# Towards global Large Eddy Simulation: Super-parameterization revisited

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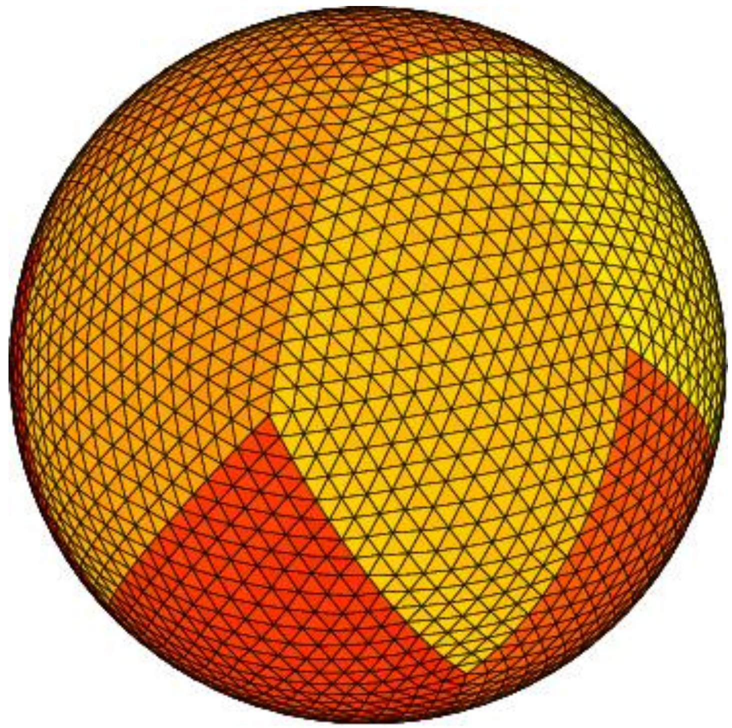
# Why LES?

# Why LES?

Why not?

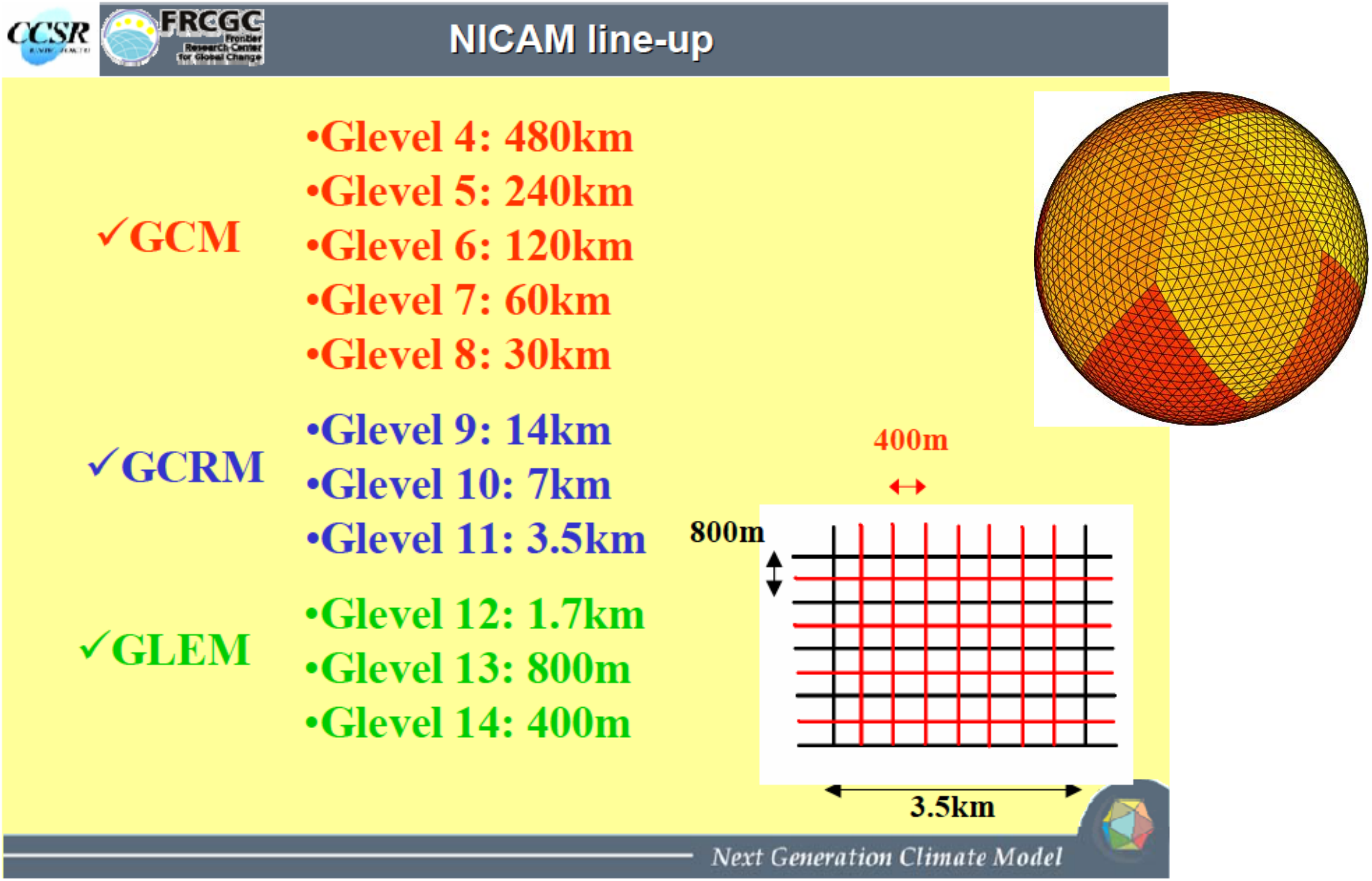
# Early 2000s:

## NICAM: Nonhydrostatic ICosahedral Atmospheric Model



NICAM is used as a Global Cloud Resolving Model (GCRM).

A 3.5km-mesh global simulation has already been performed using the Earth Simulator.




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

# Why LES?

Why not?

Resolution requirements for deep convection…

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

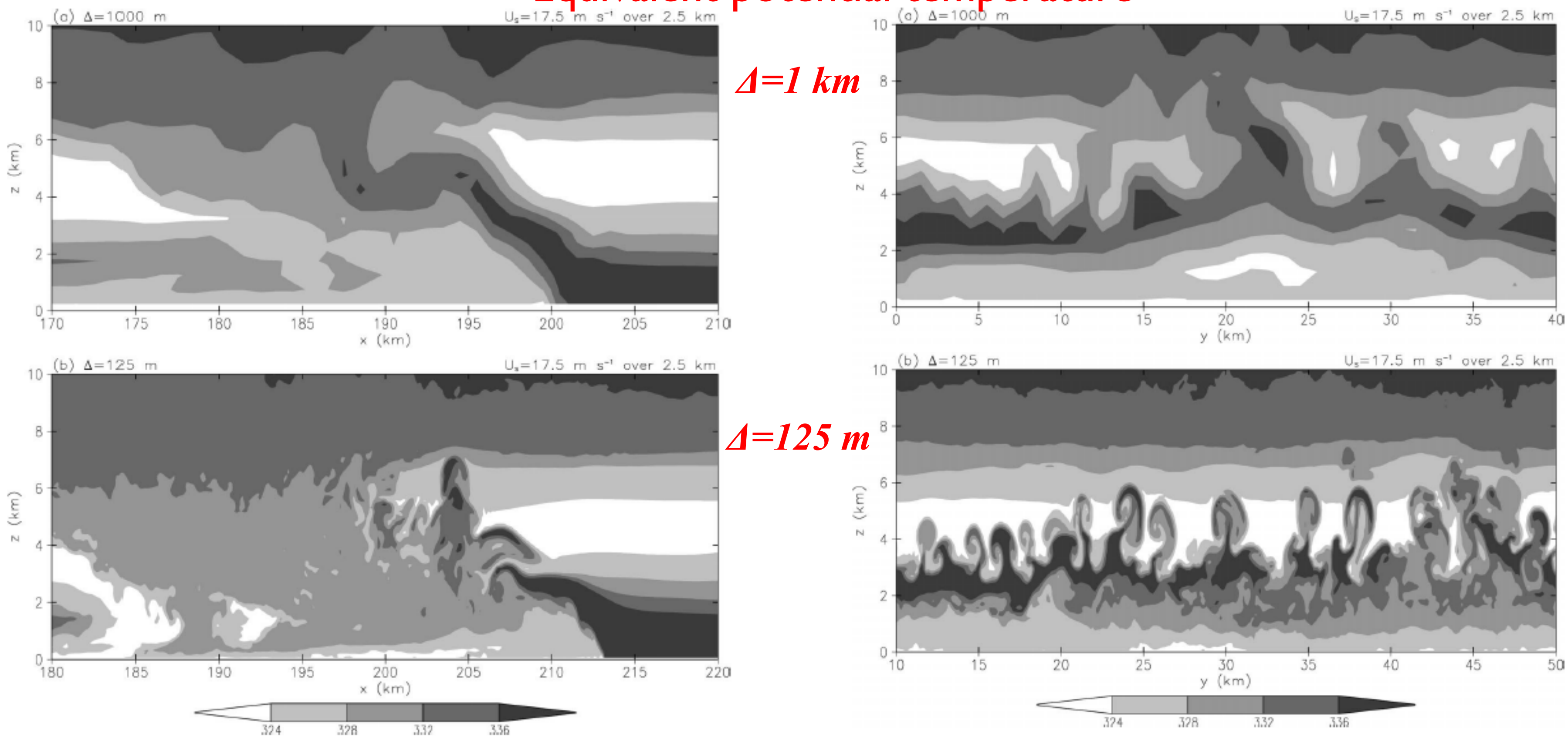
George H. Bryan, John C. Wyngaard, and J. Michael Fritsch

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

MWR 2003

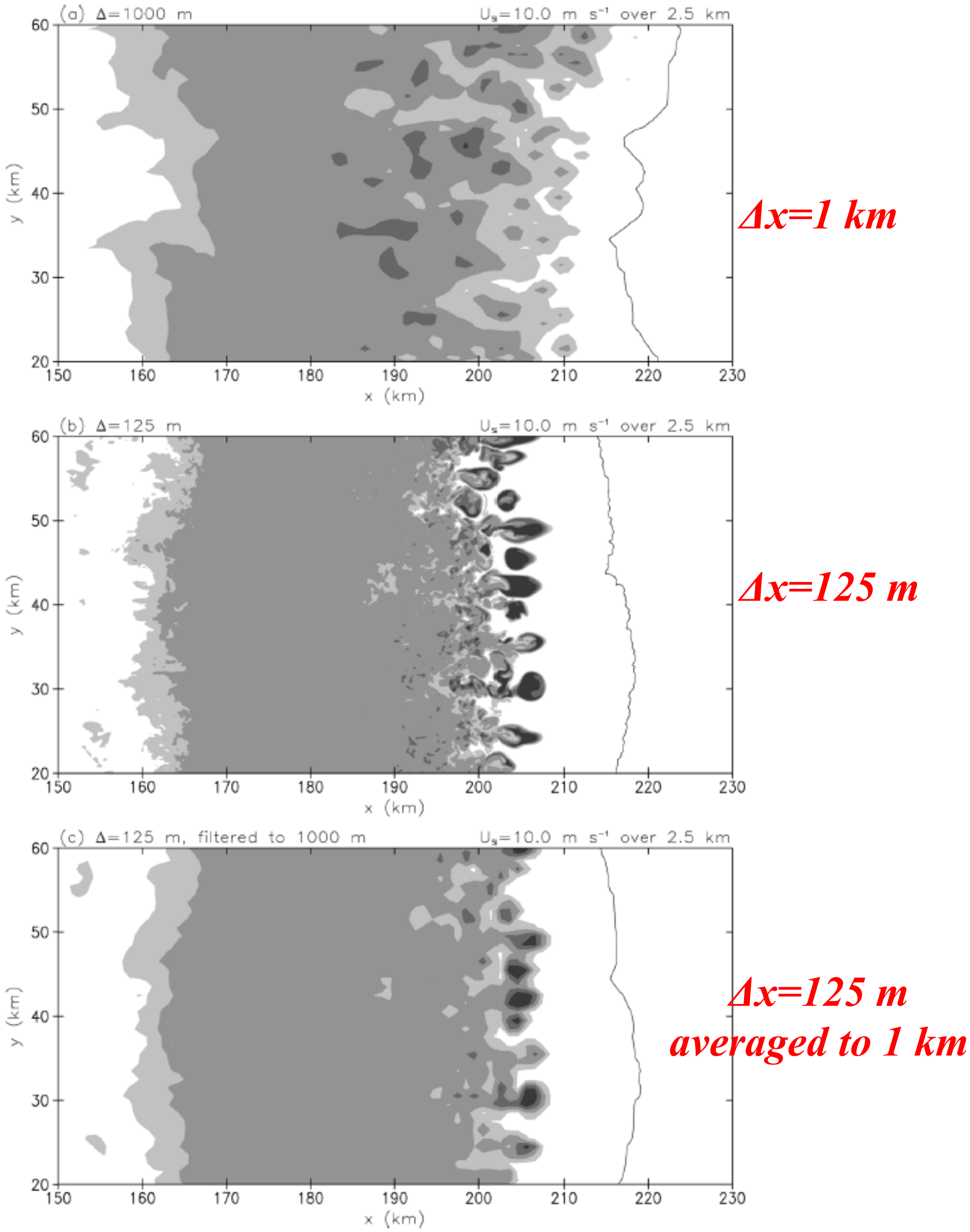
# Squall line simulation:

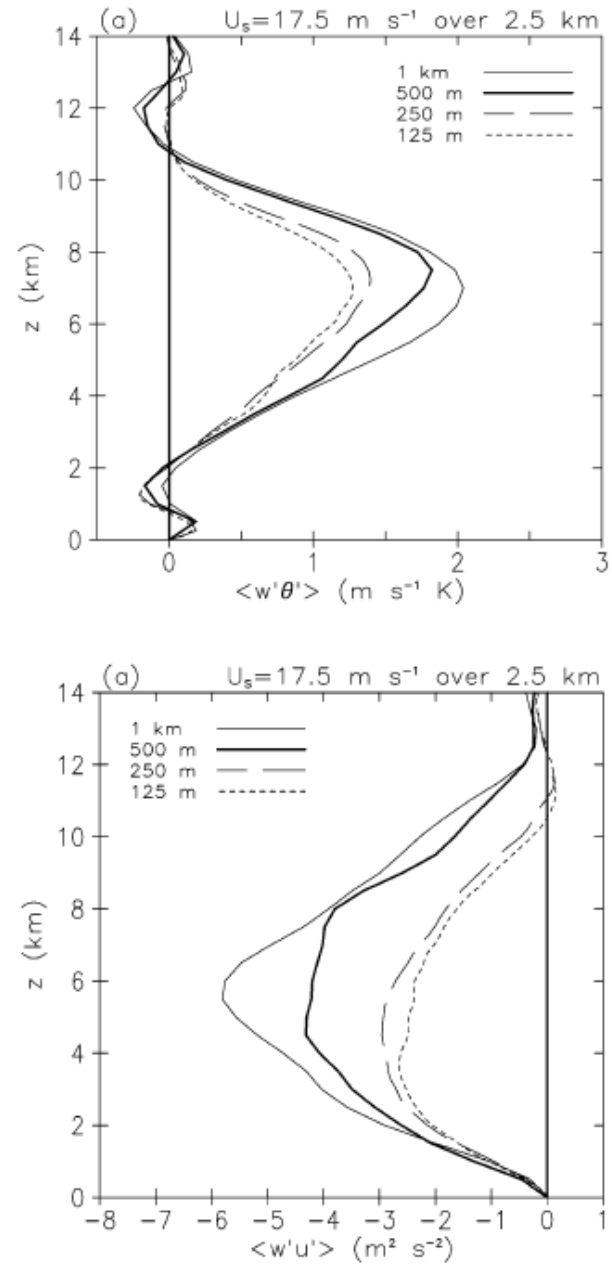
Equivalent potential temperature




Perpendicular to the leading edge

Parallel to the leading edge


(a) Δ=1000 m
$U_s$=10.0 m s⁻¹ over 2.5 km
Δx=1 km
(b) Δ=125 m
$U_s$=10.0 m s⁻¹ over 2.5 km
Δx=125 m
(c) Δ=125 m, filtered to 1000 m
$U_s$=10.0 m s⁻¹ over 2.5 km
Δx=125 m
averaged to 1 km
y (km)
x (km)


(a) $U_s$=17.5 m s⁻¹ over 2.5 km
1 km
500 m
250 m
125 m
z (km)
<w'θ'> (m s⁻¹ K)
(a) $U_s$=17.5 m s⁻¹ over 2.5 km
1 km
500 m
250 m
125 m
z (km)
<w'u'> (m² s⁻²)

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

2009

## 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]*

Giga LES

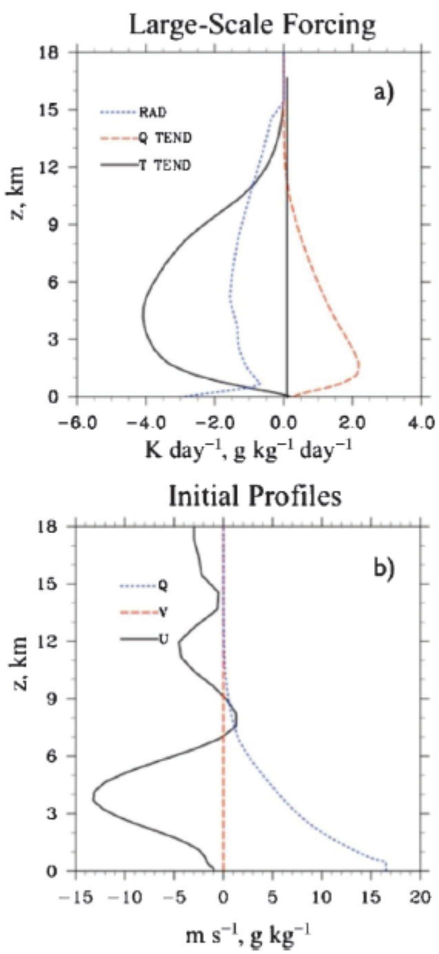
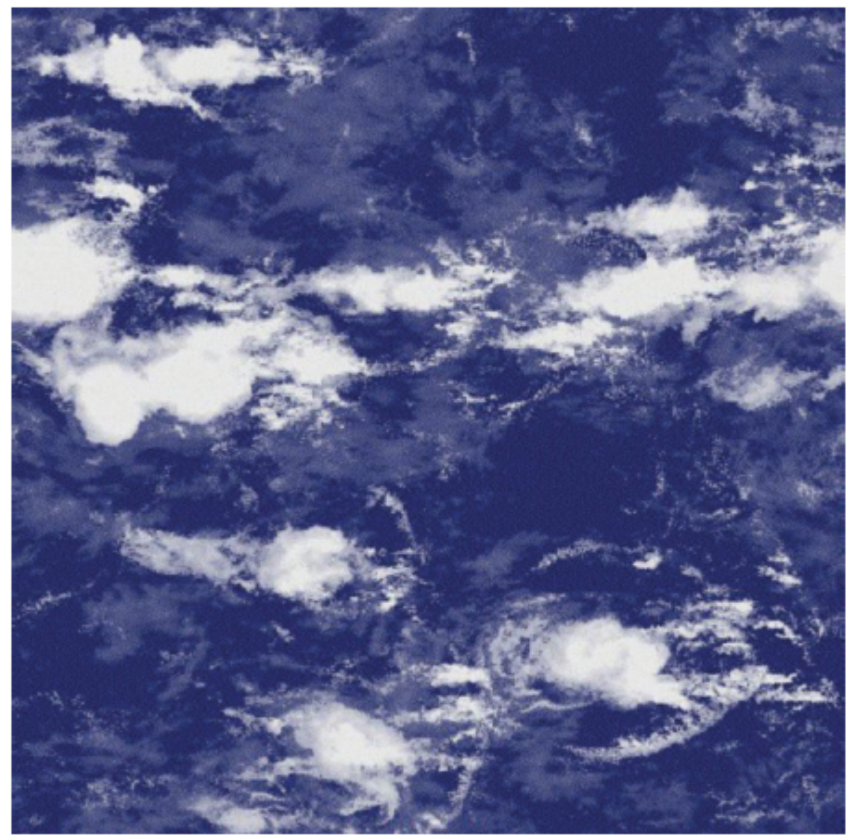


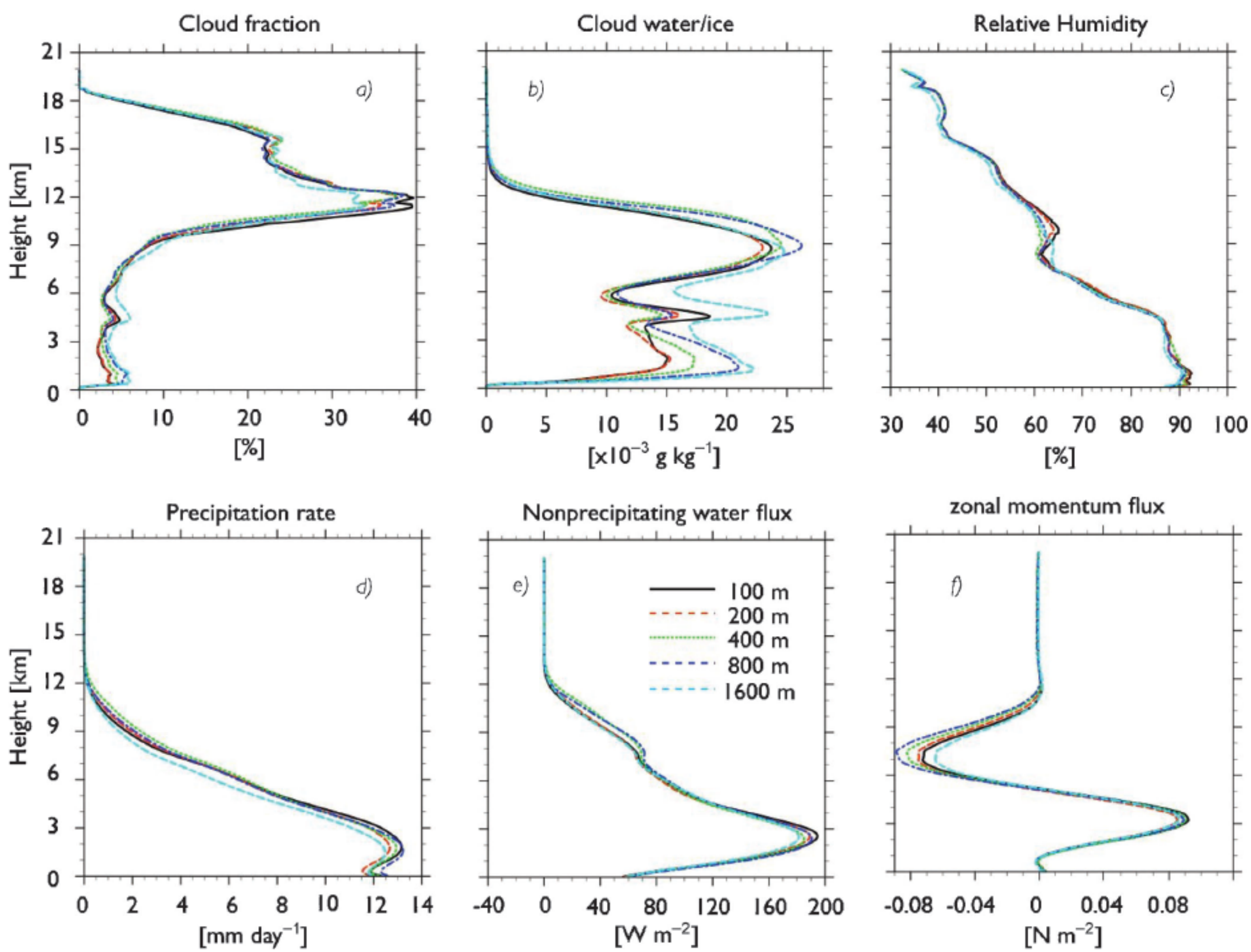

**Table 1** Summary of the numerical experiments used in this study.

| 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 |

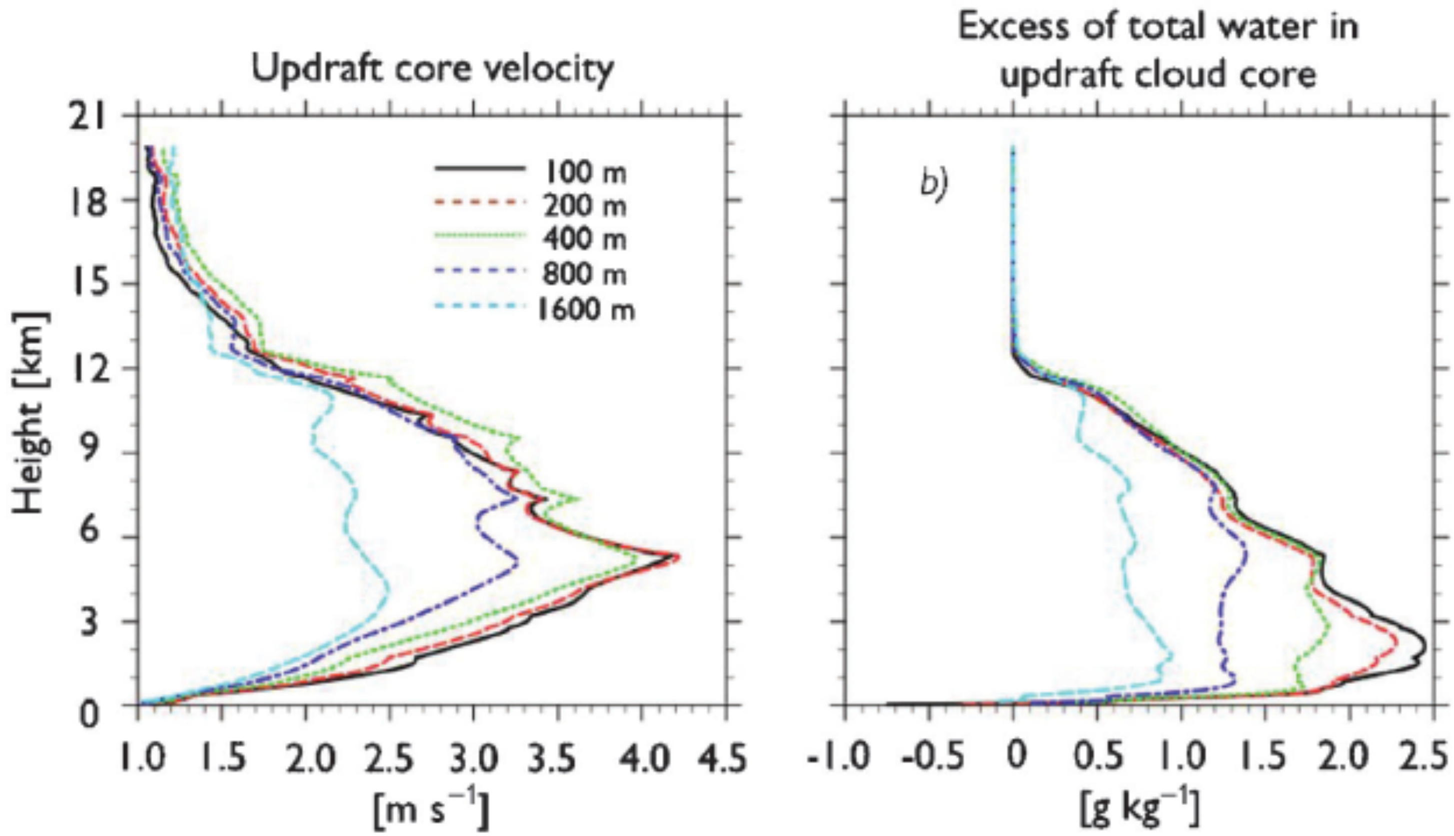


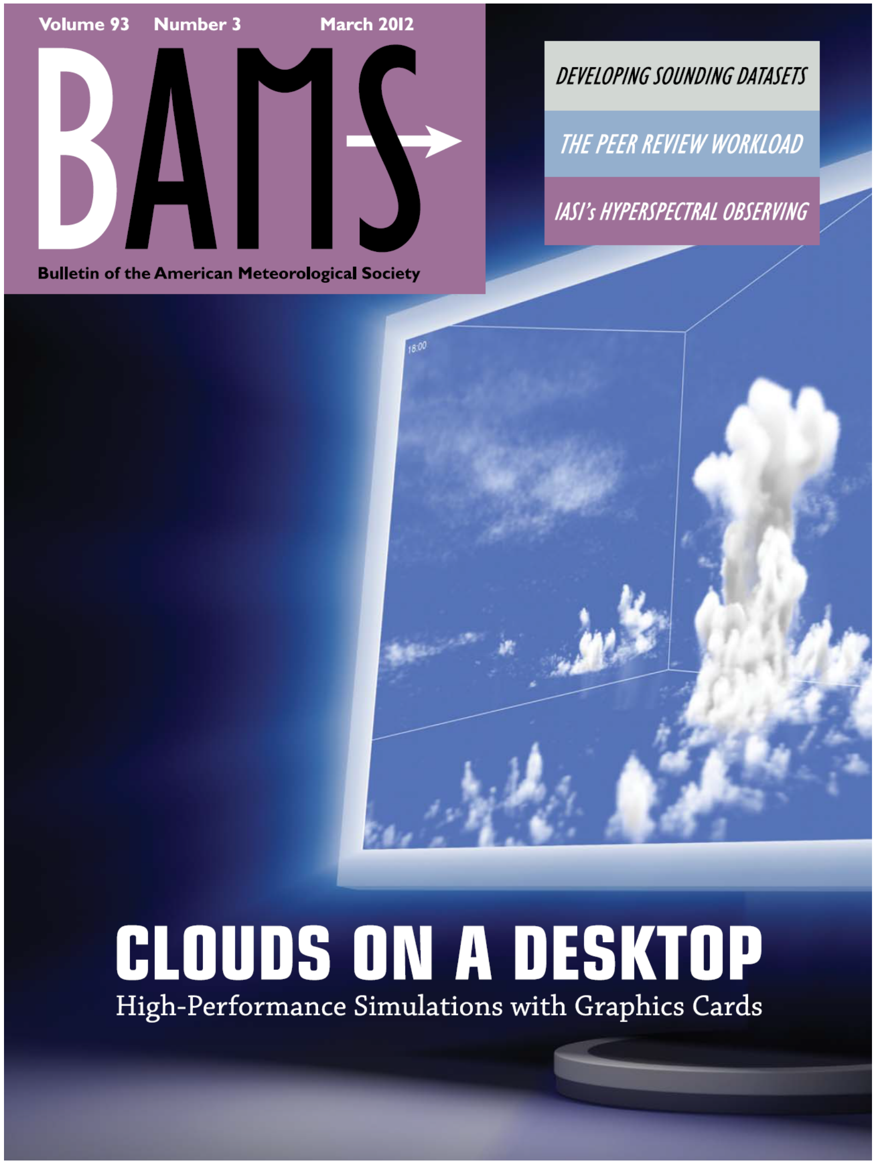
# Realistic Giga LES view of deep-convection cloud field

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

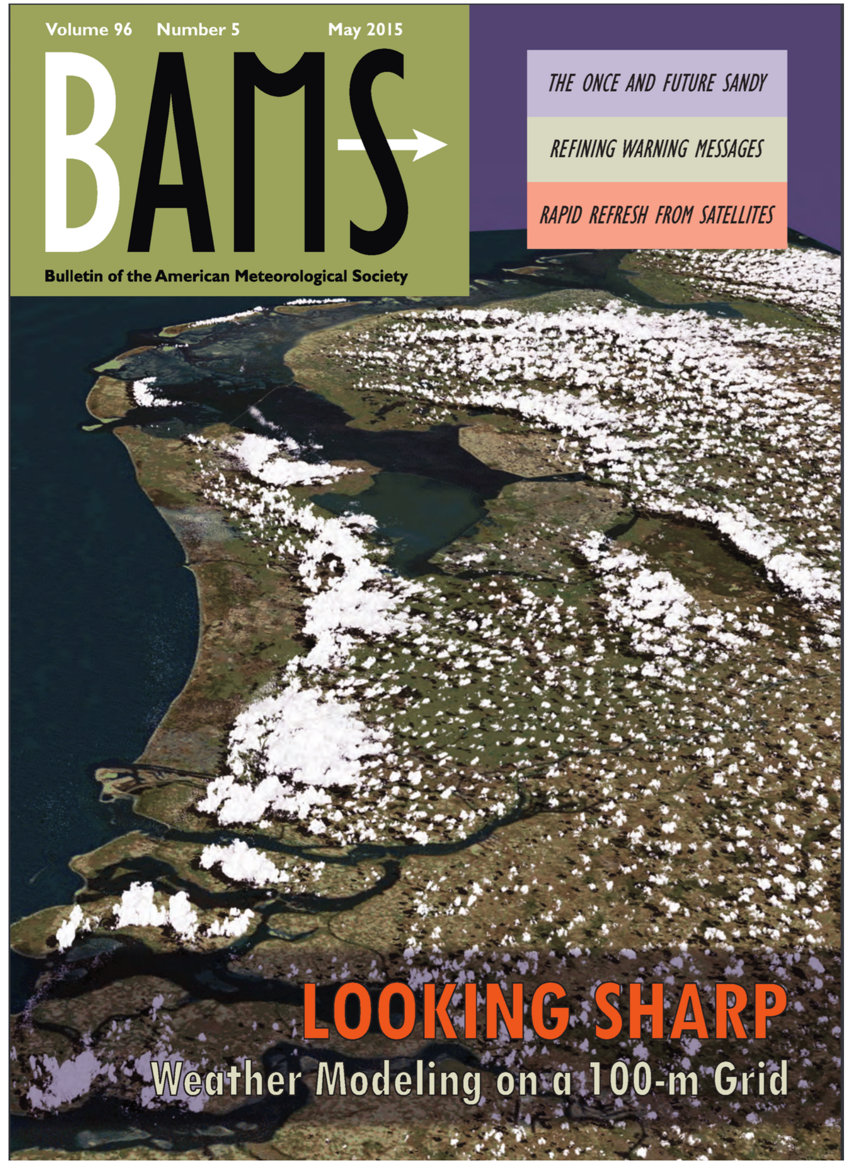


…but the impact is significant for some microphysics-relevant fields:






Schalkwijk et al *BAMS* 2012

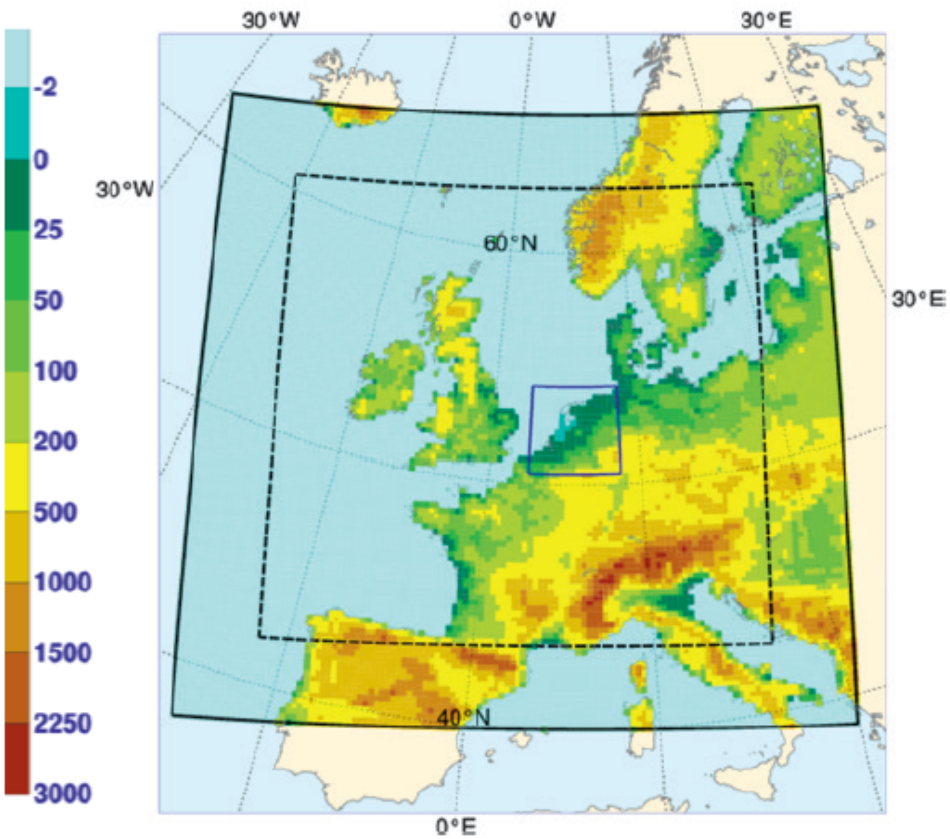



Schalkwijk et al *BAMS* 2015

# Weather Forecasting Using GPU-Based Large-Eddy Simulations

BY JERÔME SCHALKWIJK, HARMEN J. J. JONKER, A. PIER SIEBESMA, AND ERIK VAN MEIJGAARD

BAMS 2015




Super-parameterization:

What is it and what is “super” about it?

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

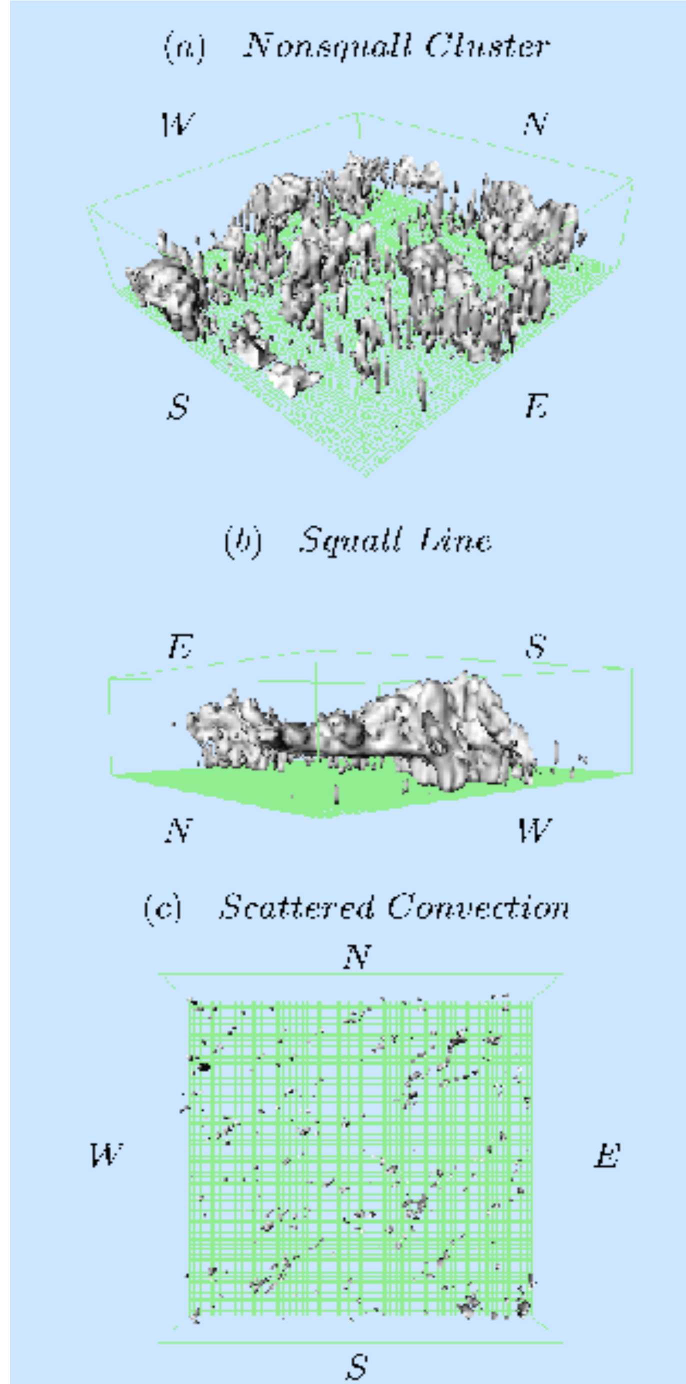
2 Sept, 1800 Z

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



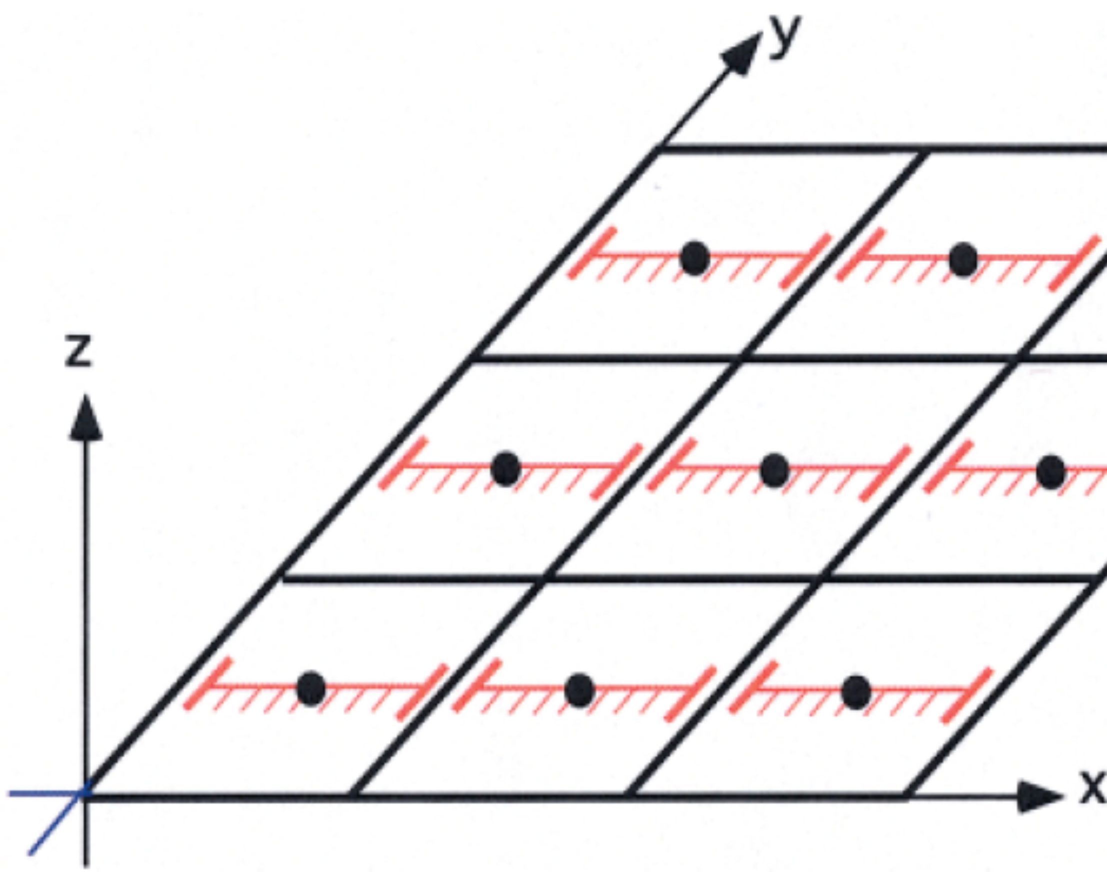
Grabowski et al. JAS 1998:

"…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?*

# Original SP proposal:

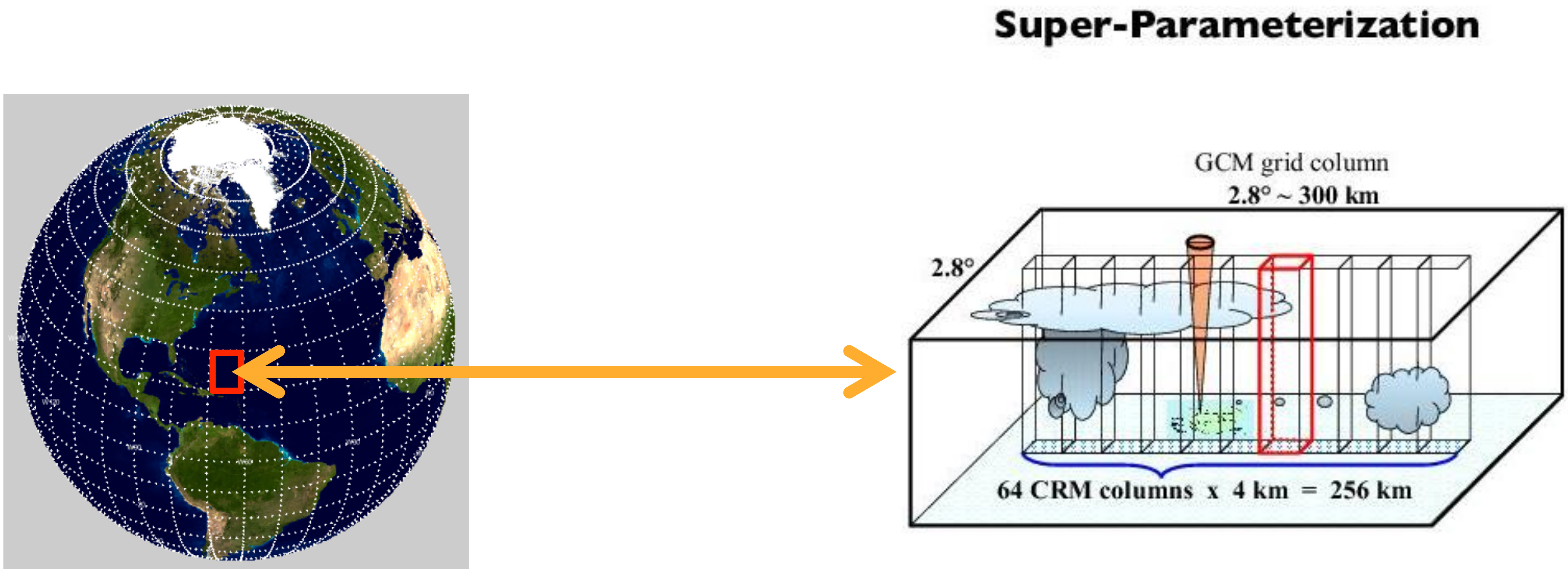



Randall et al. *BAMS* 2003

# NSF Science and Technology Center was created in 2006…


http://cmmap.org

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



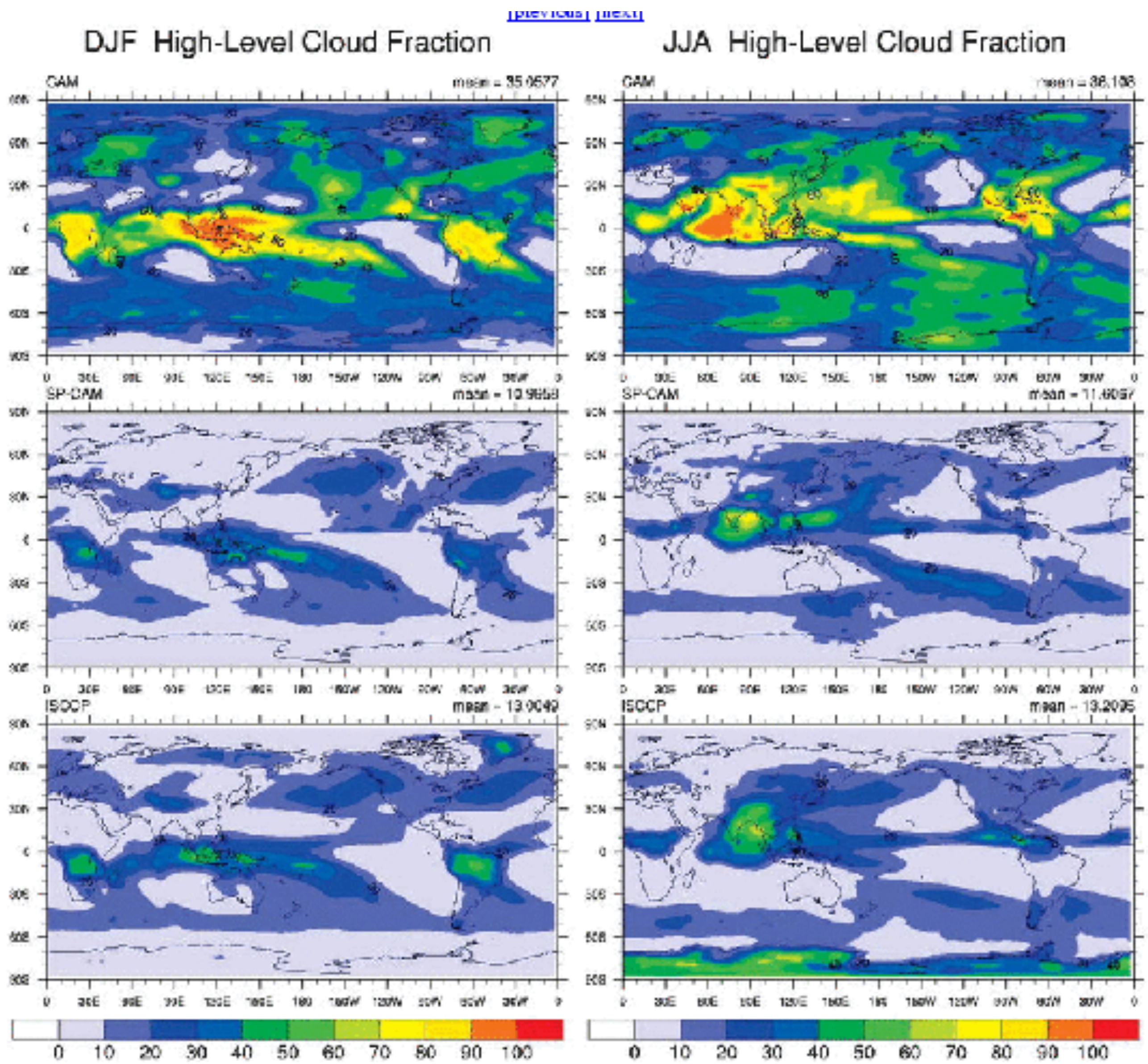

**(Khairoutdinov and Randall, 2001; Khairoutdinov et al. 2005, 2007; Wyant et al. 2006… and many more, including coupled atmosphere-ocean simulations and land-surface model moved into SP, see an impressive list of publications at** **http://www.cmmap.org/research/pubs-ref.html**

# Results from a traditional climate model versus MMF

Traditional

MMF

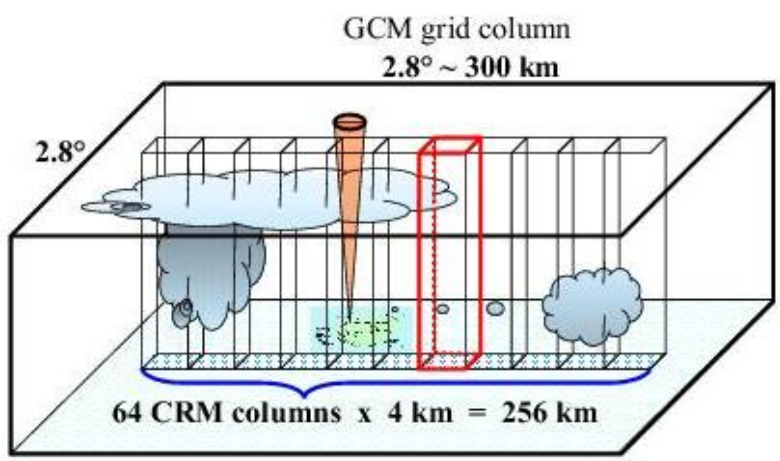
Observations




Khairoutdinov et al. JAS 2005

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…

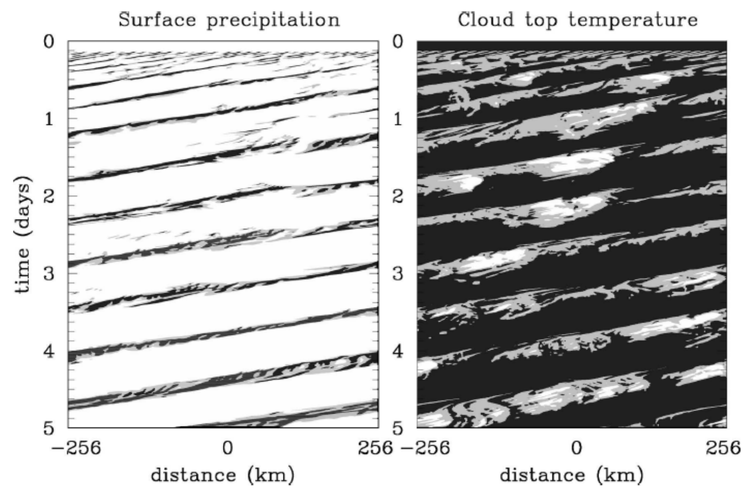


**Comments on "Preliminary Tests of Multiscale Modeling with a Two-Dimensional Framework: Sensitivity to Coupling Methods"**

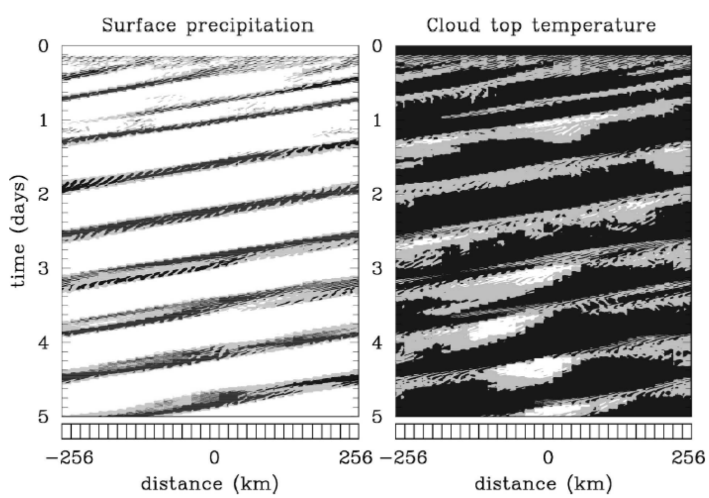
MWR 2006

Wojciech W. Grabowski

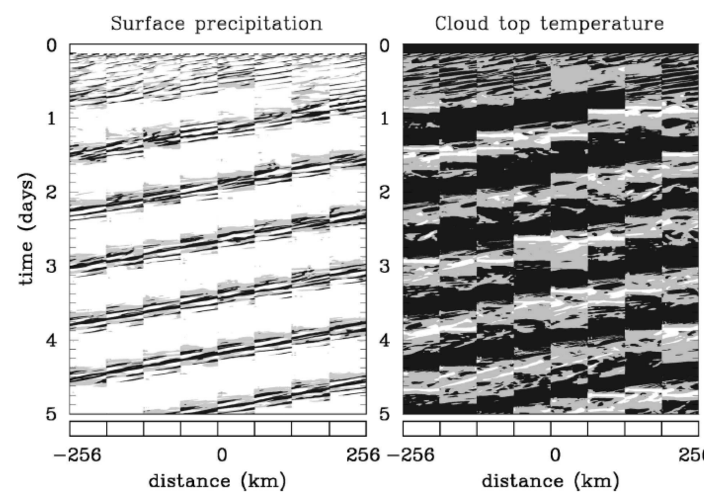
***2D simulations, Δx=2 km***




CRM
(benchmark)

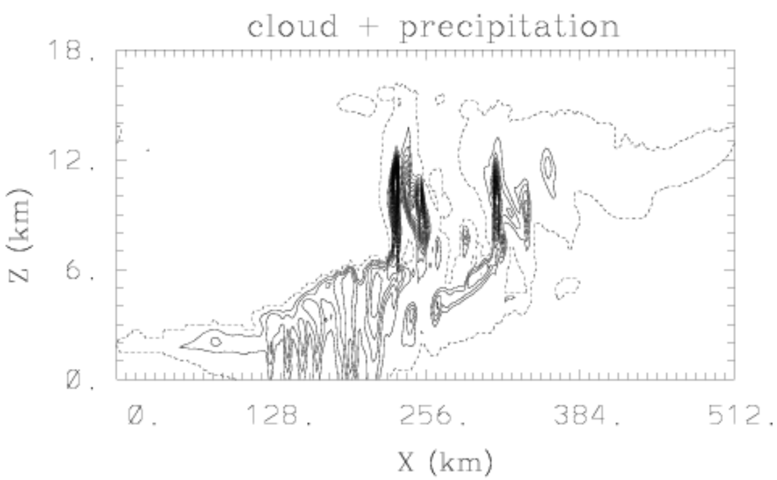



SP with 16 km domains

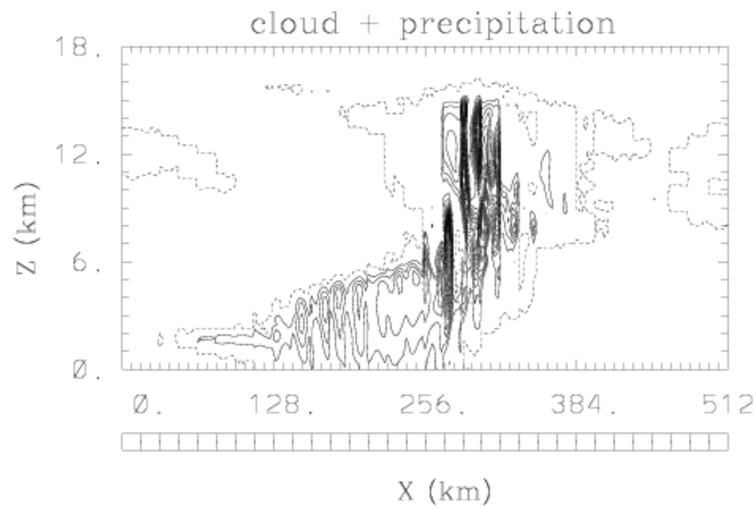



SP with 64 km domains

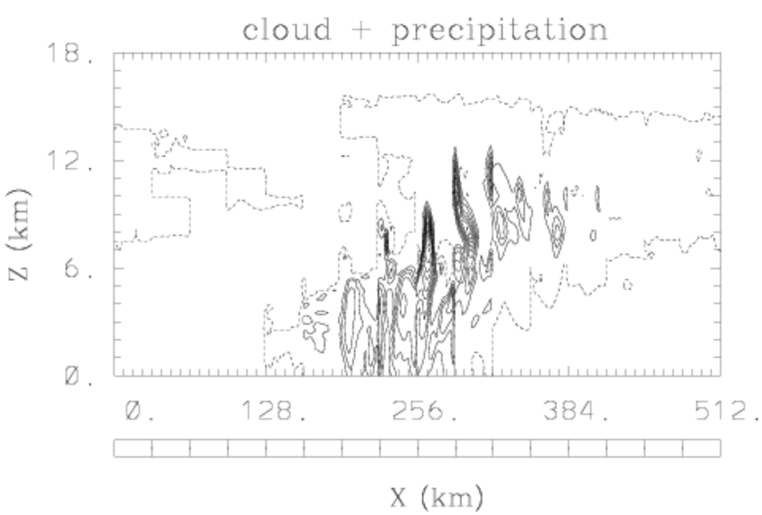
Cloud-resolving simulation (benchmark): Δx=2km



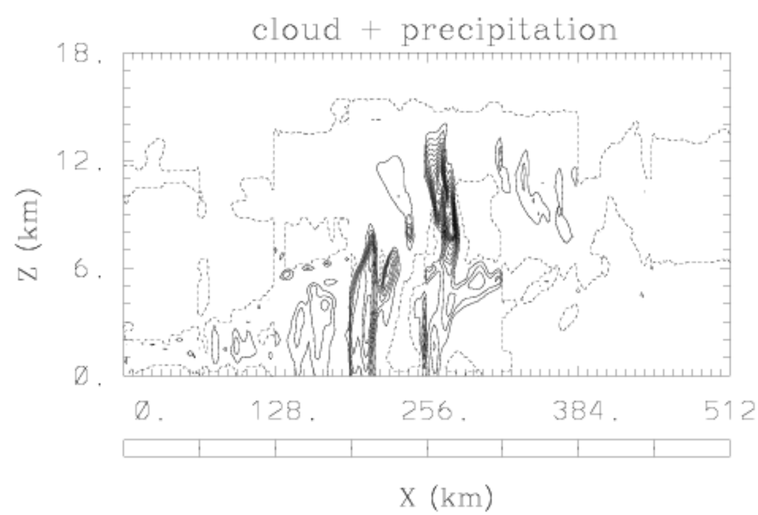

**32 columns with 16-km periodic small-scale models**




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



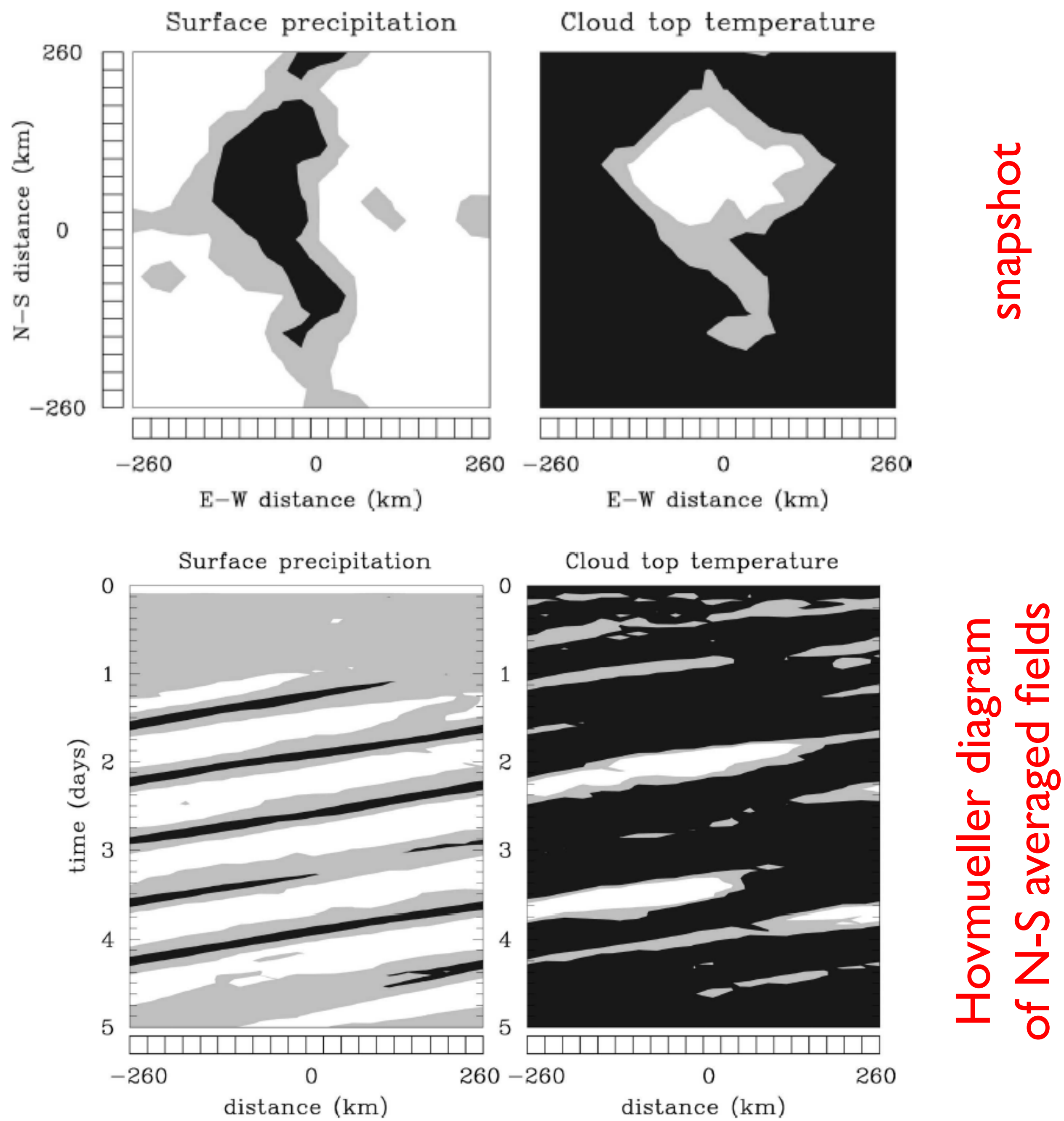

**8 columns with 64-km periodic small-scale models**



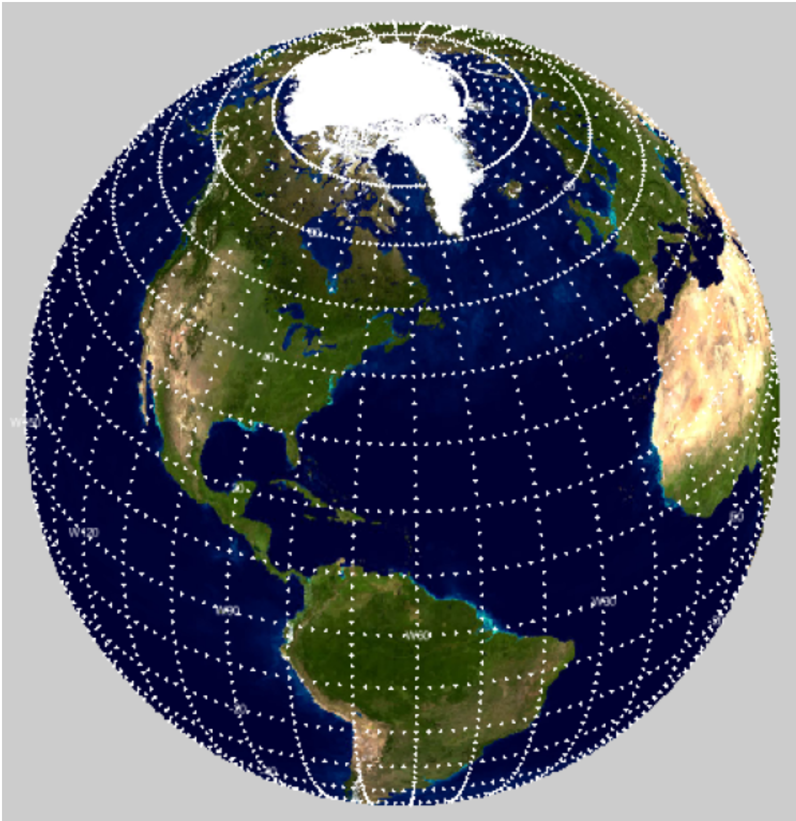
***Natural extension to a 3D outer model:***

***outer model: $\Delta x = \Delta y$=26 km***

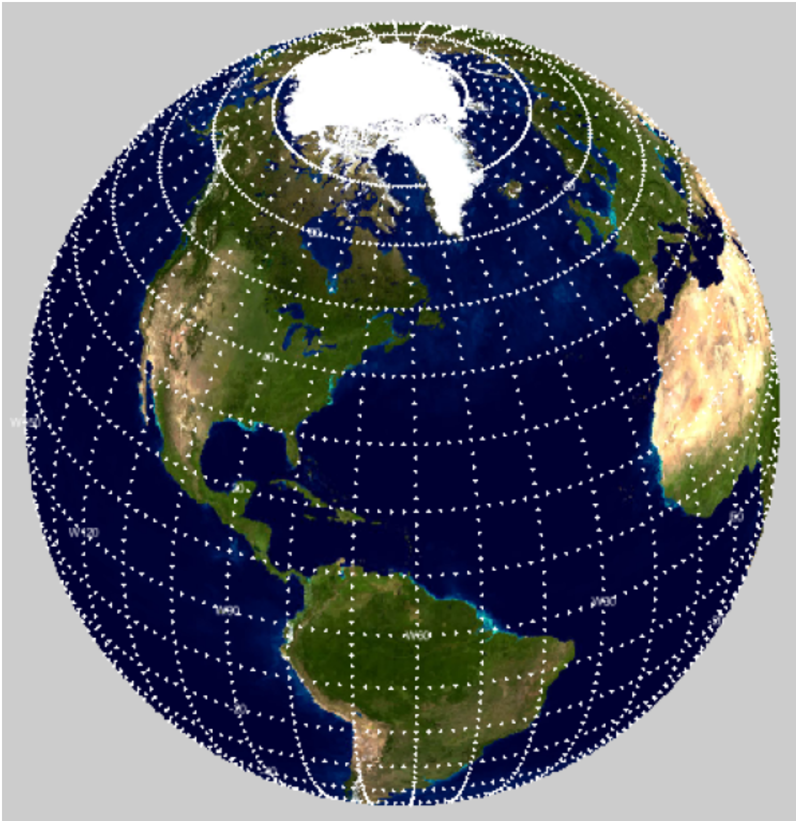
***2D SP models (aligned E-W) with $\Delta x$=2 km***



If the outer model has a horizontal gridlength around a few tens of km, it will faithfully represent mesoscale dynamics, like $20^{th}$ 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 simulated…



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



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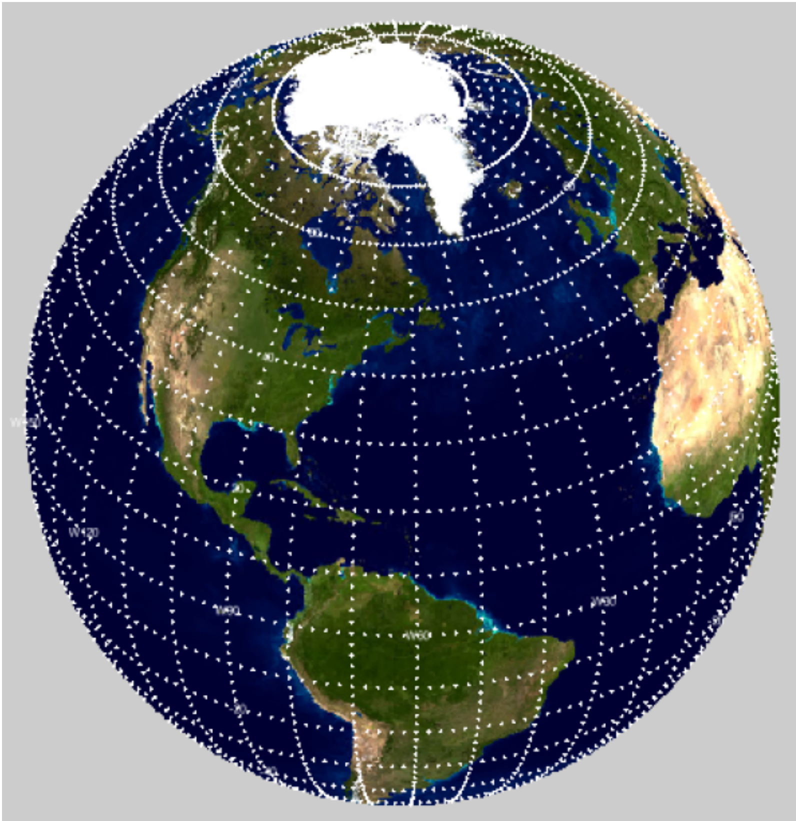
If one would like to cover the surface with LES squares of 20 km by 20 km, there will be around 1.3 million squares…



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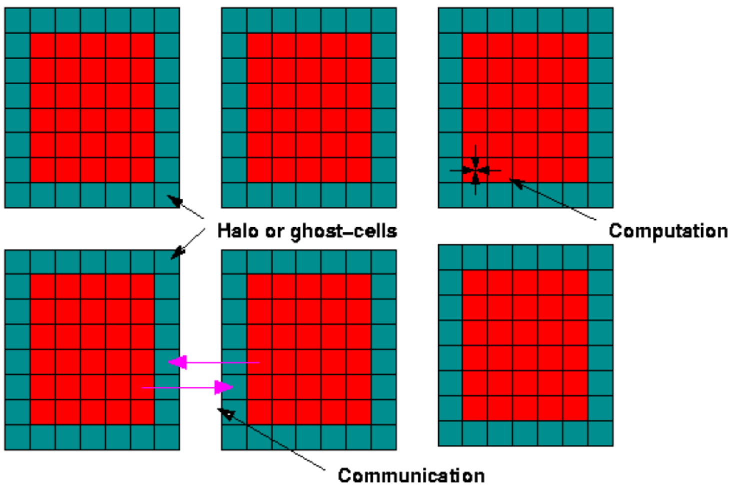
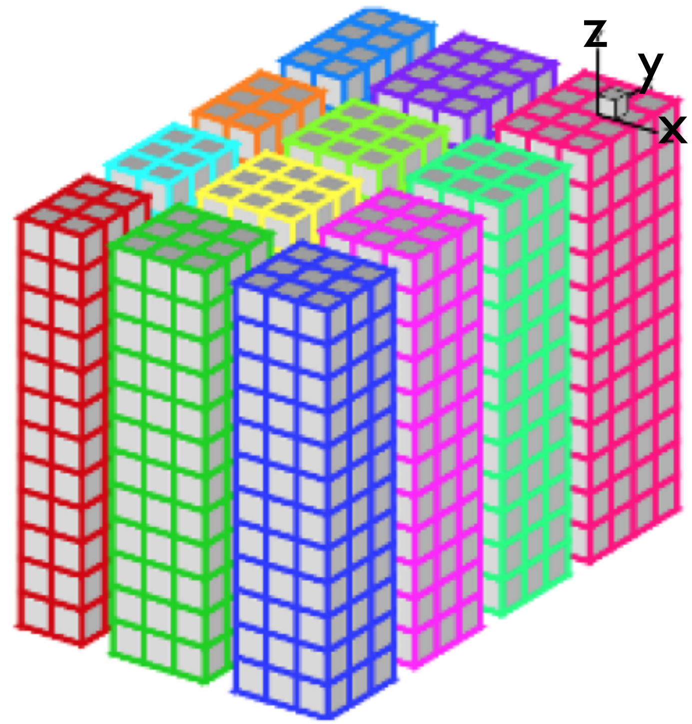
If one would like to cover the surface with LES squares of 20 km by 20 km, there will be around 1.3 million squares… This suggests that one can apply a computer with up to 1.3 million processors for parallel simulations…

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.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2013: Towards multiscale simulationof moist flows with soundproof equations. *J. Atmos. Sci.*, **70**, 3995-4011.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2014: Anelastic and compressible simulation of moist deep convection. *J. Atmos. Sci.,* **71**, 3767-3787.

Smolarkiewicz, P. K., C. Kuehnlein, and N. Wedi, 2014: A consistent framework for discrete integrations of soundproof and compressible PDEs of atmospheric dynamics. *J. Comput. Phys*., **263**, 185–205.

Kurowski, M. J., W. W. Grabowski, P. K. Smolarkiewicz, 2015: Anelastic and compressible simulation of moist dynamics at planetary scales. *J. Atmos. Sci*. (in press).

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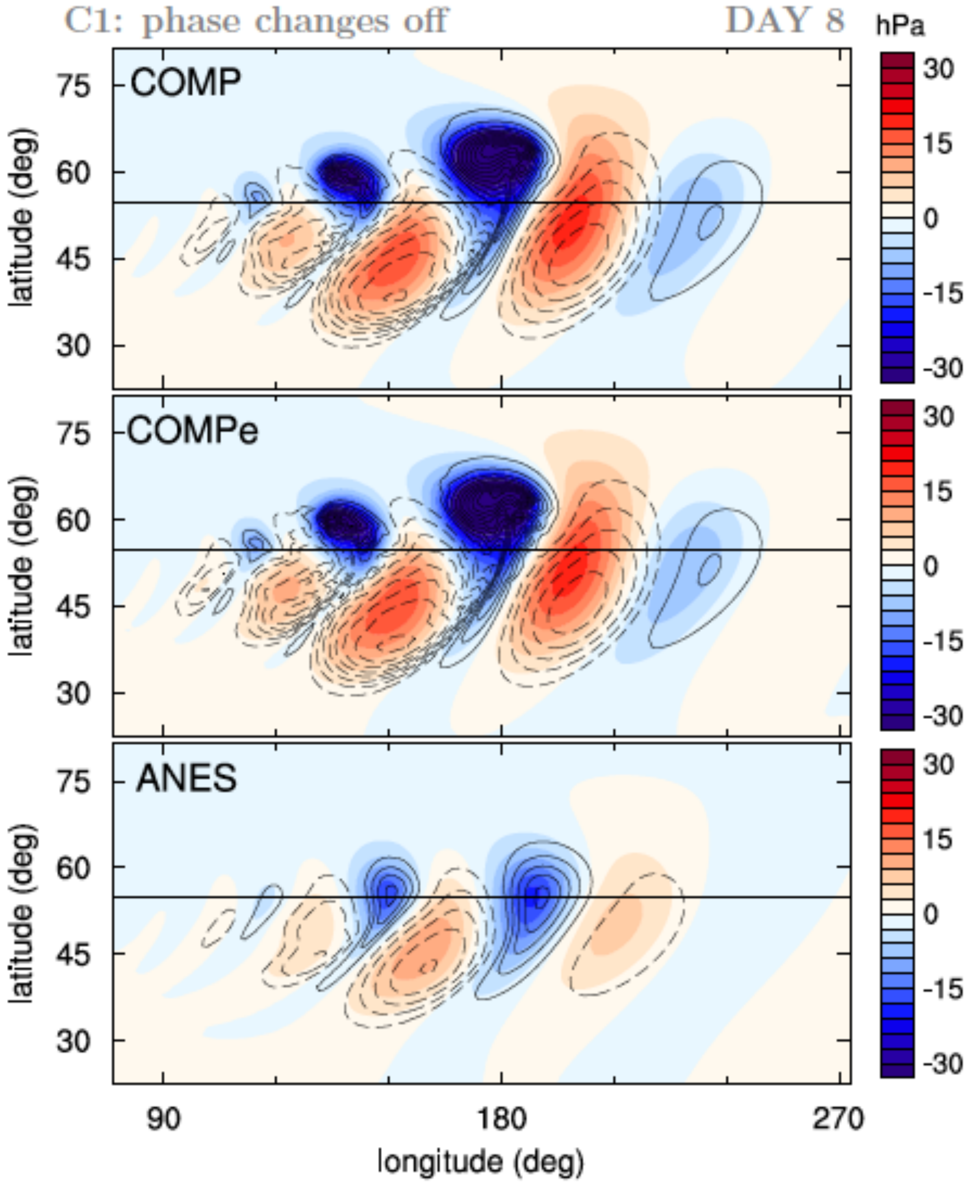
Implicit compressible scheme planned to become
the nonhydrostatic dynamical core of the ECMWF IFS model…

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




Implicit compressible model with $\Delta t = 300$ s

Explicit compressible model with $\Delta t = 2$ s

Anelastic model with $\Delta t = 300$ s

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

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

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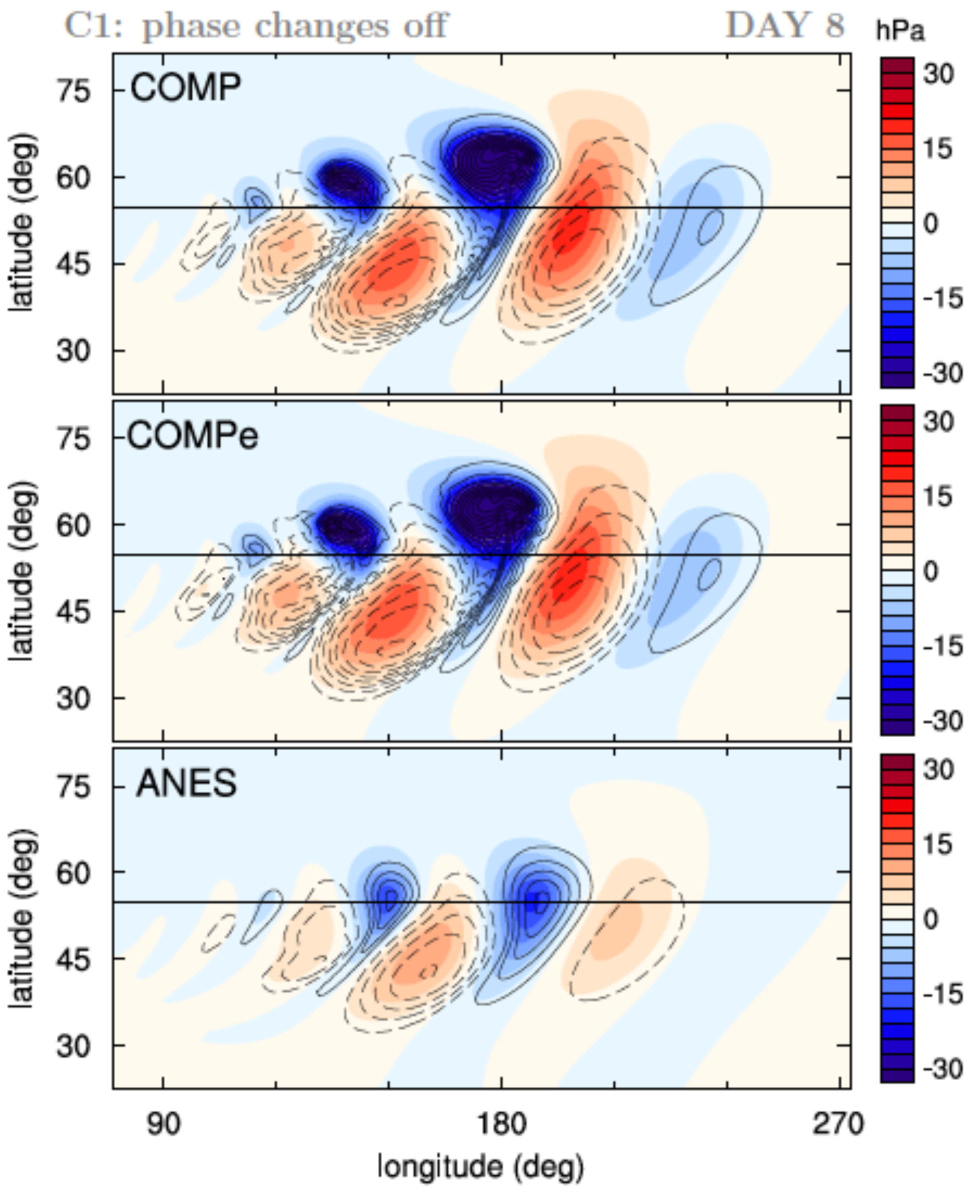


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## Conclusions:

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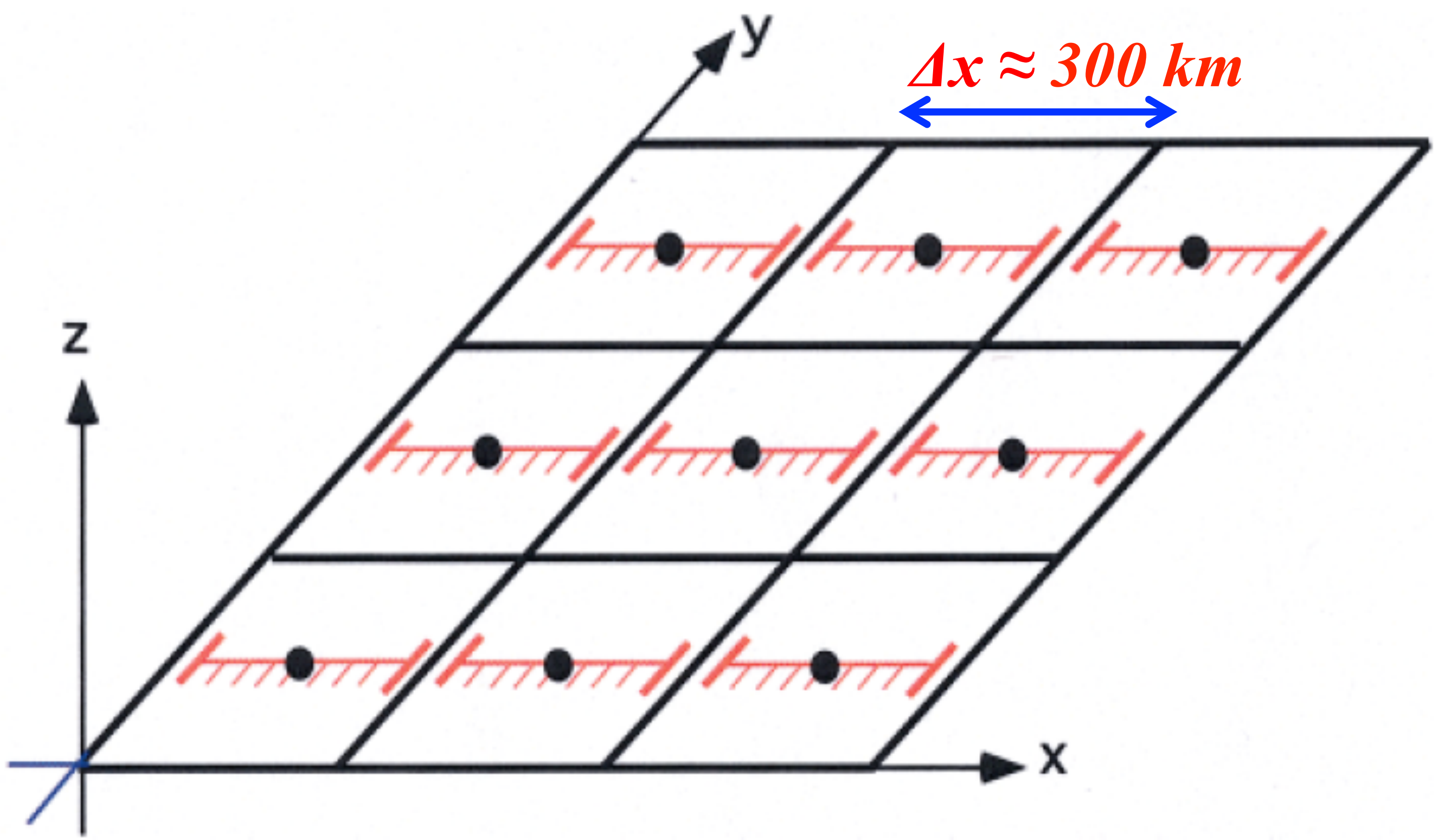
**However, pressure solver in the implicit compressible model (significantly more cumbersome than in the anelastic system, see Smolarkiewicz et al. *JCP* 2014) would need to work really hard when global LES is the target…**

Issues:

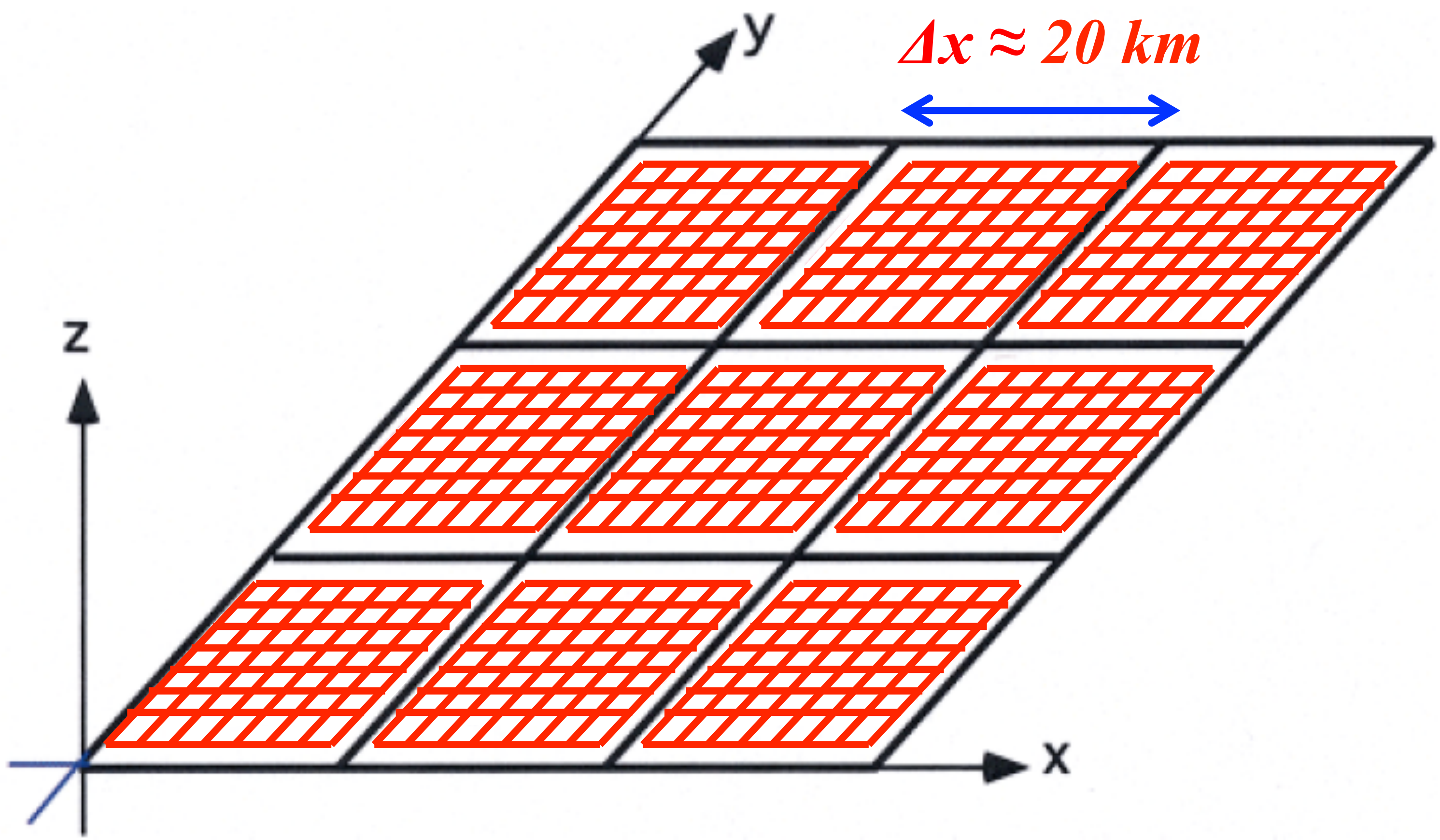
- Parallel processing?
- What equations to use?

SP can help! And can also provide additional benefits…

# Original SP proposal:



# Next generation SP proposal:



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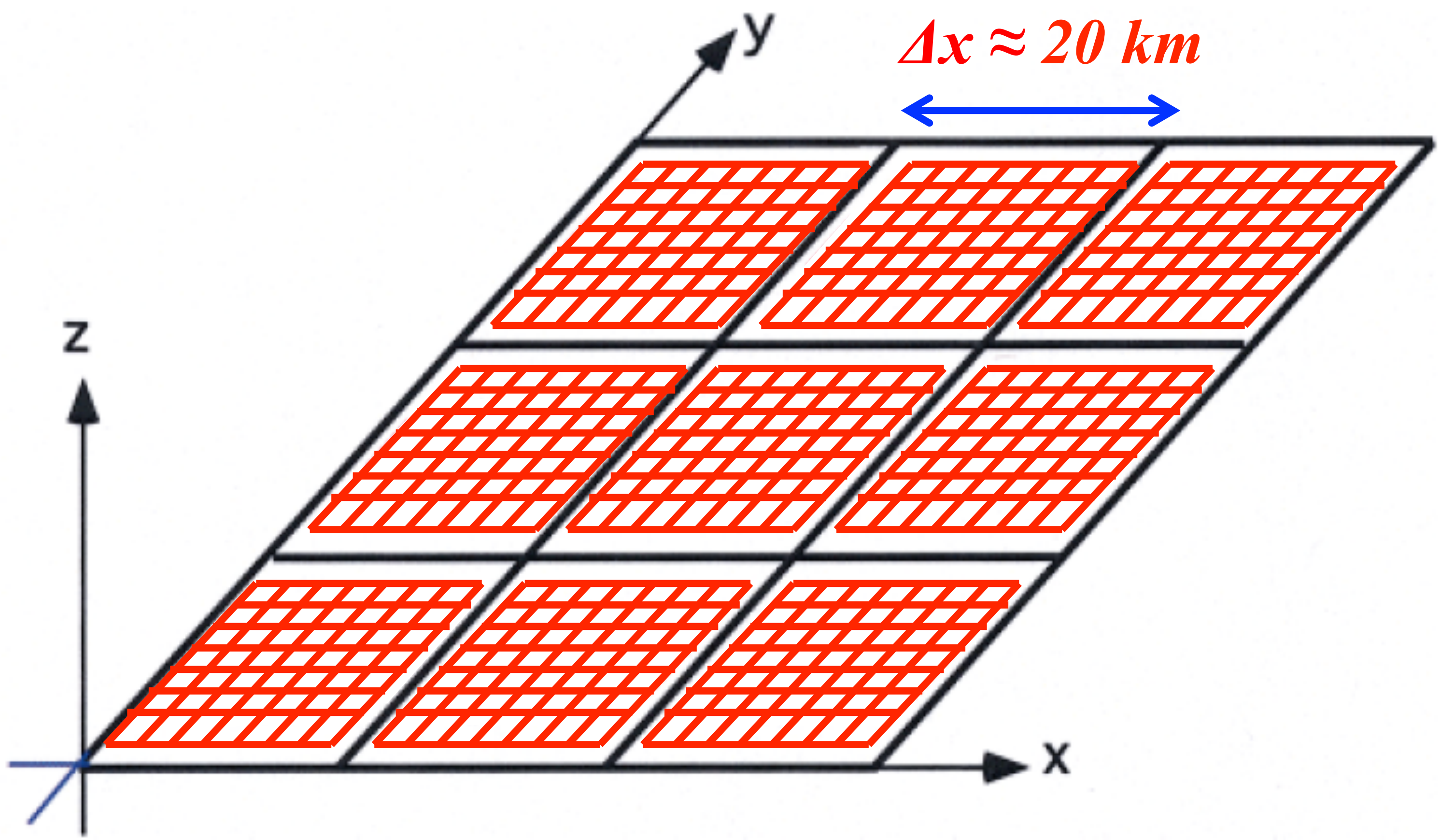


Communication between the outer model and SP models takes place only through the profiles, see Grabowski (*JAS* 2004)

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- 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.

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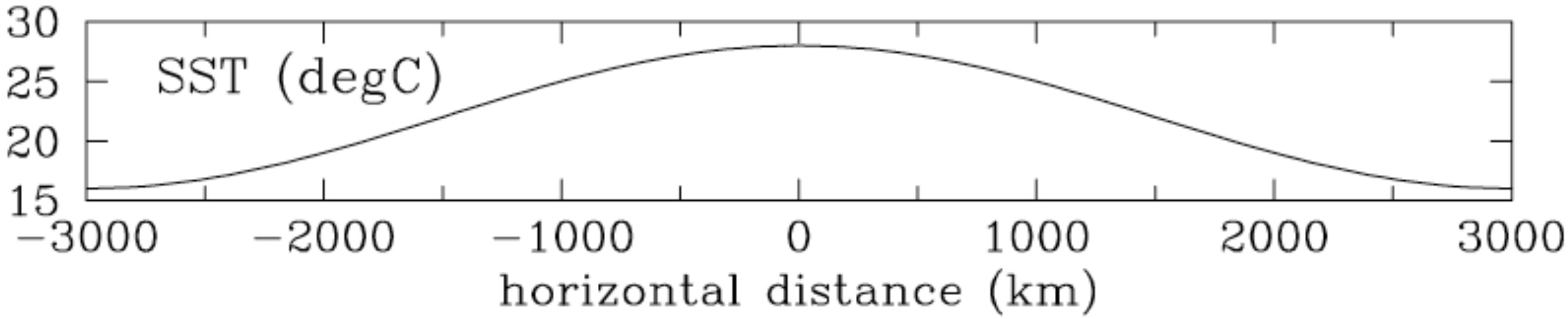
## Illustration: the 2D mock-Hadley circulation

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

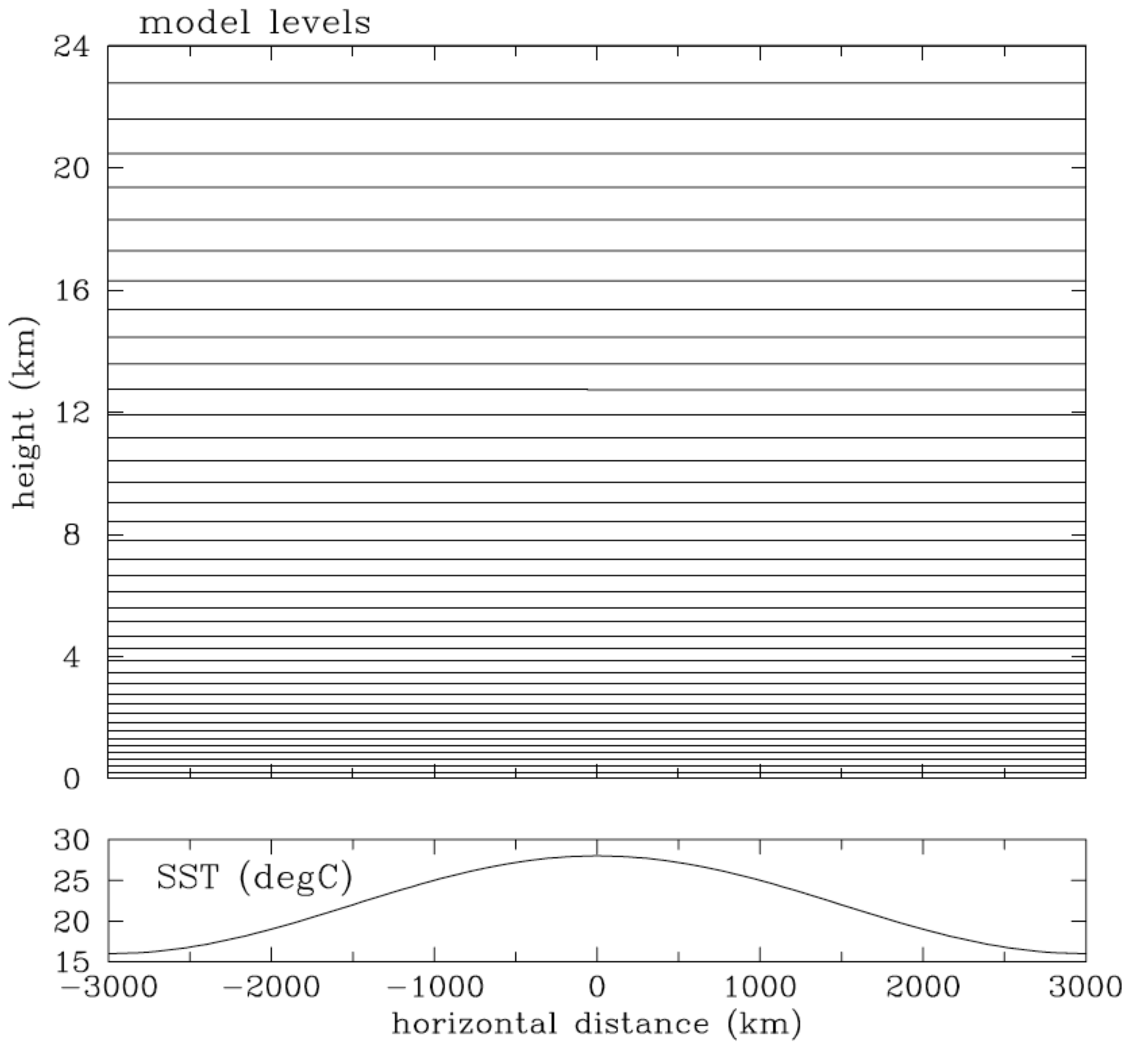
SST: 16 to 28 degC, varying as cos(distance)

No mean flow

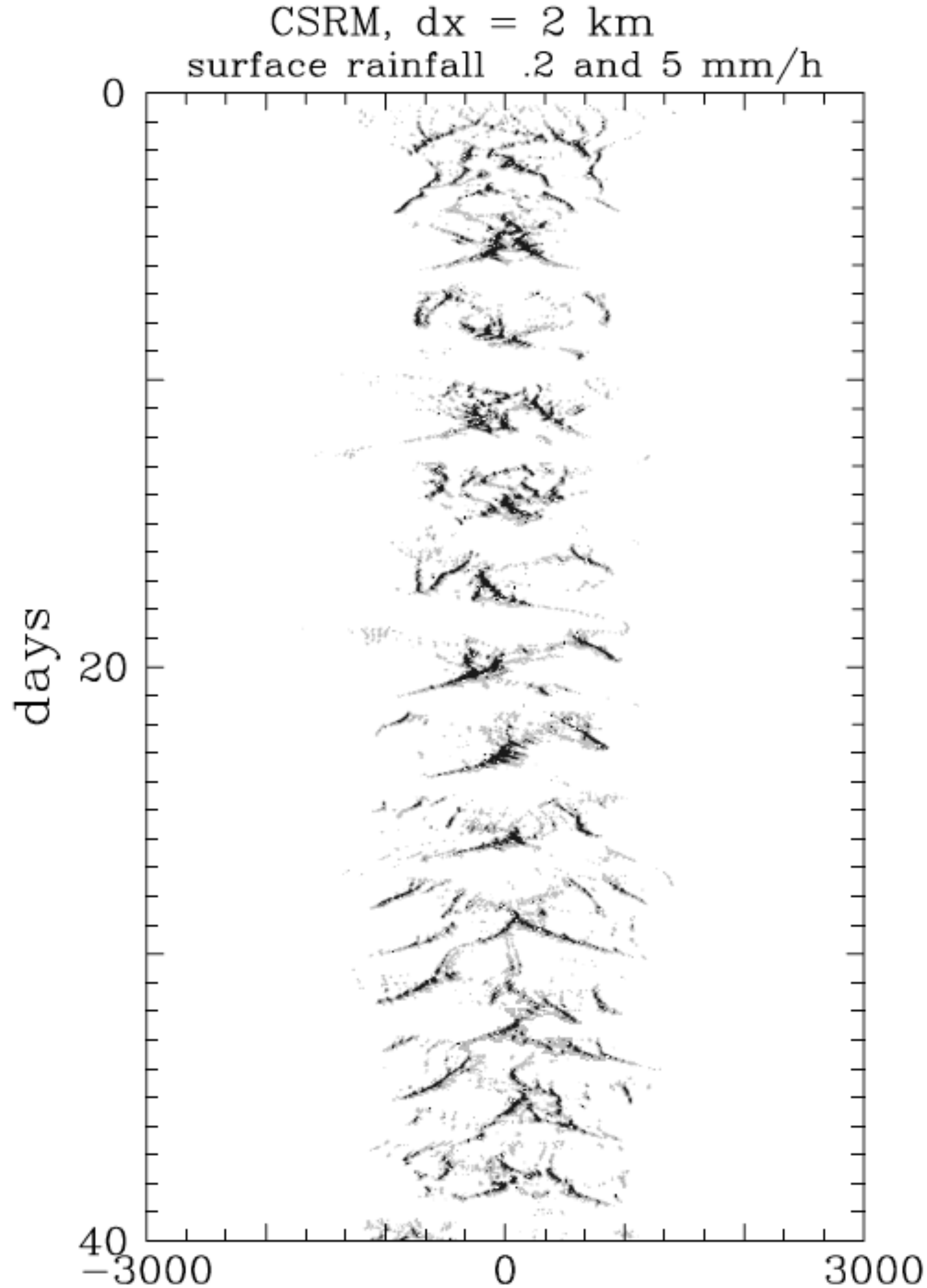
Prescribed radiative cooling: 1.5 K/day below 12 km, decreasing linearly to zero at 15km

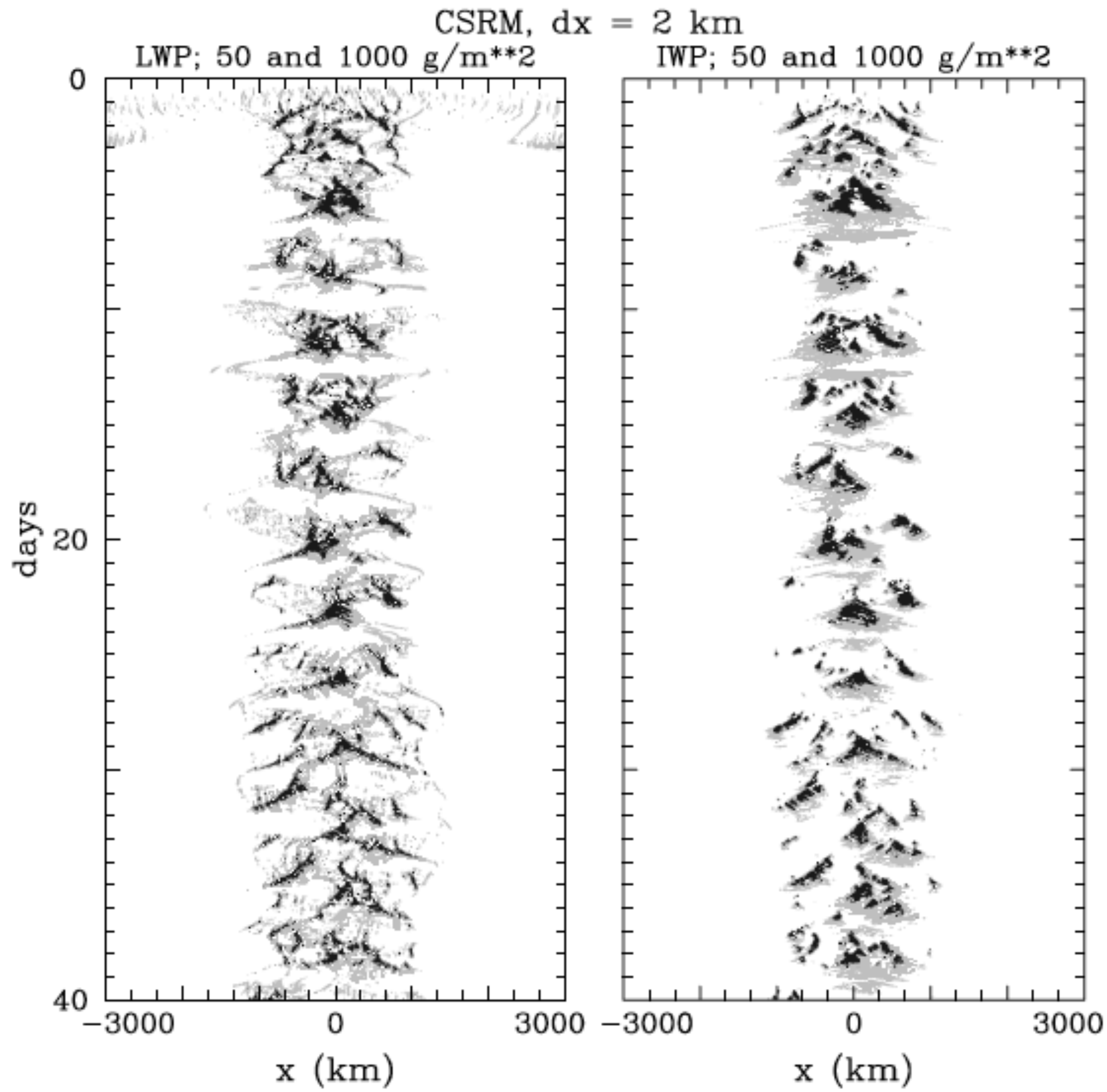
No SGS model in either outer or SP models (implicit LES)

Simple formulation of surface sensible and latent heat fluxes

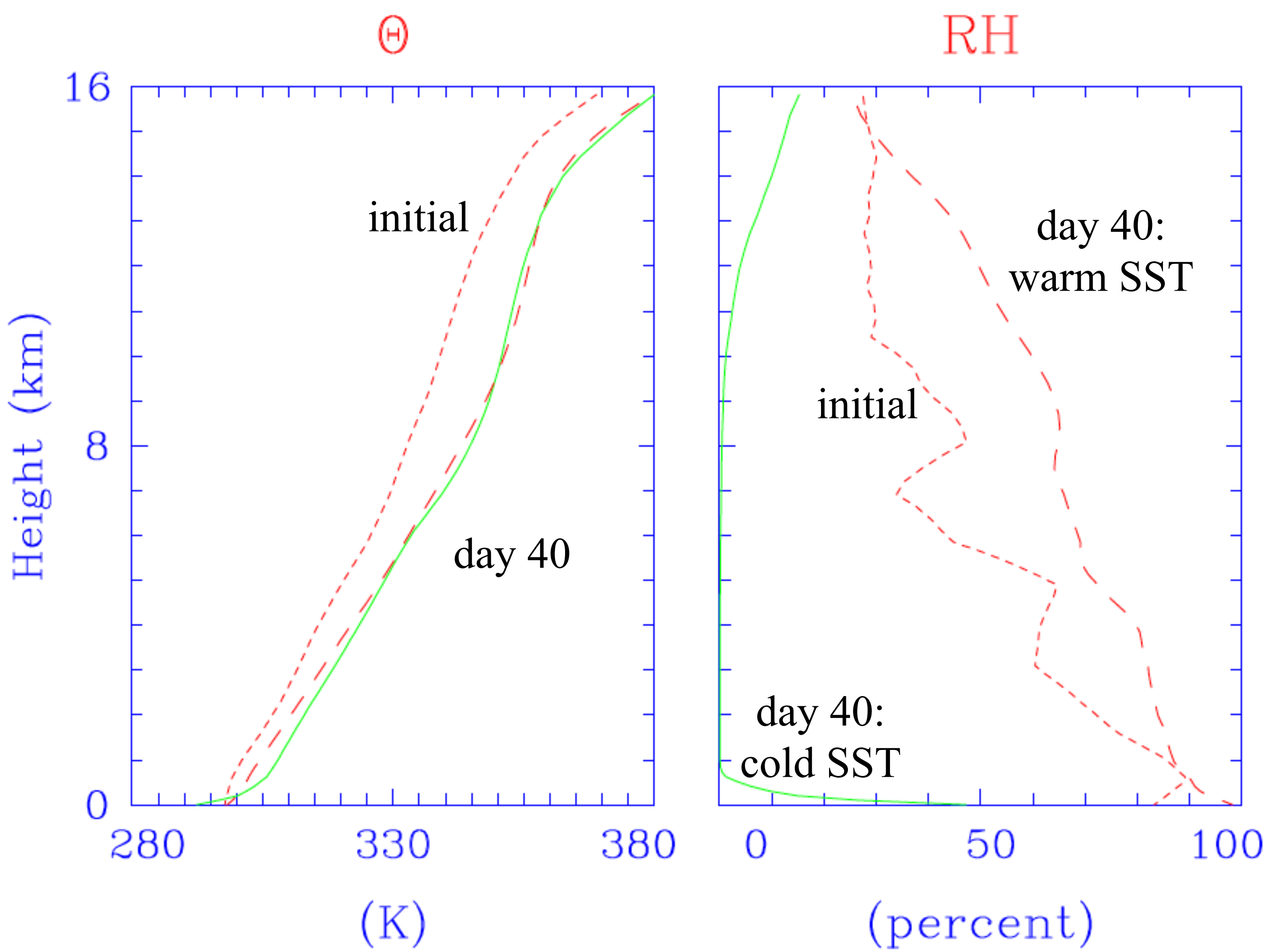


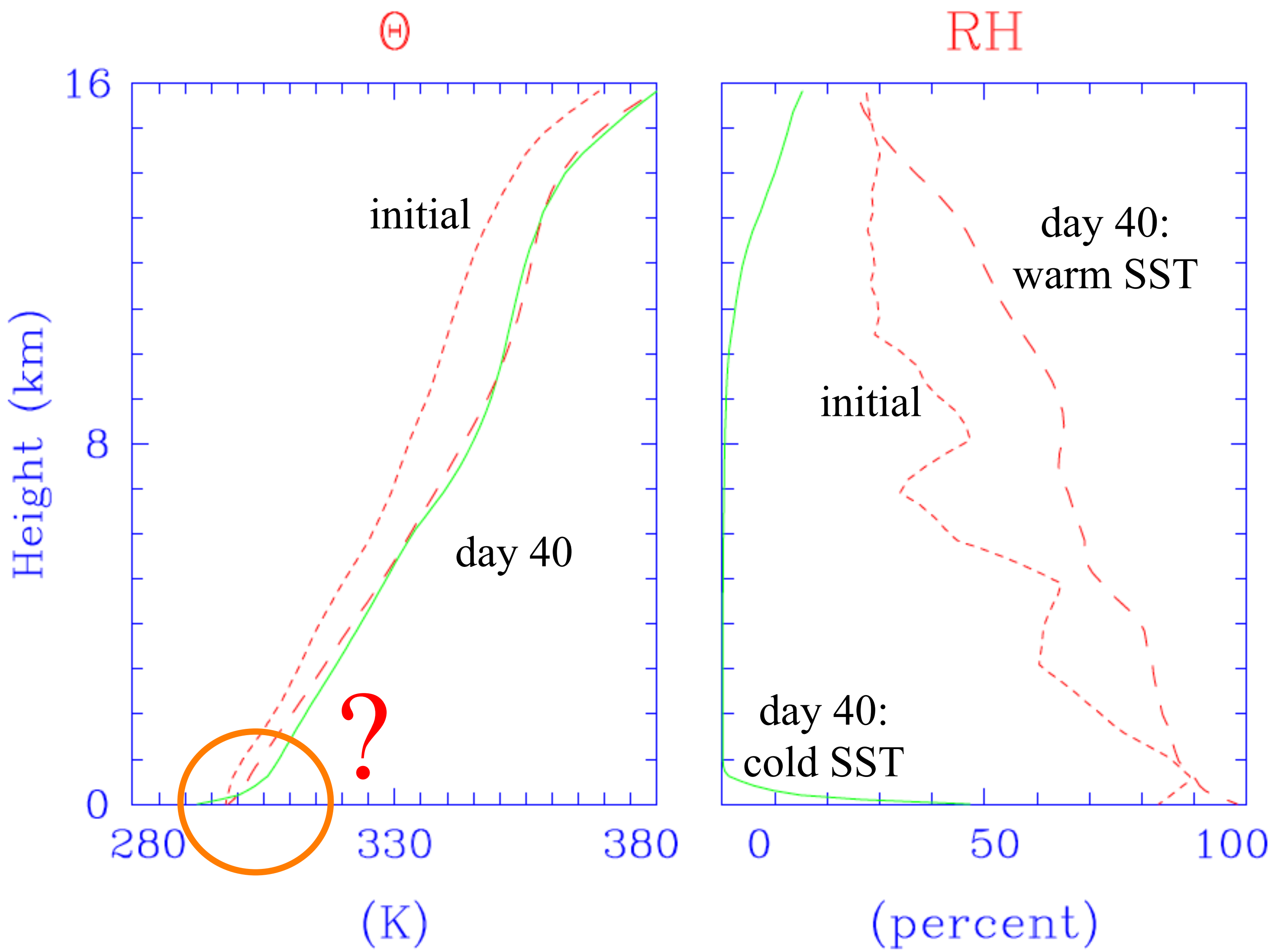

***Horizontal domain and vertical grid for CRM simulation, Δx=2 km, 3000 points in the horizontal, 81 levels.***

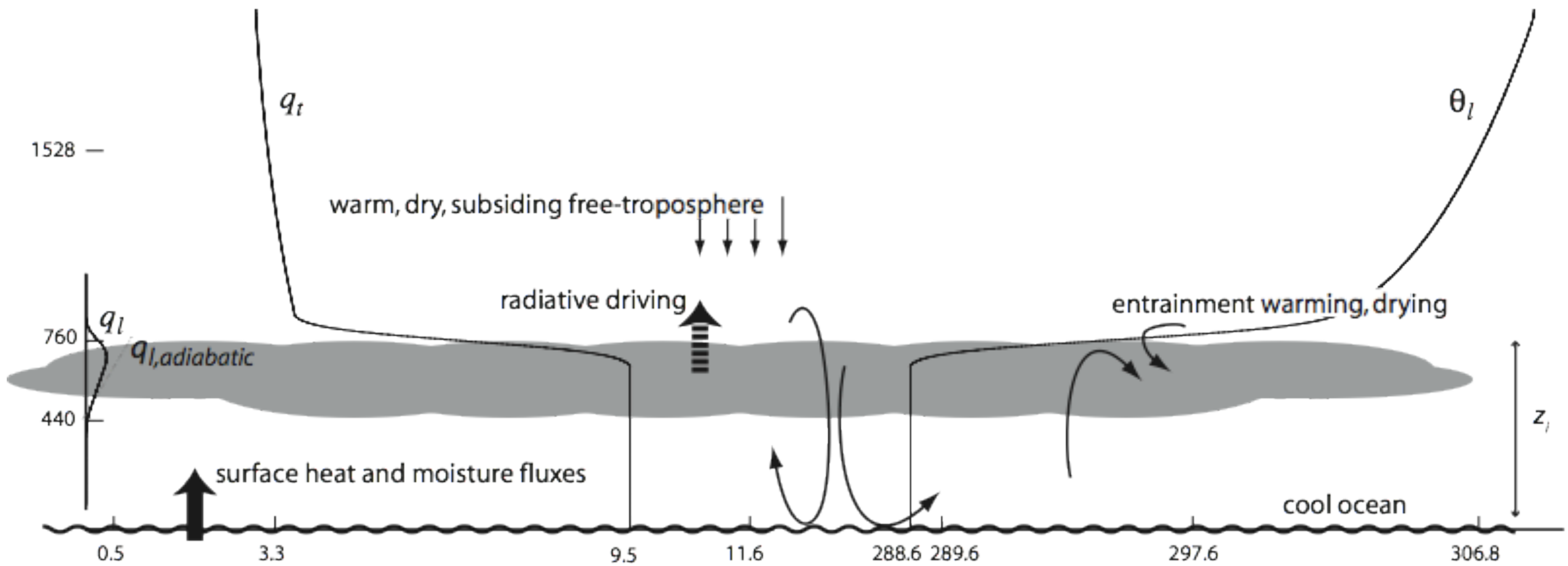

CSRM, dx = 2 km
surface rainfall .2 and 5 mm/h
0
20
40
days
−3000
0
3000



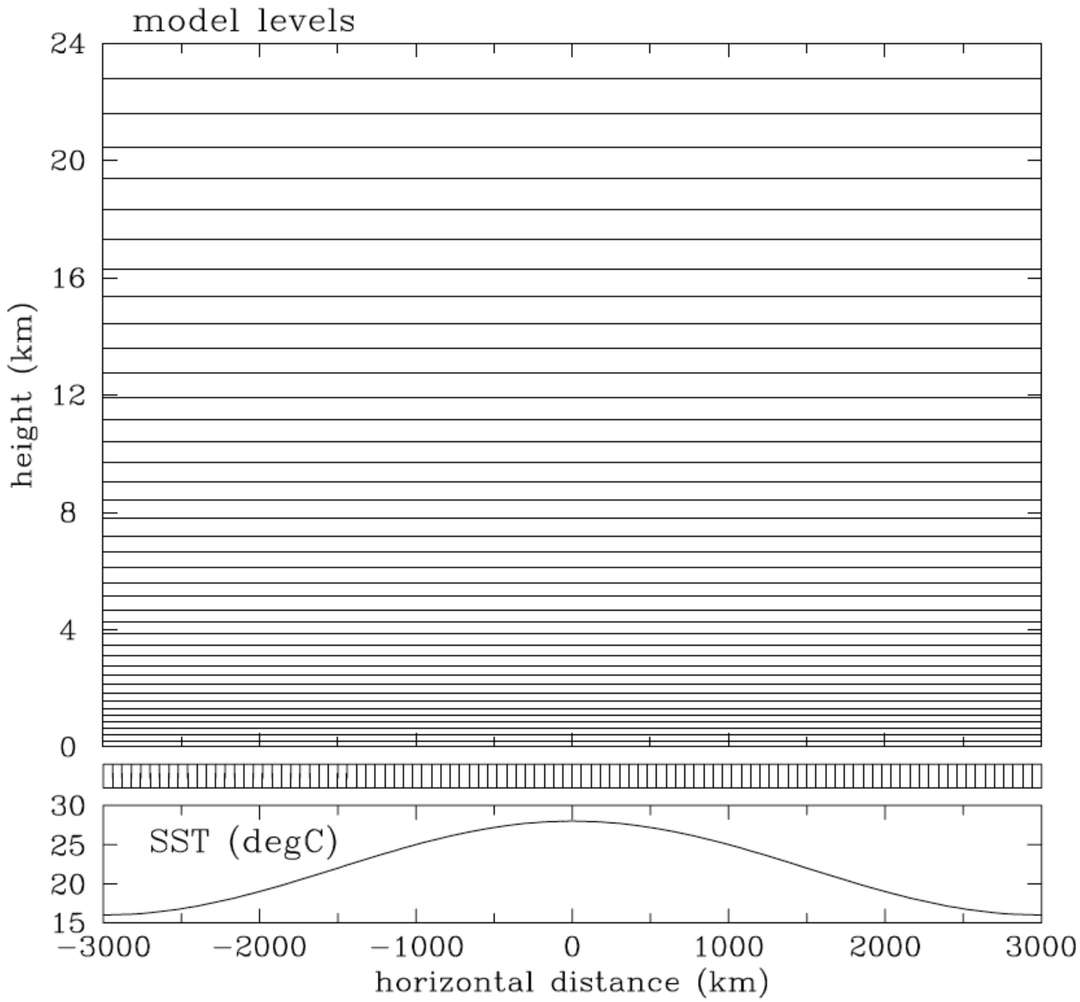
CSRM, dx = 2 km
LWP; 50 and 1000 g/m**2
IWP; 50 and 1000 g/m**2
days
0
20
40
−3000
0
3000
x (km)
−3000
0
3000
x (km)


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

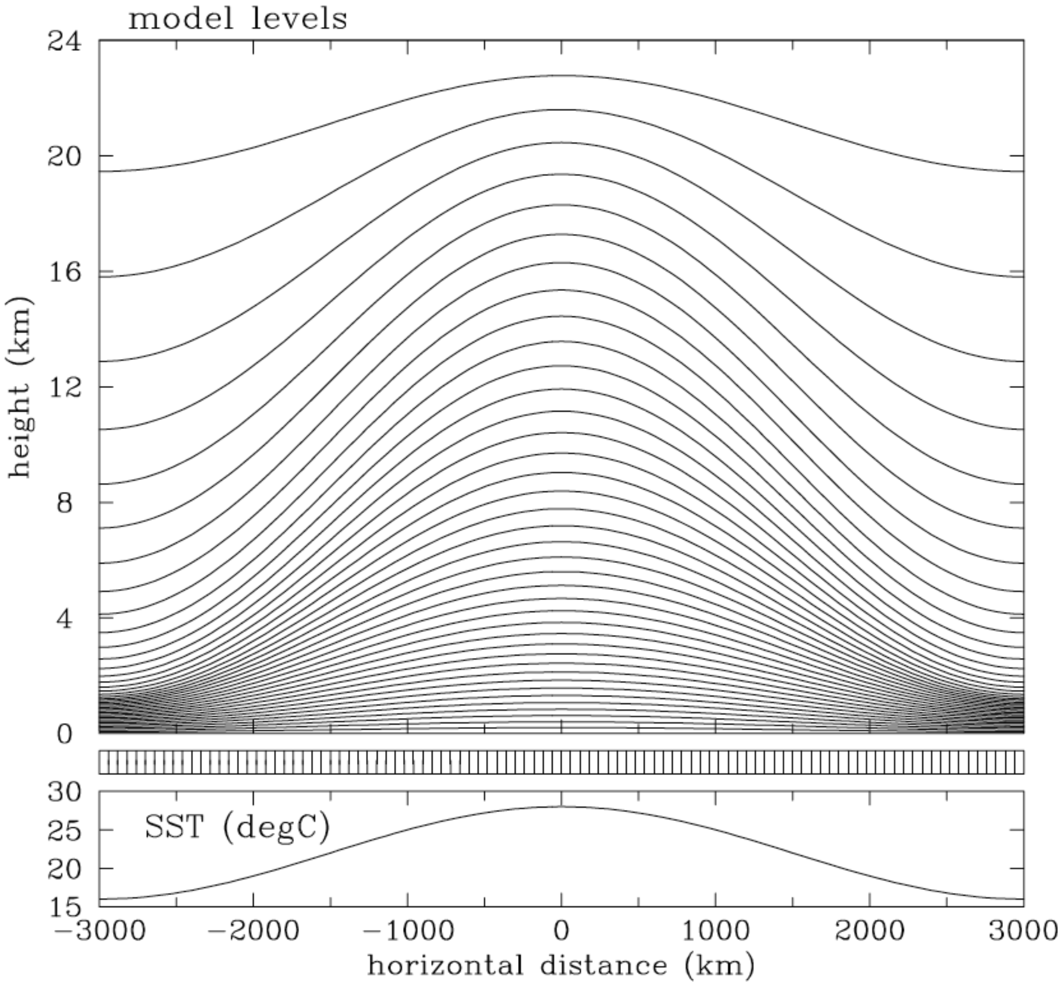



## Traditional SP model:

***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.***

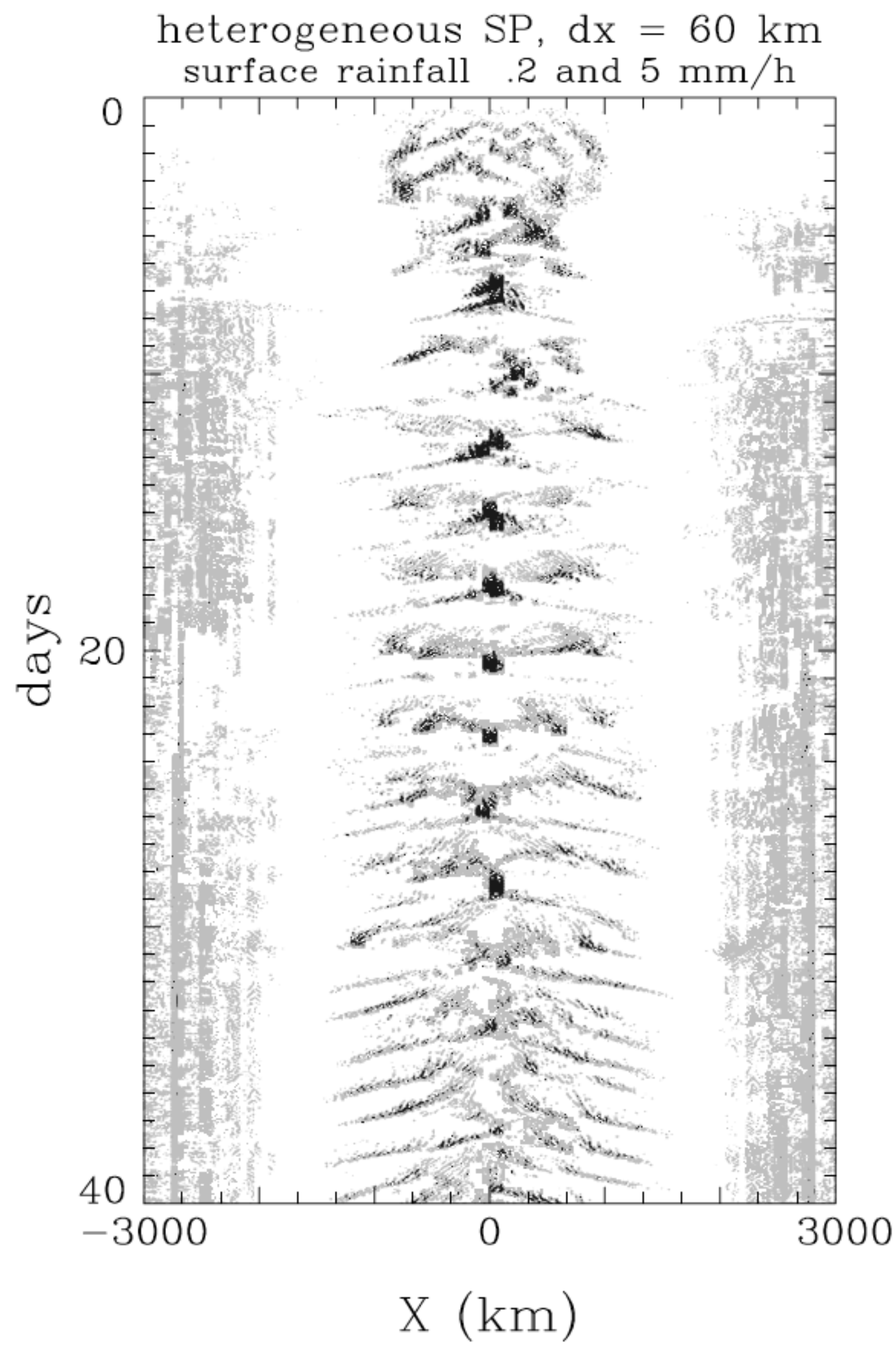
***SP models at high SST:***

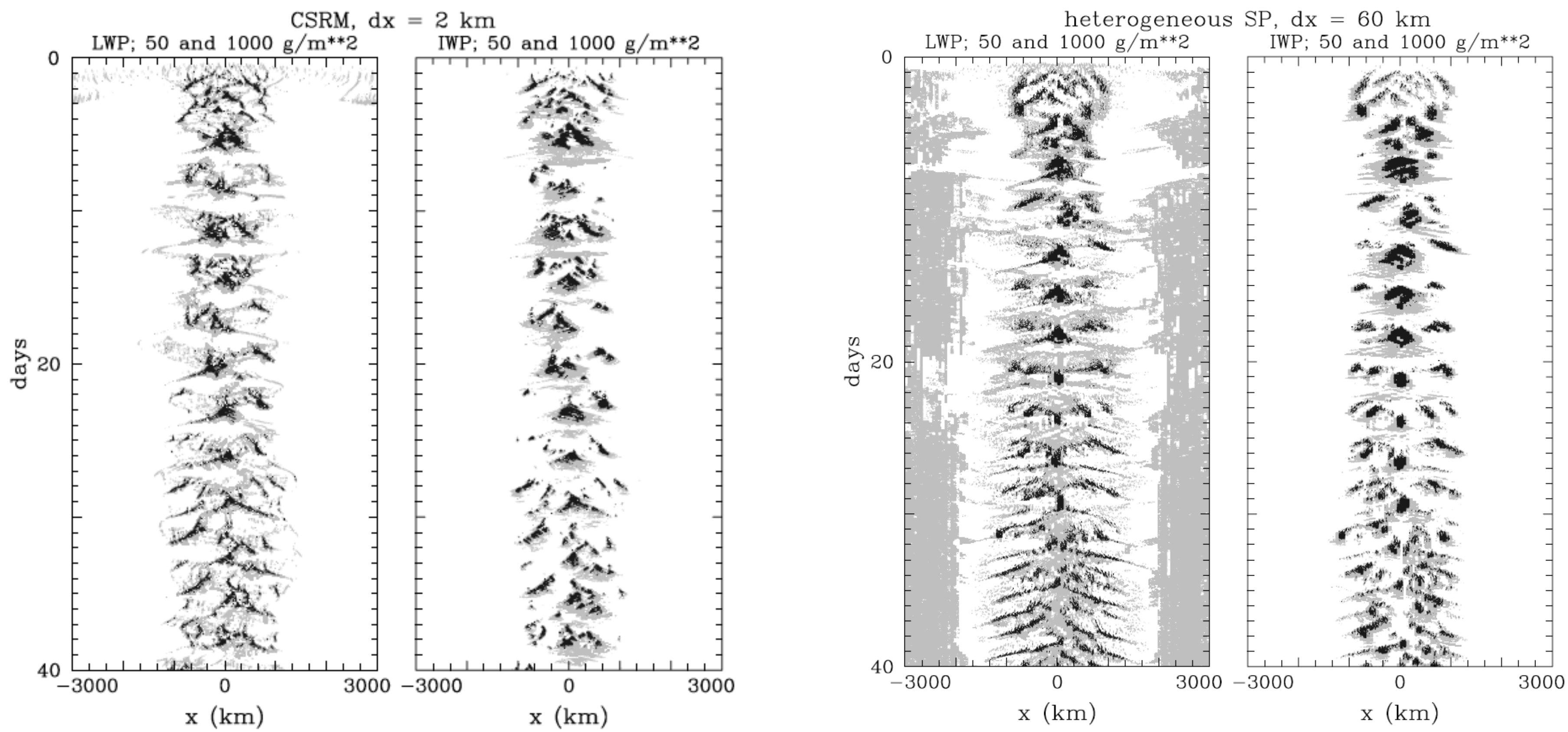
***CRM: Δx=2 km, the same vertical grid as the outer model.***

***SP models at low SST:***

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

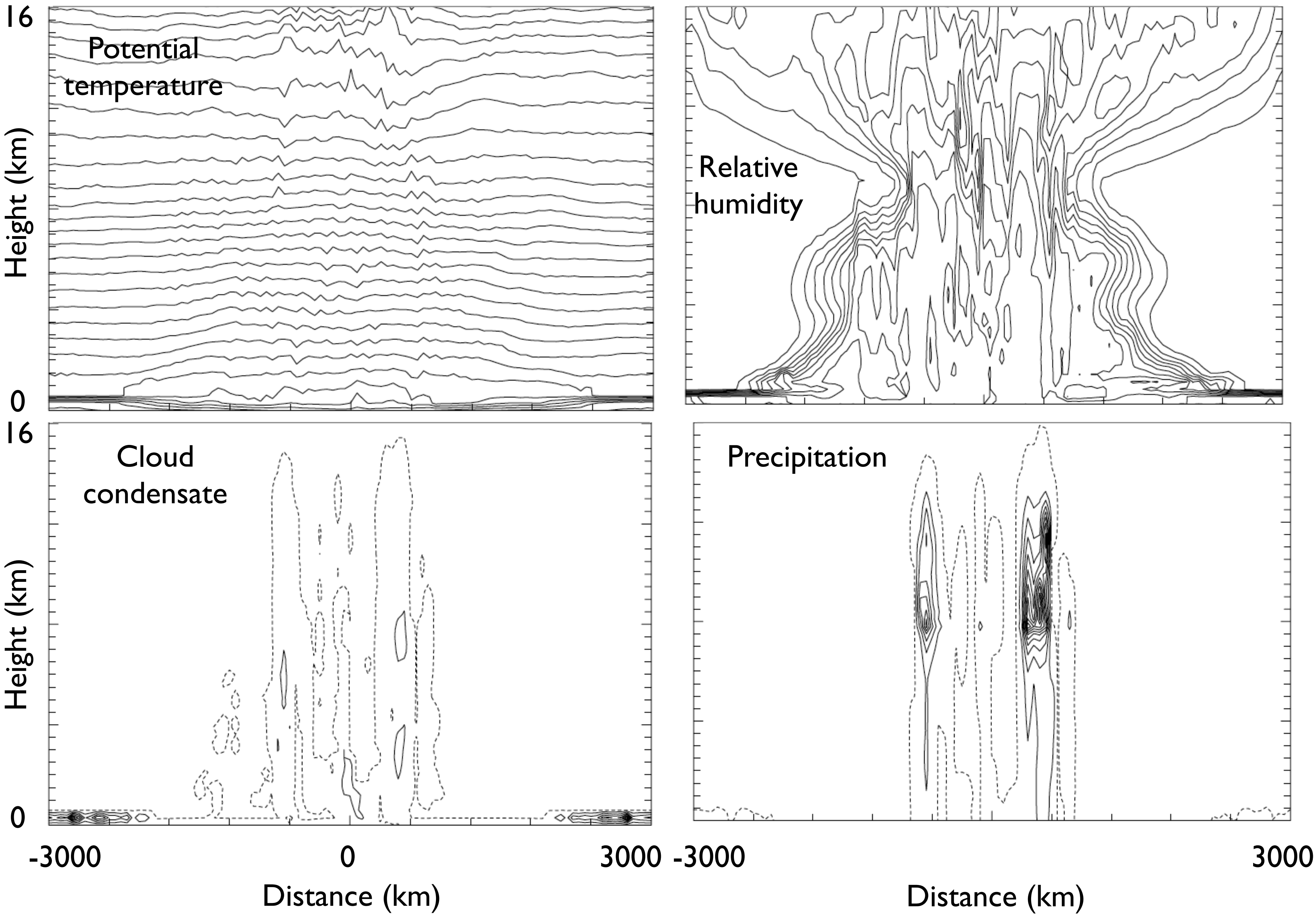
***Linear interpolation of profiles between outer and SP models.***


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, global LES extending global convection-permitting models (such as the Japanese NICAM or German ICON) 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, cntd:**

**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 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. The SP system should run efficiently on massively parallel systems based on GPUs.**