FRSGC Frontier Research System for Global Change

Development of the nonhydrostatic icosahedral atmospheric model in Frontier Research System for Global Change

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The Integrated Modeling Research Program

Frontier Research System for Global Change

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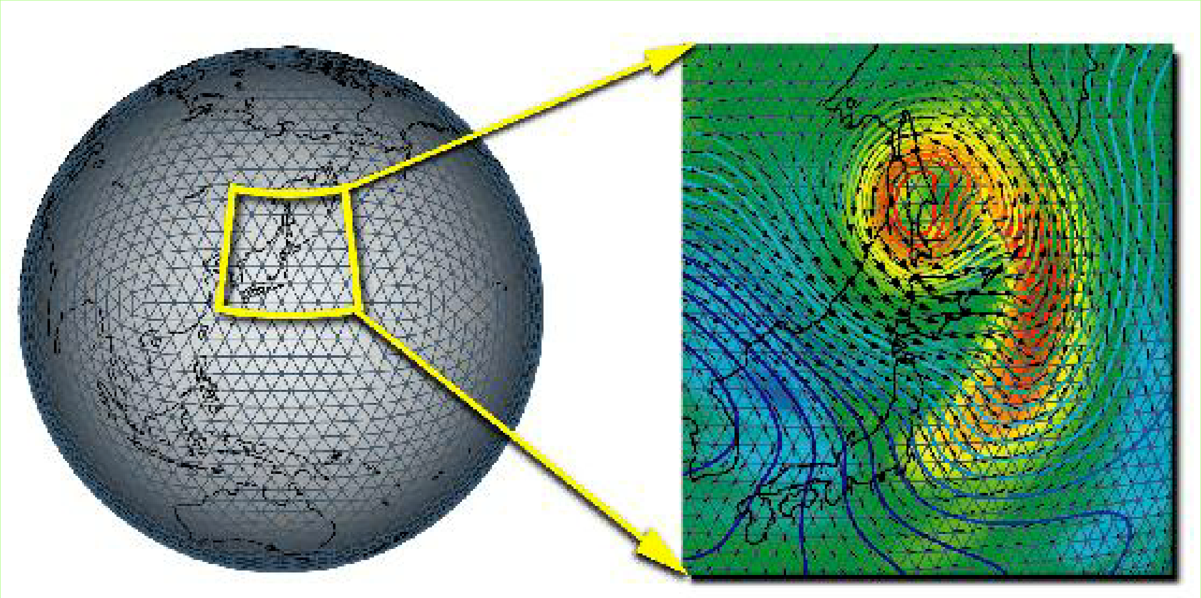
Contents

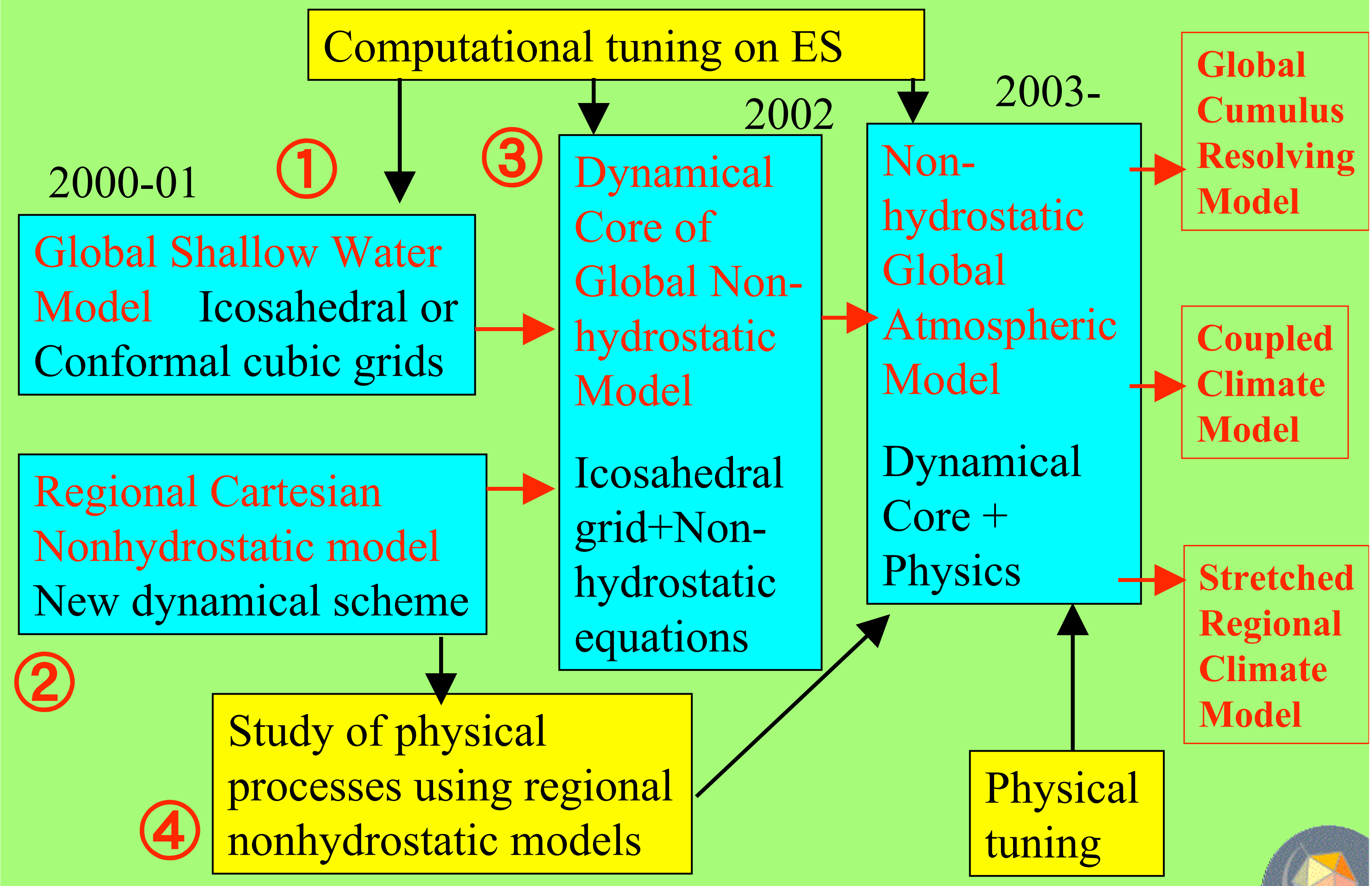
Nonhydrostatic
ICosahedral
Atmospheric
Model
(NICAM)



Introduction

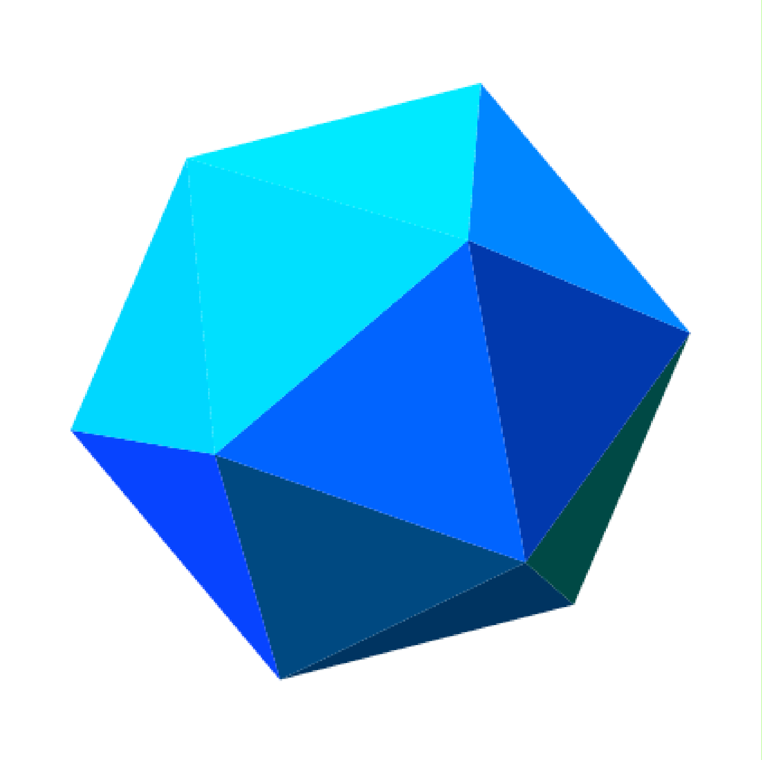
- **Mission**
  - **Development of a global cloud resolving model**
    - **A few km in horizontal directions, a few 100m in vertical direction**
    - **No need of cumulus parameterization**
  - **Use of the Earth Simulator**
  - **Climate study**
- **Strategies of development**
  - **Quasi-uniform grid: the icosahedral grid (CSU, DWD, MPI,…)**
    - **Spectral method is inefficient in high resolution simulations.**
      - **Legendre transformation**
      - **Massive data transfer between computer nodes**
    - **The latitude-longitude grid point method has the pole problem.**
      - **Severe limitation of time interval by the CFL condition.**
      - **Inhomogeneous near the poles.**
  - **Non-hydrostatic equations: a new conservative scheme**
  - **Physics suitable for the fine mesh global model**

Development procedure

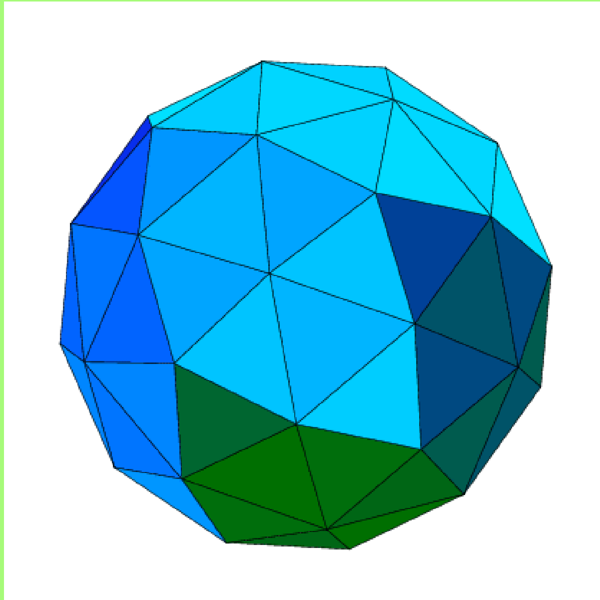


1. Icosahedral grid modeling

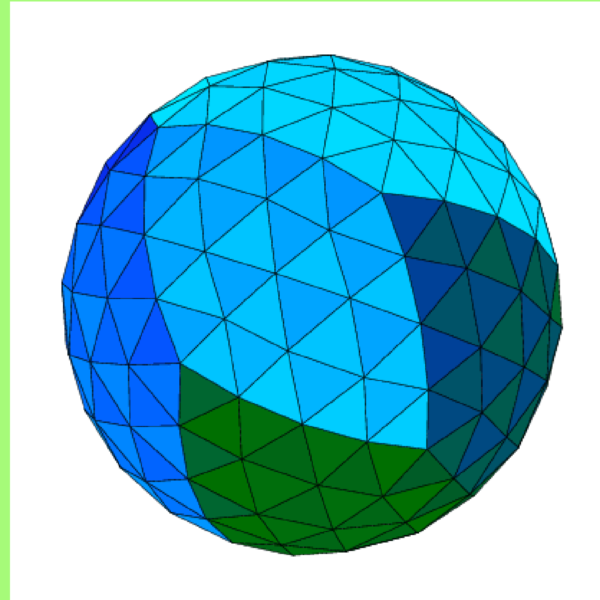
- Grid generation
- Spring grid
- Stretched grid



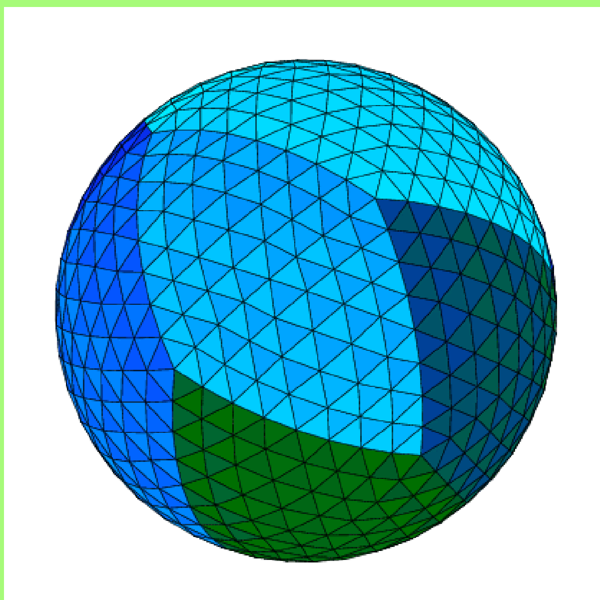
glevel-1



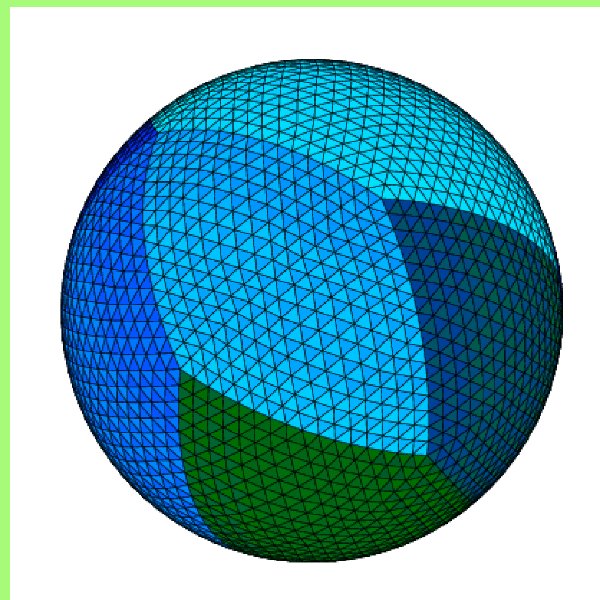
glevel-2

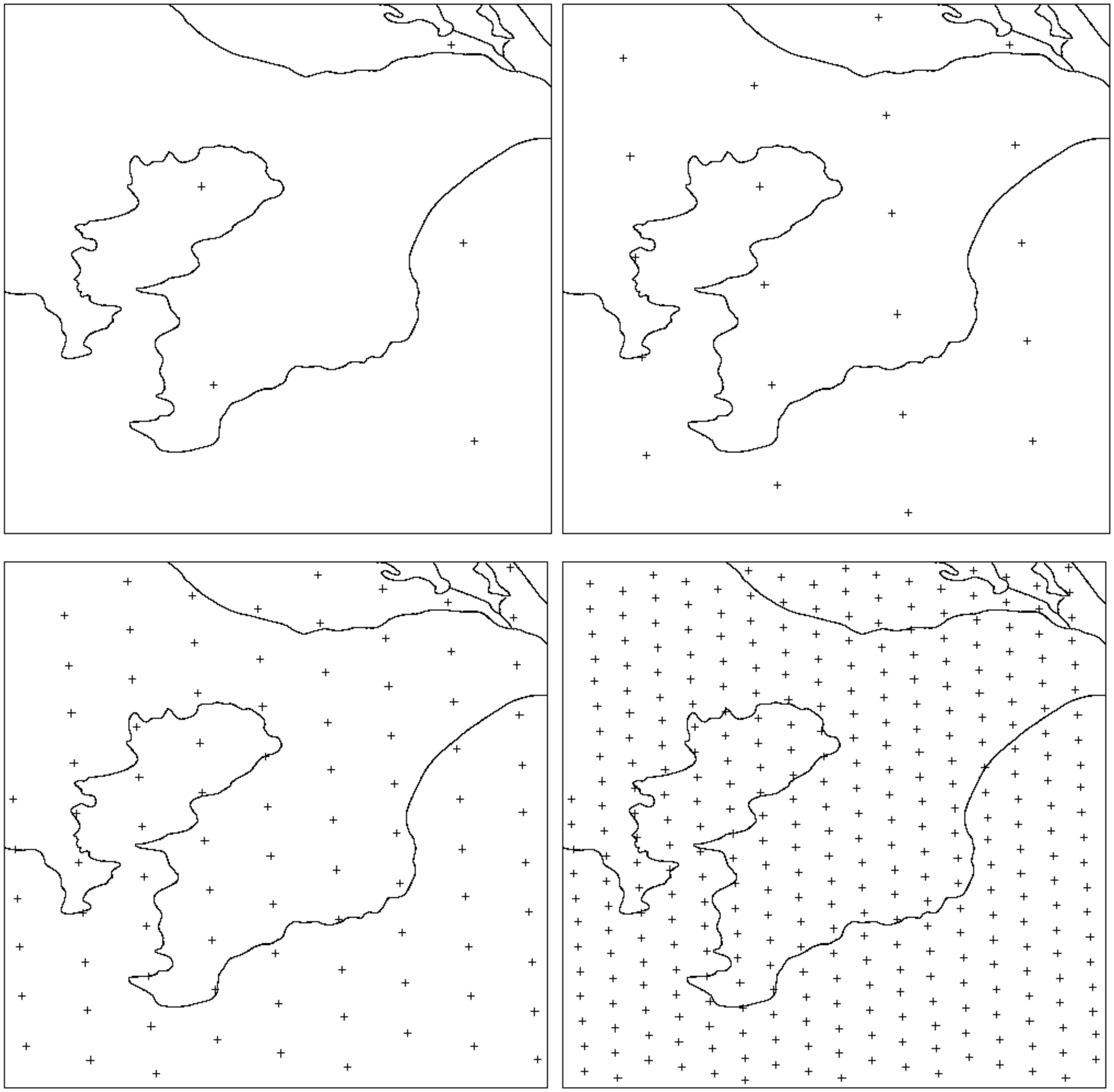


glevel-3



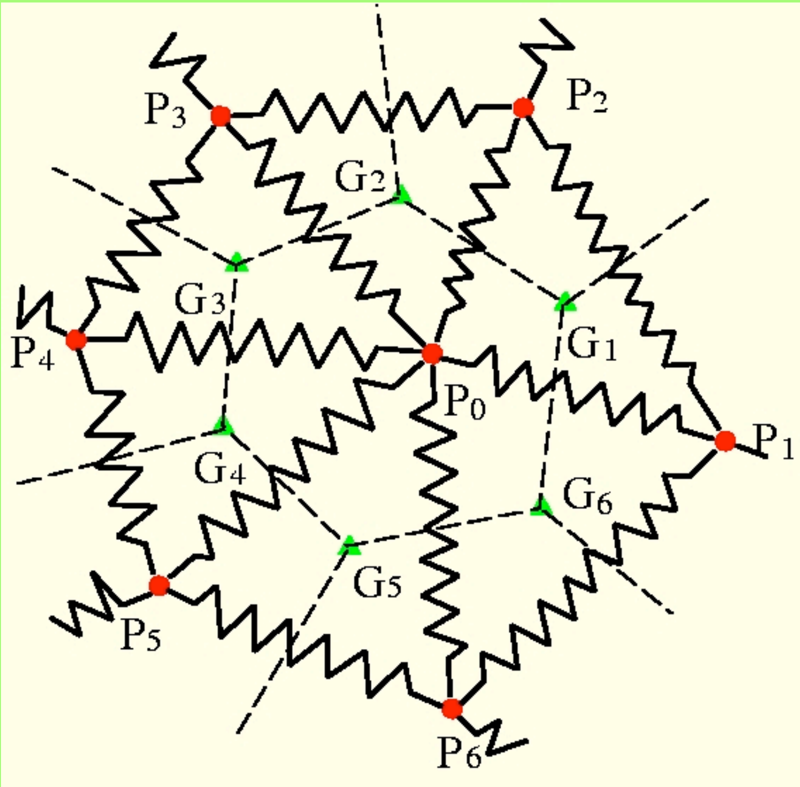
glevel-4




glevel-7
(~56km)
glevel- 8
(~28km)
glevel-9
(~14km)
glevel-10
(~7km)

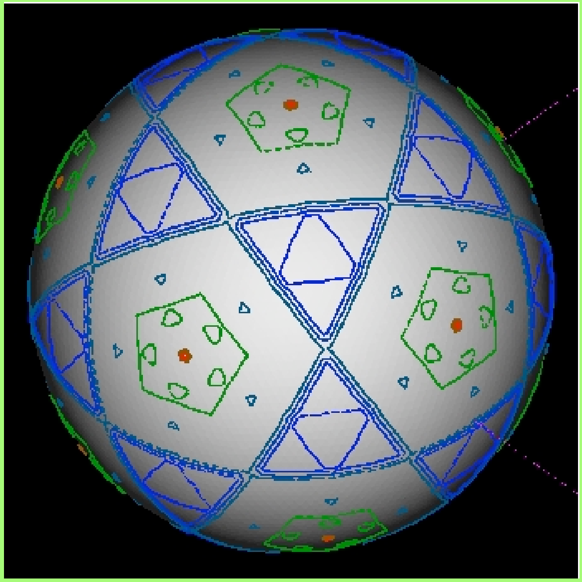
Spring grid

- Spring dynamics are used to reduce the grid-noise

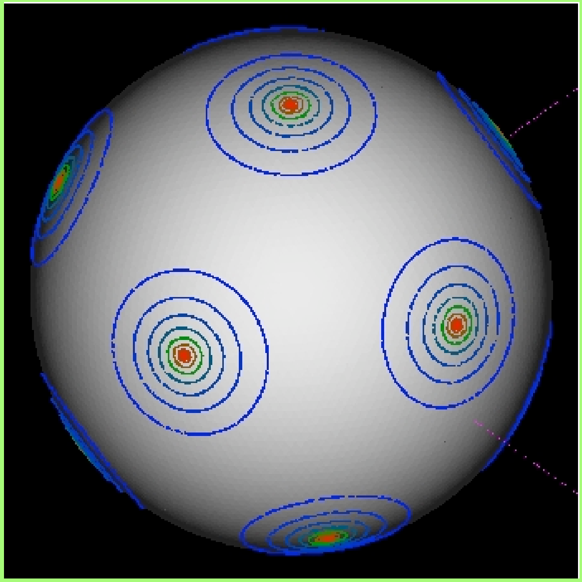


⇒ **Flexible grid configuration**
e.g. concentration in low-latitudes,
stretched grid,…

Area of control volume



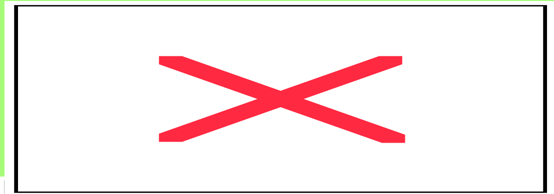
Standard grid



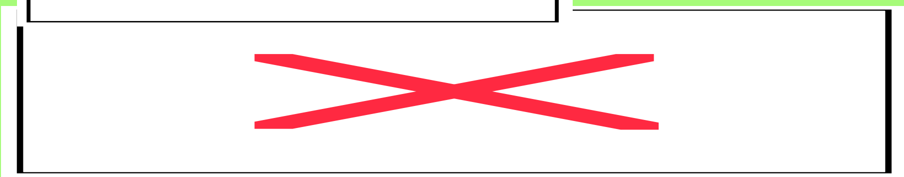
Spring grid

Stretched grid (1)

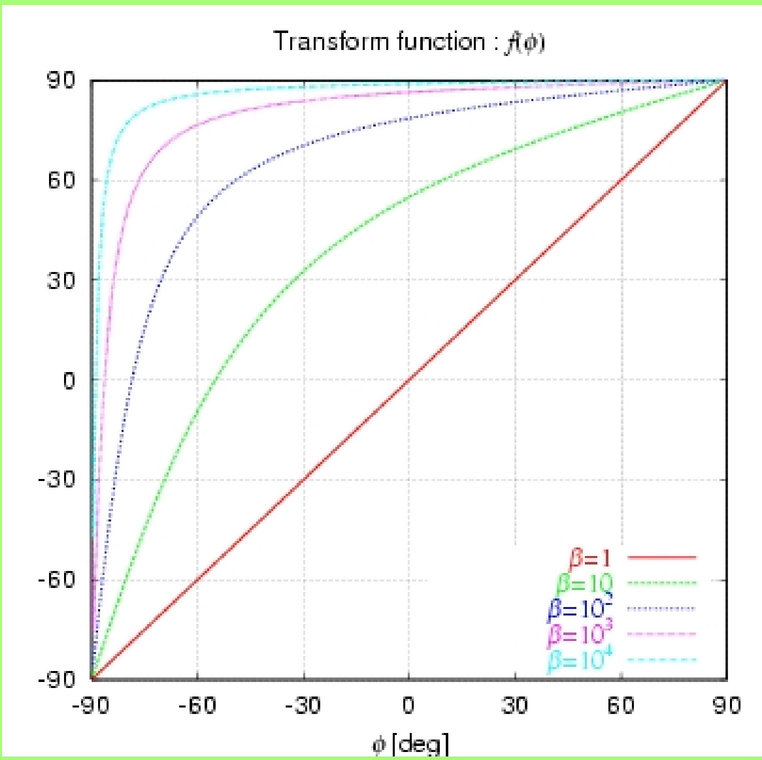
Schmidt transformation

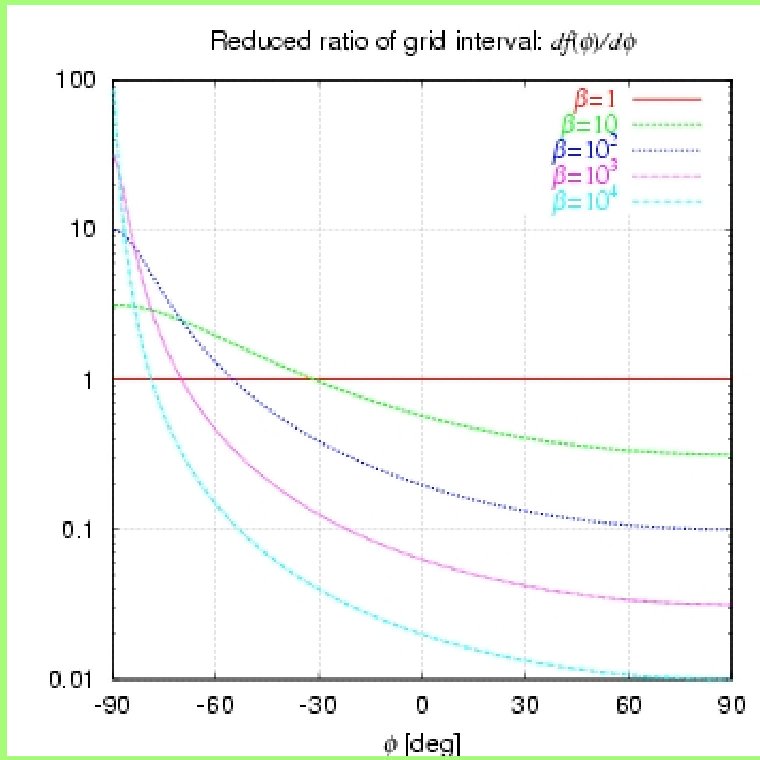


(isotropy)



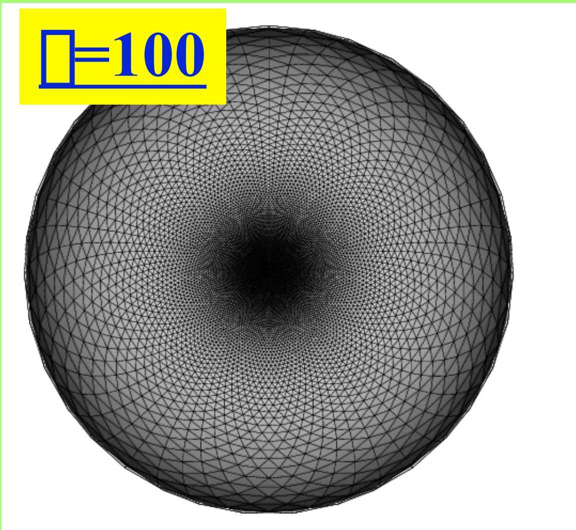
β : stretch parameter

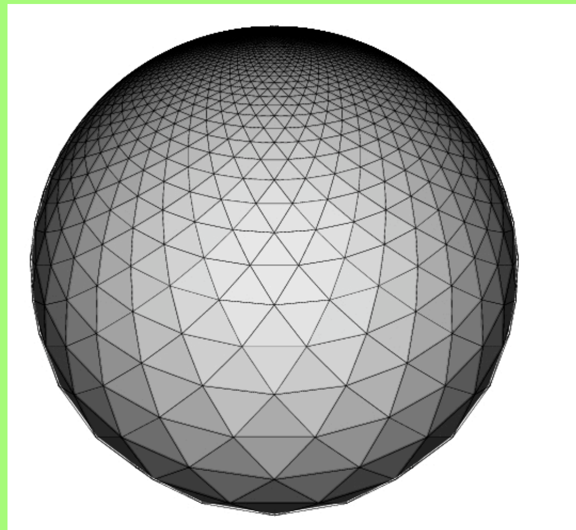


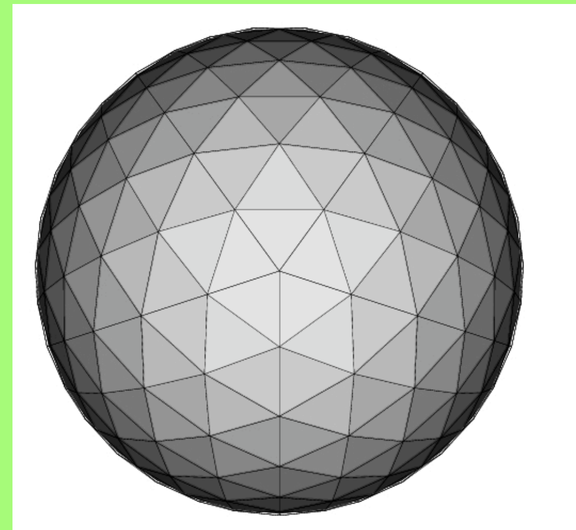


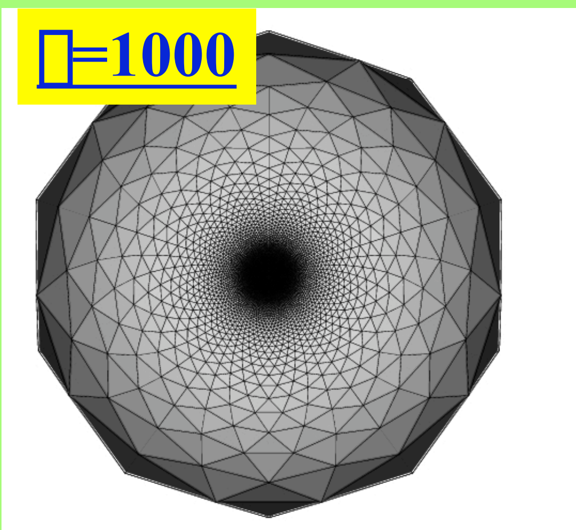
Stretched grid (2)

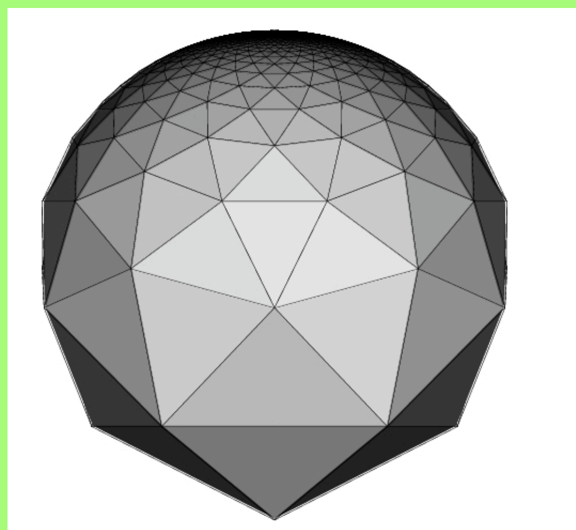
Finer hemisphere | **Side view** | **Coarser hemisphere**

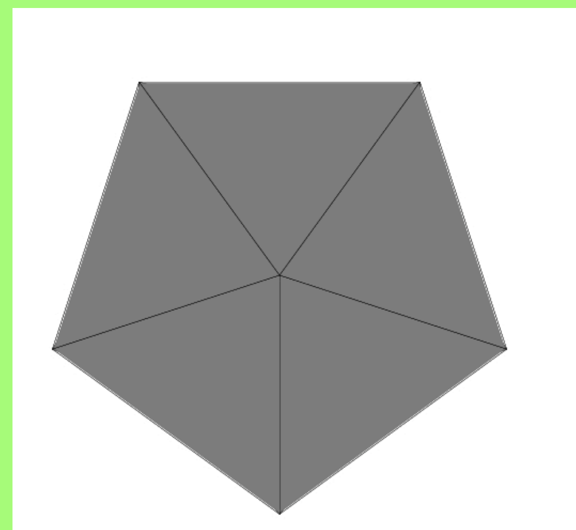






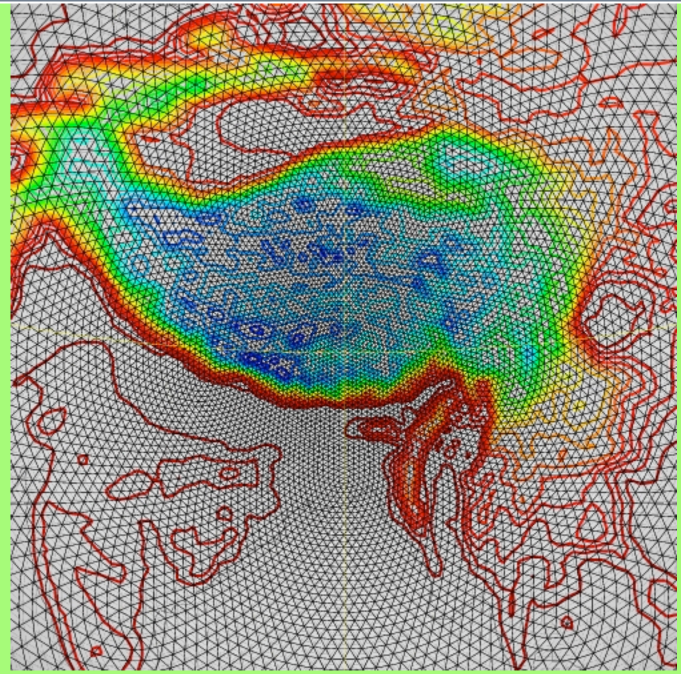


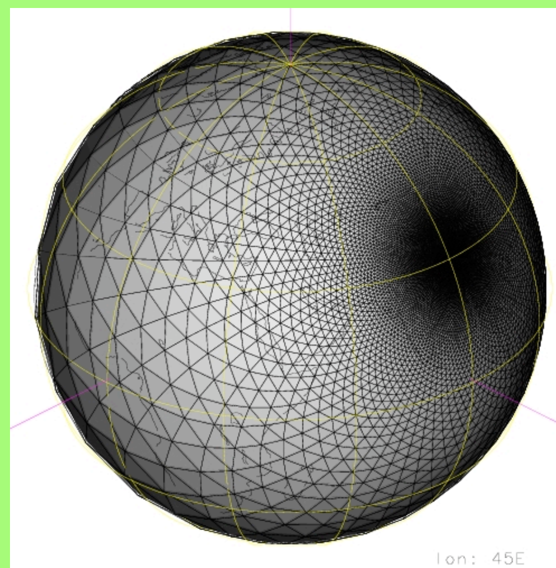




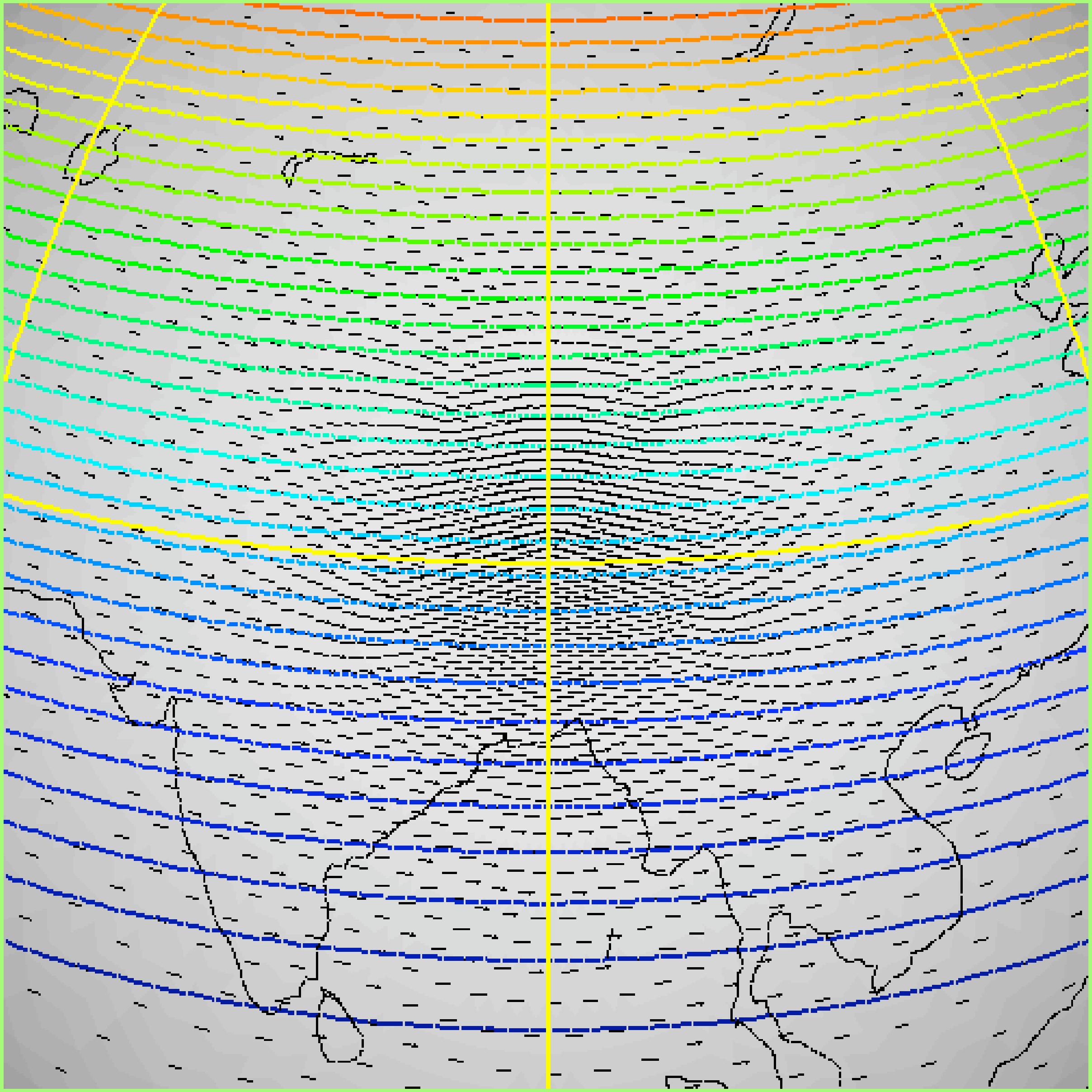
Stretched grid (3)

- **Shallow water experiment**
  - **Initial condition**
    - **Rigid body rotation (5m/s)**
    - **Geostrophic balance**
  - **Realistic topography**
    - **to resolve Tibet**
  - **A few days simulation**
  - **Stretched grid using the Schmidt transformation with □=100 concentrated around (30N，120E)**

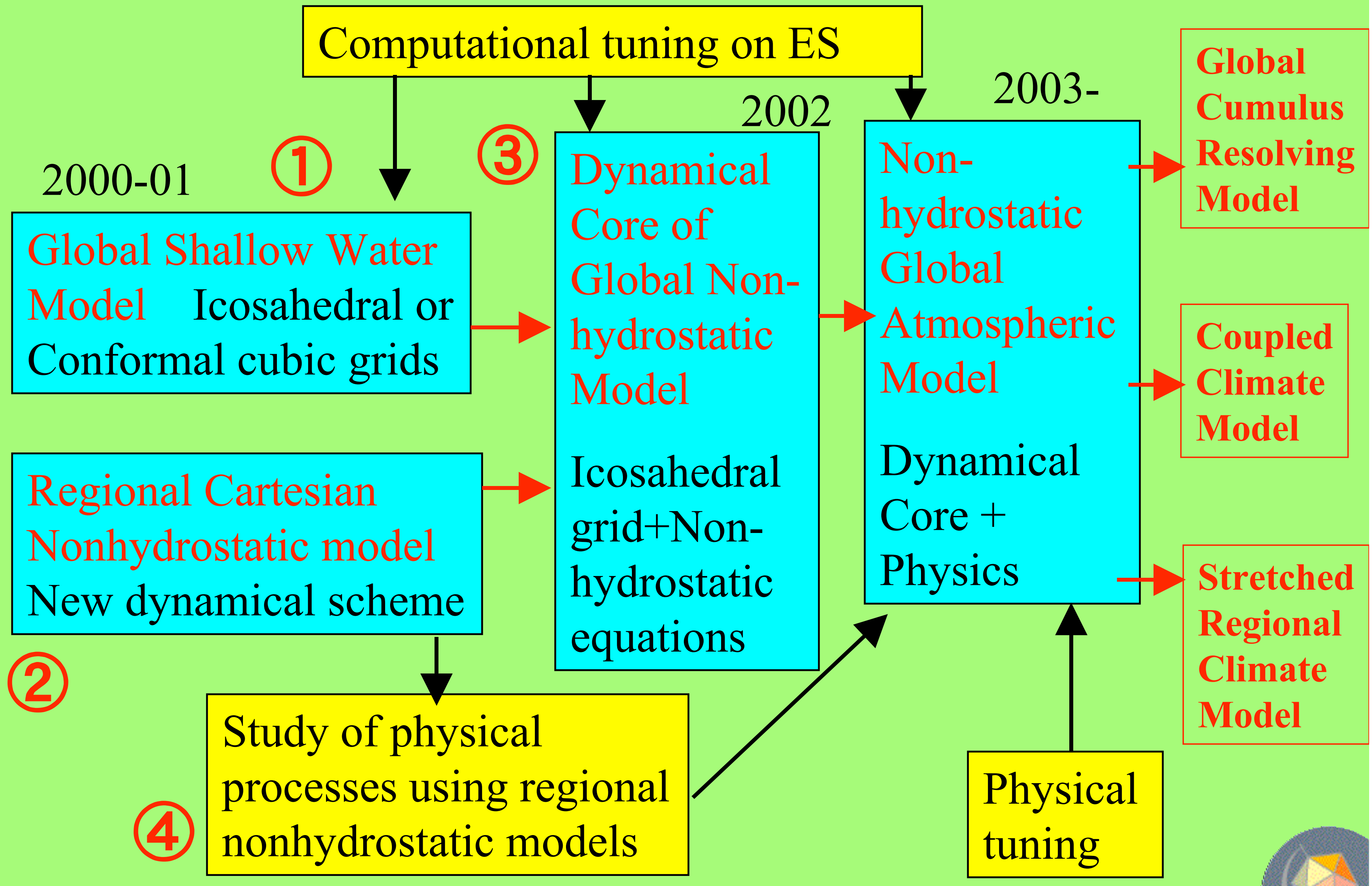




Animation for a week with 6 hours interval



Development procedure



2. Nonhydrostatic modeling

- Characteristics of the nonhydrostatic core
- Dry formulation
- Moist formulation

Characteristic s of the nonhydrostatic model (1)

- **Fully compressible non-hydrostatic equations**
  - Horizontally explicit and vertically implicit time integration with time splitting
  - The Helmholtz equation is formulated for vertical velocity not for pressure:
    - > a switch for a hydrostatic/non-hydrostatic option can be introduced.
- **Conservation of the domain integrals (Satoh 2002, 2003)**
  - The finite volume method using flux form equation
  - Density, momentum, and total energy are conserved.
- **Tracer advecion**
  - Third order upwind, or UTOPIA
  - Consistency with Continuity
- **Exact treatment of moist thermodynamics (Ooyama 1990, 2001).**
  - Dependency of latent heat on temperature and specific heats of water substance
  - Transports of water, momentum, and energy due to rain.
- **An accurate transport scheme for rain (Xiao et al 2003)**
  - Conservative Semi-Lagrangian scheme with 3rd order

Characteristic s of the nonhydrostatic model (2)

- **Physics**
  - Implemented from CCSR/NIES AGCM and MRI/NPD NHM
  - Warm rain (bulk method), no ice yet
  - Turbulence: Mellor and Yamada Level 2, 2.5; Deardorff; Smagorinsky
  - Surface flux: Louis(1982)
  - Radiation: MSTRN8 (Nakajima et al, 2000)
- **A subset of the three-dimensional global non-hydrostatic model**
  - Development of new dynamical schemes: Dynamical framework and advection scheme.
  - Physics: cloud schemes (warm/ice), radiation, turbulence
  - Study of cloud-radiation interaction and cumulus parameterization:
    Radiative-convective equilibrium experiments
  - Model hierarchy: can be used as 1D-vertical, 2D-horizontal-vertical, and 3D-regional models.

Dry formulation

- **Conservative flux form equations for density *R*, momentum *V*, and internal energy *E*:**

$$
\begin{aligned}
\frac{\partial}{\partial t}R + \nabla\cdot\boldsymbol{V} &= 0,\\
\frac{\partial}{\partial t}U + \frac{\partial}{\partial x}P &= -\nabla\cdot(\boldsymbol{V}u) + \frac{\partial \sigma_{xj}}{\partial x_j} \equiv G_U,\\
\frac{\partial}{\partial t}V + \frac{\partial}{\partial y}P &= -\nabla\cdot(\boldsymbol{V}v) + \frac{\partial \sigma_{yj}}{\partial x_j} \equiv G_V,\\
\frac{\partial}{\partial t}W + \frac{\partial}{\partial z}P + Rg &= -\nabla\cdot(\boldsymbol{V}w) + \frac{\partial \sigma_{zj}}{\partial x_j} \equiv G_W,\\
\frac{\partial}{\partial t}E + \nabla\cdot(\boldsymbol{V}h) - (\boldsymbol{v}\cdot\nabla P + Rwg) + Wg &= Q.
\end{aligned}
$$

where

$$
\begin{aligned}
\boldsymbol{V} &= (U,V,W) = (\rho u, \rho v, \rho w)\\
P &= p',\\
R &= \rho',\\
E &= \rho e^{in} : \quad \text{internal energy},
\end{aligned}
$$

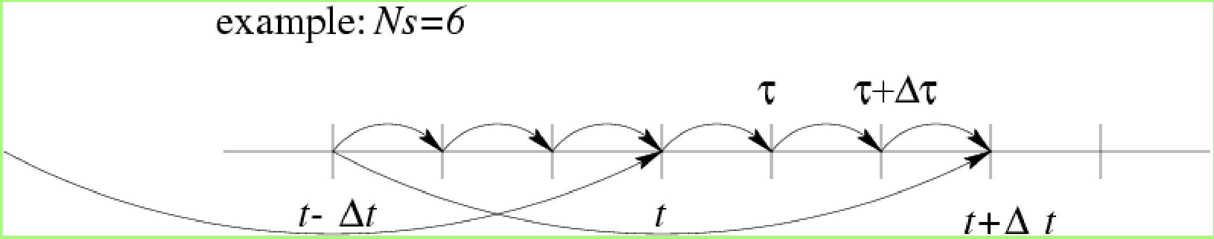
and

$$
E = \rho C_v T = \frac{C_v}{R_d} p.
$$

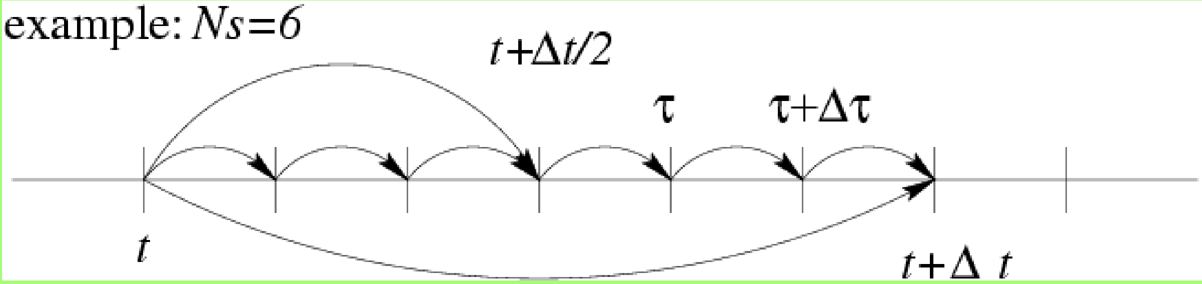
Time integration scheme: time splitting

- Large time step: t, small time step τ

Leap-frog



or RK2



The flux division method (Klemp et al.2000)

$$A^* = A - A^t, \quad \delta_t A = \frac{A^{t+\Delta t} - A^t}{\Delta t} = \frac{A^{n+1} - A^n}{\Delta t},$$

$$\begin{aligned}
\delta_\tau R^* + \frac{\partial}{\partial x}U^* + \frac{\partial}{\partial y}V^* + \frac{\partial}{\partial z}W^* &= -\left(\frac{\partial}{\partial x}U^t + \frac{\partial}{\partial y}V^t + \frac{\partial}{\partial z}W^t\right), \\
\delta_\tau U^* + \frac{\partial}{\partial x}P^* &= -\frac{\partial}{\partial x}P^t + G_U^t, \\
\delta_\tau V^* + \frac{\partial}{\partial y}P^* &= -\frac{\partial}{\partial y}P^t + G_V^t, \\
\delta_\tau W^* + \frac{\partial}{\partial z}P^* + R^* g &= -\frac{\partial}{\partial z}P^t - R^t g + G_W^t, \\
\delta_\tau E^* + \frac{\partial}{\partial x}(U^* h^t) + \frac{\partial}{\partial y}(V^* h^t) + \frac{\partial}{\partial z}(W^* h^t) &- \frac{W^*}{\rho^t}\left(\frac{\partial P^t}{\partial z} + R^t g\right) + W^* g \\
= -\frac{\partial}{\partial x}(U^t h^t) - \frac{\partial}{\partial y}(V^t h^t) - \frac{\partial}{\partial z}(W^t h^t) &+ u^t \frac{\partial}{\partial x}P^t + v^t \frac{\partial}{\partial y}P^t + w^t\left(\frac{\partial P^t}{\partial z} + R^t g\right) \\
-W^t g + Q^t &
\end{aligned}$$

Small time integration(1)

- **Explicit for U and V**

$$\delta_\tau U^* = -\frac{\partial}{\partial x} P^{*\tau} + G'^t_U,$$
$$\delta_\tau V^* = -\frac{\partial}{\partial y} P^{*\tau} + G'^t_V,$$

- **Implicit for R, W, E: using**

$$\delta_\tau R^* = -\frac{\partial}{\partial z} W^{*\tau+\Delta\tau} + G'^{\tau+\Delta\tau}_R,$$
$$\delta_\tau W^* = -\frac{\partial}{\partial z} P^{*\tau+\Delta\tau} - R^{*\tau+\Delta\tau} g + G'^t_W,$$
$$\delta_\tau P^* = -\frac{R_d}{C_v}\frac{\partial}{\partial z}(W^{*\tau+\Delta\tau} h^t) - \frac{R_d}{C_v} W^{*\tau+\Delta\tau} \bar{g} + \frac{R_d}{C_v} G'^{\tau+\Delta\tau}_E,$$

$$P^* = \frac{R_d}{C_v} E^*$$

> **1D-Helmholtz eq. for W**

$$-\frac{\partial^2}{\partial z^2}\left(\Delta\tau^2 \frac{R_d}{C_v} h^t W^{*\tau+\Delta\tau}\right) - \left[\frac{\partial}{\partial z}\left(\Delta\tau^2 \frac{R_d}{C_v} \bar{g} W^{*\tau+\Delta\tau}\right) + \Delta\tau^2 g \frac{\partial}{\partial z} W^{*\tau+\Delta\tau}\right] + \alpha W^{*\tau+\Delta\tau}$$
$$= \alpha W^{*\tau} + \alpha\Delta\tau G'^t_W - \Delta\tau \frac{\partial}{\partial z}\left[P^{*\tau} + \Delta\tau \frac{R_d}{C_v} G'^{\tau+\Delta\tau}_E\right] - \Delta\tau g \left[R^{*\tau} - \Delta\tau G'^{\tau+\Delta\tau}_R\right].$$

$\alpha = 0$ ： Hydrostatic option

Small time integration(2)

> **Integrate for *R* in the flux form**

$$R^{\tau+\Delta\tau} = R^{\tau} - \Delta t \left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} \right)^{\tau+\Delta\tau}$$

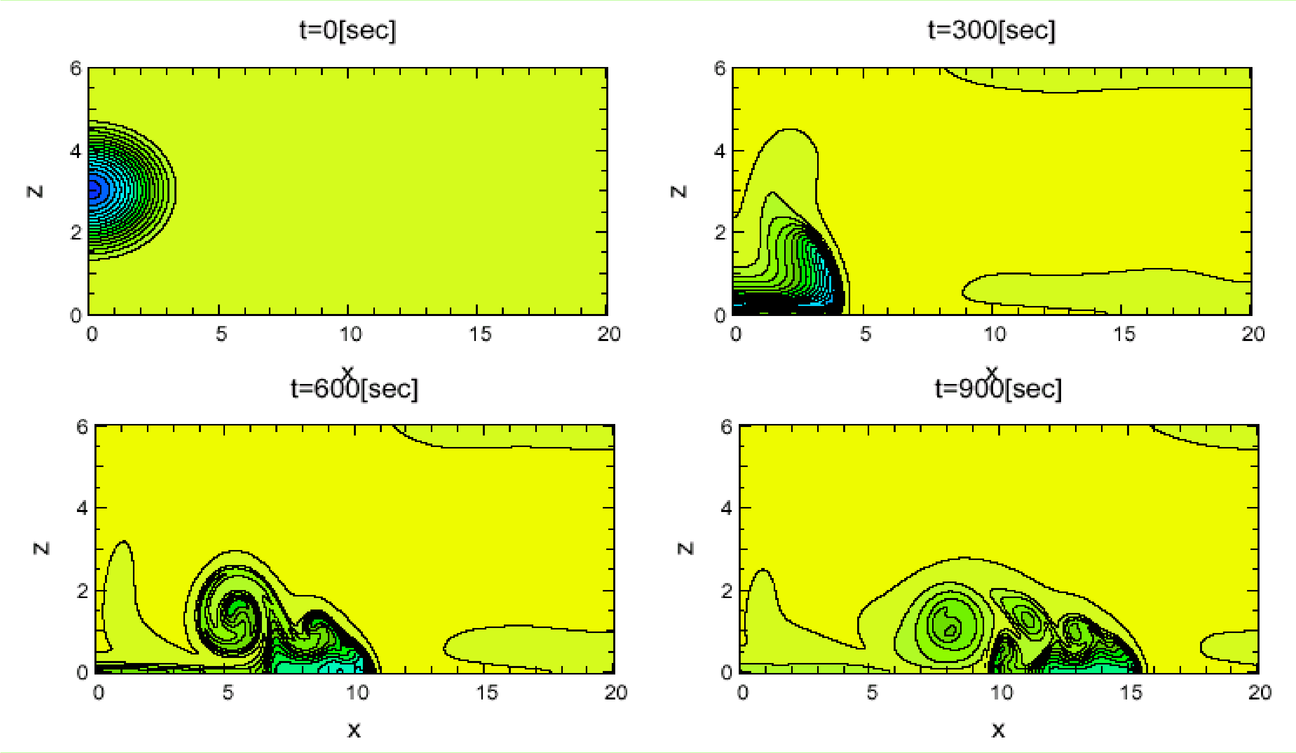
> **Energy correction: integrate for total energy in the flux form**

$$\delta_\tau (E + K + G) = -\nabla \cdot \left[\boldsymbol{V}^{\tau+\Delta\tau} \left(h + \frac{\boldsymbol{v}^2}{2} \right)^t \right] - \nabla \cdot \boldsymbol{F}^t + \nabla \cdot (\boldsymbol{v} \cdot \underline{\boldsymbol{\sigma}})$$

where *E*: internal energy, *K*: kinetic energy, and *G*: potential energy:

$$K = \rho \frac{u^2 + v^2 + w^2}{2}$$
$$G = \rho \Phi = \rho g z$$

Density current experiment (Straka et al, 1993)

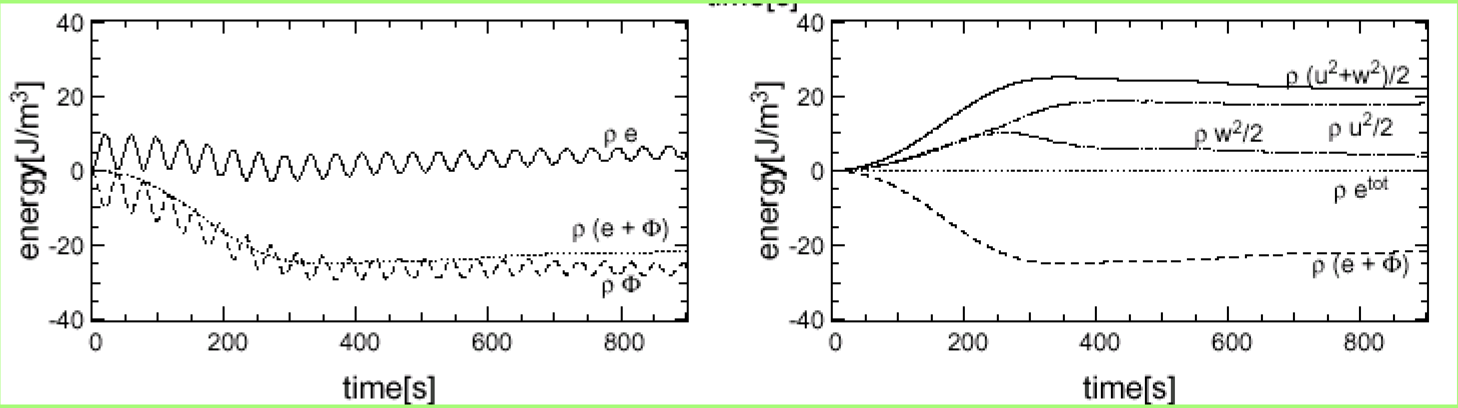


Initial cold bubble:

$\theta' = -15K$

$\Delta x = \Delta z = 50m$

$\Delta t = 0.1s$



Moist formulation

- **Prognostic variables (warm rain):**

> **water vapor q_v**

> **cloud water q_c**

> **rain water q_l**

> **total density ρ**

> **momentum $V = (U, V, W) = (\rho u, \rho v, \rho w)$**

> **Sensible part of internal energy E_a:**

Effects of specific heats of water substance are considered:

$$
\begin{aligned}
E_m &= q_d C_{vd} T + q_v (C_{vv} T + L_{00}) + q_l C_l T \\
&= (q_d C_{vd} + q_v C_{vv} + q_l C_l) T + L_{00} q_v = E_a + L_{00} q_v
\end{aligned}
$$

Governing equations (Ooyama, 1990,2000)

Water vapor:

$$\frac{\partial(\rho q_v)}{\partial t} + \nabla_H \cdot (\rho q_v \boldsymbol{v}_H) + \frac{\partial(\rho q_v w)}{\partial z} = -C + E + D_v,$$

Cloud water:

$$\frac{\partial(\rho q_c)}{\partial t} + \nabla_H \cdot (\rho q_c \boldsymbol{v}_H) + \frac{\partial(\rho q_c w)}{\partial z} = C - (S_{auto} + S_{accr}) + D_c,$$

Rain water:

$$\frac{\partial(\rho q_r)}{\partial t} + \nabla_H \cdot (\rho q_r \boldsymbol{v}_H) + \frac{\partial}{\partial z}[\rho q_r(w + \underline{W_r})] = (S_{auto} + S_{accr}) - E + D_r,$$

Density:

$$\frac{\partial \rho}{\partial t} + \nabla_H \cdot (\rho \boldsymbol{v}_H) + \frac{\partial}{\partial z}(\rho w + \underline{\rho q_r W_r}) = 0,$$

Transports due to rain

Horizontal components of momentum:

$$\frac{\partial(\rho \boldsymbol{v}_H)}{\partial t} + \nabla_H \cdot (\rho \boldsymbol{v}_H \boldsymbol{v}_H) + \frac{\partial}{\partial z}(\rho \boldsymbol{v}_H w + \underline{\rho q_r \boldsymbol{v}_H W_r}) = -\nabla_H p + \boldsymbol{F}_H,$$

Vertical component of momentum:

$$\frac{\partial(\rho w)}{\partial t} + \nabla_H \cdot (\rho w \boldsymbol{v}_H) + \frac{\partial}{\partial z}(\rho w w + \underline{\rho q_r w W_r}) = -\frac{\partial p}{\partial z} - \rho g + F_z,$$

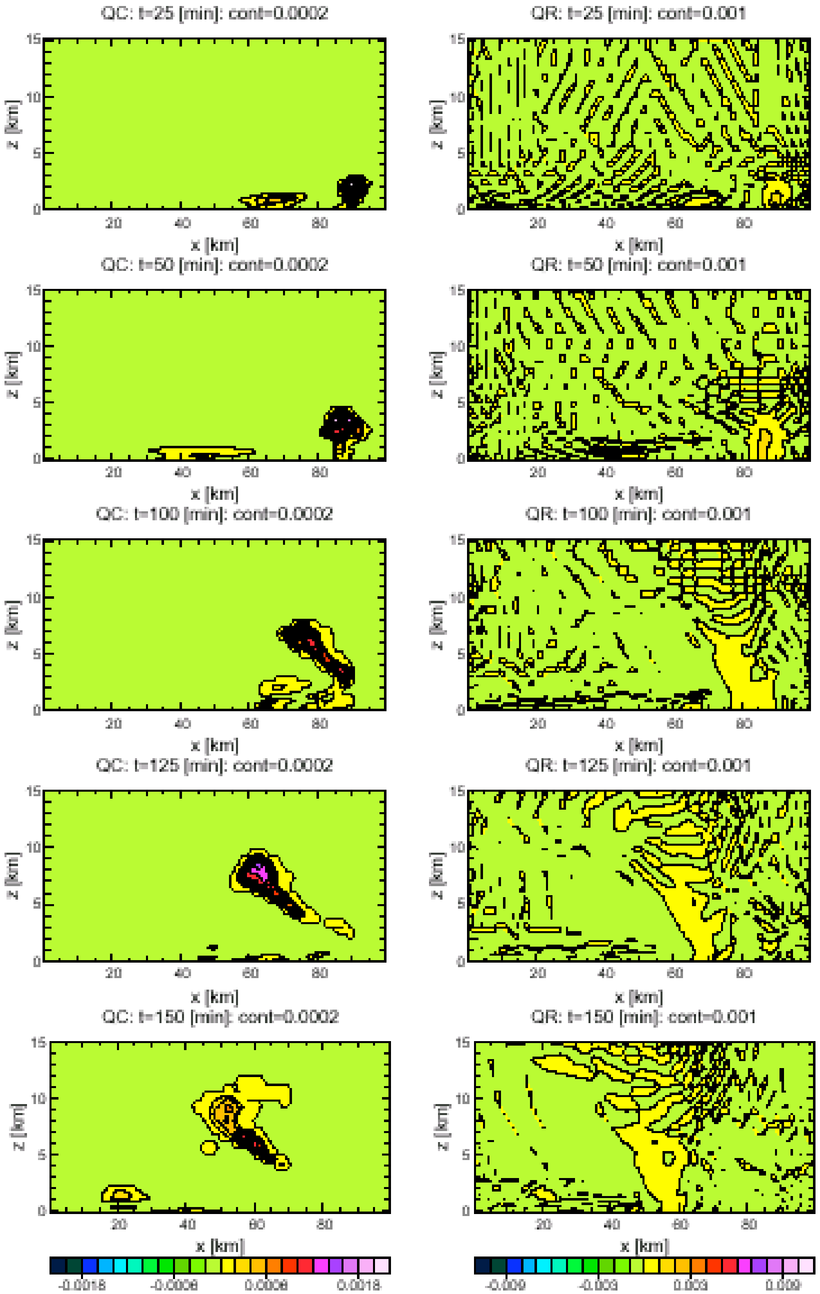
Internal energy:

$$\frac{\partial}{\partial t}(\rho e_a) + \nabla_H \cdot (\rho h_a \boldsymbol{v}_H) + \frac{\partial}{\partial z}(\rho h_a w + \underline{\rho q_r e_r W_r})$$
$$= -\boldsymbol{v} \cdot \nabla p - \underline{\rho q_r W_r g} + L_{00}(C - E) + Q_H,$$

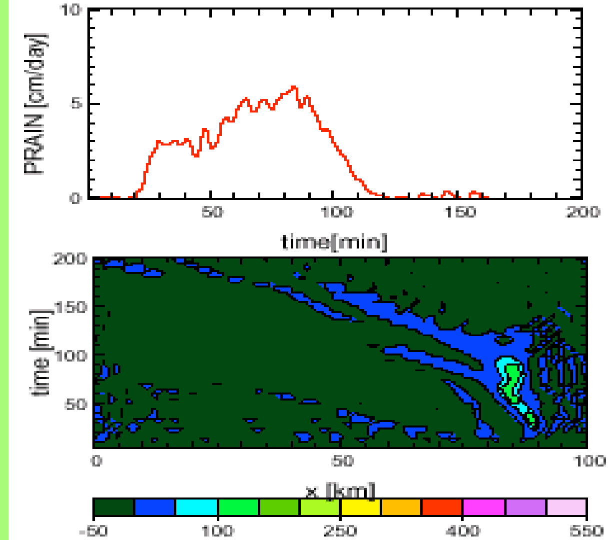
Release of potential energy of rain

Squall line exp.: 2D, Δx=1.25km, L=100km

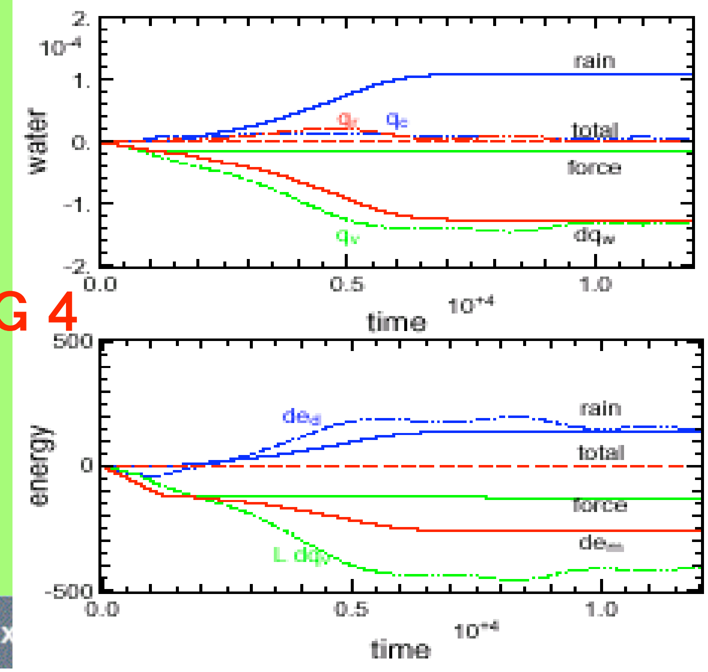
Cloud water and rain



Precipitation



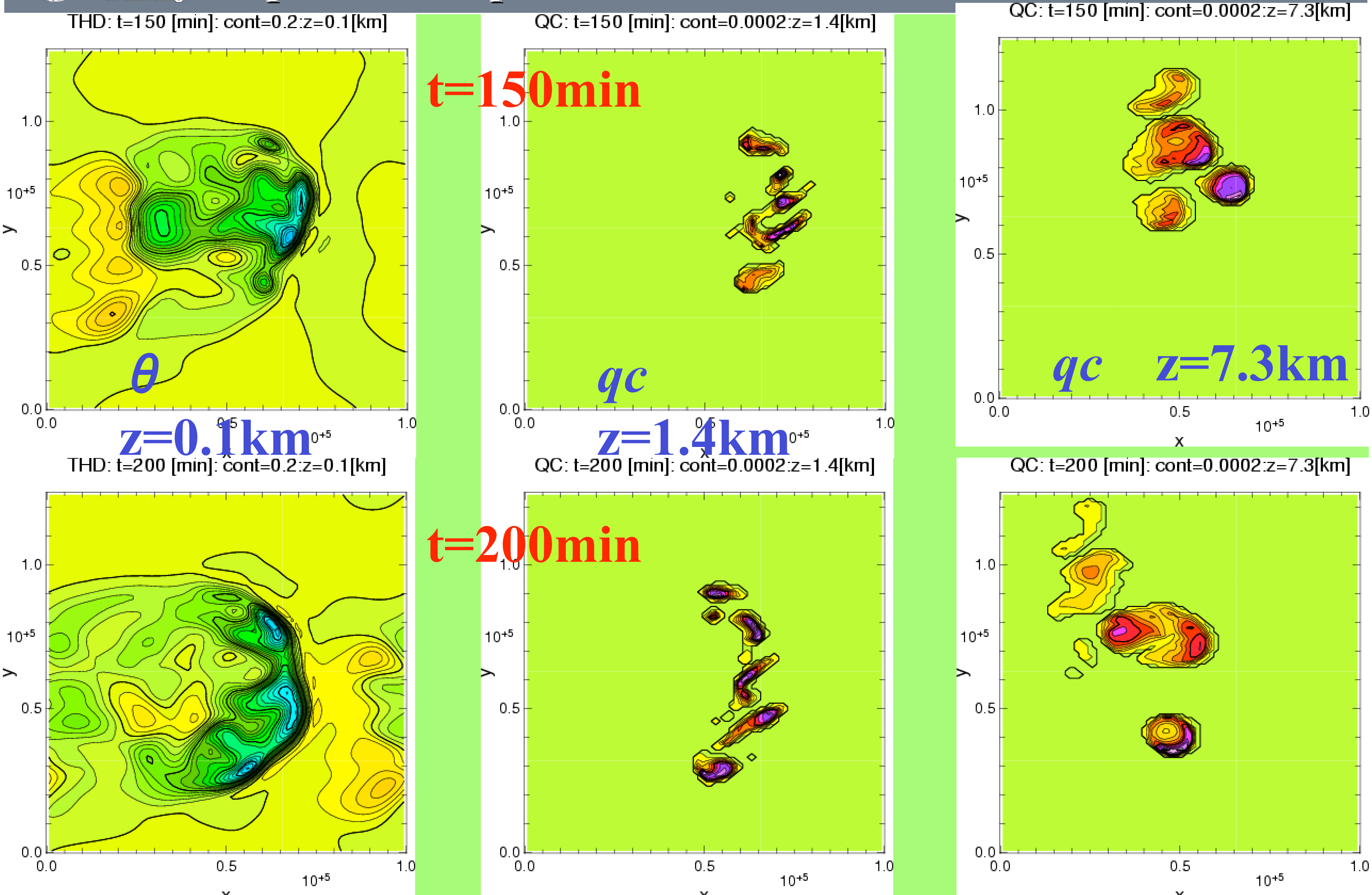
Water & Energy budgets



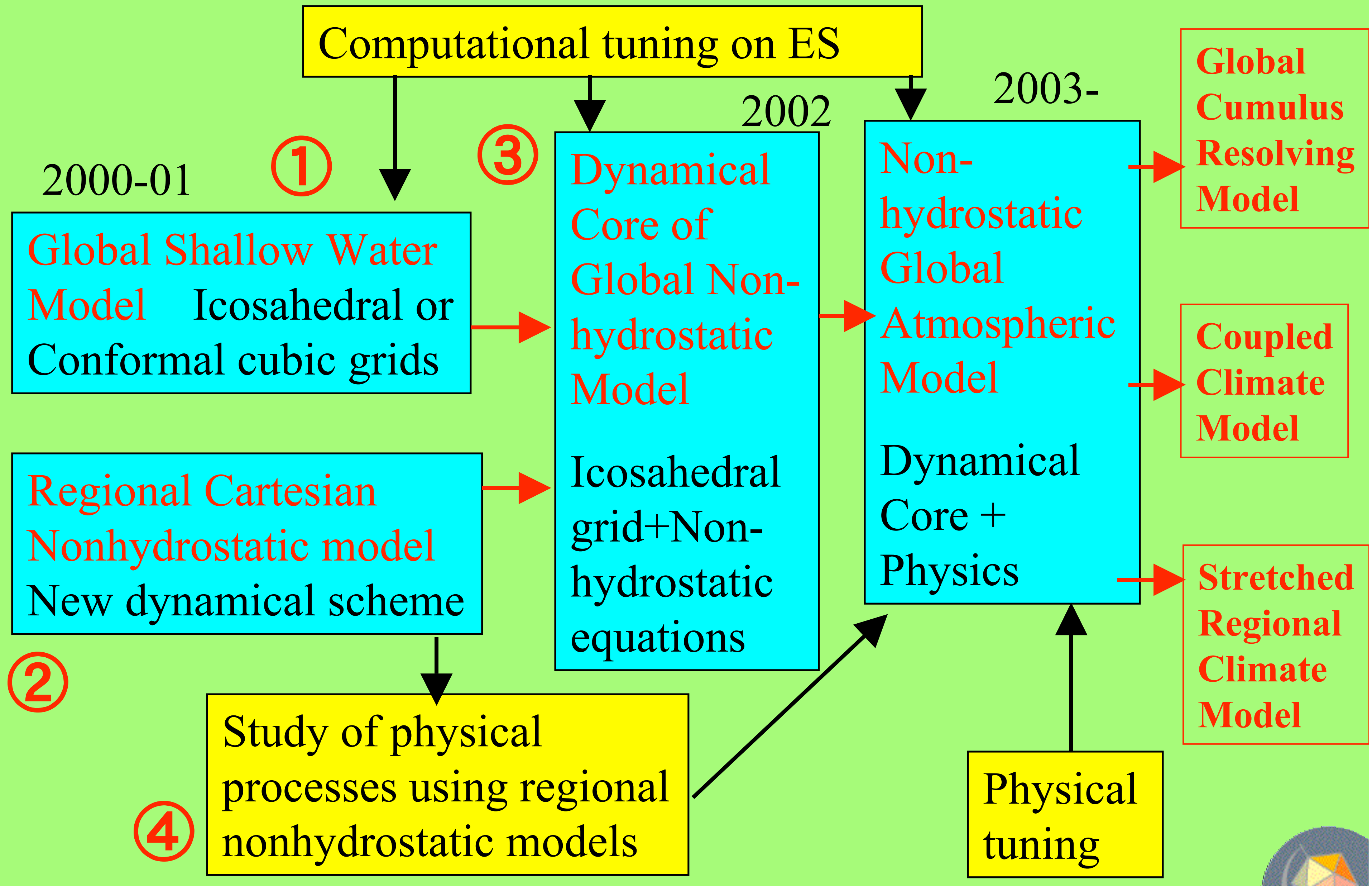
GCSS WG4
CASE1

Nex

Squall line exp.: 3 D: 100km x 125km x 21km



Development procedure



3. Nonhydrostatic Icosahedral Ａｔｍｏｓｐｈｅric model

－Dynamical Core－

- Model feature
- Life cycle of extratropical cyclone experiment
- Held and Suarez experiment
- Runs on the Earth Simulator

Global nonhydrostatic model

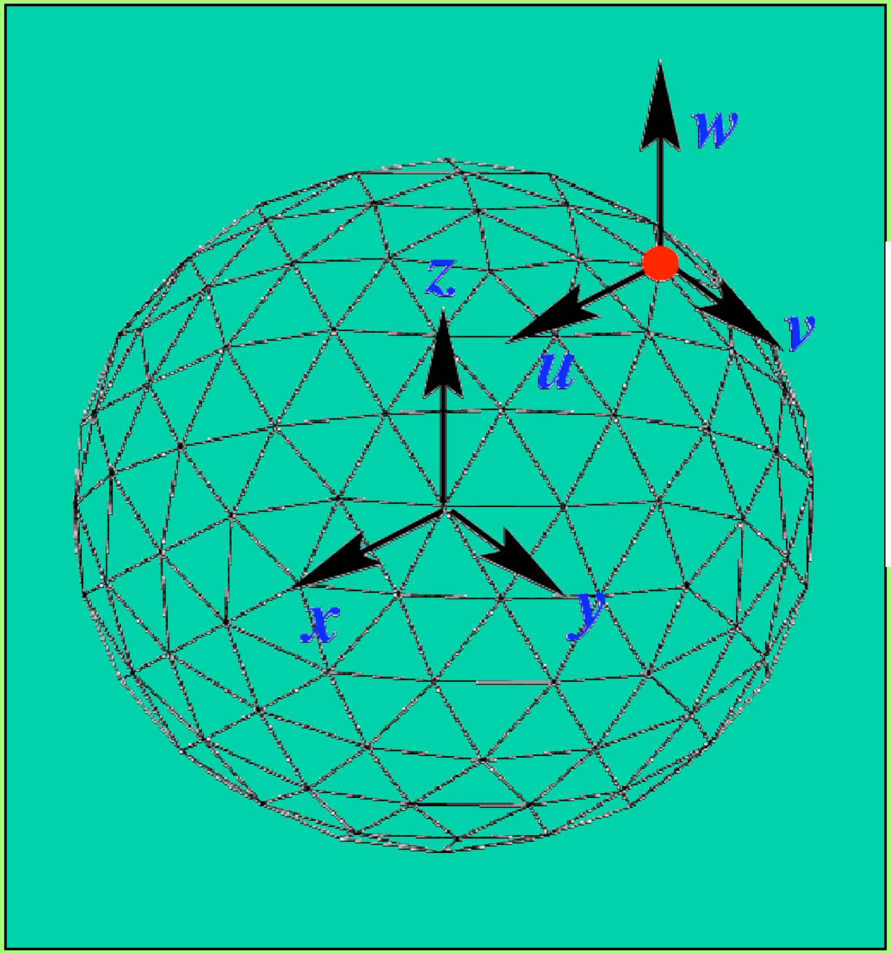
■ Model feature

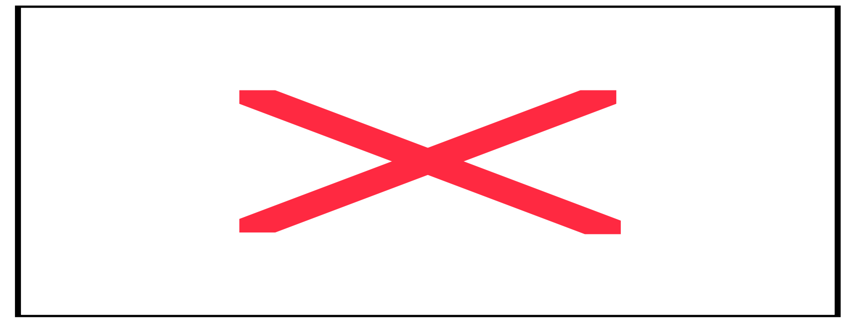
Governing equations	Fully compressible non-hydrostatic system
Spatial discretization Horizontal grid configuration Vertical grid configuration Topography	Finite Volume Method Icosahedral grid Lorenz grid Terrain-following coordinate
Conservation	Total mass, total energy
Temporal scheme	Slow mode ー explicit scheme （RK2） Fast mode ー Horizontal Explicit Vertical Implicit scheme （HEVI）
Physical parameterization	Not yet implemented

■ Computational tuning

Vectorization	Well tuned for NEC SX5 architecture
Parallelization	2D decompostion, Flexible configuration against load imbalance
Current target machine	Earth Simulator

Advection of momentum and Coriolis terms

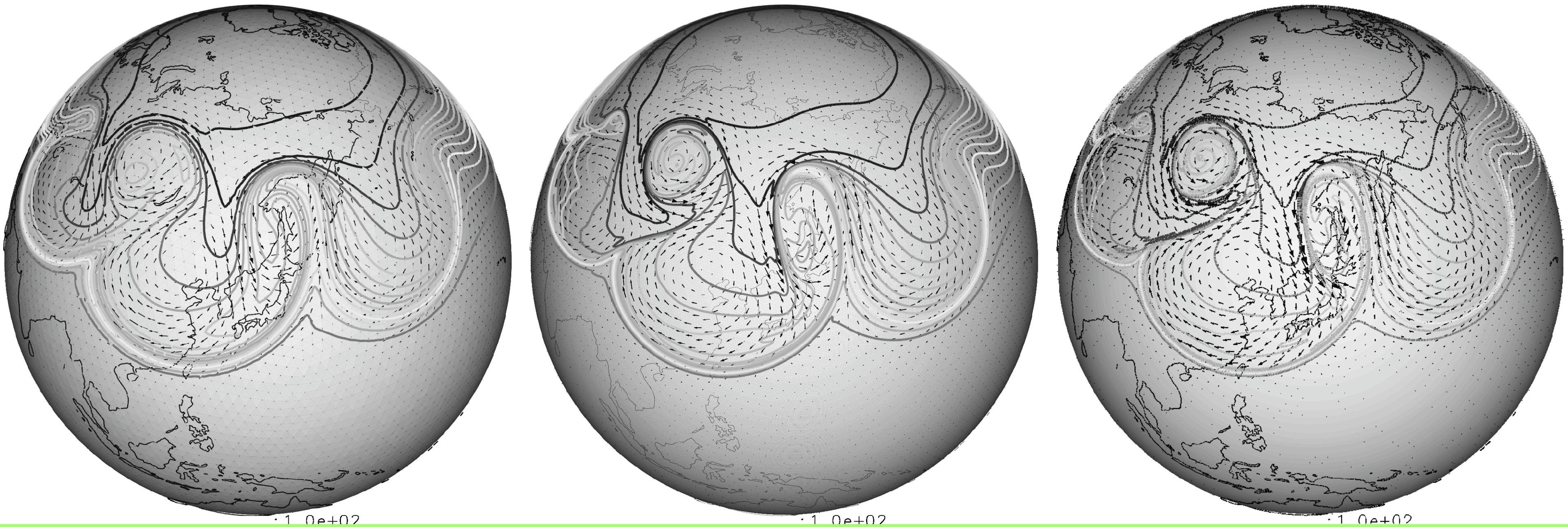




Only the advection term is evaluated with the Cartesian components.

Life Cycle of Extratropical Cyclone Exp.(1)

Polvani and Scott(2002)

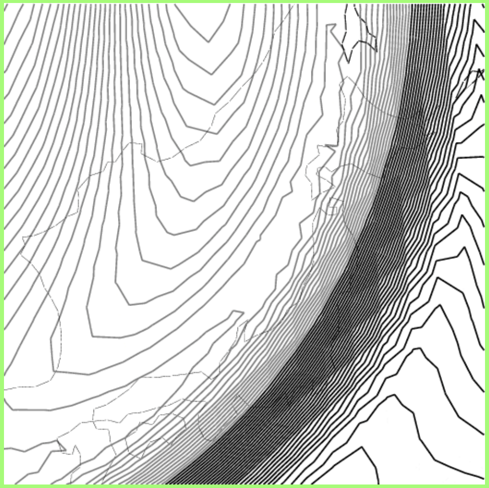


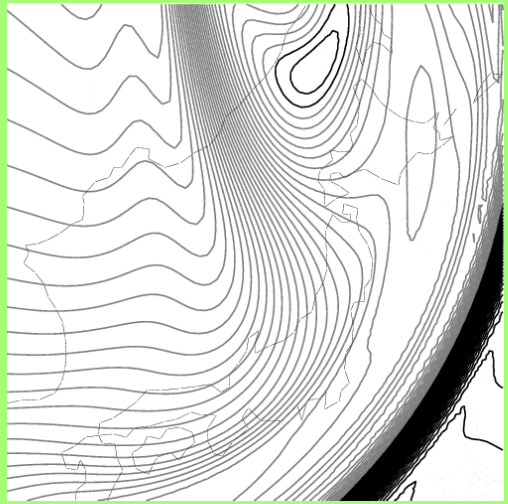
glevel 6
Δx=112km

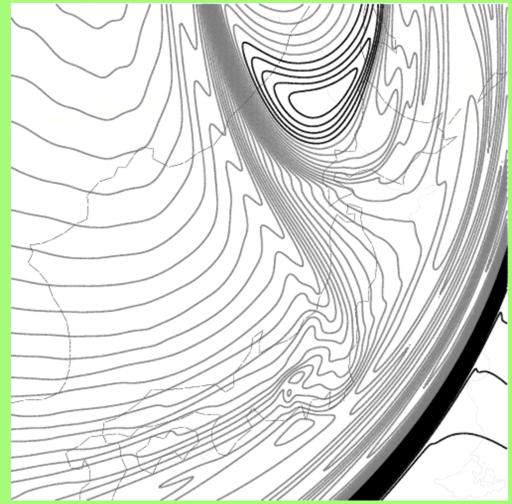
glevel 8
Δx=28km

glevel 10
Δx=7km

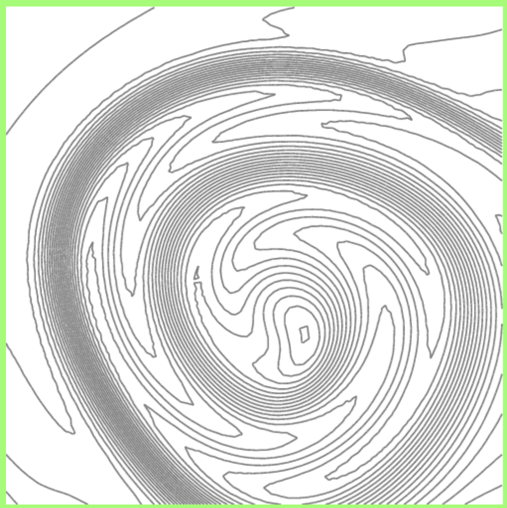
Life Cycle of Extratropical Cyclone Exp.(2)

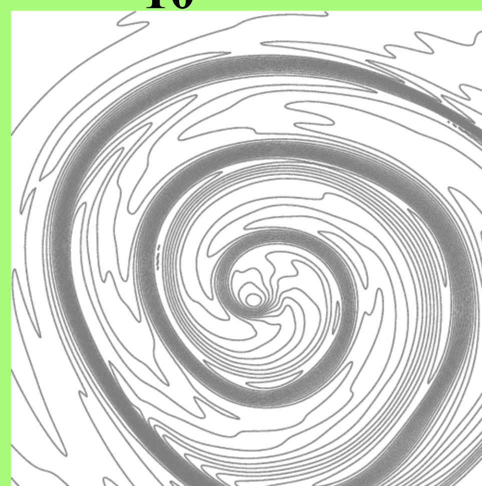






glevel 6 **glevel 8** **glevel 10**





Held & Suarez Dynamical Core Exp. (1)

Pseudo physics

Radiation

- A simple radiation as Newtonian Cooling of temperature field :

where

with zonally symmetric equilibrium temperature:

where

Surface friction

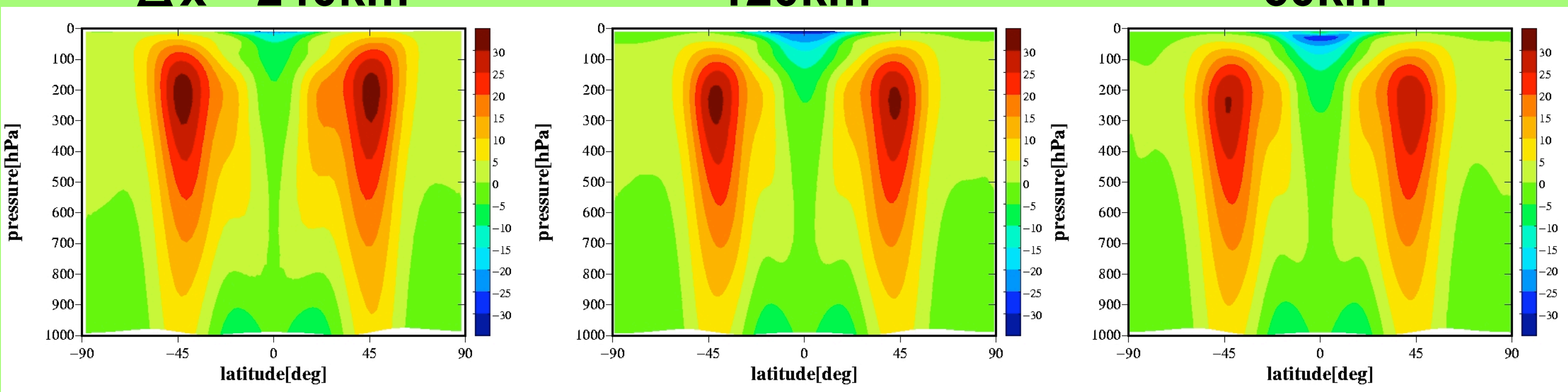
- Surface friction is imposed in the lower atmosphere as a Rayleigh damping :

where

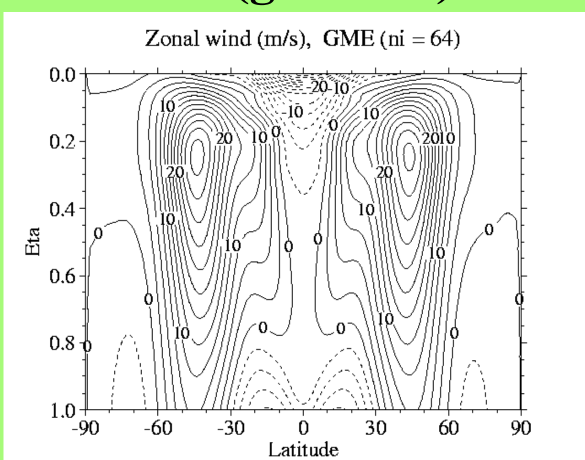
Held & Suarez Dynamical Core Exp. （4）

■ Zonal mean of zonal wind

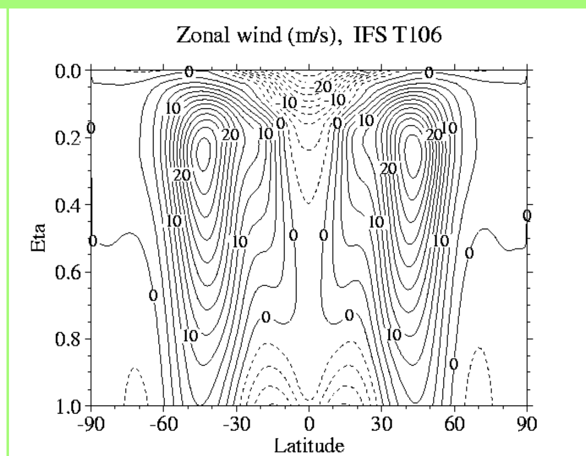
(a) glevel-5 Δx～240km　(b) glevel-6 ～120km　(c) glevel-7 ～60km



GME(DWD) ni=64(g-level 6)



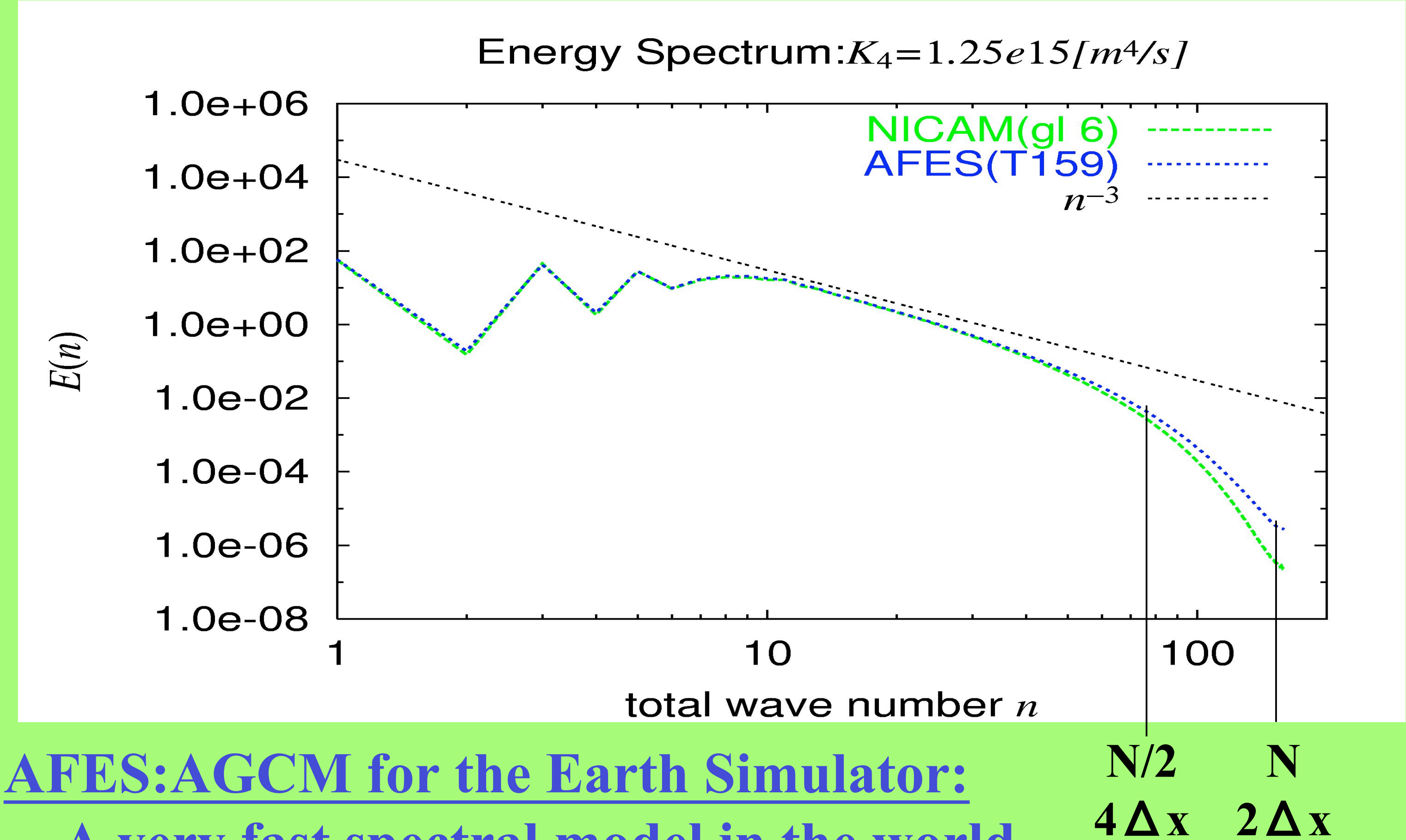
IFS(ECMWF) T106



Comparison with spectral model(2)

Energy spectrum

glevel-6 vs T159 ： 2Δx=2π/N=240km



AFES:AGCM for the Earth Simulator:
A very fast spectral model in the world

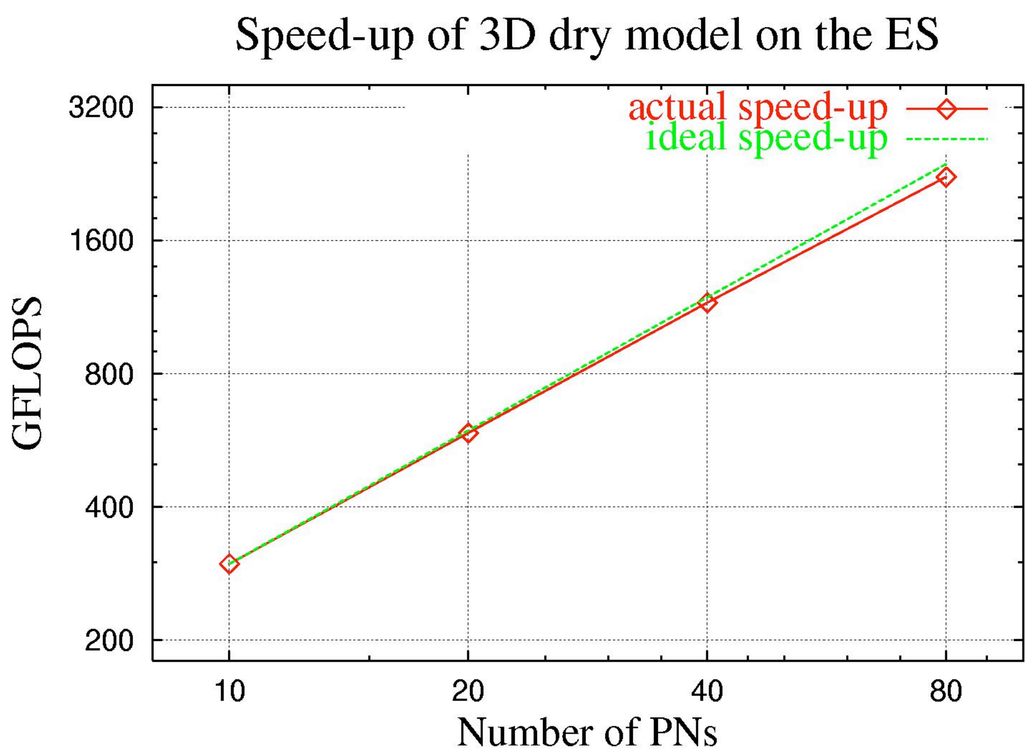
Computational Performance (1)

Performance on the Earth Simulator

Earth Simulator

- Massively parallel super-computer based on NEC SX-5 architecture.
  - 640 computational nodes.
  - 8 vector-processors in each of nodes.
  - Peak performance of 1CPU : 8GFLOPS
  - Total peak performance : 8x8x640 = 40TFLOPS

Computational Performance (2)



Configuration

- Horizontal resolution : glevel-8
- Vertical layers : 100

Fixed

- The used computer nodes increases from 10 to 80.

Results

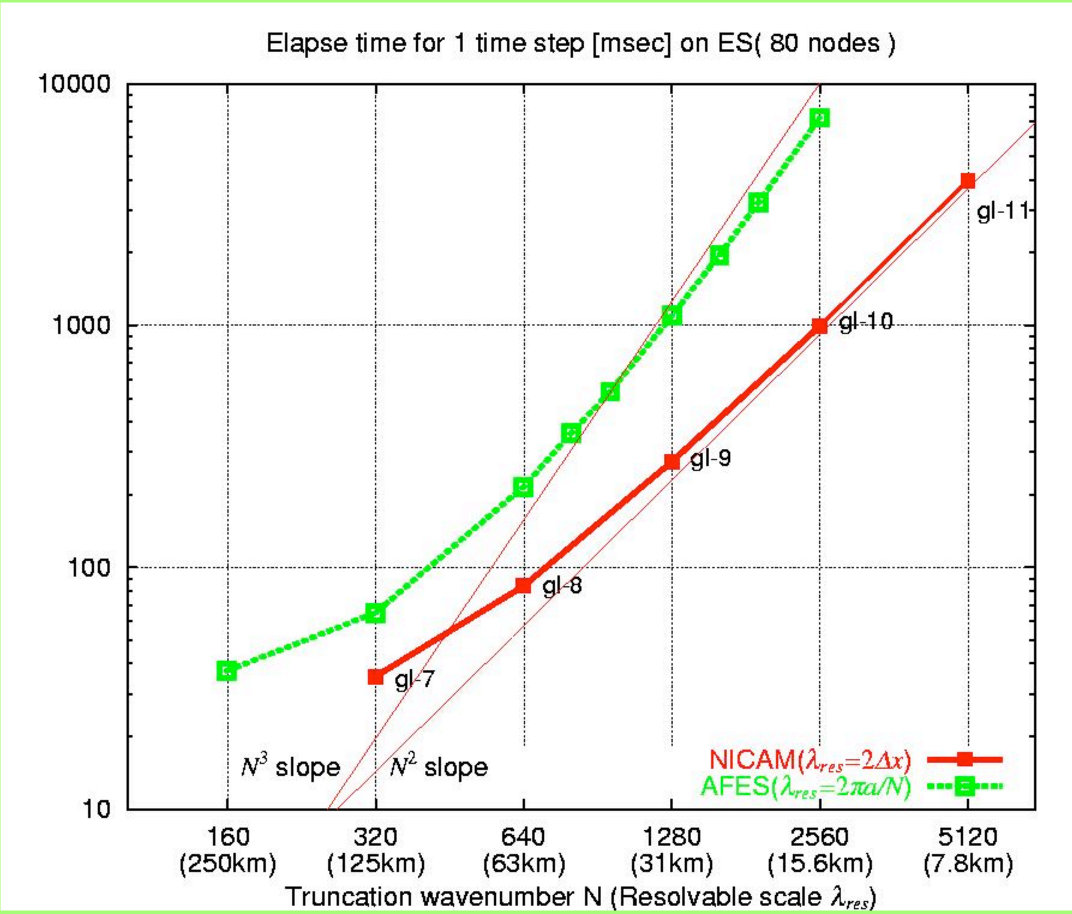
Red : actual speed-up line
Green : ideal speed-up line

The GFLOPS value at 80 nodes is **7.48** times faster than that at 10 nodes.

Sustained performance at 80 nodes is **43.5**%

Comparison with a spectral model (2)

Elapse time of 1step for NICAM and AFES

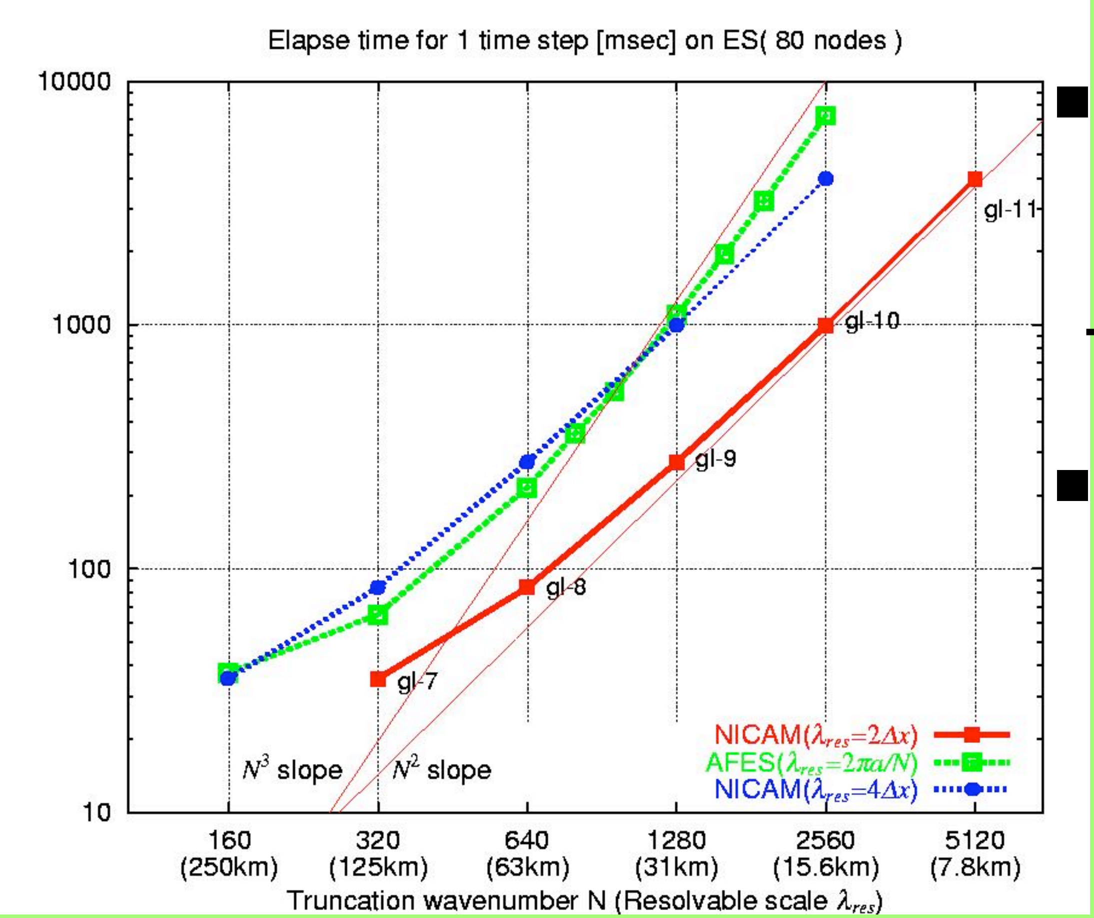


- **AFES (green line)**
  Elapse time increases in the sense O(n^3).
  → Legendre transformation
- **NICAM(red line)**
  Elapse time increases in the sense O(n^2).
- **In all resolutions,**
  NICAM is faster than AFES!

Caution: what is the resolvable scale? 2Δx or 4Δx?

Comparison with a spectral model (3)

- To consider 4-grid scale as a resolvable scale.



- **Resolution correspondance**

  glevel-7 → T160

  glevel-8 → T320

  → The red line shifts to the blue line.

- **Cross point**

  resolvable scale : 30km

NICAM is faster than AFES at the 30km resolution.

Comparison with a spectral model (4)

■ Maximum time step and one-day simulation time

If L = 2 πR / N = 4 Δx

NICAM	gl7	gl8	gl9	gl10	gl11
×	450	225	113	57	29
1day time	6.70	32.1	210	1519	12200

AFES	T159	T319	T639	T1279	T2559
×	400	200	100	50	25
1day time	8.02	27.9	184	1884	24930

- Time step of NICAM can be larger than AFES

At T1279 & glevel-10, NICAM is faster than AFES.

Estimated integration time on the Earth Simulator

- **Dry model, 7km grid (glevel-10)**

  30min for one day simulation if 80 nodes are used.

Estimated time for a full physics model

- **3.5km grid (glevel-11)**

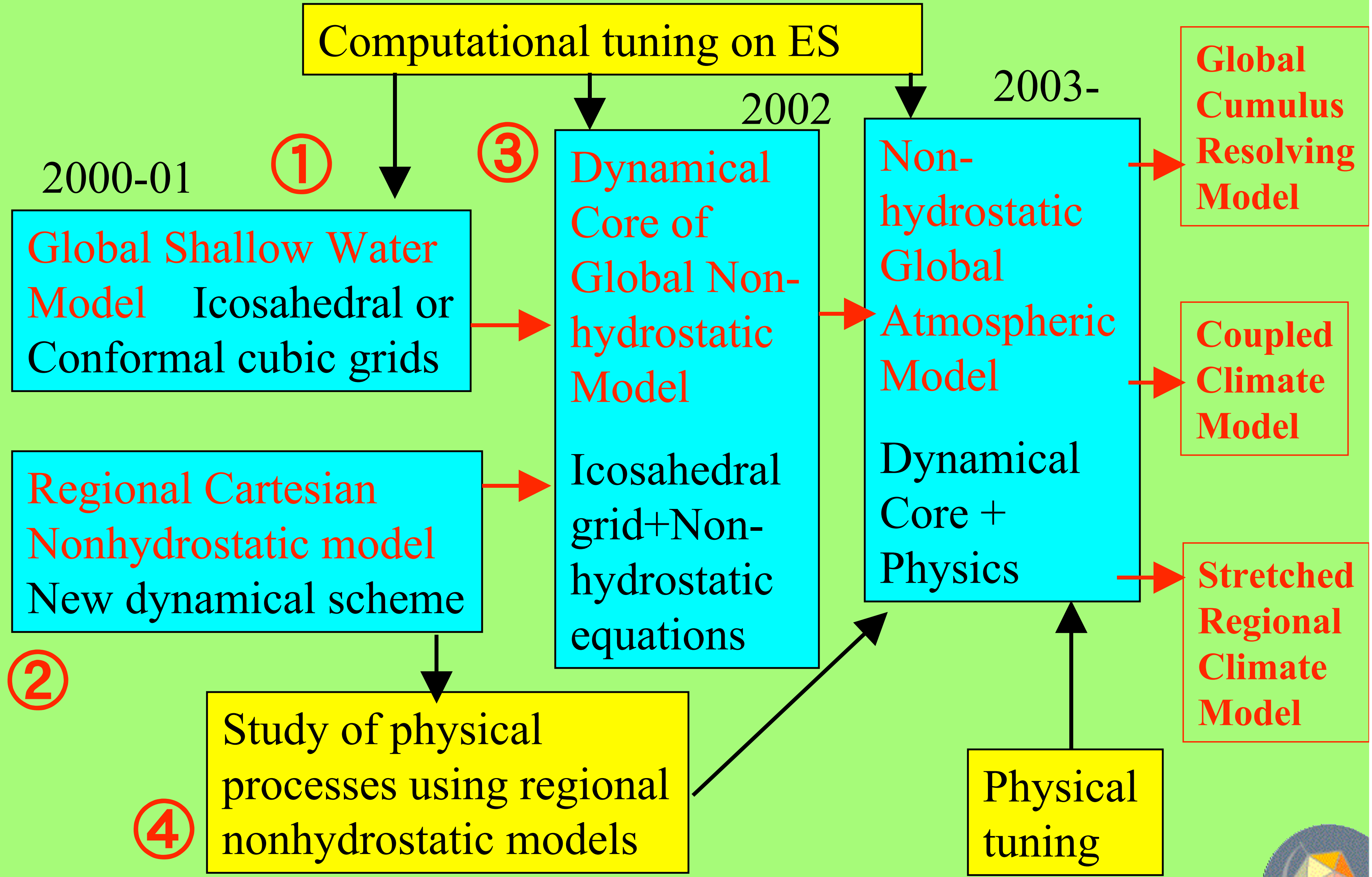
  2hours for one day simulation if 320 nodes are used

- **30km grid (glevel-8)**

  6hours for one year simulation if 80 nodes are used

⇒ requires physical parameterization for 7-30km grids

Development procedure



4. Study of cloud processes
Resolution dependency with CRMs

- Methodology
- Squall line experiment
- Radiative-convective equilibrium experiment

Methodology (1)

- We need cloud parameterization somehow.
- Candidates of cloud parameterization
  - Traditional approach
    - Arakawa: borrowed from CCSR/NIES AGCM
    - Emanuel: Testing on AFES (Dr. Enomoto)
    - Kain & Fritcsh
    - Yamasaki, Kurihara,…
  - Super-parameterization?
    - Appropriate for the 10-30km grid model?

Methodology (2)

- Validation of cloud parameterization
  - Studies through model hierarchy (GCSS, EUROCS)
    GCM～CRM~SCM & stretched model
  - Define a true solution and compare with parameterized experiments.
- Resolution dependency
  - Deterministic test
    - Squall line (by Dr. Nasuno)
  - Statistical test
    - Radiative-convective equilibrium
      Dr. Nasuno; Satoh (a preliminary result)
- Global model study (planned)
  - *NICAM is a powerful tool to study cloud parameterization issues.*
  - Global cloud resolving model ~3.5km mesh model
  - Stretched grid with explicit convection
    vs uniform grid with/without cloud parameterization scheme
  - Aqua planet experiment
  - AMIP, THORPEX, ….

Squall line experiment

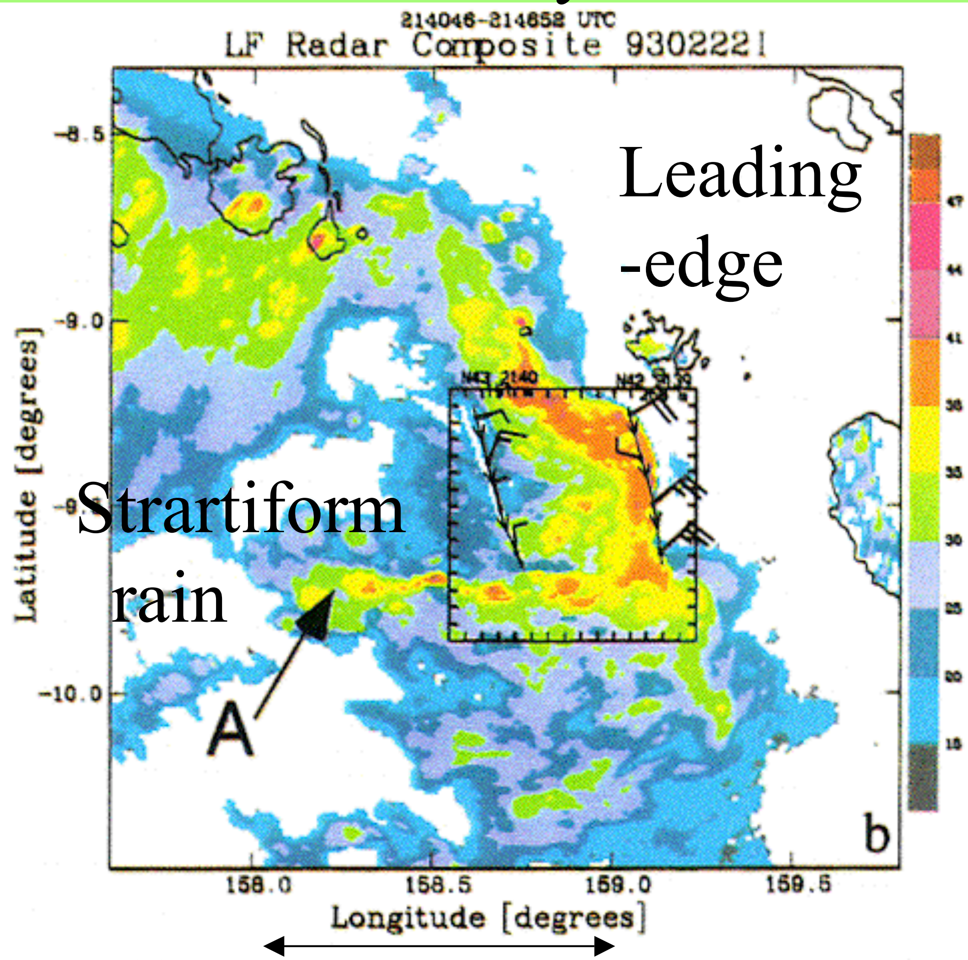
- **Dependence of Convective Behavior on Horizontal Resolution**

Tropical Squall Line
--- GCSS WG4 Case1
Redelsperger et al.(2000)

TOGA COARE (1993/2/22)
900 km x 900 km x 21 km
Δx= 1.5, 2.5, 3.75, 5, 7.5 km

Nasuno and Saito (2003)
MRI/NPD Nonhydrostatic model

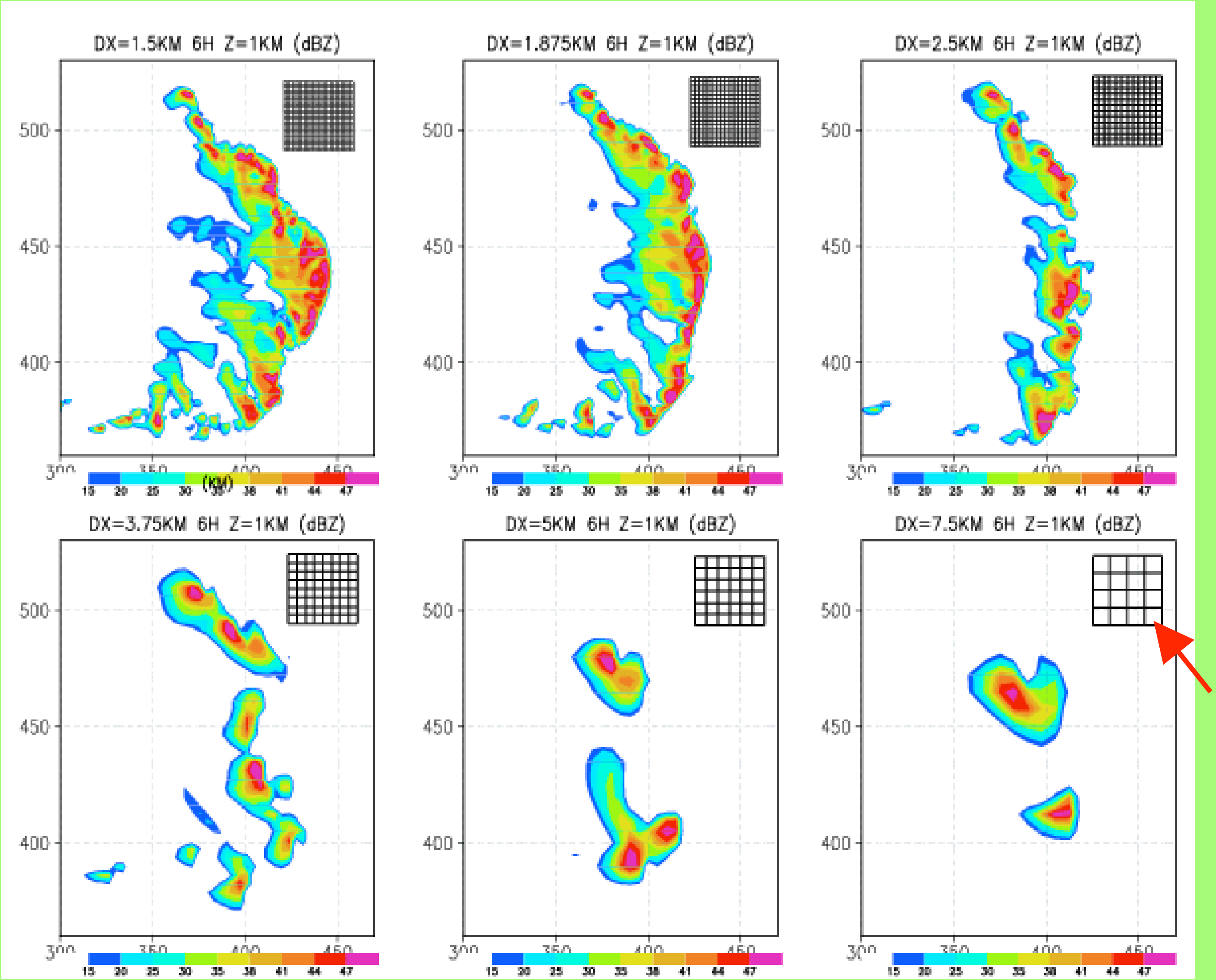
Radar Reflectivity



100 km

Jorgensen et al. (1997)

Dependency on grid interval



1.5km

Mesh size

3.75km

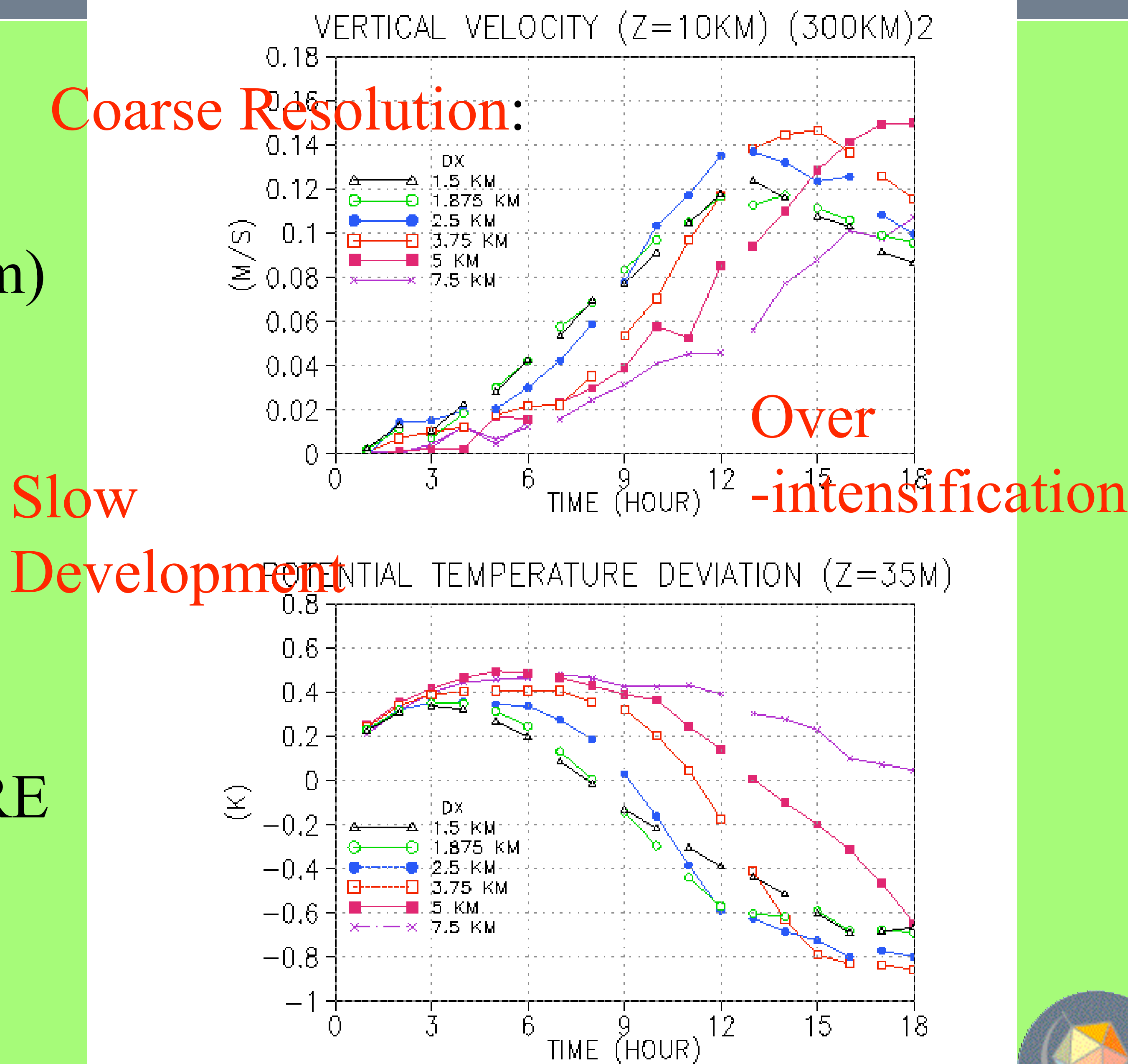
5km

7.5km

AVERAGE SUB-DOMAIN (300km x 300km)

VERTICAL VELOCITY (z=10km)

POTENTIAL TEMPERATURE DEVIATION (z=35m)



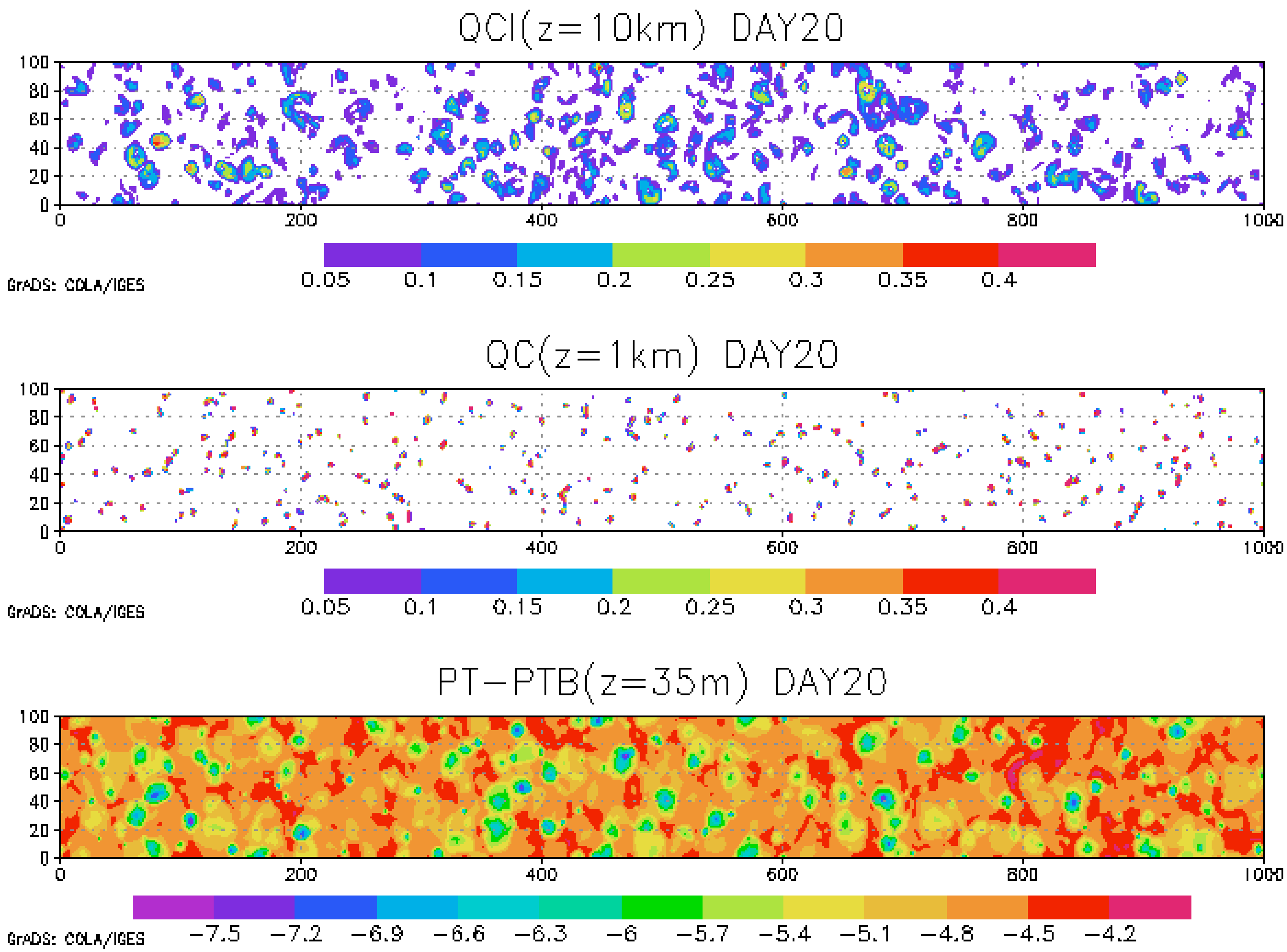
Radiative-convective equilibrium experiment

- **3D domain; 1000 km x 100 km x 21 km**

  by Nasuno (2003)

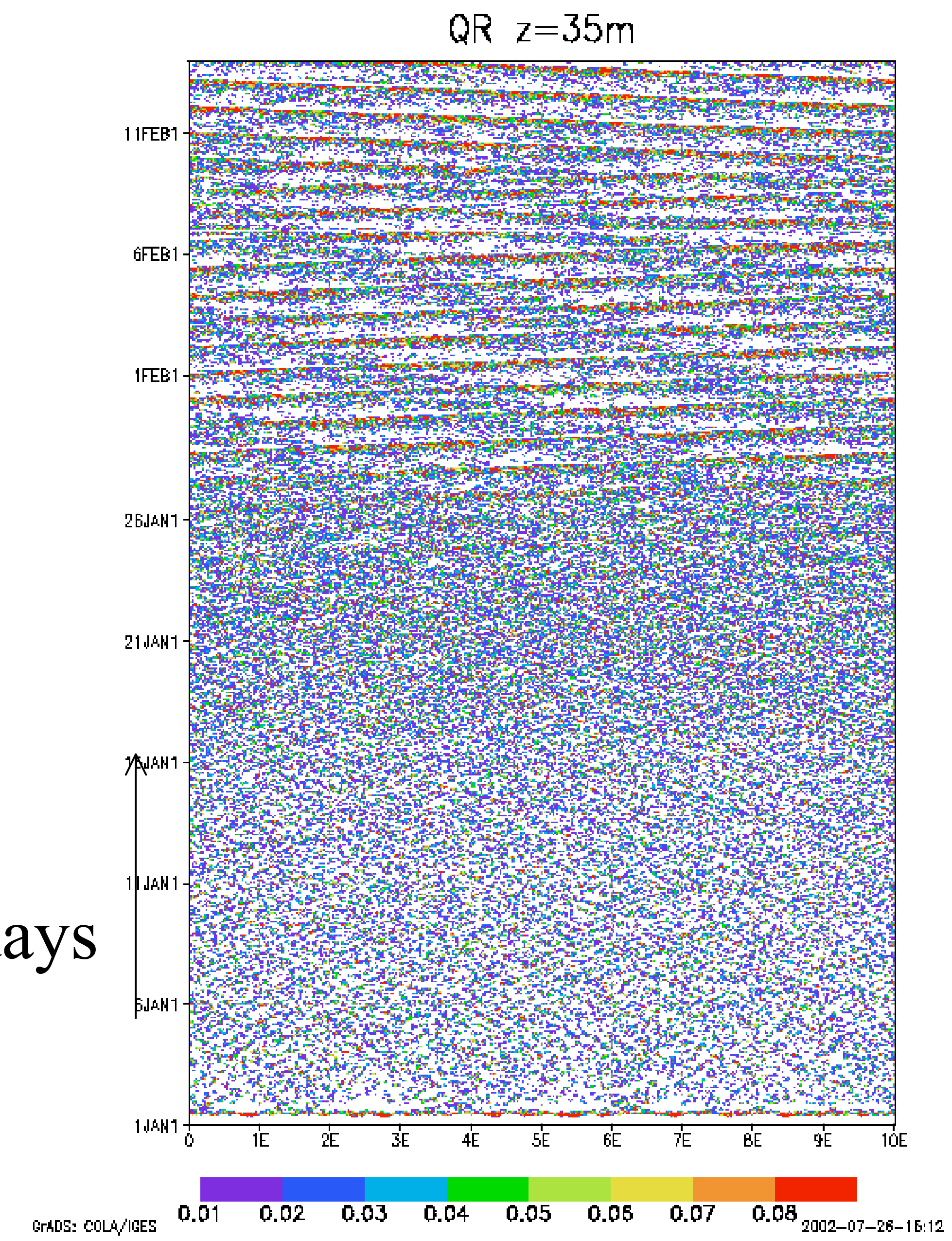
  - **Δx= 2 km**
  - **Uniform Radiative Cooling (-2K/day)**
  - **Tropical SST(302K)**
  - **Long-time Simulation (56 days)**
  - **No large scale forcing: pure RCE exp.**

cf. Tompkins (2001)


QCI(z=10km) DAY20
100
80
60
40
20
0
0
200
400
600
800
1000
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
GrADS: COLA/IGES
QC(z=1km) DAY20
100
80
60
40
20
0
0
200
400
600
800
1000
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
GrADS: COLA/IGES
PT−PTB(z=35m) DAY20
100
80
60
40
20
0
0
200
400
600
800
1000
−7.5
−7.2
−6.9
−6.6
−6.3
−6
−5.7
−5.4
−5.1
−4.8
−4.5
−4.2
GrADS: COLA/IGES

Rainwater
(z=35m)

y-averaged
(100 km)



10 days

Large-scale organizatio n

Loosely organized (small scale)

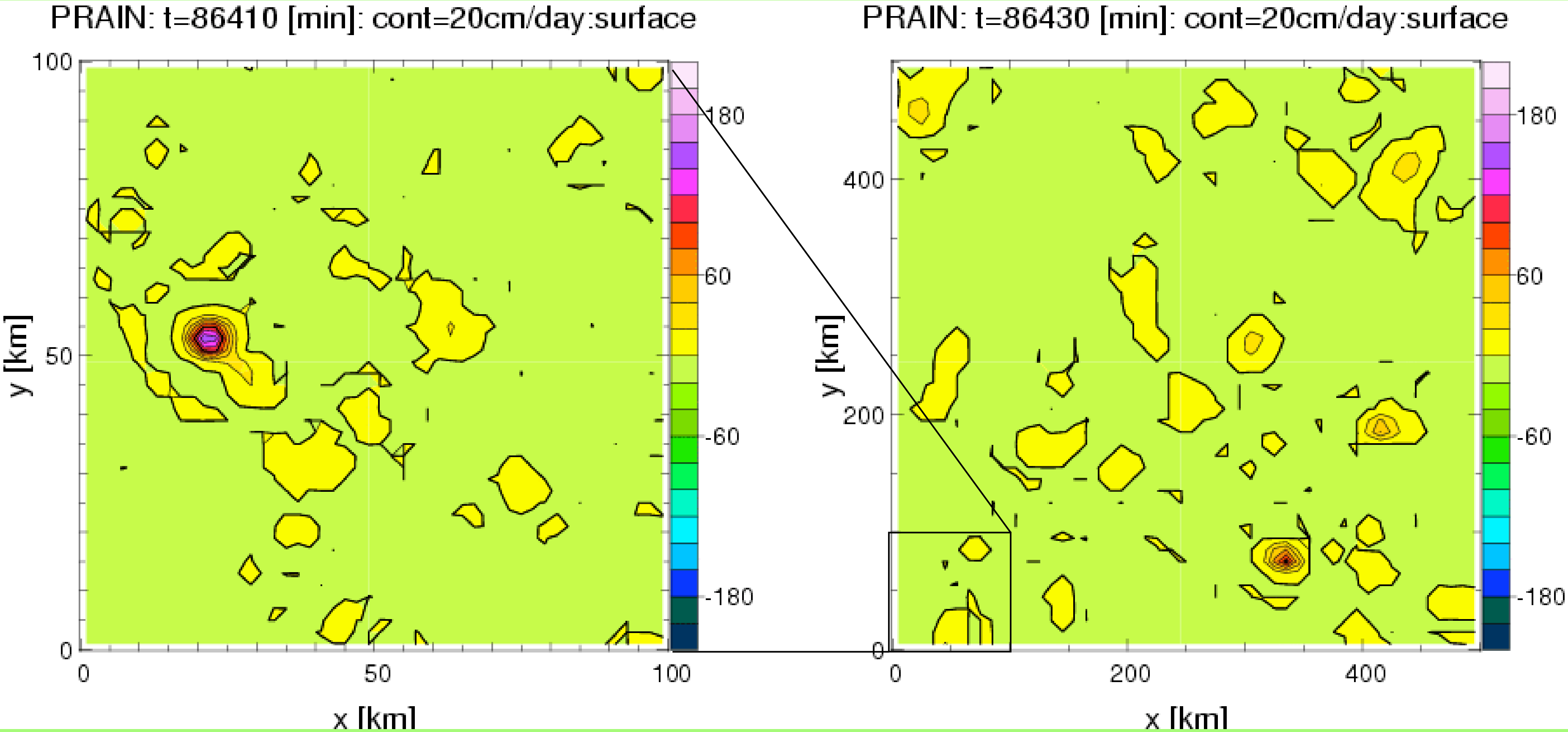
1000 km

- **Issues of the radiative-convective equilibrium experiment**
  - **Strong dependence on artificial parameters:**
    - **Surface flux with bulk formula:**
      Depends on minimum surface velocity
    - **Control of the shear: Mean winds develop internally.**
    - **Numerical diffusion.**
    - **Rayleigh friction.**
  - **Interactive radiation vs fixed radiation: about -2K/day**
  - **Larger domain is better: at least 1000km × 1000km**
    - **To internally calculated large scale forcing and cumulus convection by self-organization of convection**
      or by giving a sea surface temperature gradient
      or by imposing a large scale forcing (not desirable)
    - **But Time consuming**
  - **2D vs 3D**
    - **2D model can cover the equator**

- **Requires suitable setup of a feasible standard experiment**
- **Proposal: basically follows Tompkins & Craig (1998)**
- **Control experiment**
  - **100km × 100km × 25km**
  - **$\Delta x = \Delta y = 2$km**
  - **Lowest level 20m, 54 layers**
  - **Fixed radiative cooling: 2K/day (z<9km) decreseas to zero at z=12km**
  - **Minimum wind speed for bulk formula: 4m/s**
  - **Total integration time: 75days**
- **Preliminary experiments: Coarser resolution experiment**
  - **500km × 500km × 25km**
  - **$\Delta x = \Delta y = 10$km**
  - **The other conditions are the same as the control experiment.**
  - ***No cumulus parameterization***

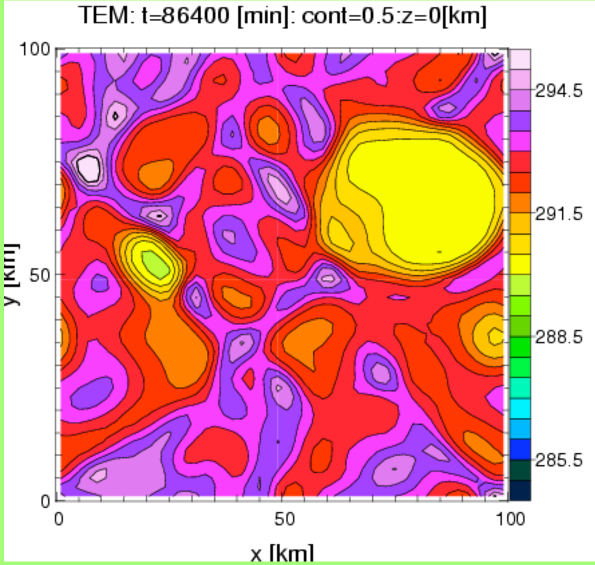
Precipitation

100km × 100km, $\Delta x = 2$km　　　　**500km × 500km, $\Delta x = 10$km**

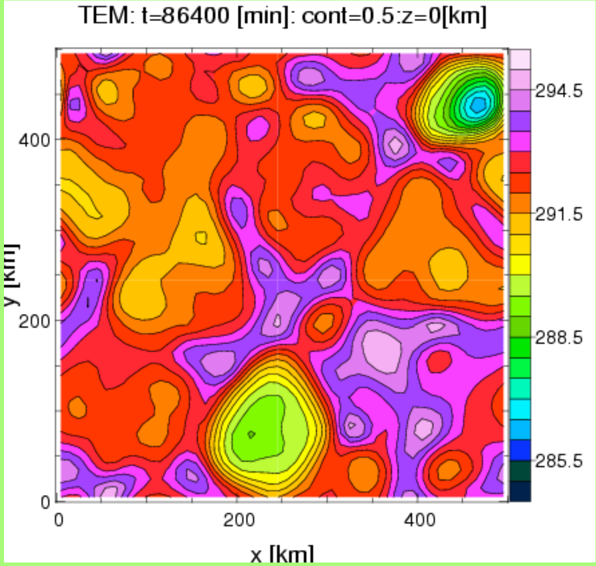


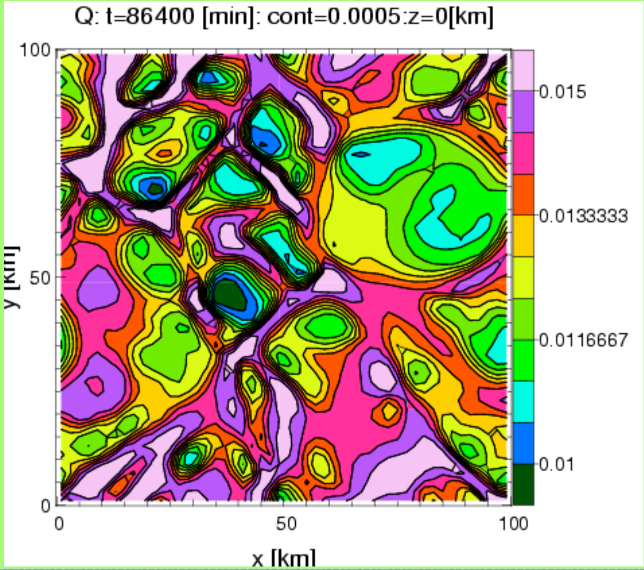
Temparature and humidity at the lowest layer(z=20m)

100km × 100km, Δx＝2km | **500km × 500km, Δx＝10km**

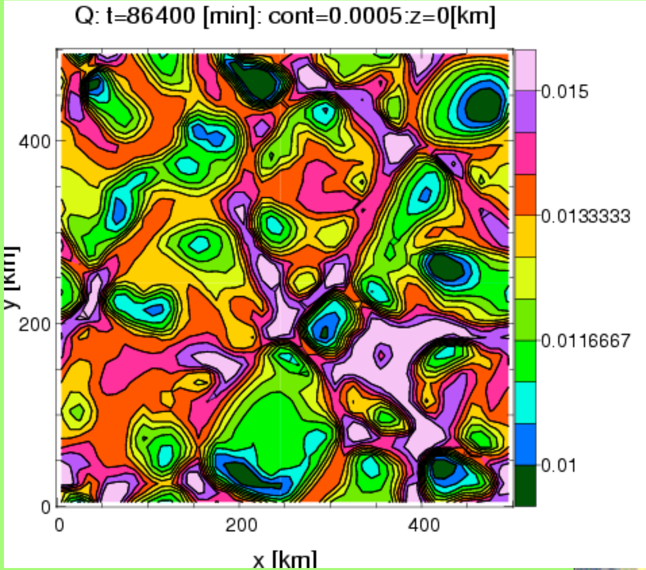


Temperature





Specific humidity

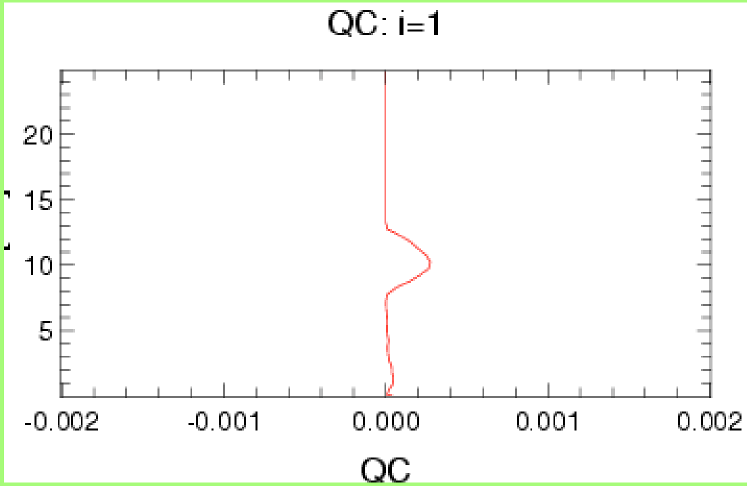


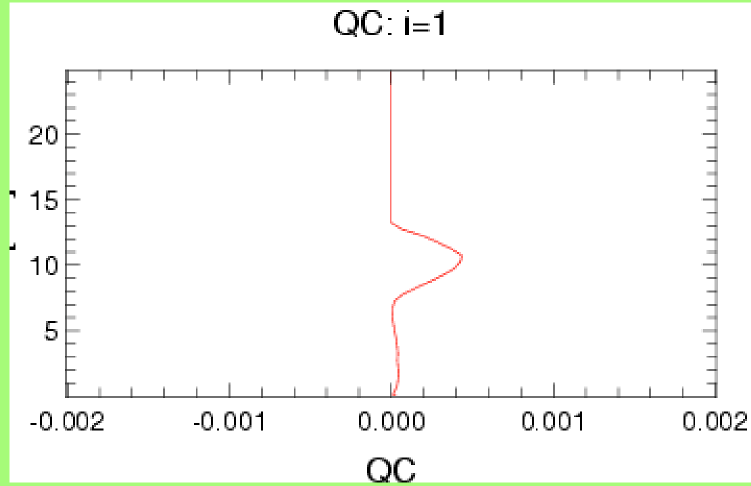
Cloud and humidity

100km × 100km, $\Delta x = 2km$

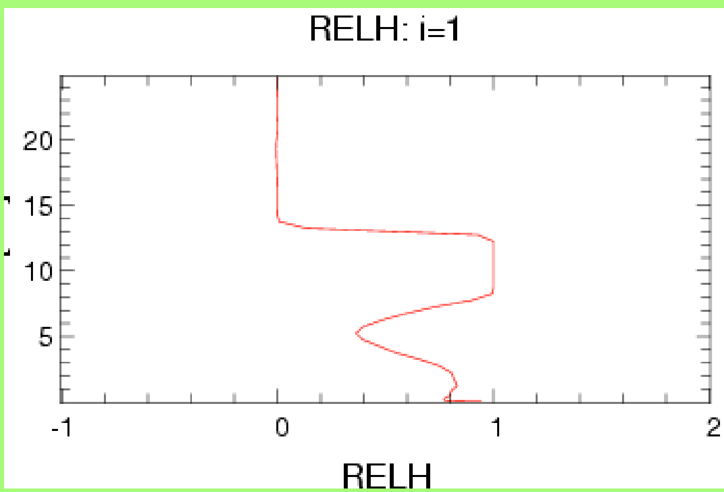
500km × 500km, $\Delta x = 10km$

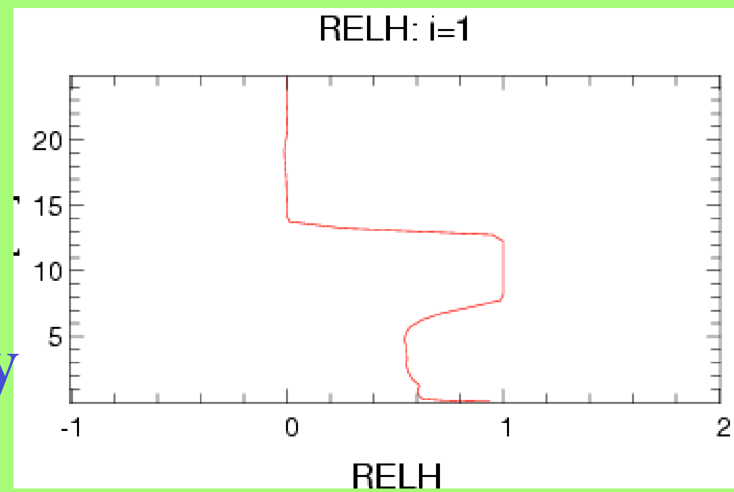
Cloud water





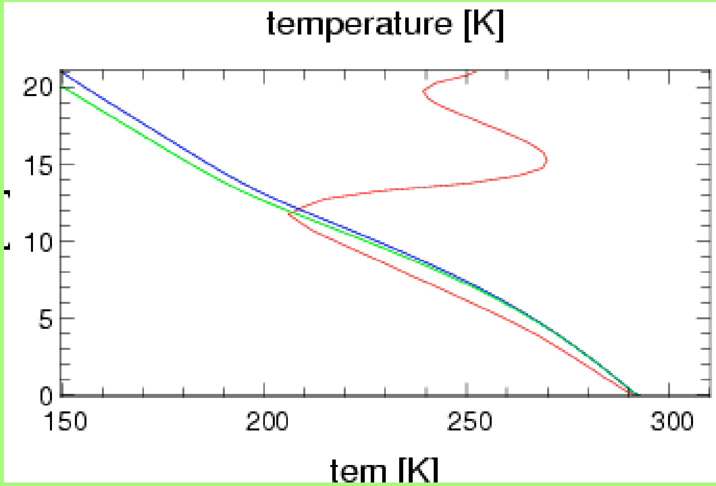
Relative humidity

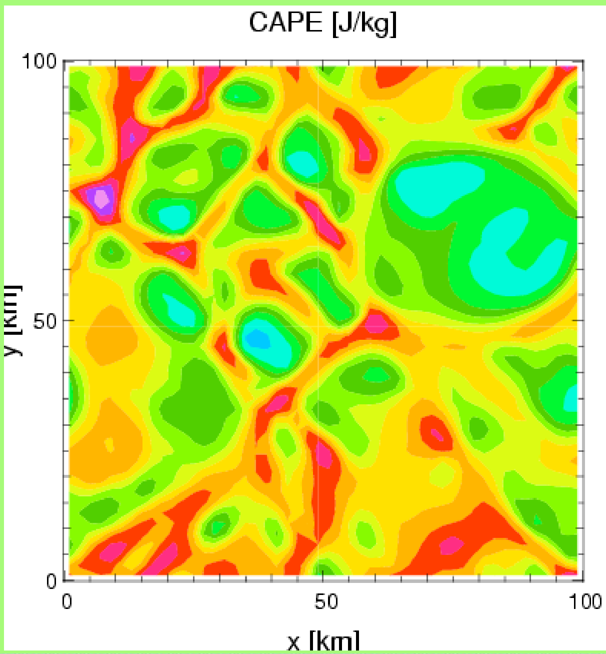




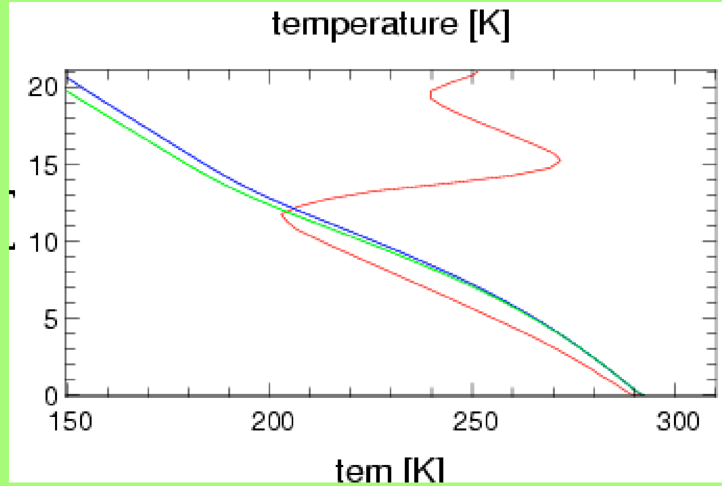
CAPE　for parcel at 20m (0-40m avg.)

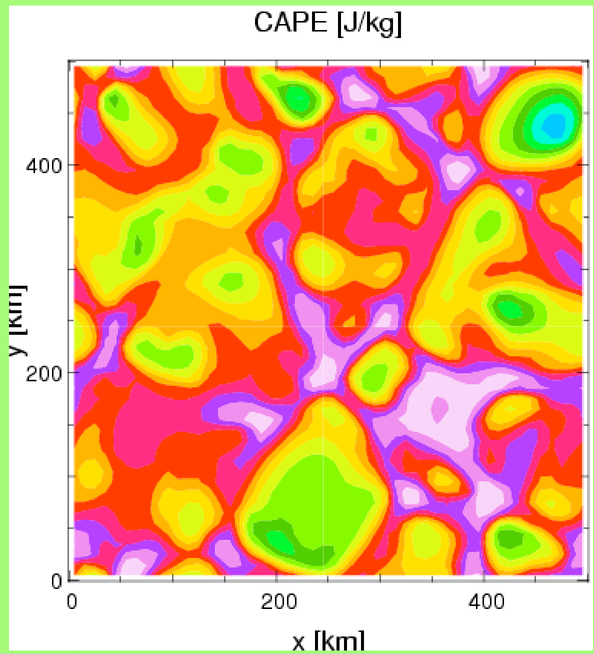
100km × 100km, Δx＝2km





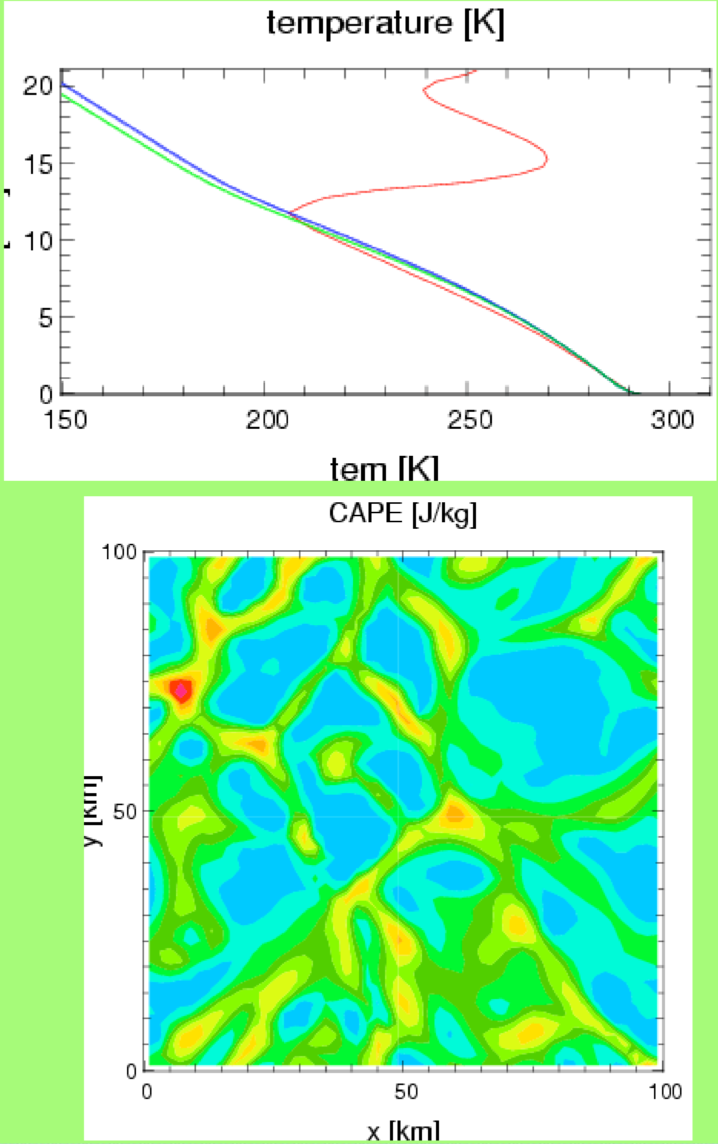
500km × 500km, Δx＝10km



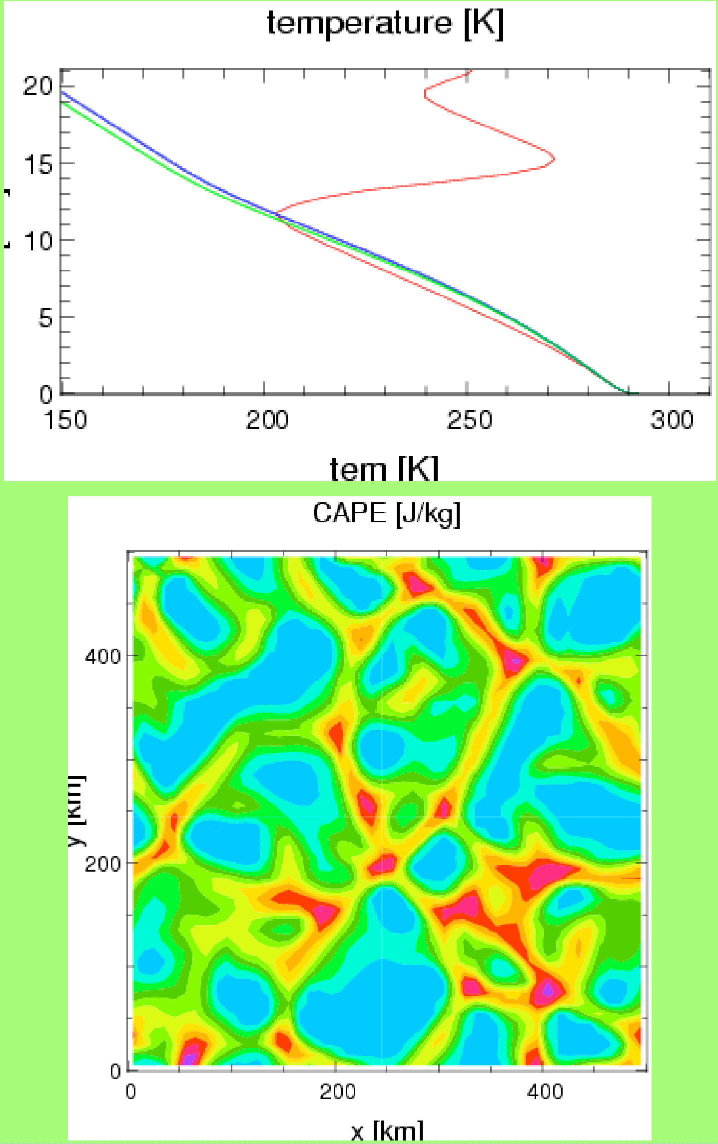


CAPE for parcel at 60m (0-160m avg.)

100km × 100km, Δx=2km

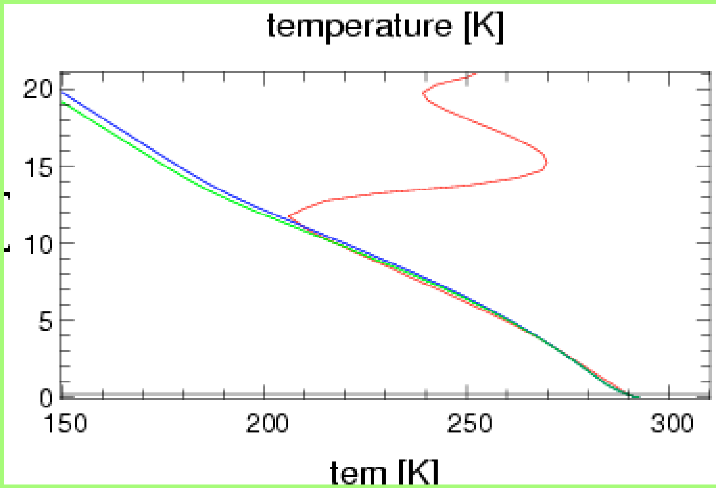


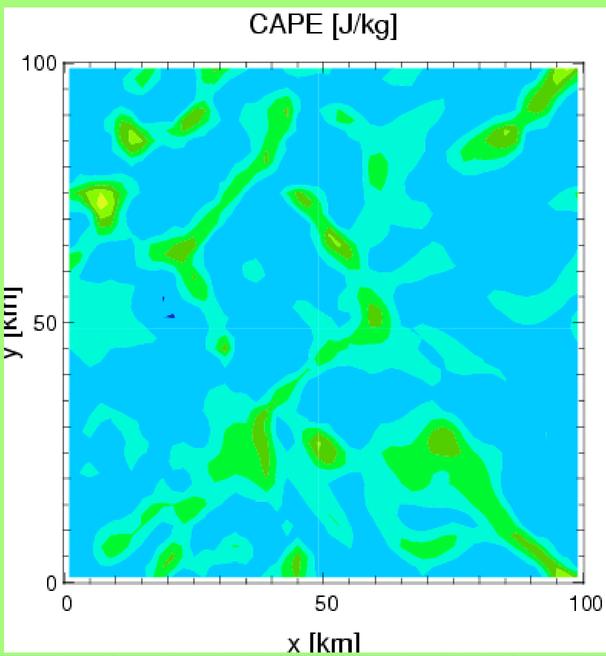
500km × 500km, Δx=10km



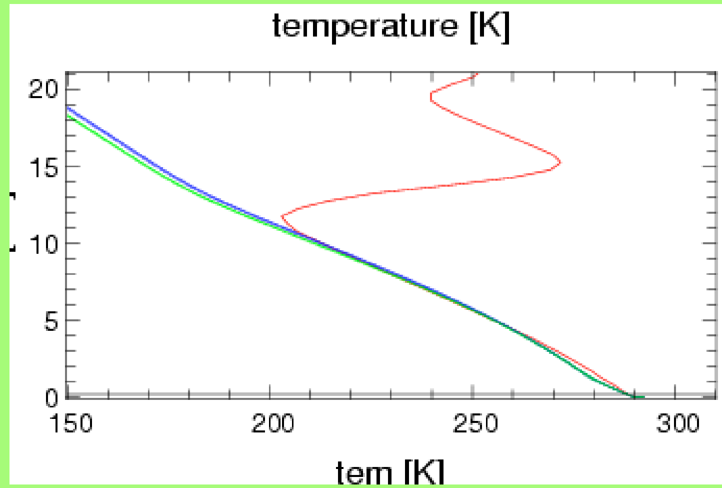
CAPE　for parcel at 240m(0-640m avg.)

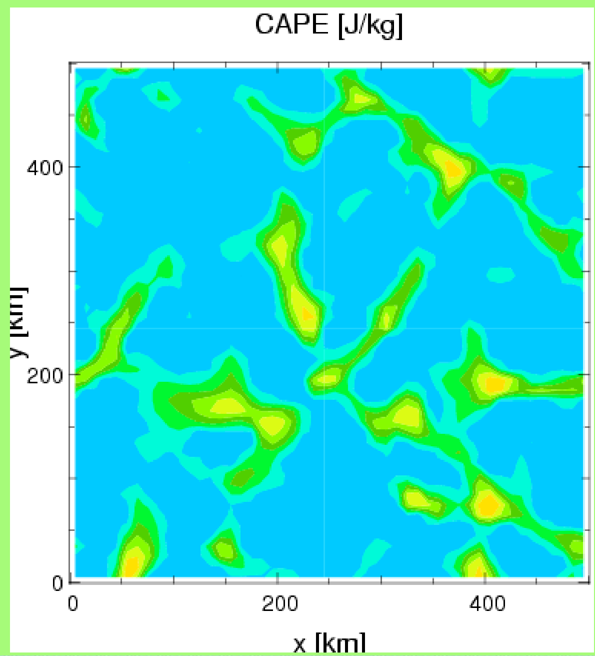
100km × 100km, Δx＝2km



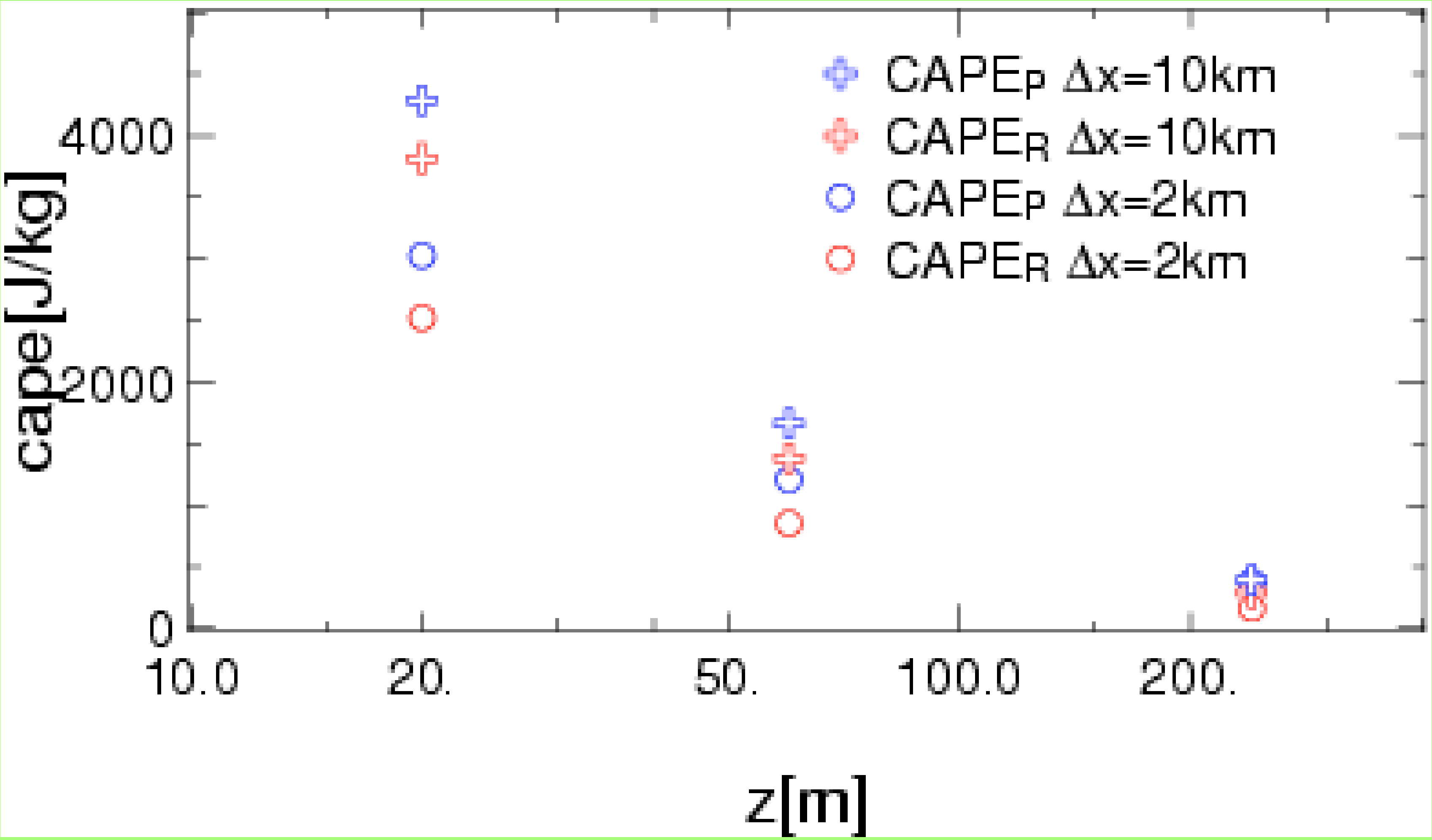


500km × 500km, Δx＝10km





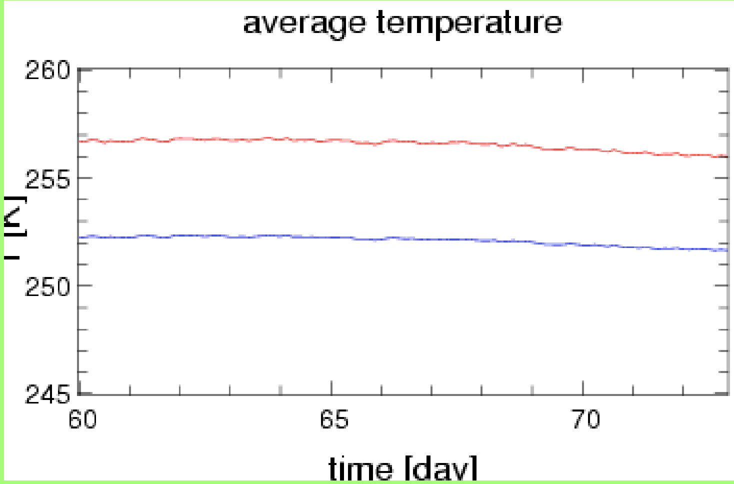
CAPE vs Height of parcel level

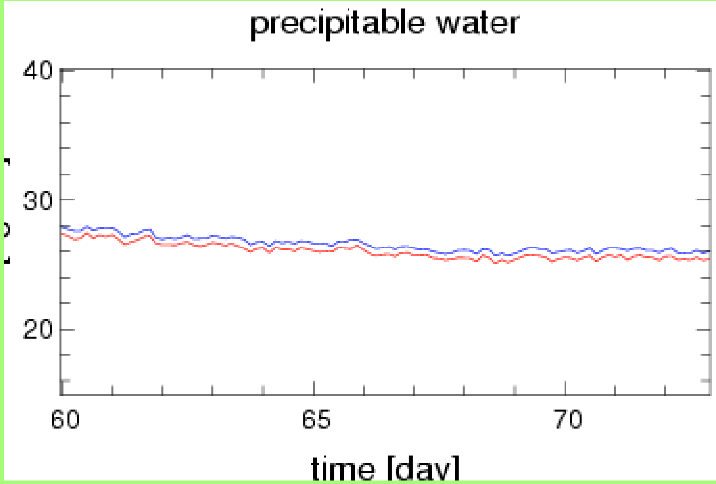


FRSGC Frontier Research System for Global Change

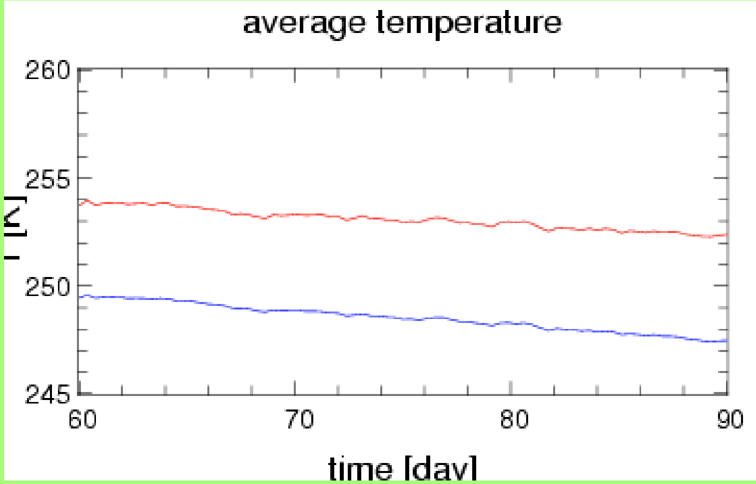
Mean temperature and precipitatable water

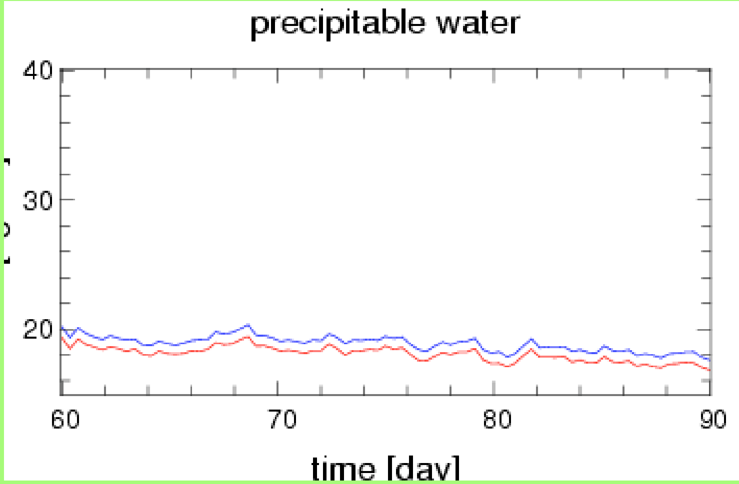
100km × 100km, Δx＝2km





500km × 500km, Δx＝10km





Summary of radiative-convective equilibrium experiment

- Preliminary study suggests that as the grid is coarser,
  - Colder mean temperature and less precipitable water
  - Dry surface boundary layer, a little humid in the middle layer
  - A slightly more cloud water
  - Larger CAPE
  - Very dry in comparison to other study: maybe because of warm rain
- Future study: validation of traditional parameterization
  - Define a reference state
    - Understand model behaviors on artificial parameters
    - Large domain experiment: (500km × 500km with Δx=2km)
    - Convergence for finer meshes: Δx=1km, 500m, …
  - Introduce cloud parameterizations in the coarser grid model 500km × 500km, Δx=10km
    - Cloud parameterization must reduce the resolution dependency.
  - Introduce effects of ice and radiation
- Radiative-convective equilibrium experiment will provide useful information for super-parameterization.

Summary

- A new regional non-hydrostatic model using a new conservative scheme.
  - Conservation of mass and total energy.
  - Accurate formulation of moist process.
- A newly constructed icosahedral grid.
  - Quasi uniform grid using the spring dynamics.
  - A stretched grid => a regional climate model
- A new dynamical core of the nonhydrostatic icosahedral grid model: Validation of the dynamical core
  - Life cycle of extratropical cyclone experiment.
  - Held & Suarez experiment.
- Measurement of computational performance on the Earth Simulator.
  - A very good scalability and a good sustained performance (40% of peak performance).
  - Superior to a spectral model.

Summary（2）

- **Cumulus/cloud parameterization is required in NICAM for practical purposes.**
- **Study of cloud parameterization through resolution dependency of cloud resolving models.**
  - **Squall line experiment**
    - **Slow development and over-intensification of the coarser model**
  - **Radiative-convective equilibrium experiment**
    - **Propose of a standard experiment**
    - **To be used for investigation of statistical properties of cloud parameterizations**

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Icosahedral grid

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2. Tomita et al., (2002) : “An Optimization of the Icosahedral Grid Modified by the Spring Dynamics”, *J. Comput. Phys*., **183**, 307-331

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2. Goto et al., (2002) : “Computational performance of dynamical part of next generation climate model using an icosahedral grid on the Earth Simulator”, *Parallel CFD 2002*, in press
3. Tomita et al., (2002b) : “The Non-hydrostatic Icosahedral Global Model for the Earh Simulator”, *Max-Planck Institute for Meteorology technical Report 2002*
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