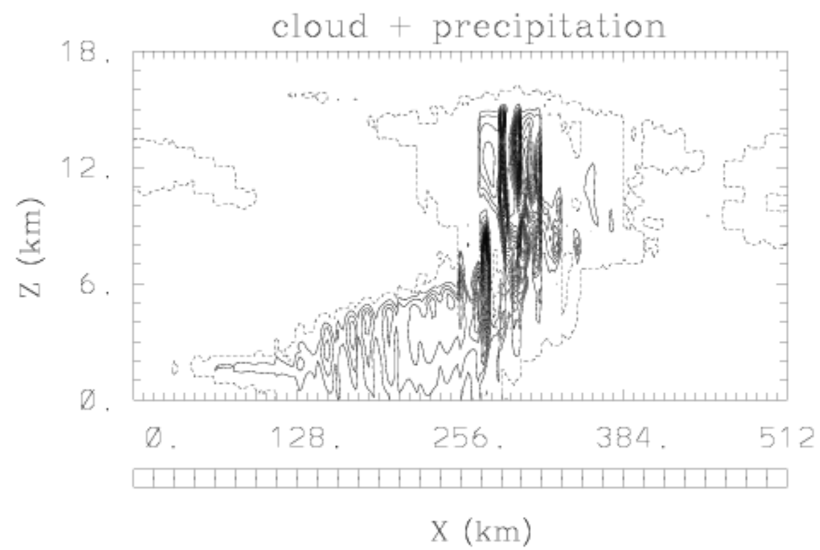
# SP simulation: 8 columns with 64-km periodic small-scale models



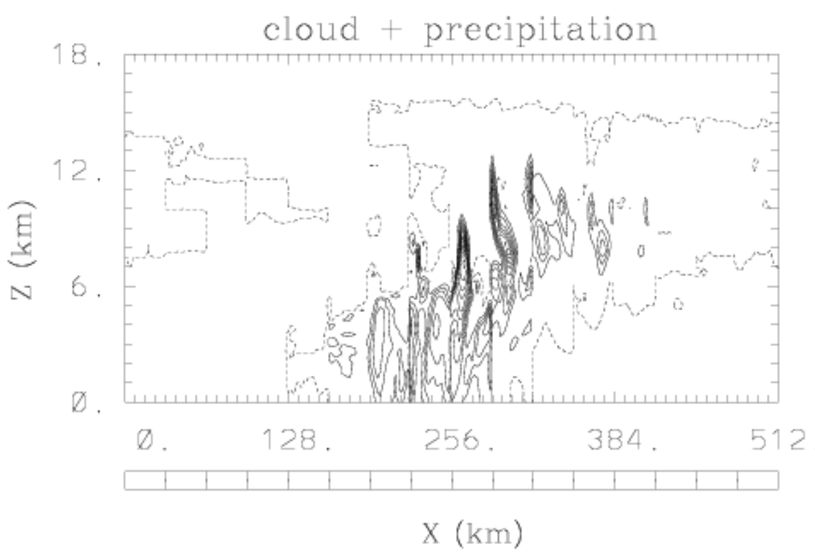
Cloud-resolving simulation (benchmark): Δx=2km



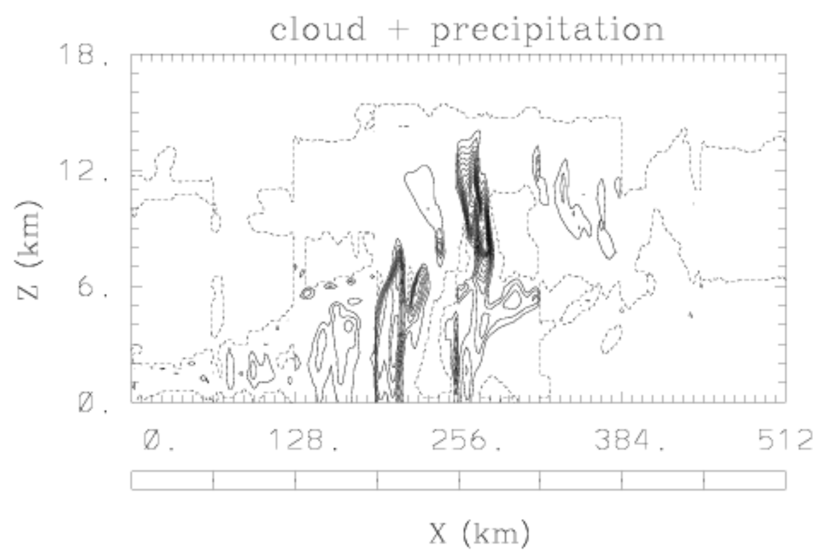

**32 columns with 16-km periodic small-scale models**




**16 columns with 32-km periodic small-scale models**

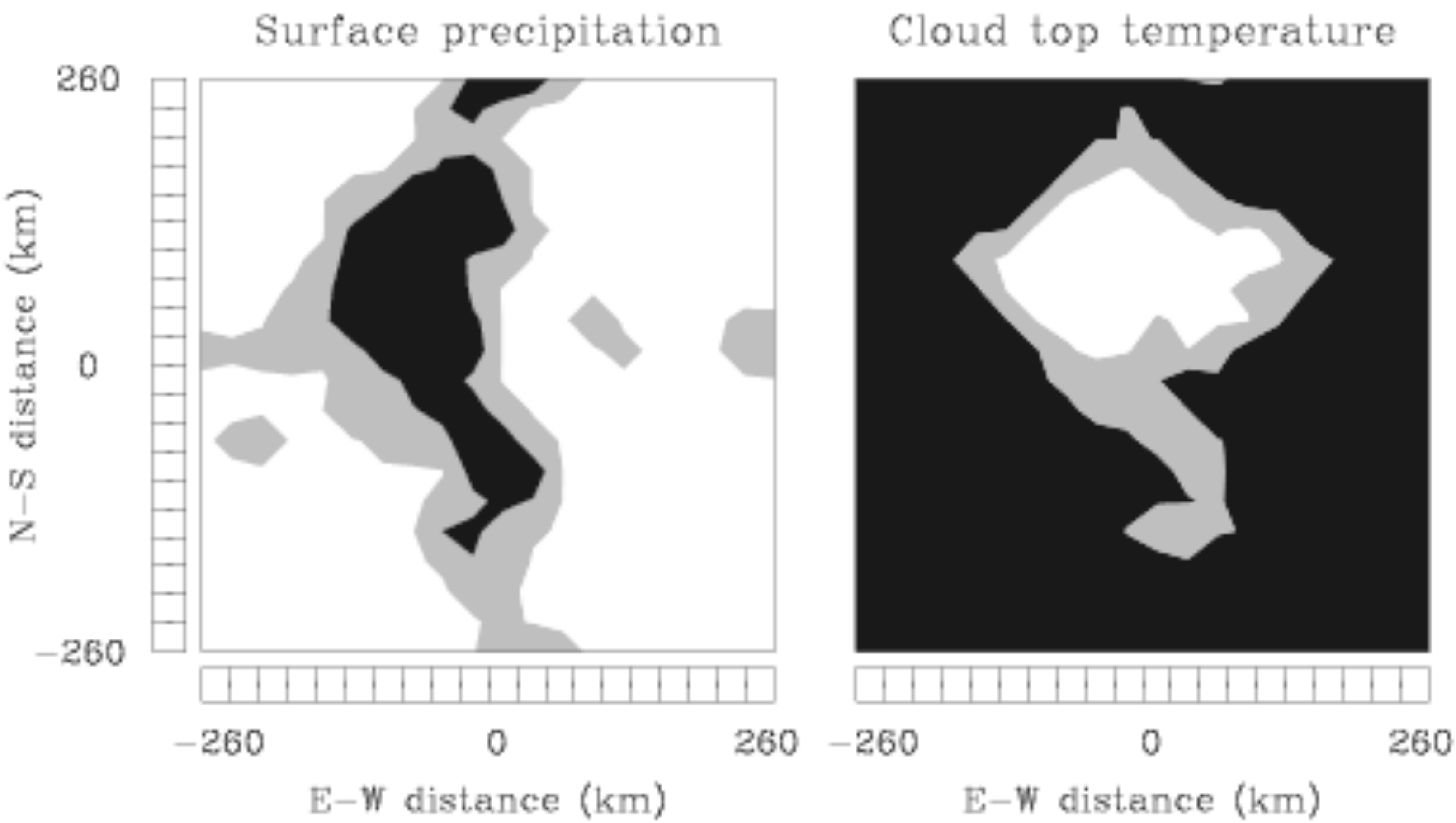



**8 columns with 64-km periodic small-scale models**

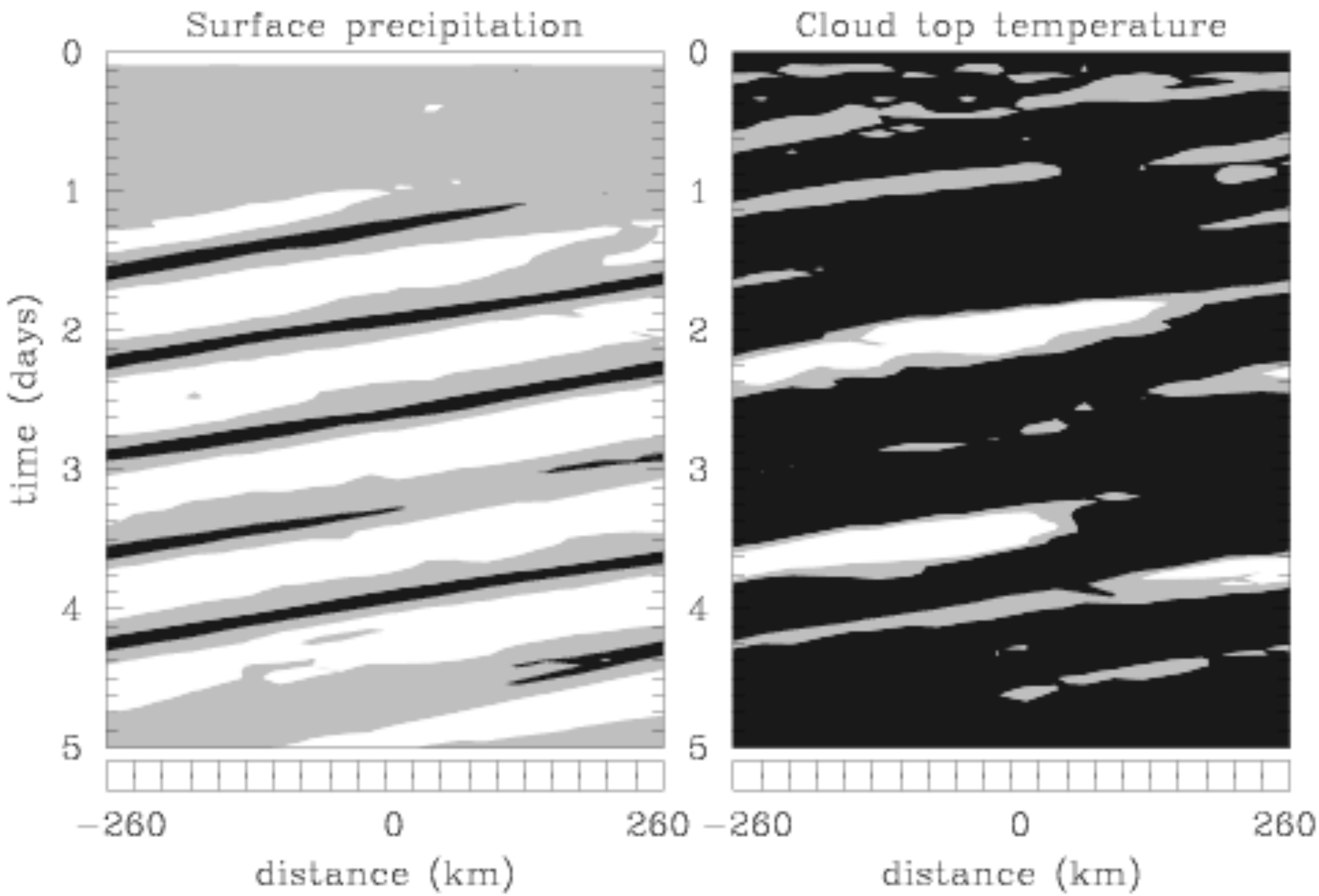


# This approach extends naturally into 3D mesoscale model: 2D convective dynamics plus 3D mesoscale dynamics

Snapshots from a 3D simulation in the same setup as before, 520-km mesoscale domain, 26-km grid; 26-km SP domains aligned E-W



Hovmoeller diagrams of N-S averaged surface precipitation and cloud-top temperature from the 3D simulation



***My take on these results: Super-parameterization (SP) seems a better-posed approach for limited-area mesoscale models, such as regional climate models, than for temporary general circulation models.***

***This is because SP in a mesoscale model has to treat only convective-scale dynamics; mesoscale dynamics is left for the 3D mesoscale model.***

The work after CMMAP:

- ultra-parameterization (Prof. Mike Pritchard, UC Irvine);
- SP-IFS (Marat at ECMWF, Reading);
- Indian SP-climate model (Marat at IITM, Pune);
- continuation of SP-CAM use at CSU (e.g., CREMIP project)

# Towards global large-eddy simulation: Super-parameterization revisited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The National Center for Atmospheric Research
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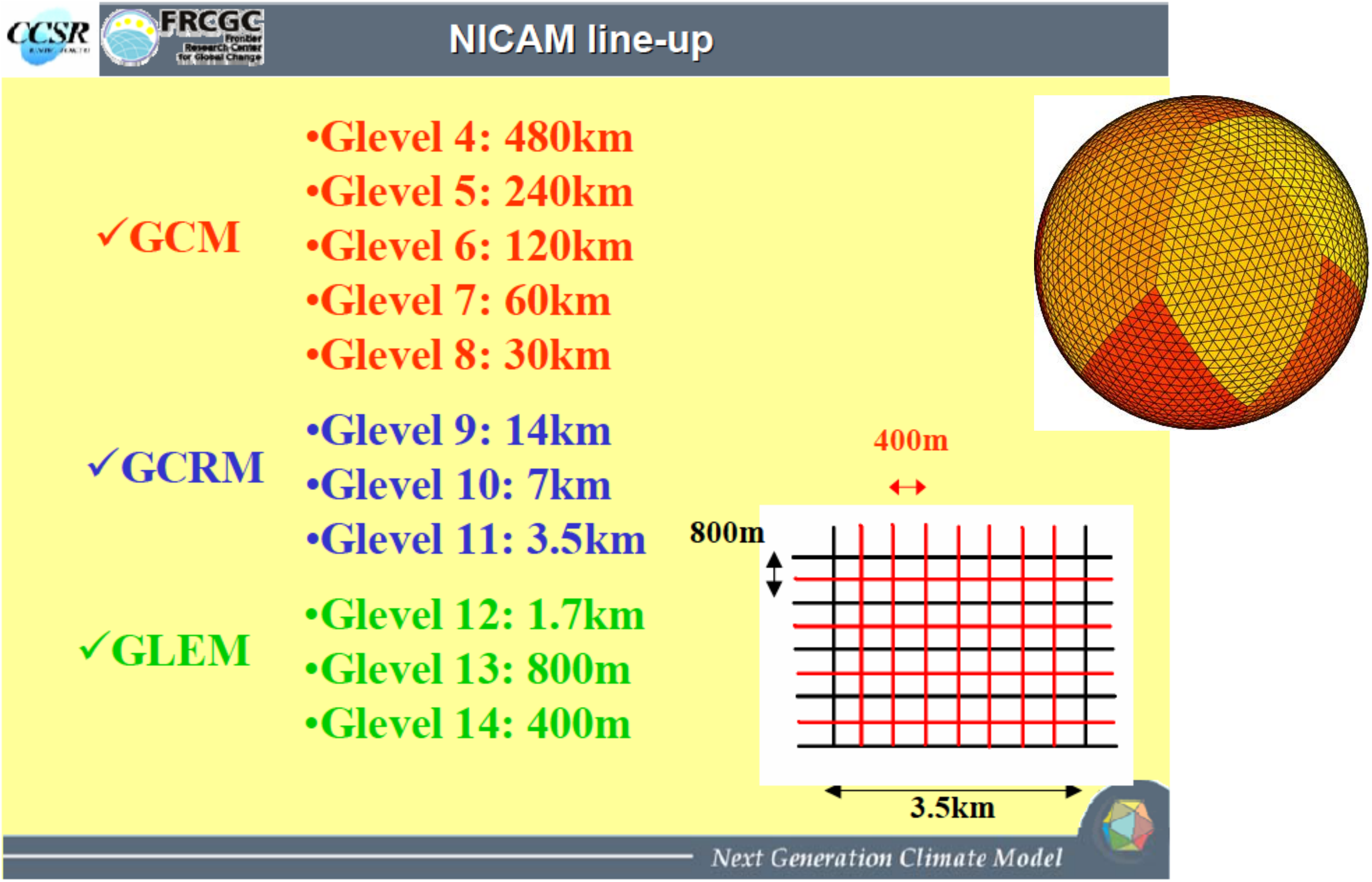
CMMAP
Reach for the sky

NSF

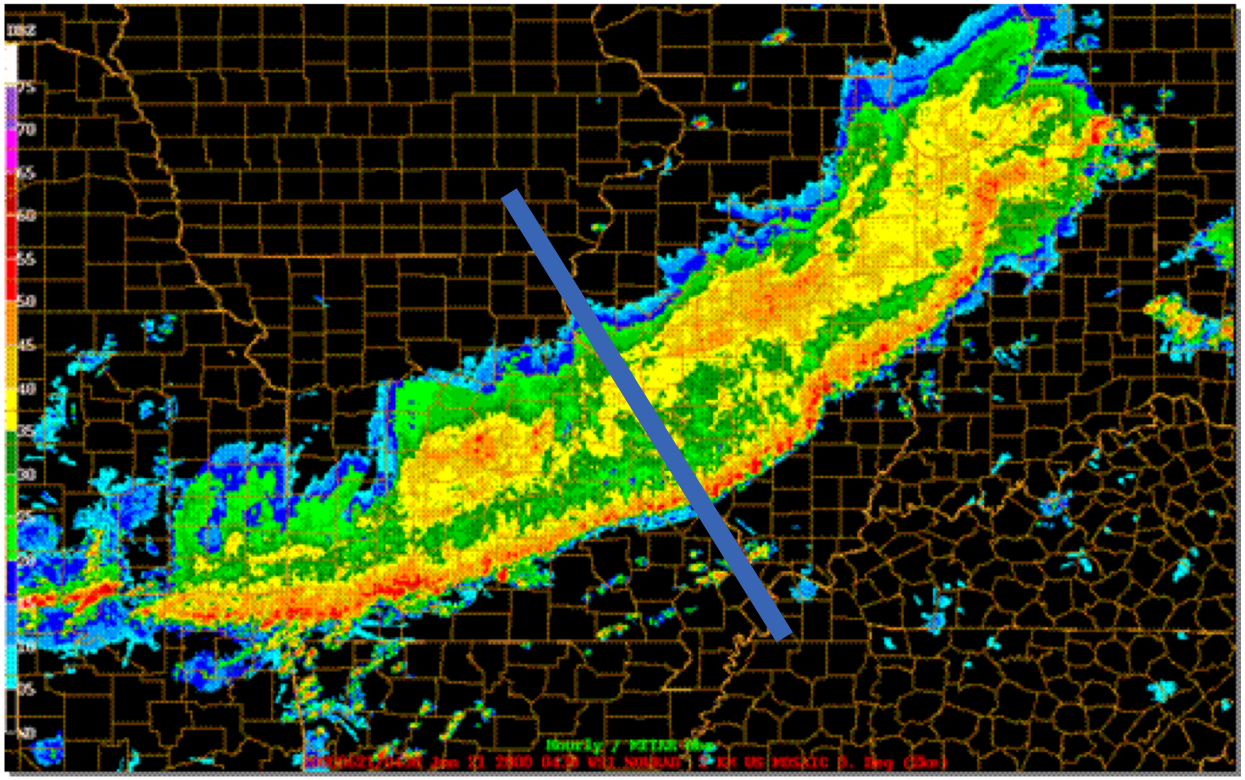
Grabowski, W. W., 2016, Towards global large eddy simulation: super-parameterization revisited. *J. Met. Soc. Japan,* **94**, 327-344.

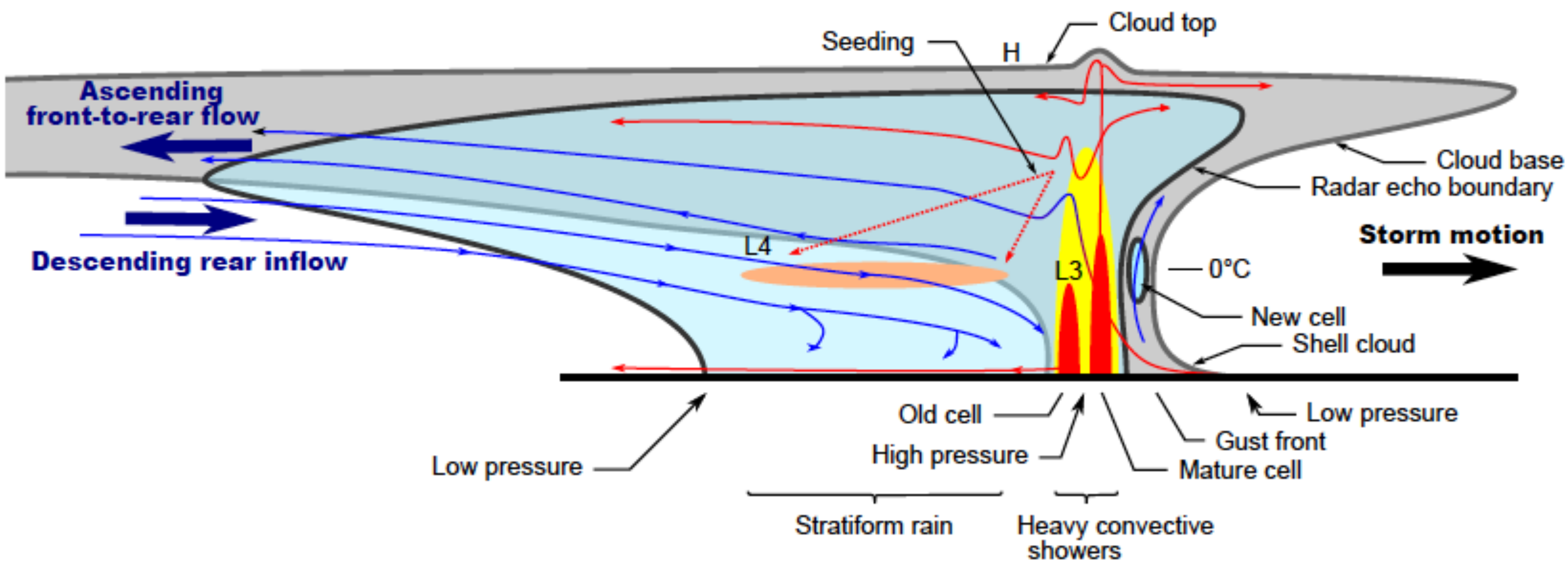



Prof. Satoh's presentation at CMMAP Team Meeting, Fort Collins, 2006

# Why LES?

Resolution requirements for deep convection…




Cloud top
Seeding
H
Ascending
front-to-rear flow
Cloud base
Radar echo boundary
Storm motion
L4
L3
0°C
Descending rear inflow
New cell
Shell cloud
Old cell
Low pressure
High pressure
Gust front
Low pressure
Mature cell
Stratiform rain
Heavy convective
showers

**Resolution Requirements for the Simulation of Deep Moist Convection**


George H. Bryan, John C. Wyngaard, and J. Michael Fritsch

*Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania*

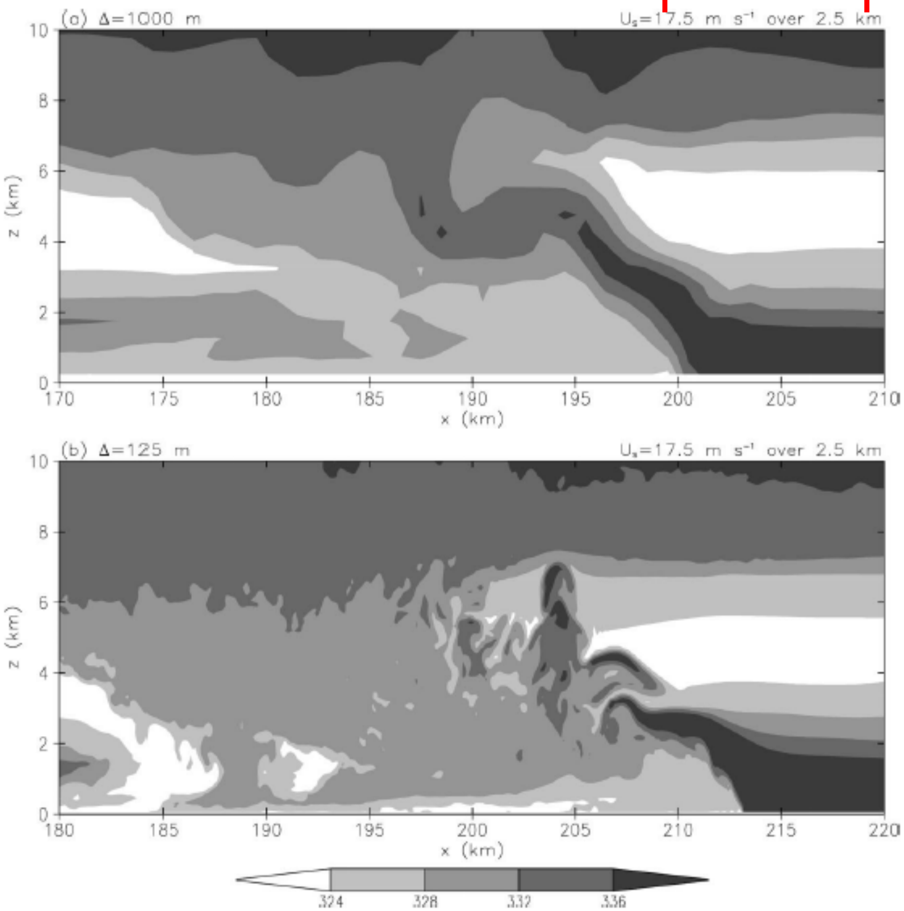

MWR 2003

# Squall line simulation:

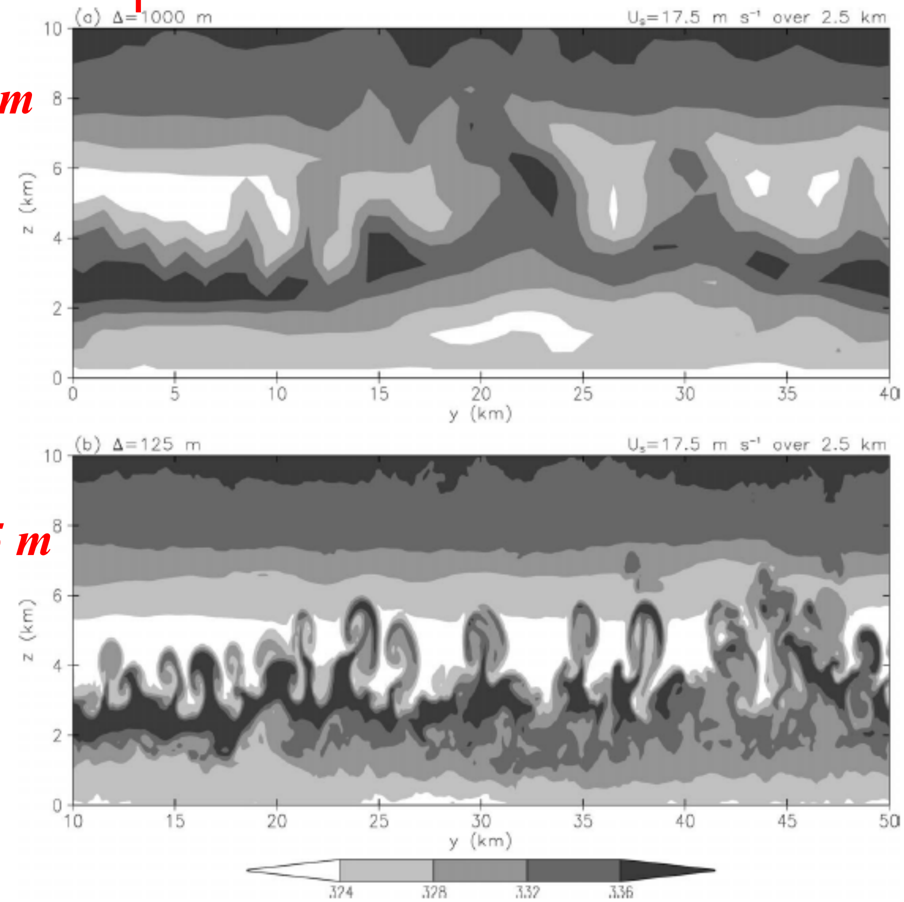
Equivalent potential temperature

*Δ=1 km*

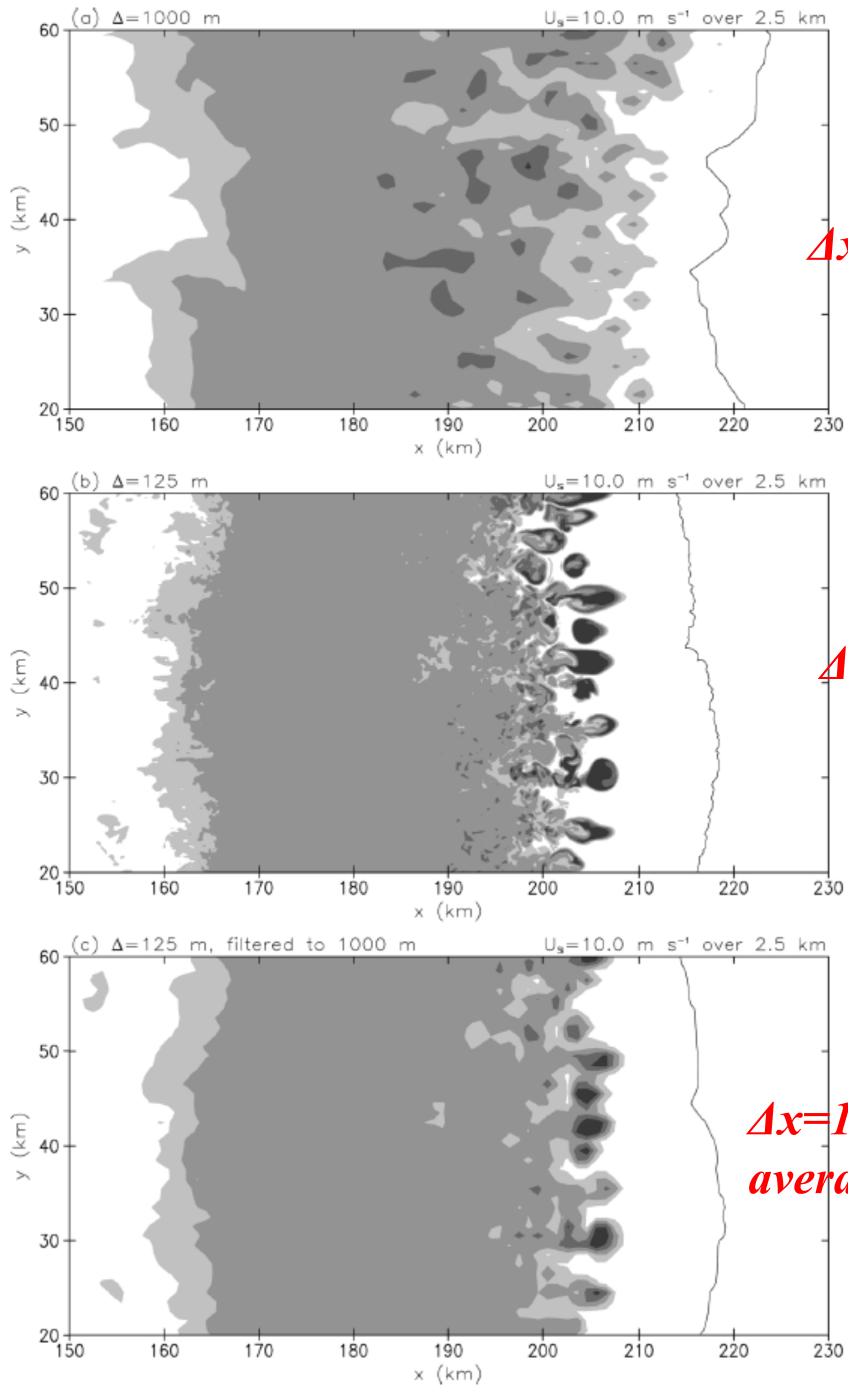
*Δ=125 m*




Perpendicular to the leading edge



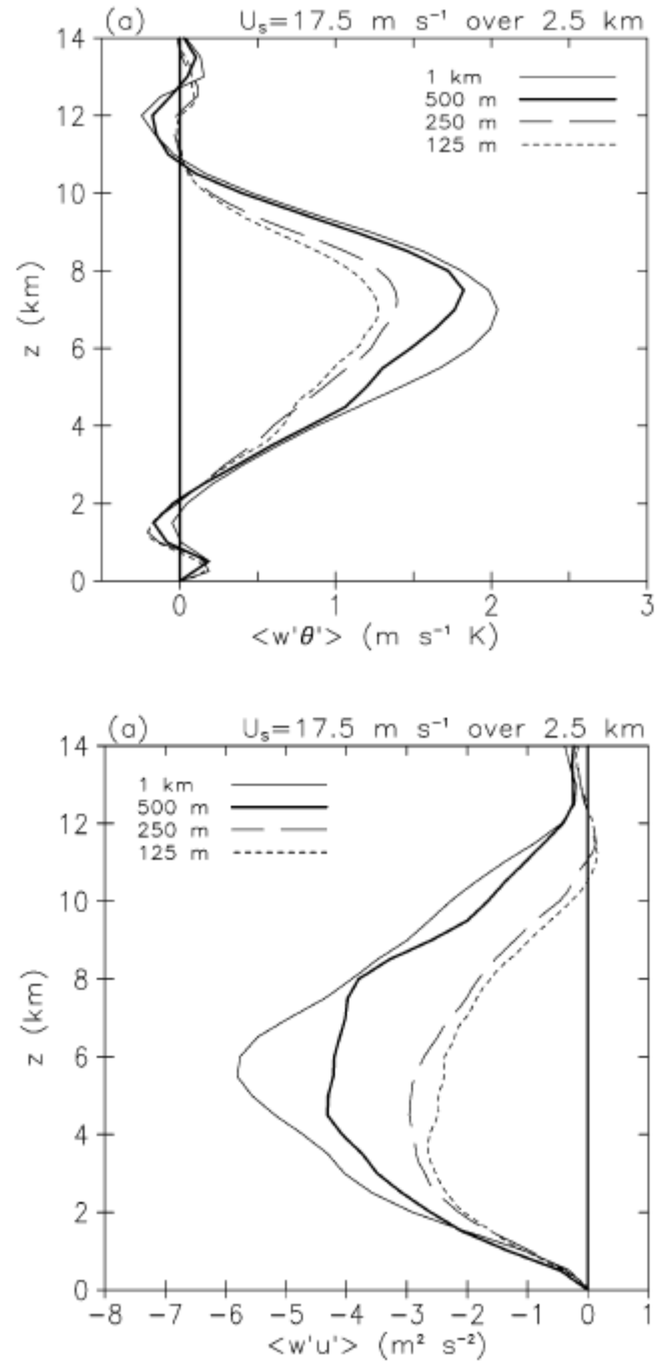

Parallel to the leading edge




*Δx=1 km*

*Δx=125 m*

*Δx=125 m*
*averaged to 1 km*



J. Adv. Model. Earth Syst., **Vol. 1**, Art. #15, 13 pp.

2009

JAMES JOURNAL OF ADVANCES IN MODELING EARTH SYSTEMS

# Large-Eddy Simulation of Maritime Deep Tropical Convection

*Marat F. Khairoutdinov[1], Steve K. Krueger[2], Chin-Hoh Moeng[3], Peter A. Bogenschutz[2] and David A. Randall[4]*

CMMAP Reach for the sky

Giga LES

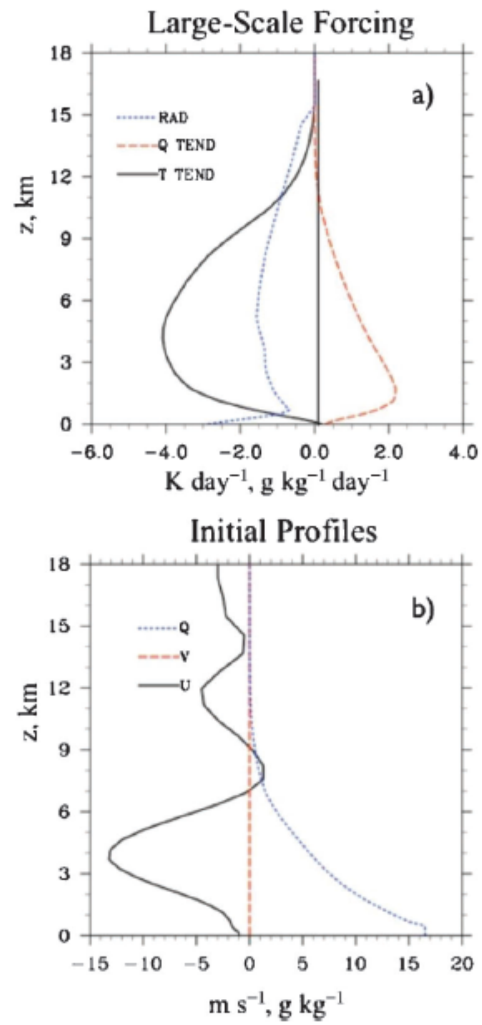
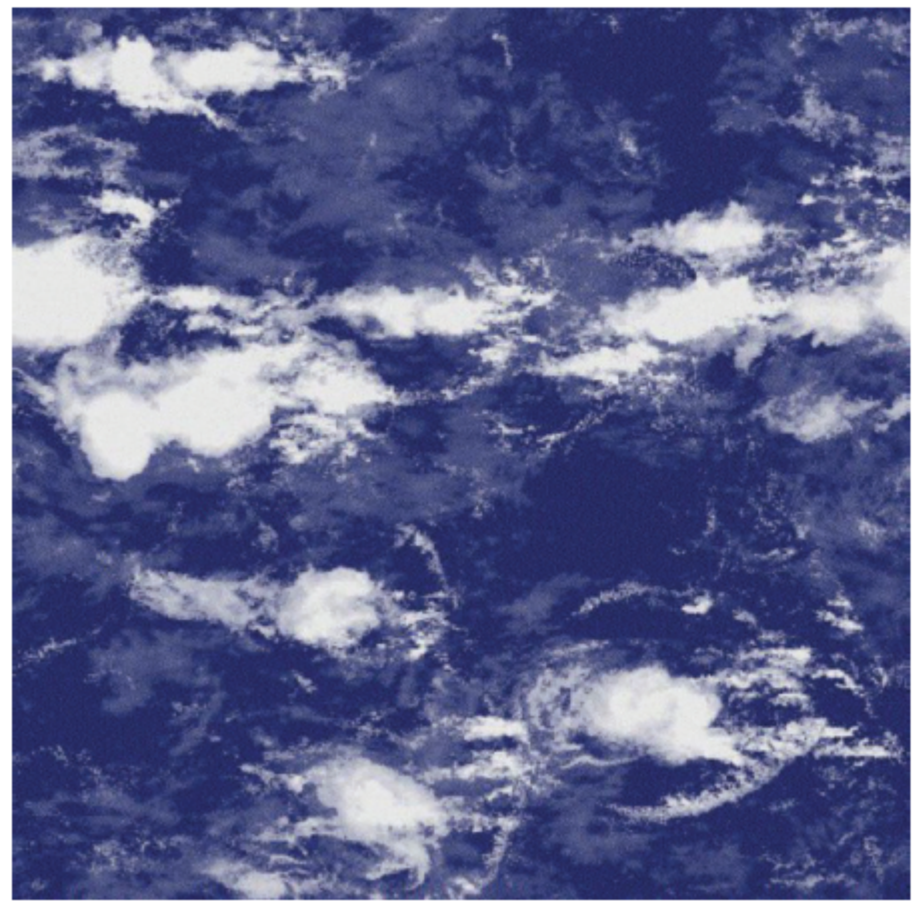


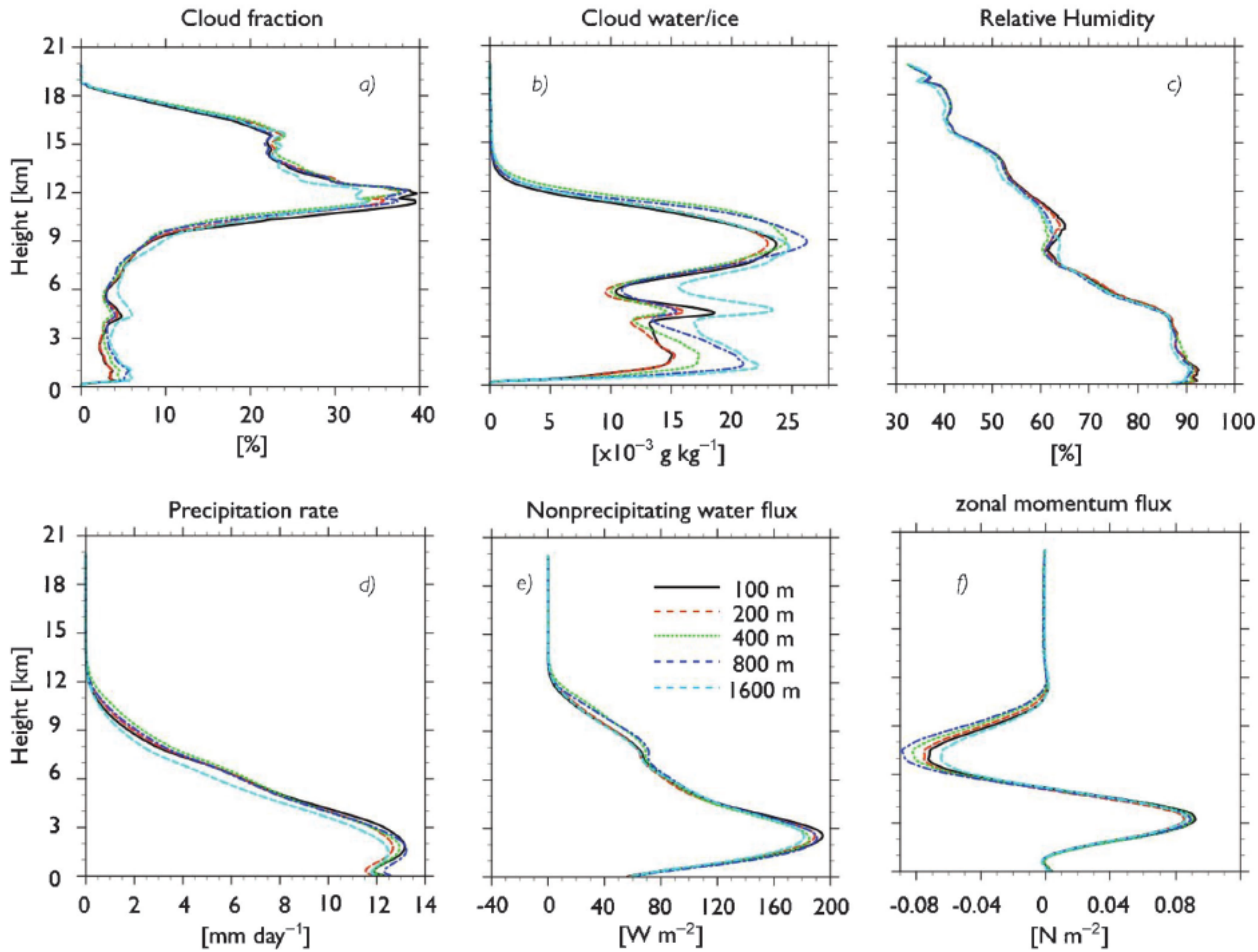

**Table 1** Summary of the numerical experiments used in this study.

| Simulation | Grid size $N_x \times N_y \times N_z$ | Horizontal Grid spacing $\Delta x = \Delta y$ (m) | Vertical grid spacing $\Delta z_{min}$ - $\Delta z_{max}$ (m) |
|---|---|---|---|
| BASE | 2048 × 2048 × 256 | 100 | 50 - 300 |
| H200 | 1024 × 1024 × 256 | 200 | 50 - 300 |
| H400 | 512 × 512 × 256 | 400 | 50 - 300 |
| H800 | 256 × 256 × 256 | 800 | 50 - 300 |
| H1600 | 128 × 128 × 256 | 1600 | 50 - 300 |
| L64 | 256 × 256 × 64 | 800 | 75 - 500 |
| NOEVP | 1024 × 1024 × 256 | 200 | 50 - 300 |

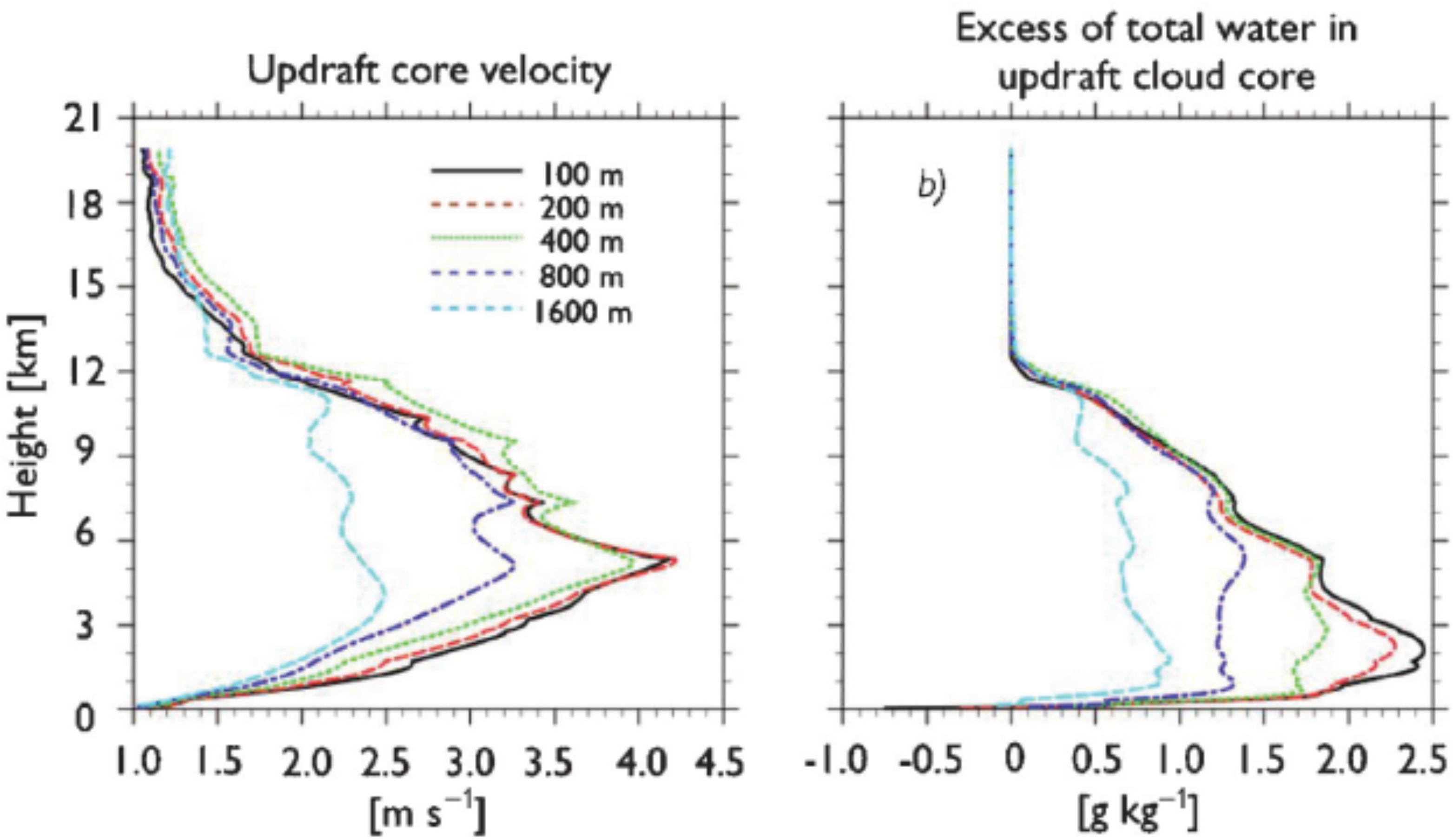


Realistic Giga LES view of deep-convection cloud field

# Resolution has a relatively small impact for most bulk fields…

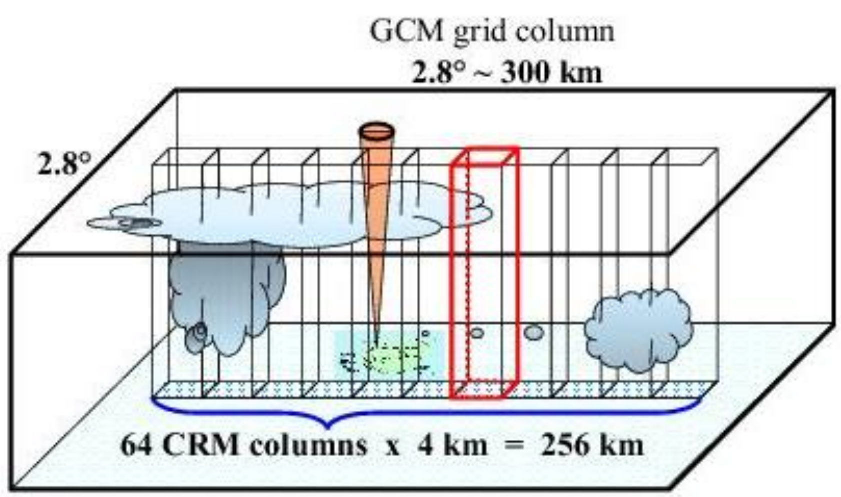


…but the impact is significant for some microphysics-relevant fields:



The original SP applications assumed relatively large outer model domain (100s of km, as in a climate model), implying that both mesoscale and convective dynamics have to be treated in the SP model. What should be the outer model domain size to capture mesoscale dynamics?

Think about NWP models in the 80ies…

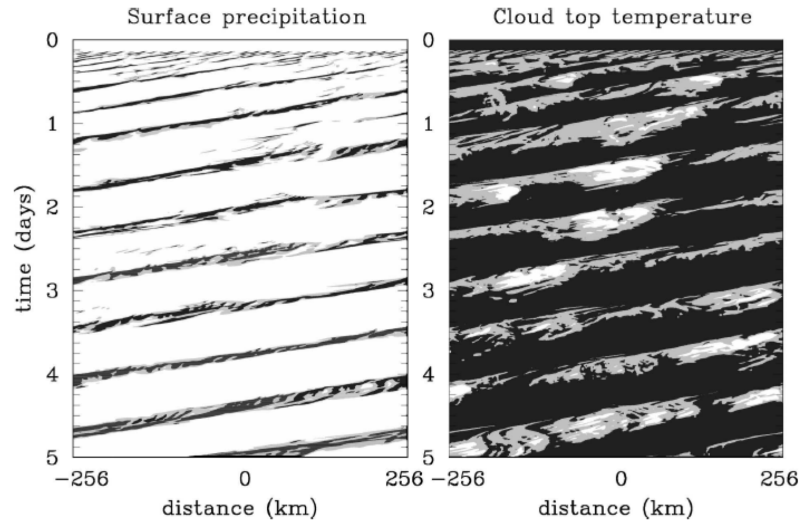


**Comments on "Preliminary Tests of Multiscale Modeling with a Two-Dimensional Framework: Sensitivity to Coupling Methods"**

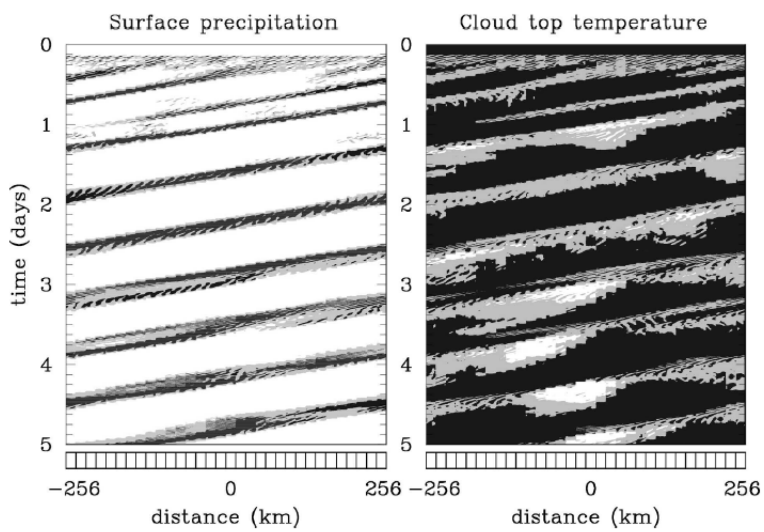
MWR 2006

WOJCIECH W. GRABOWSKI

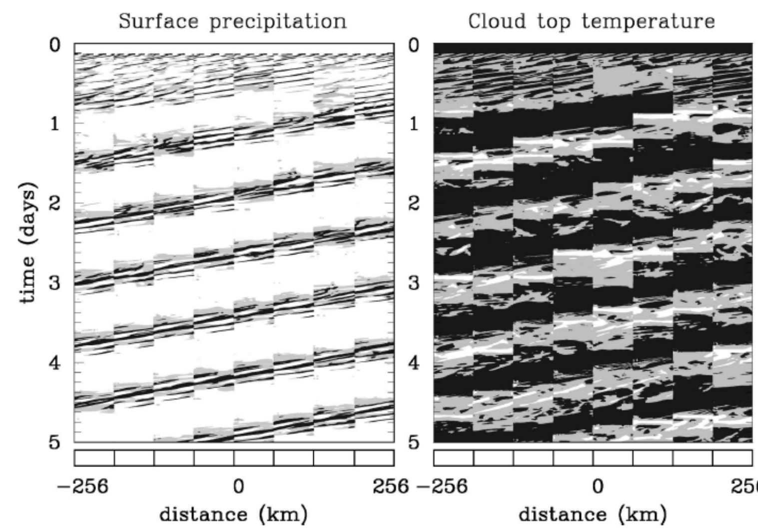
*2D simulations,*
*Δx=2 km*




CRM
(benchmark)




SP with 16 km domains

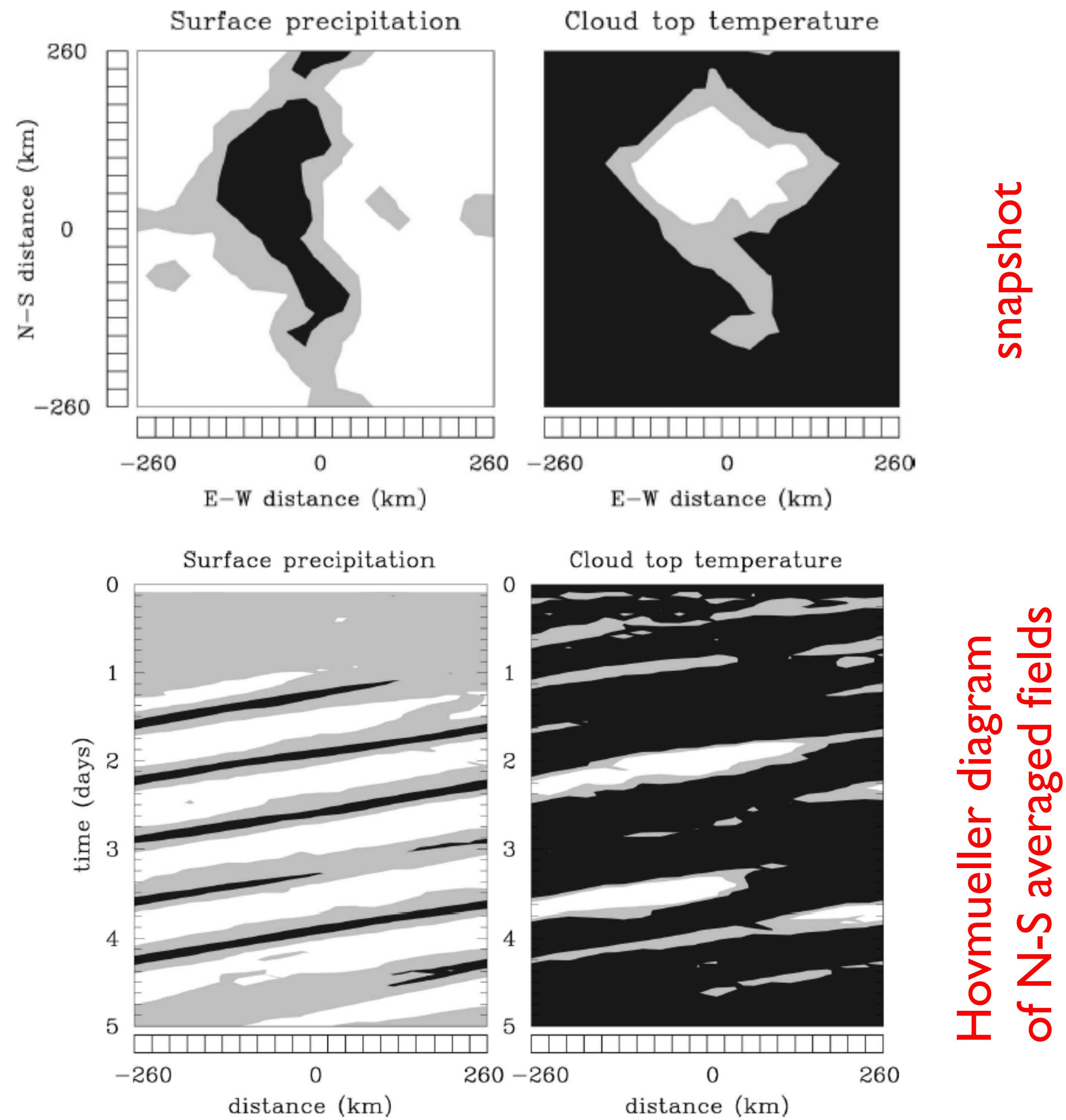



SP with 64 km domains

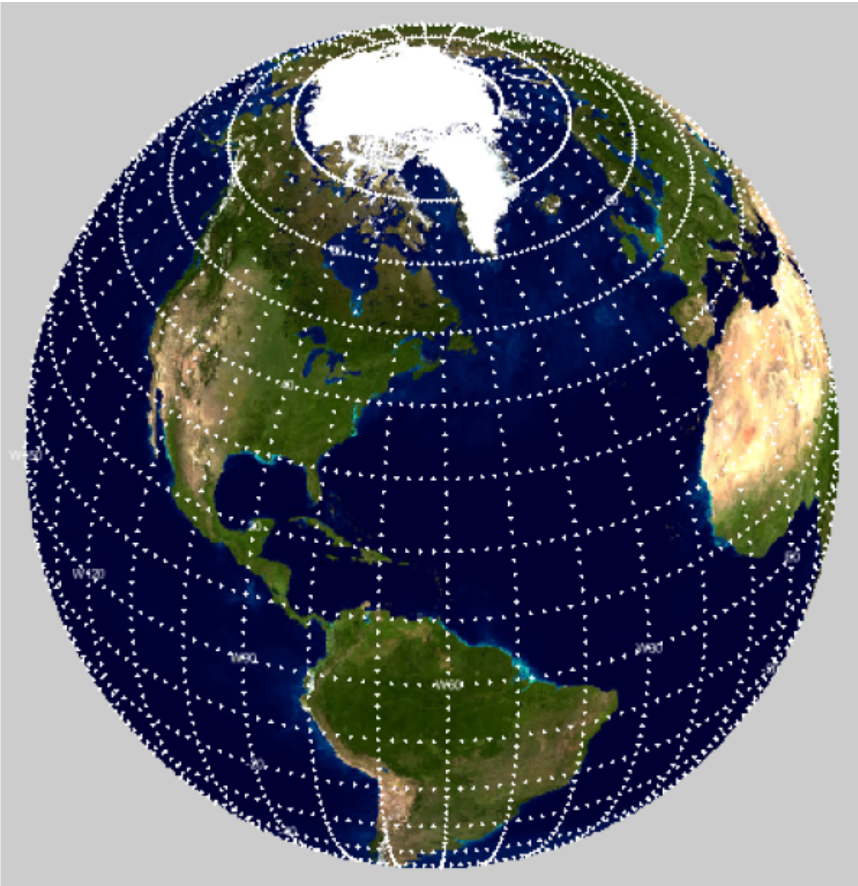
***Natural extension to a 3D outer model:***

***outer model:***
***Δx = Δy=26 km***

***2D SP models (aligned E-W) with Δx=2 km***

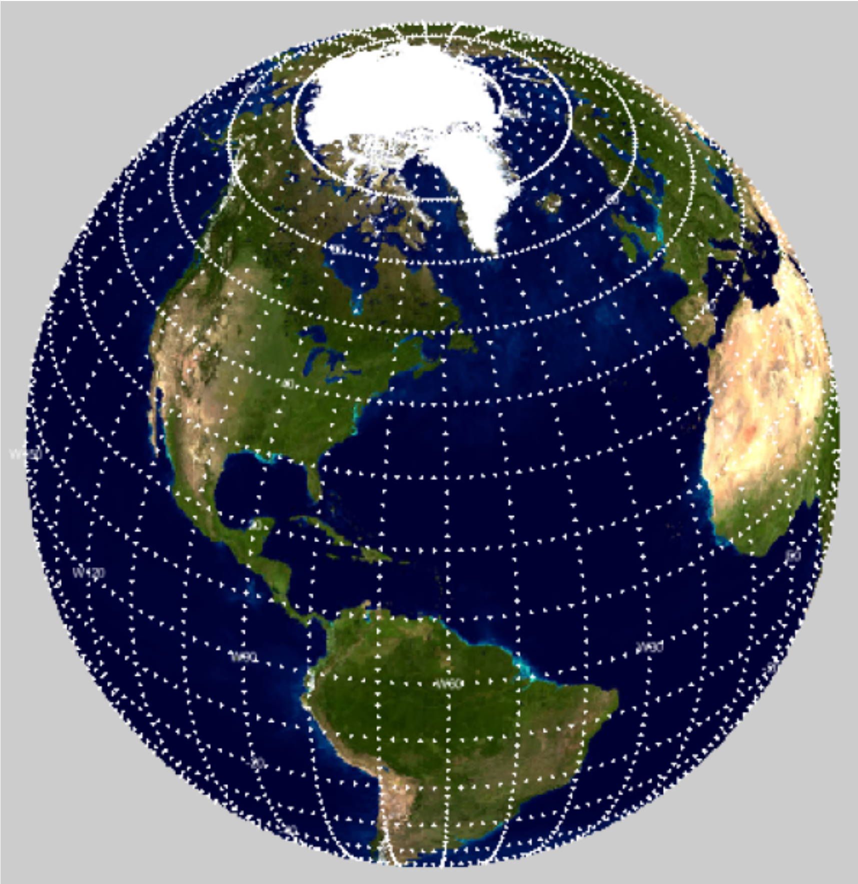


If the outer model has a horizontal grid length around a few tens of km, it will faithfully represent mesoscale dynamics, like 20th century NWP models. The embedded SP models need only to cope with small-scale processes, such as convective-scale dynamics. They can be 2D as in the examples above, but they can be 3D, and even LES if boundary layer dynamics or shallow convection is to be well simulated…



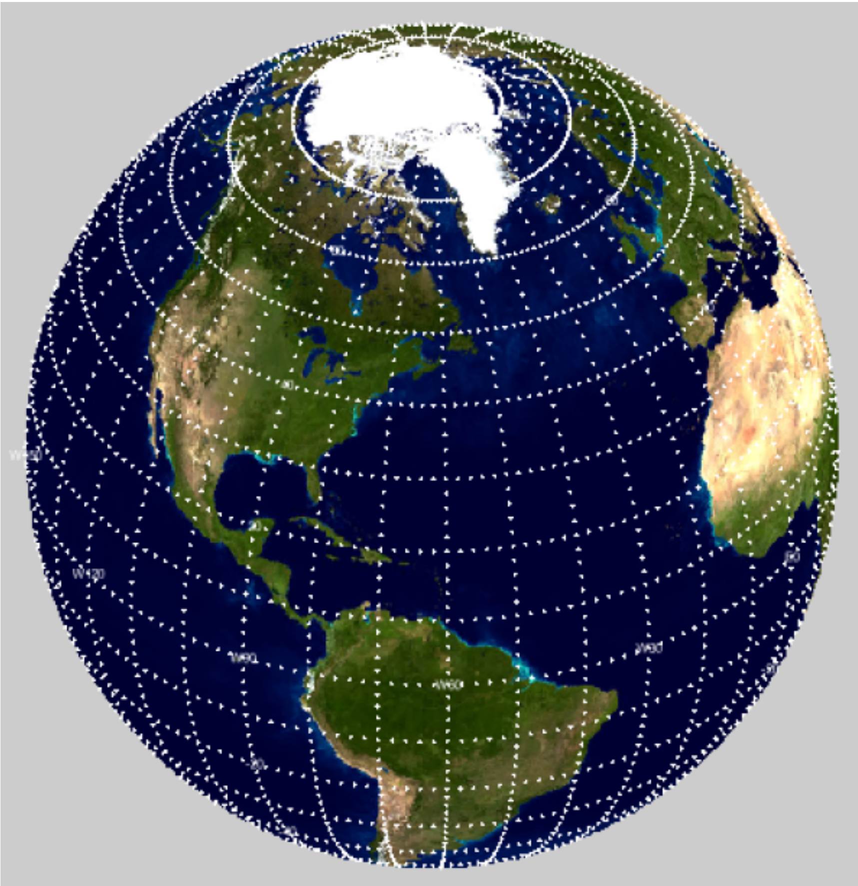
Radius: $R \approx 6.4 \times 10^3$ km

Surface area: $S \approx 5.1 \times 10^8$ km$^2$



Radius: $R \approx 6.4 \times 10^3$ km
Surface area: $S \approx 5.1 \times 10^8$ km$^2$

If one would like to cover the surface with LES squares of 20 km by 20 km, there will be around 1.3 million squares…



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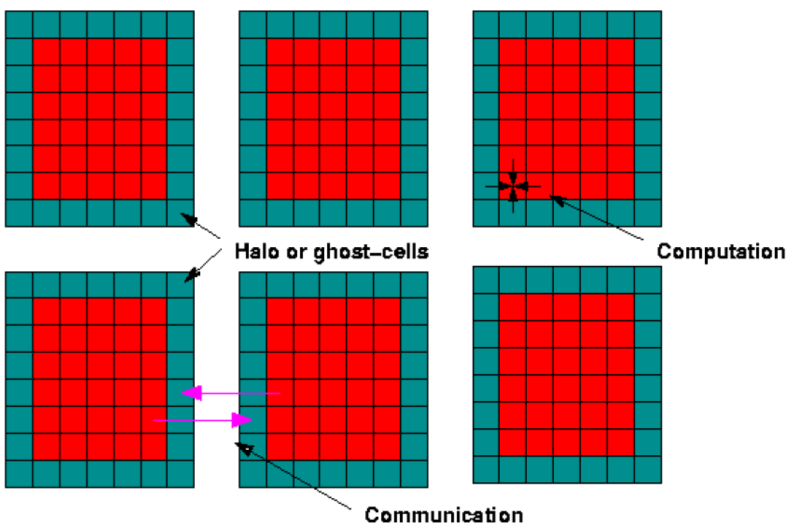
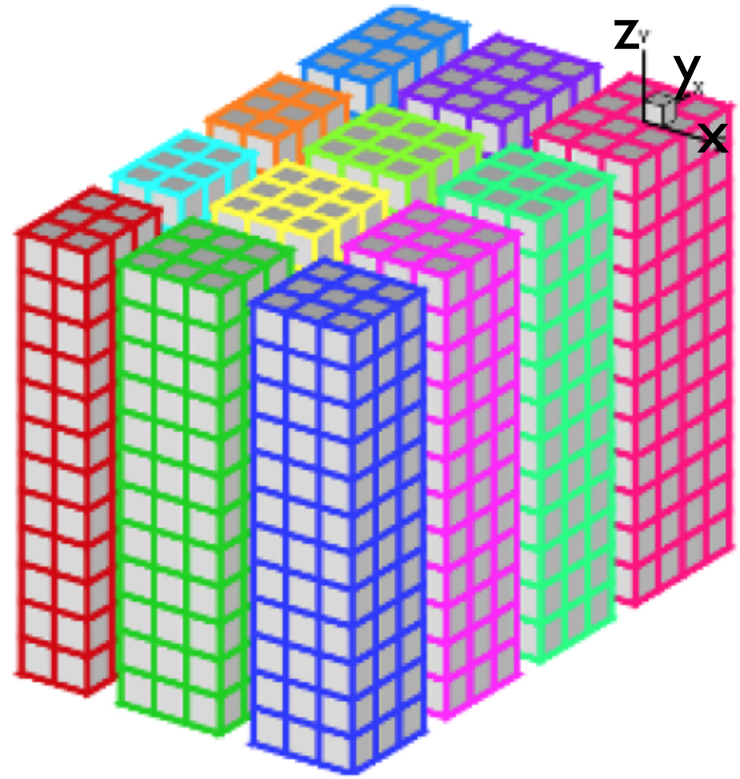
If one would like to cover the surface with LES squares
of 20 km by 20 km, there will be around 1.3 million squares…
This suggests that one can apply a computer with up to 1.3 million
processors for parallel simulations…

Issues:

- Parallel processing?
- What equations to use?

# Domain decomposition for the finite-difference parallel processing




*Large amount of data needs to be exchange at every time step in the halos at the sub-domain boundaries. This makes the parallel processing difficult.*

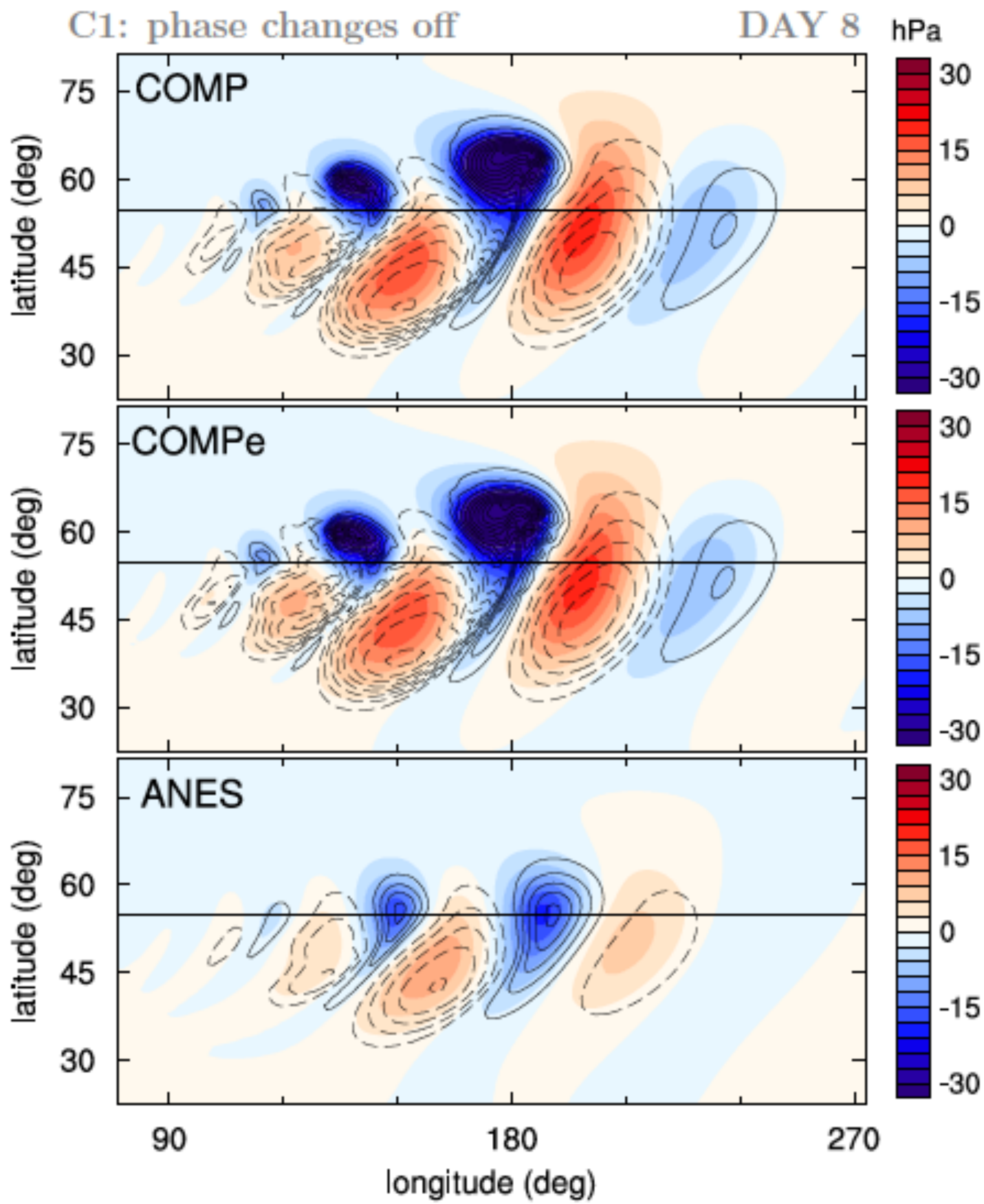
What governing equations to use?

Extension of the small-scale nonhydrostatic equations to the global scale is not trivial.

Compressible dynamics is valid across all scales, but it is numerically cumbersome due to presence of pesky sound waves that can be argued irrelevant for weather and climate.

Anelastic equations are appropriate for small-scale and mesoscale dynamics, but validity of its extension to the global scale is questionable.

## Jablonowski and Williamson (2006) baroclinic wave test:




**Implicit compressible model with Δt = 300 s**

**Explicit compressible model with Δt = 2 s**

**Anelastic model with Δt = 300 s**

Surface virtual temperature (contours) and pressure perturbations (colors).

Smolarkiewicz et al. *JCP* 2014
Kurowski et al. *JAS* 2015

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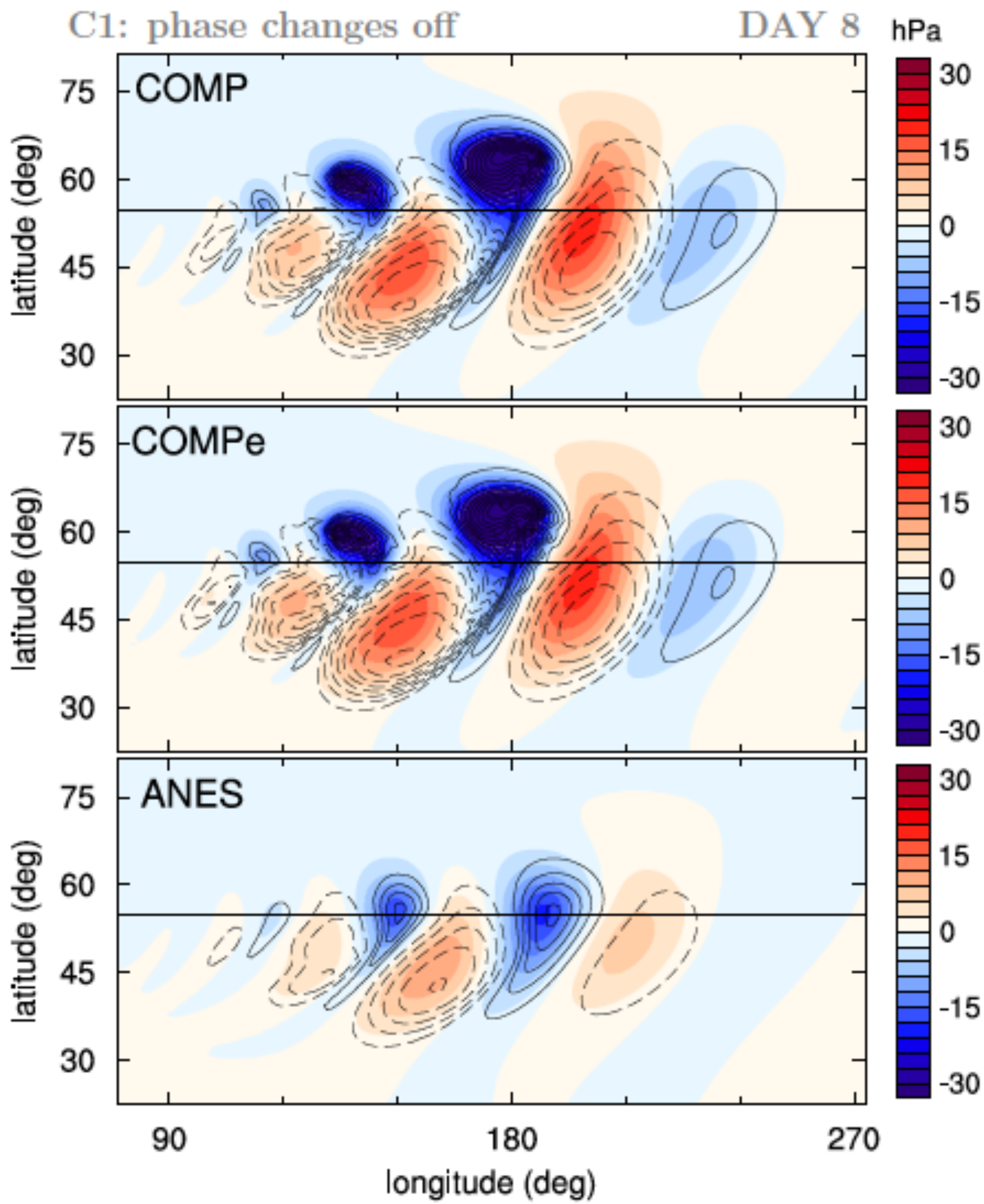


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## Conclusions:

- Anelastic equations are not appropriate for global scales;

- Implicit model based on compressible equations works well.

**Conclusions:**

**-Anelastic equations are not appropriate for global scales;**

**-Implicit model based on compressible equations works well.**

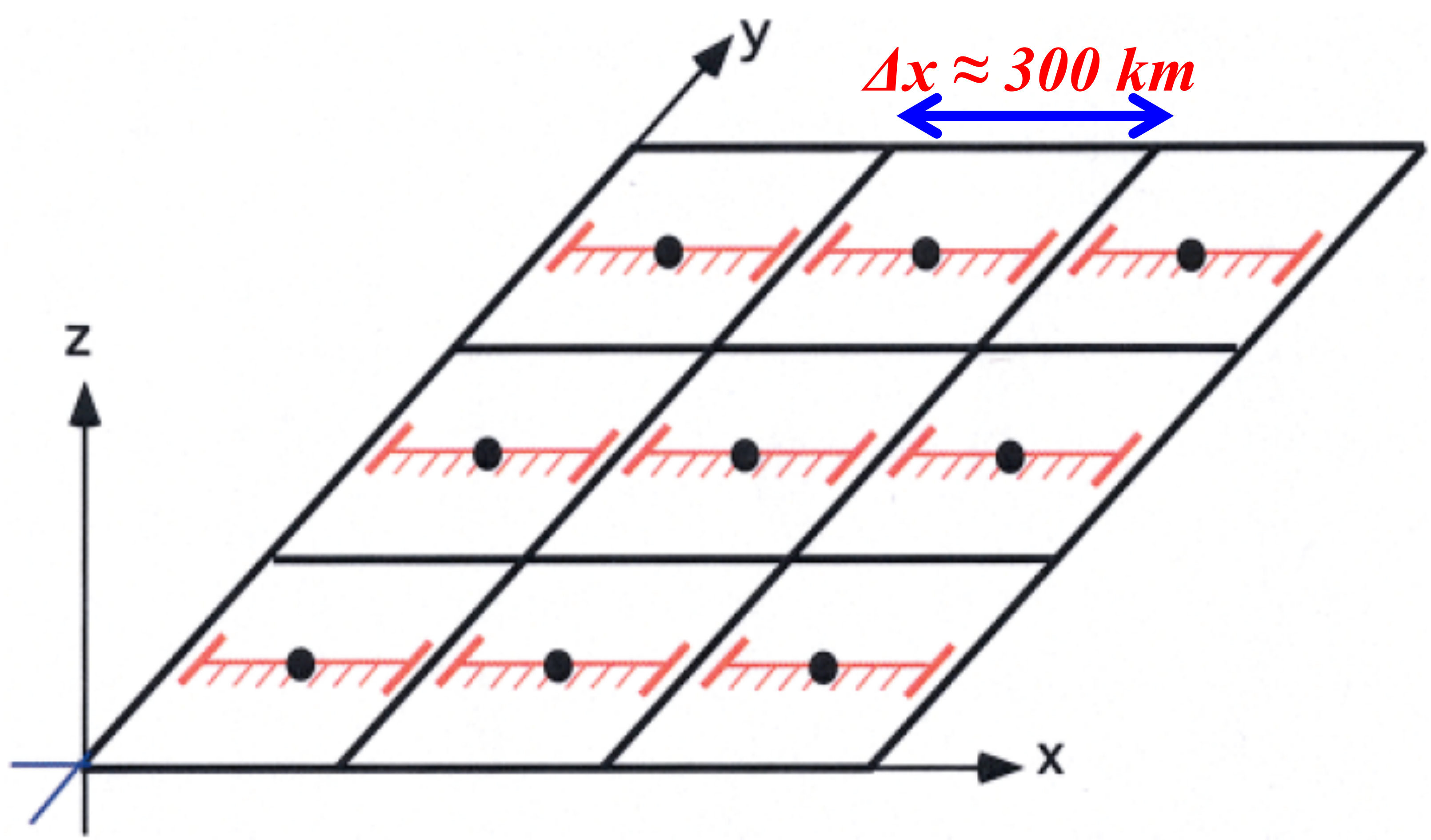
**However, pressure solver in the implicit compressible model (significantly more cumbersome than in the anelastic system, see Smolarkiewicz et al. *JCP* 2014) would need to work really hard when global LES is the target…**

Issues:

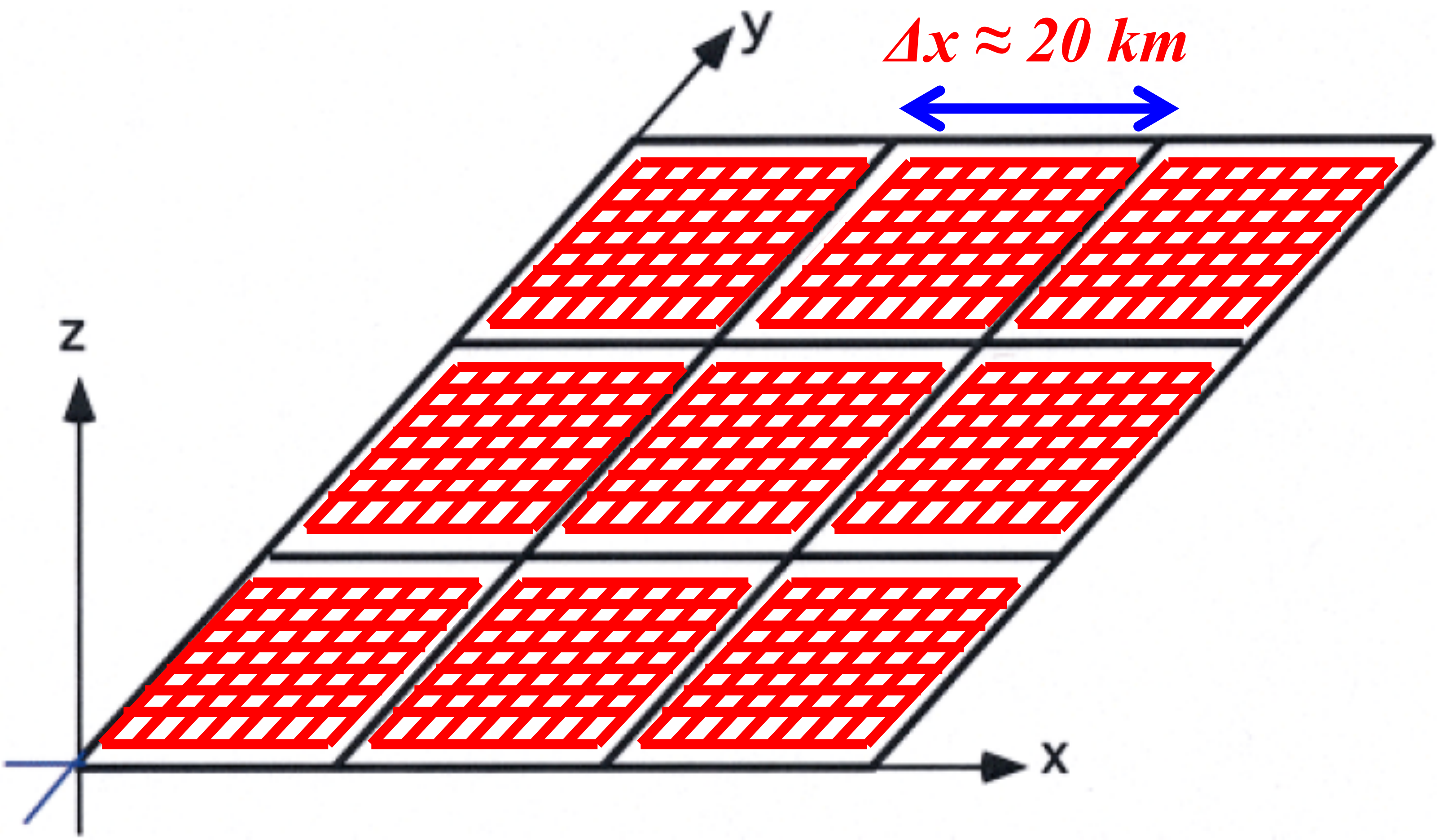
- Parallel processing?
- What equations to use?

SP can help! And can also provide additional benefits…

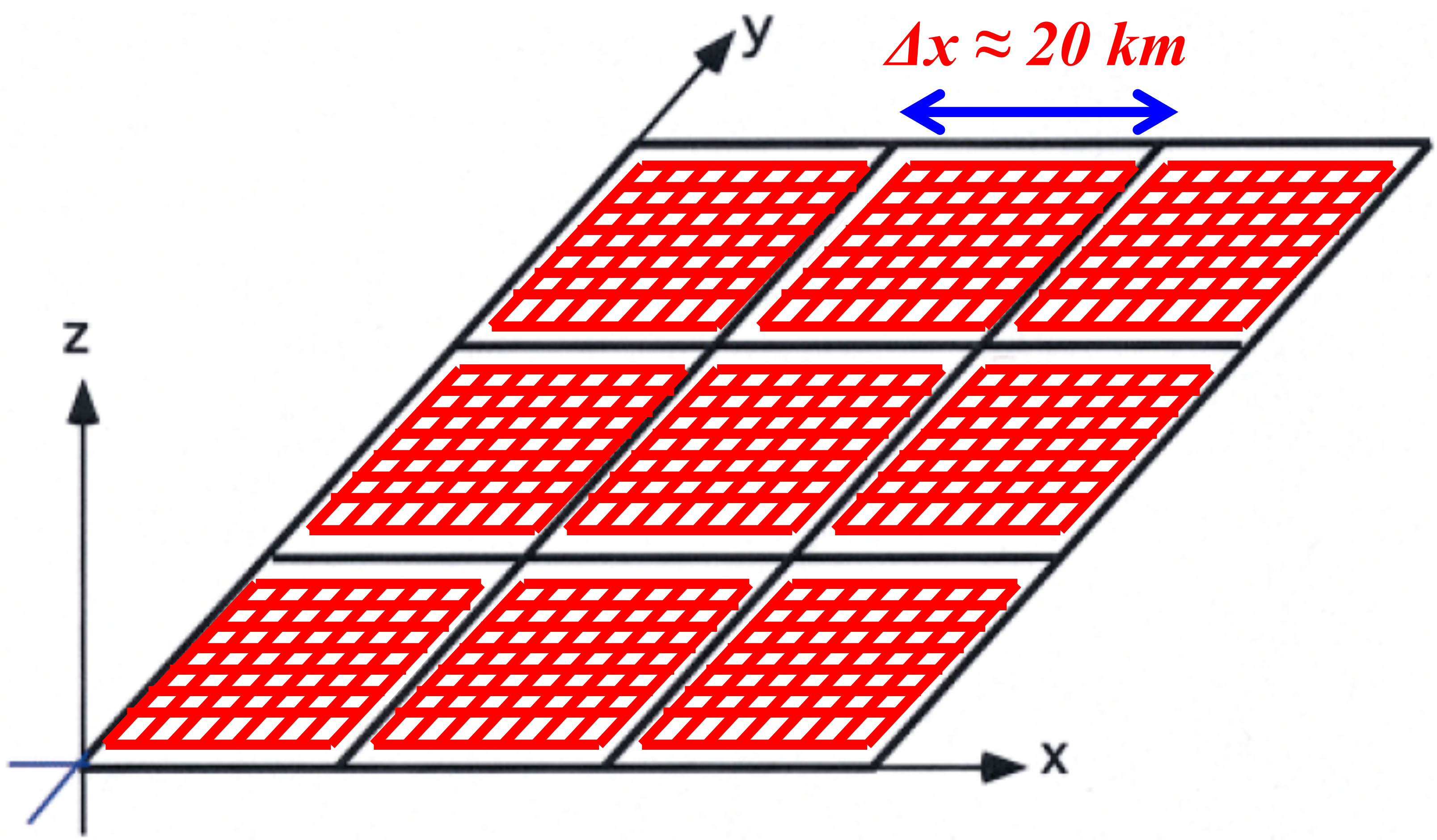
# Original SP proposal:



# Next generation SP proposal:



# Next generation SP proposal:




Communication between the outer model and SP models takes place only through the profiles, see Grabowski (*JAS* 2004)

Issues:

- Parallel processing?

Not a problem! SP is embarrassingly parallel with small amount of data that needs to be transfer infrequently between the host model and SP 3D models (only the profiles). Ideal for GPUs!

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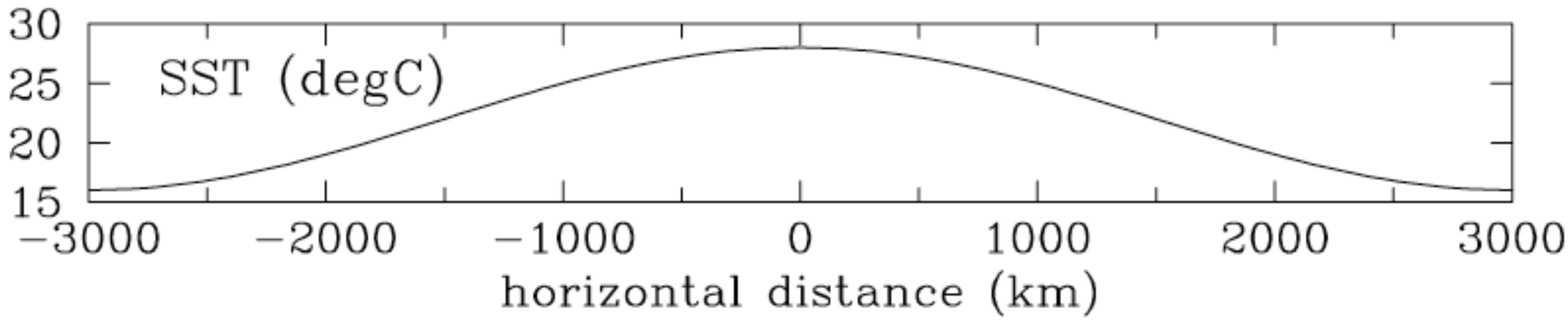
- SP can provide additional benefits:

SP models can have different grids, essentially allowing unstructured grid system with no additional cost.

## Illustration: the 2D mock-Hadley circulation

Similar to mock-Walker circulation (Grabowski *JAS* 2000) but with a larger SST difference between ascending and descending branches (4 degC in mock-Walker versus 12 degC in mock-Hadley)

One expects deep convection over warm SSTs and stratocumulus-topped boundary layer over cold SSTs…



30
25
20
15
SST (degC)
−3000
−2000
−1000
0
1000
2000
3000
horizontal distance (km)

Model setup:

6,000 km horizontal domain

24 km vertical extent, with stretched grid

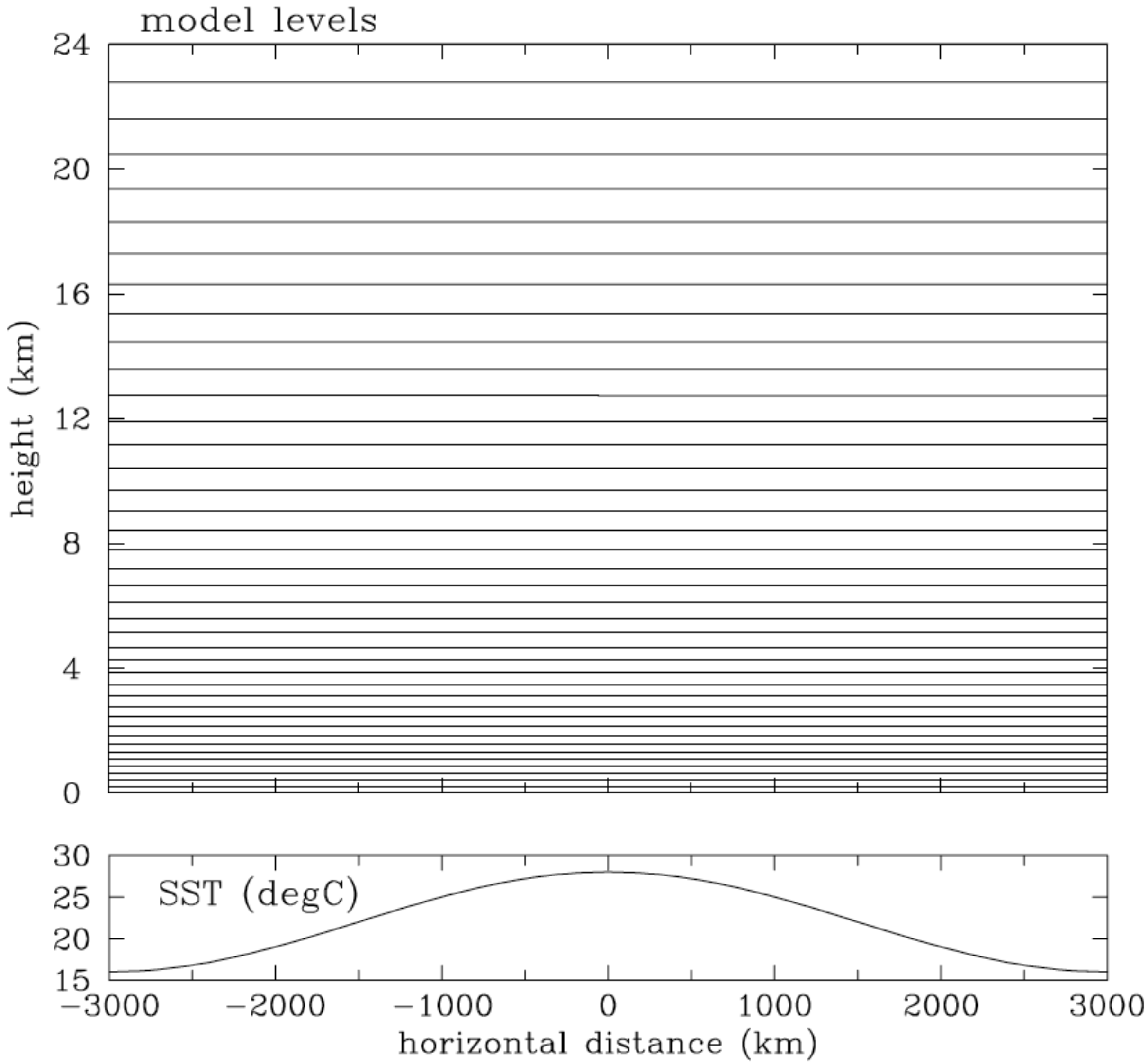
SST: 16 to 28 degC, varying as cos(distance)

No mean flow

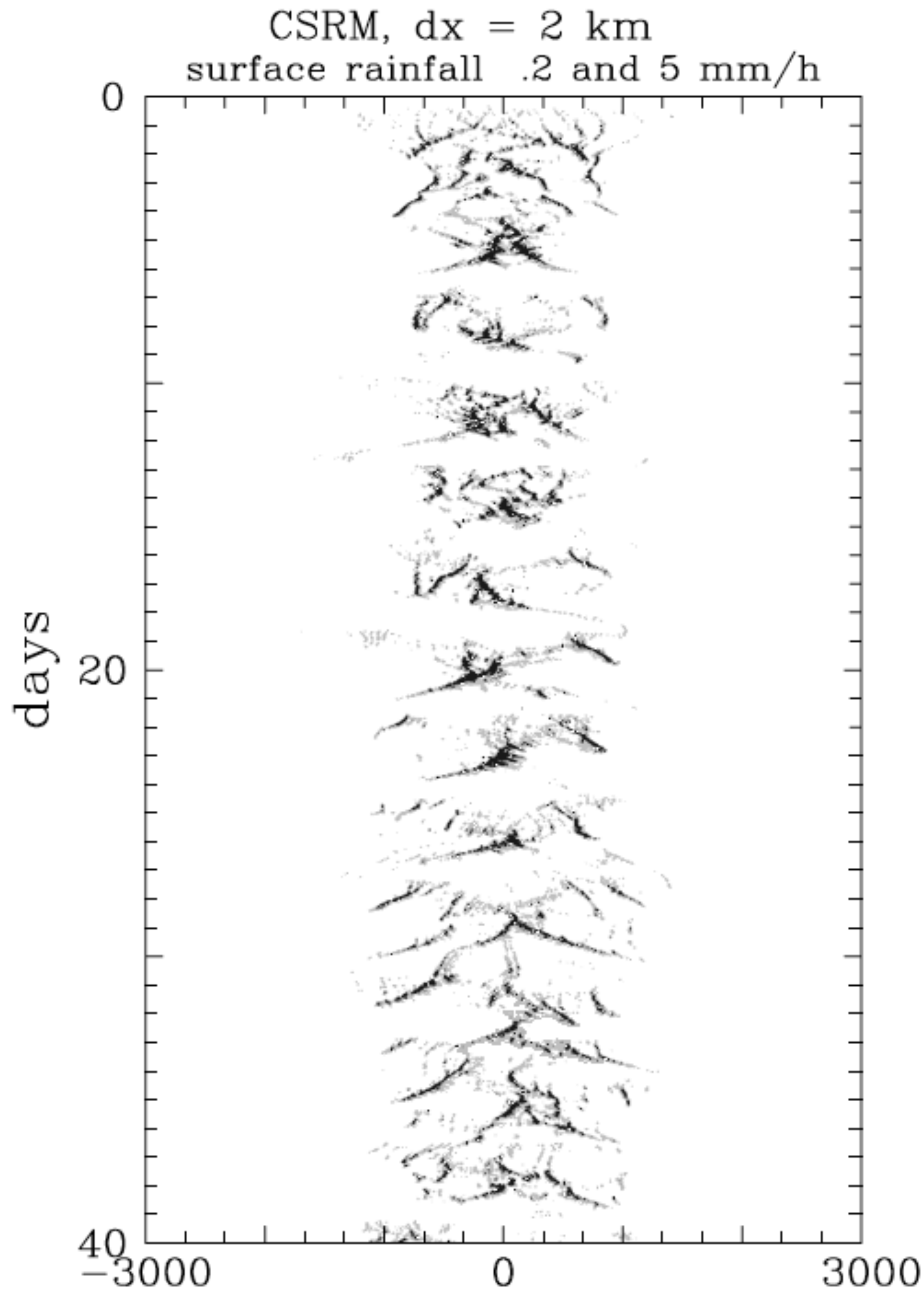
Prescribed radiative cooling: 1.5 K/day below 12 km, decreasing linearly to zero at 15km

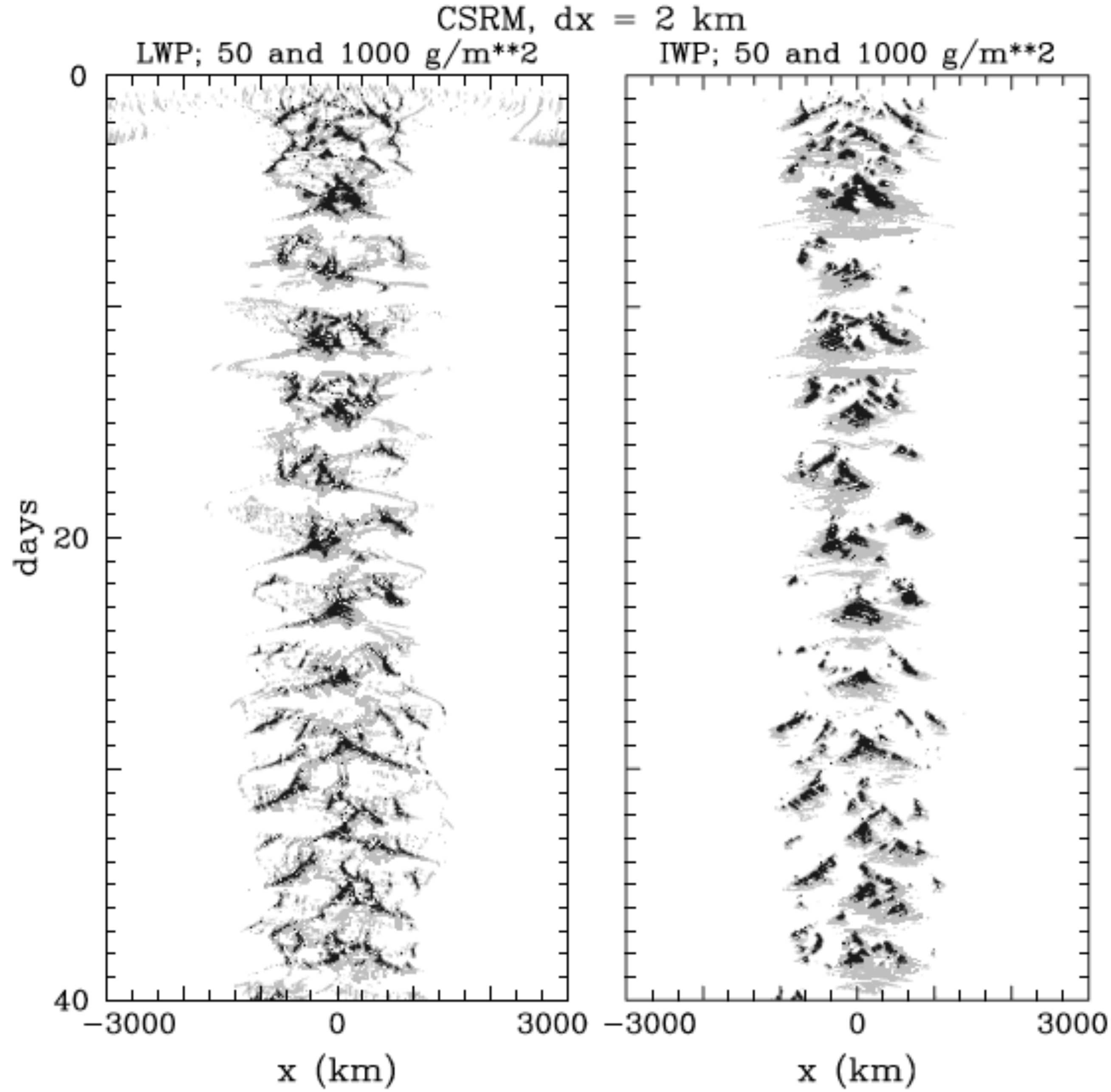
No SGS model in either outer or SP models (implicit LES)

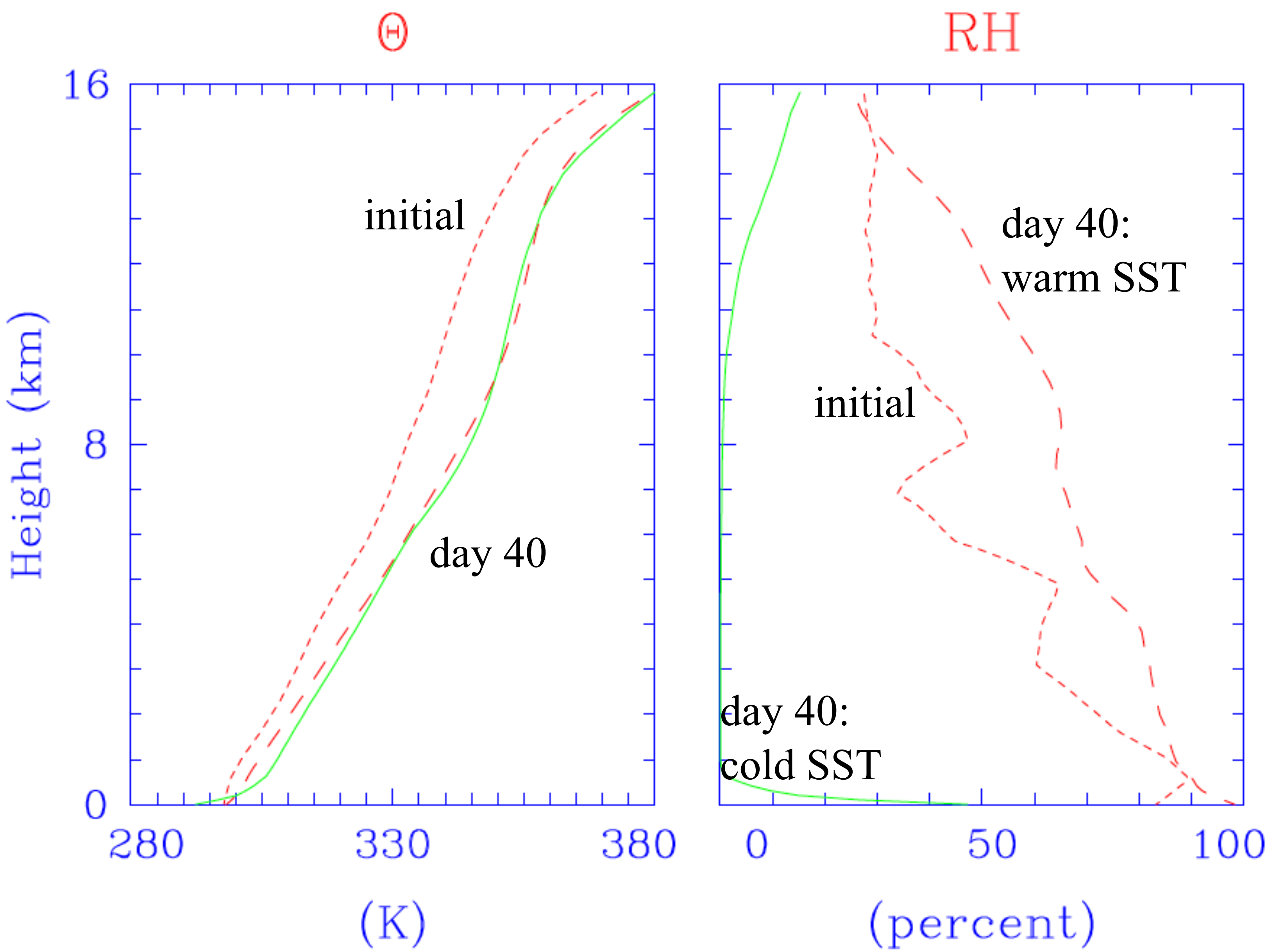
Simple formulation of surface sensible and latent heat fluxes



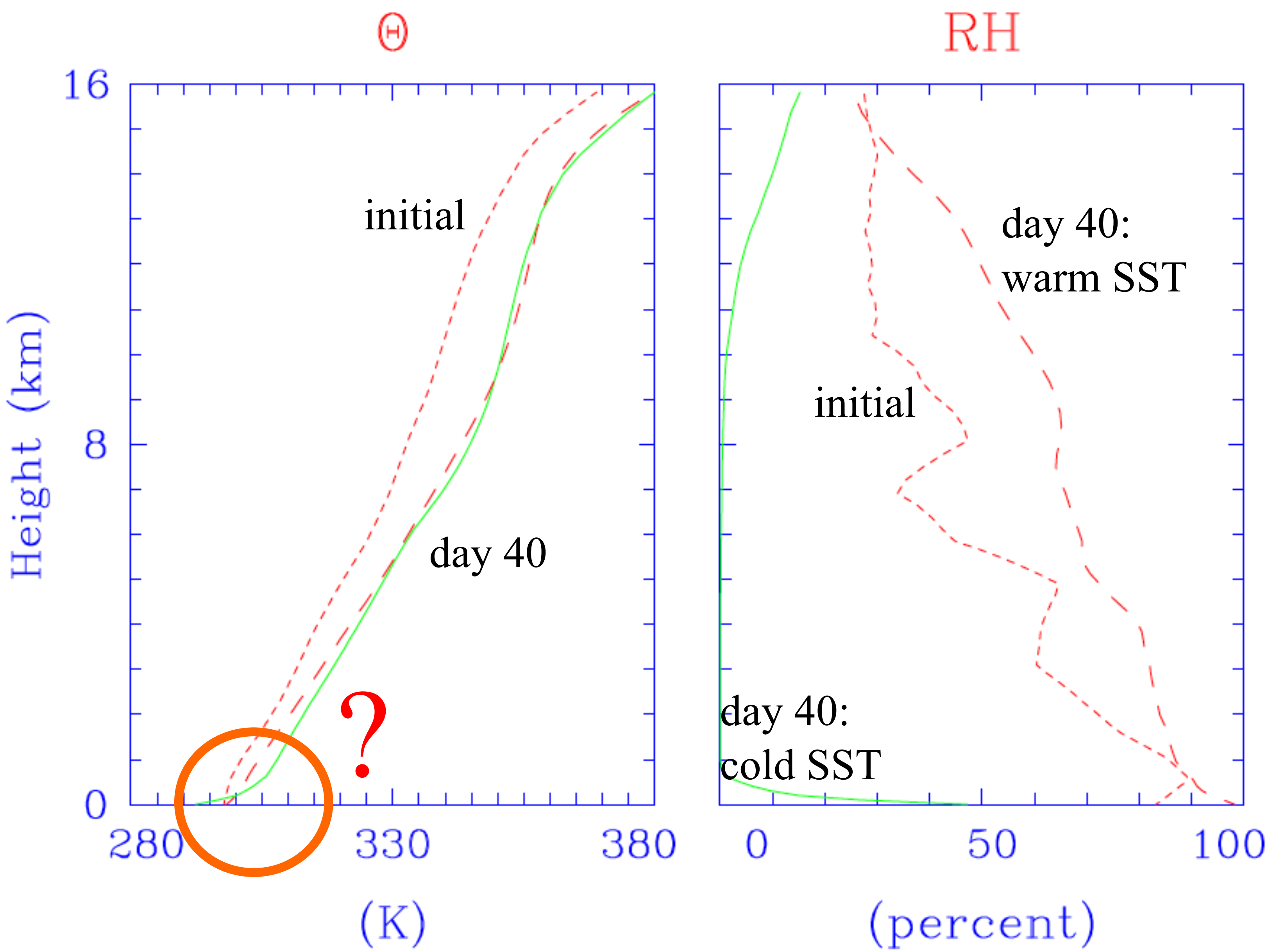

***Horizontal domain and vertical grid for CRM simulation, Δx=2 km, 3000 points in the horizontal, 81 levels.***


CSRM, dx = 2 km
surface rainfall .2 and 5 mm/h
0
20
40
days
−3000
0
3000

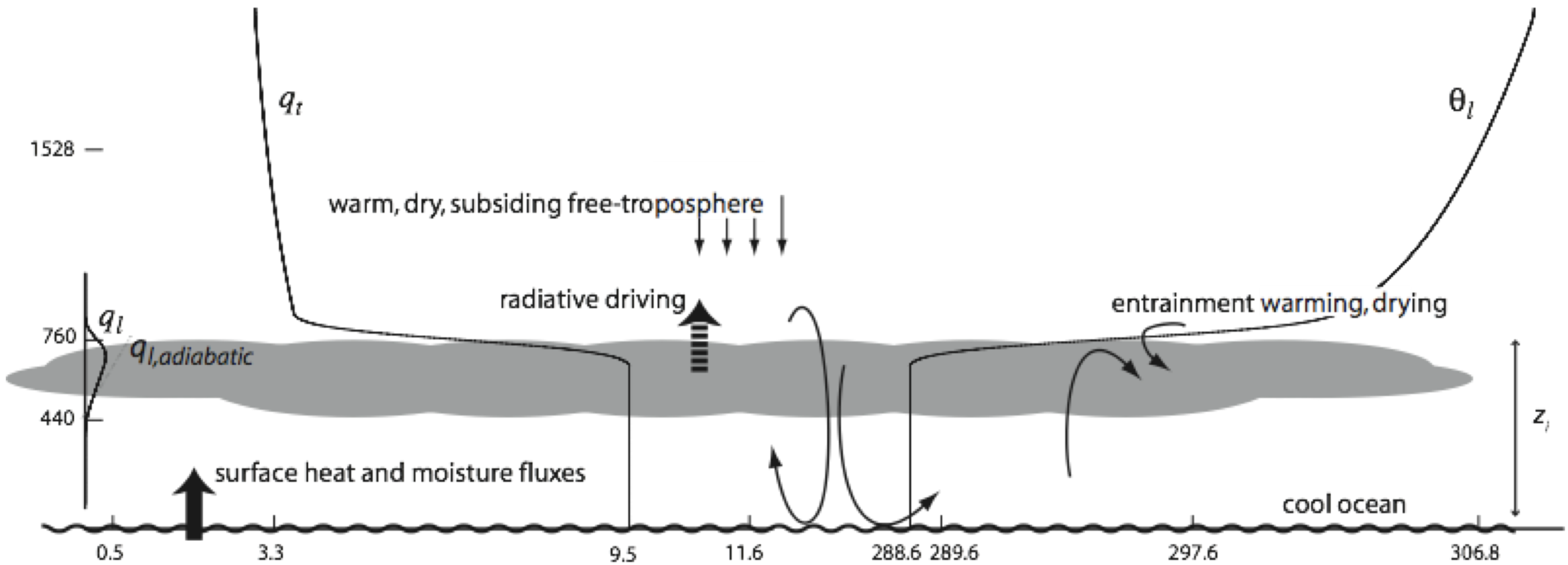

CSRM, dx = 2 km
LWP; 50 and 1000 g/m**2
IWP; 50 and 1000 g/m**2
days
0
20
40
−3000
0
3000
x (km)
−3000
0
3000
x (km)



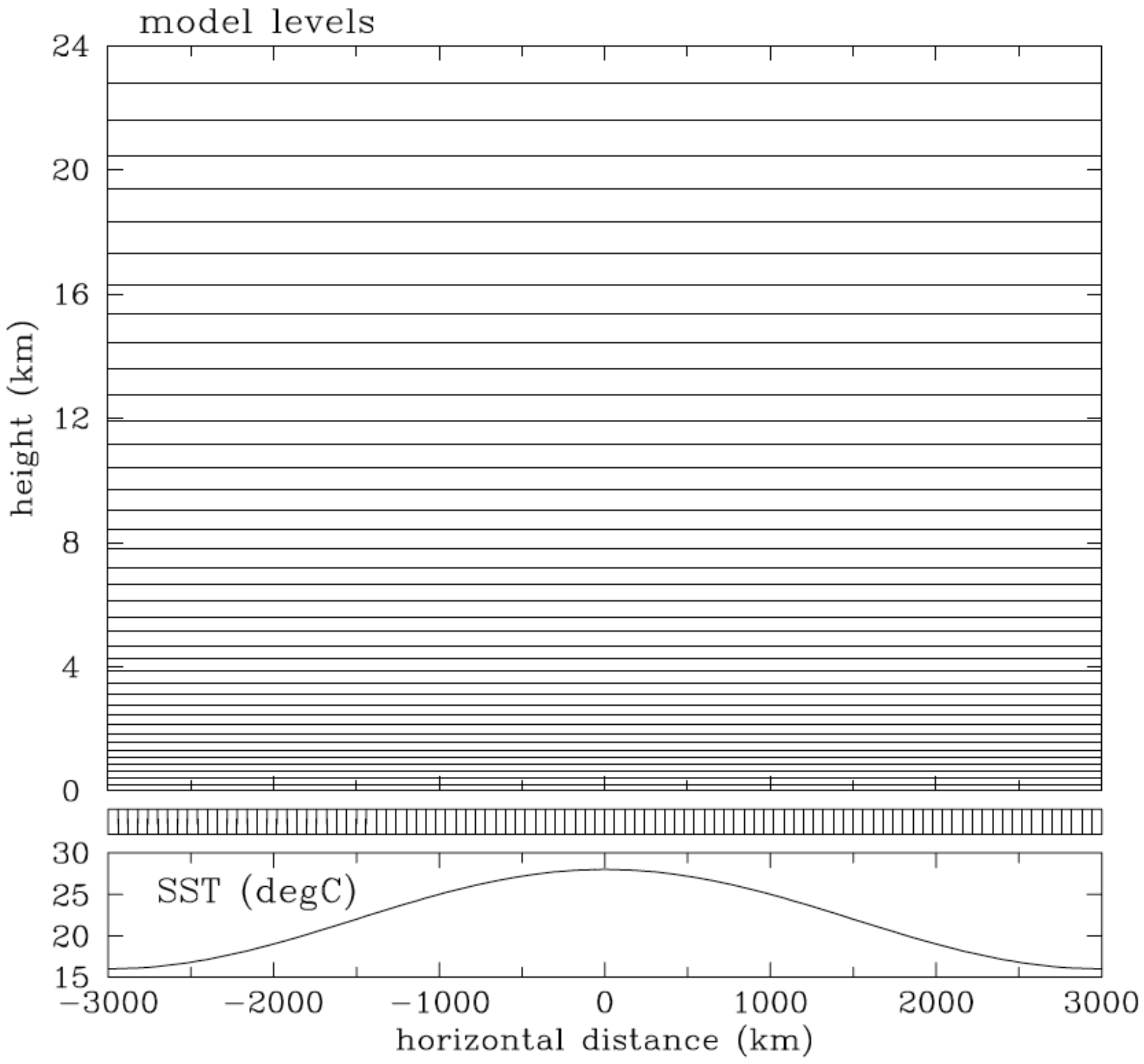
Θ
RH
16
8
0
Height (km)
initial
day 40
280
330
380
(K)
day 40:
warm SST
initial
day 40:
cold SST
0
50
100
(percent)



Θ
RH
16
8
0
Height (km)
initial
day 40
?
280
330
380
(K)
day 40:
warm SST
initial
day 40:
cold SST
0
50
100
(percent)




Stevens et al., 2006 , MWR

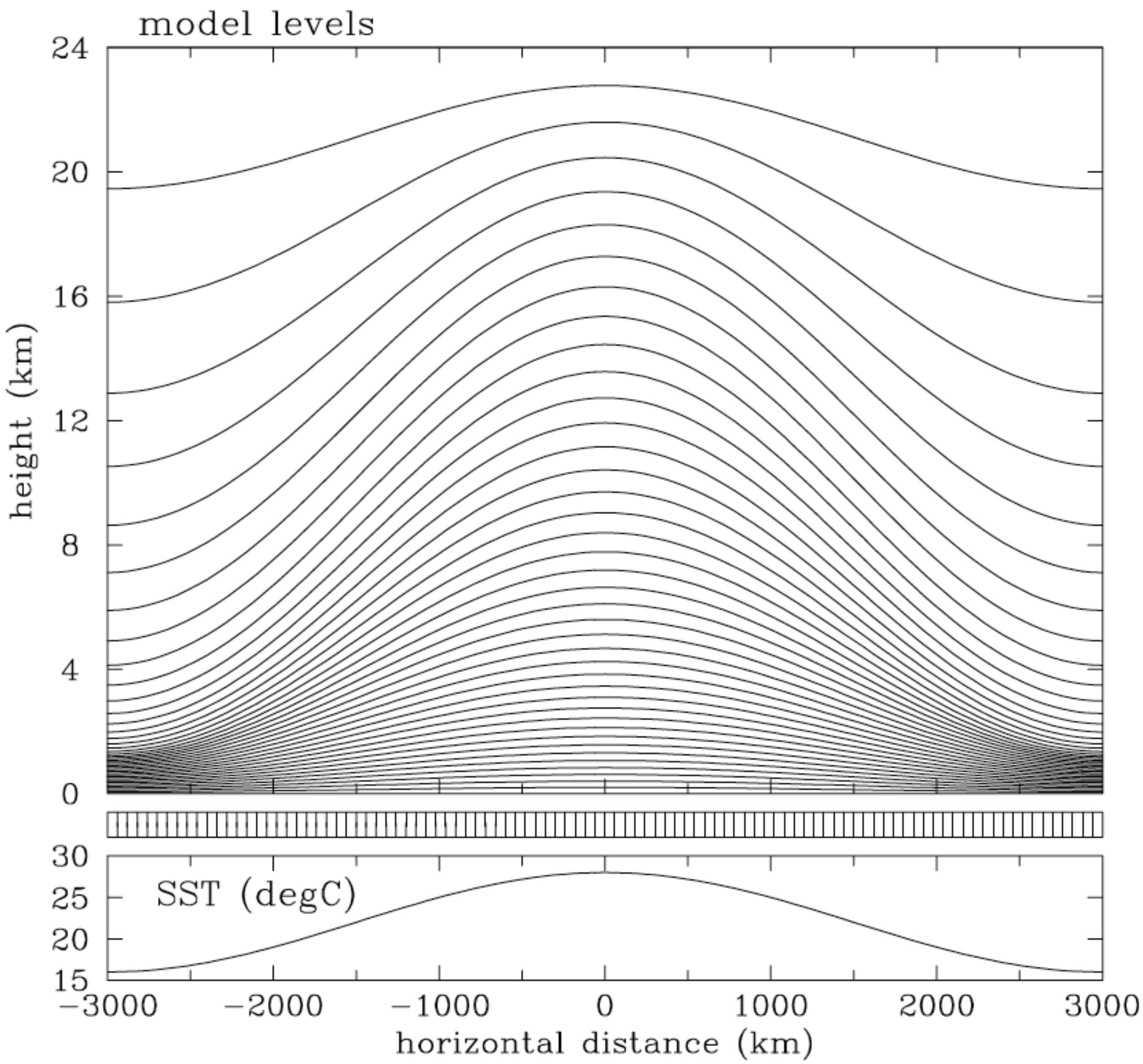



## Traditional SP model:

***Outer model: Δx=60 km, 100 points in the horizontal, 81 levels.***

***SP models: Δx=2 km, the same vertical grid as the outer model.***

# Heterogeneous SP model:

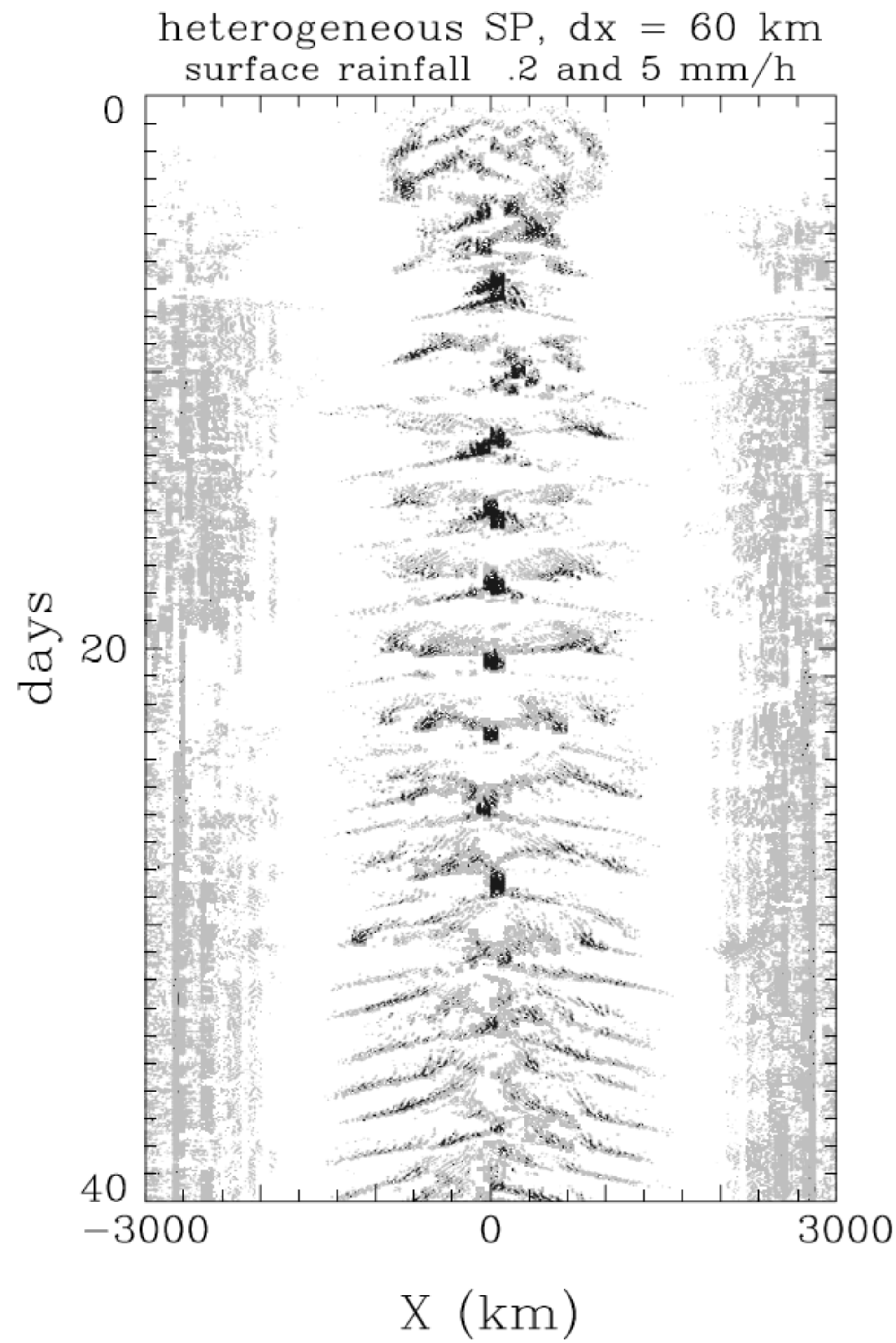


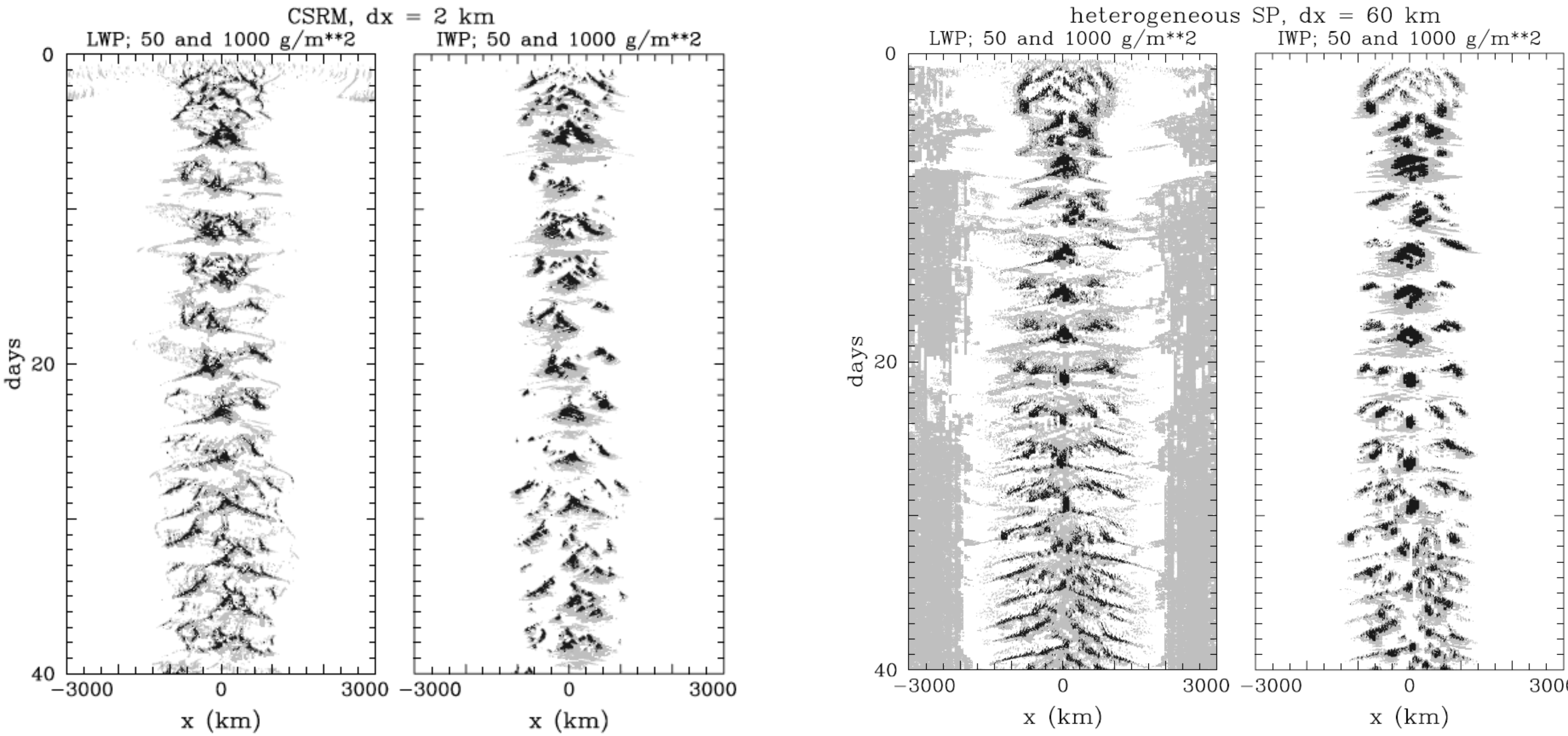

***Outer model: Δx=60 km, 100 points in the horizontal, 81 levels.***

***SP models at high SST:***
***CRM: Δx=2 km, the same vertical grid as the outer model.***

***SP models at low SST:***
***"2D LES": Δx=200 m, stretched vertical grid with Δz=30 m below 1 km, stretching strongly above.***

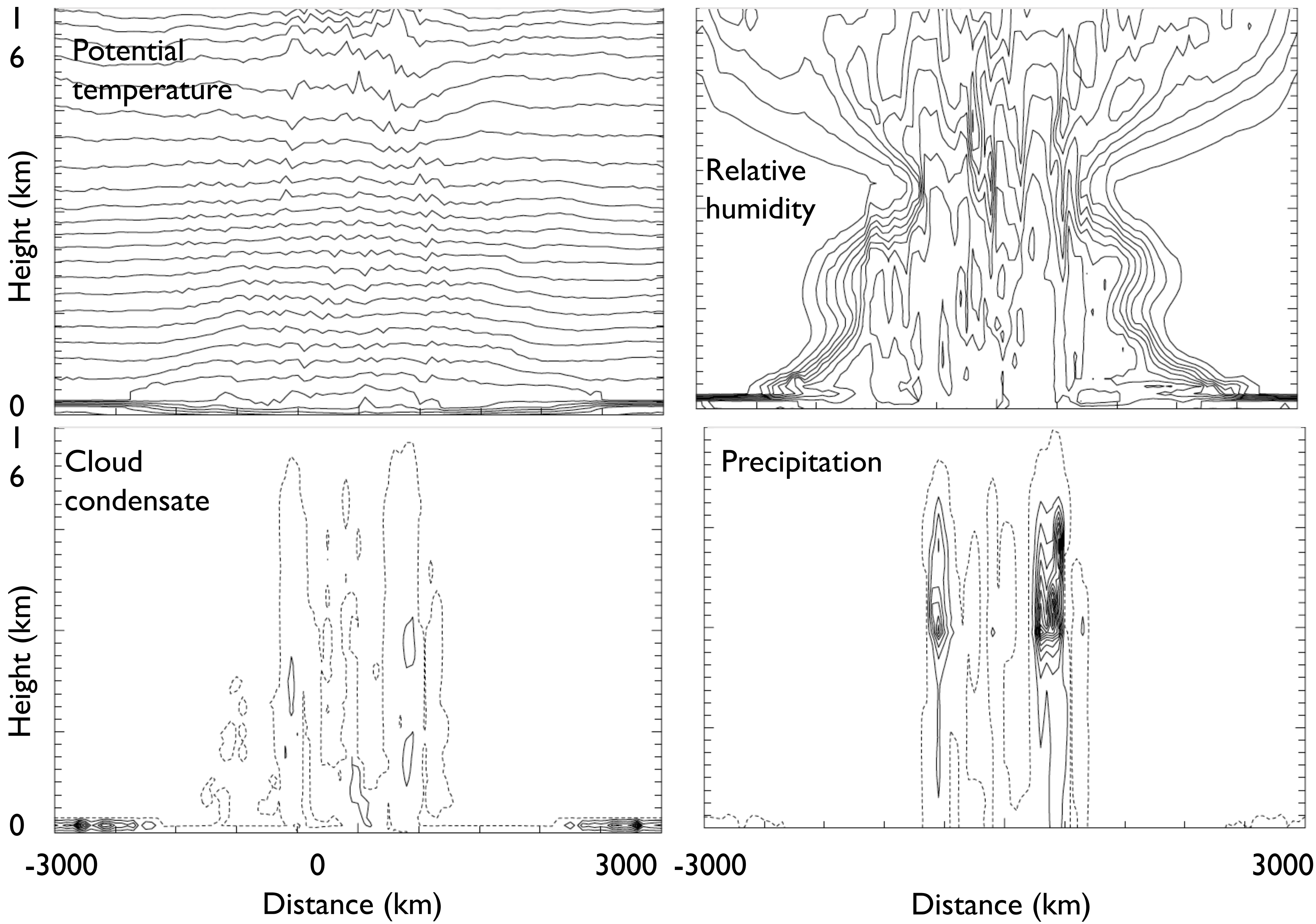
***Linear interpolation of profiles between outer and SP models.***


heterogeneous SP, dx = 60 km
surface rainfall .2 and 5 mm/h
days
0
20
40
−3000
0
3000
X (km)



CSRM, dx = 2 km
LWP; 50 and 1000 g/m**2
IWP; 50 and 1000 g/m**2
heterogeneous SP, dx = 60 km
LWP; 50 and 1000 g/m**2
IWP; 50 and 1000 g/m**2
days
0
20
40
−3000
0
3000
x (km)

Snapshots of fields at day 40 as seen on the outer model grid…



**Conclusions:**

**1. *Large eddy simulation (LES)* provides an appropriate framework for modeling cloud processes in both shallow boundary layer clouds and deep convection. The race towards *global LES* is on.**

**2. A brute force approach, that is, extending global convection-permitting models (such as the Japanese NICAM or German ICON) to global LES will be computationally extremely expensive because of the amount of data that needs to be transferred between subdomains in traditional parallelization methodologies. The efficiency of the compressible dynamical framework at such resolutions is also unclear.**

**Conclusions, continued:**

**3. The super-parameterization (SP) methodology provides a rapid way forward towards global LES. Outer model should have tiles of 100s km$^2$ (say 20 by 20 km) and can be hydrostatic. 3D SP models can be anelastic with base-state and environmental profiles varying between equator and the poles, and they can have different grids depending on geographic location. Parallelization of such a system is trivial with only profiles exchanged infrequently between outer and SP models. Such a global LES system based on SP methodology should run efficiently on massively parallel systems, for instance, those based on GPUs.**