The Global Nonhydrostatic Model NICAM

Numerics and performance of its dynamical core

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Contents

Motivation (1)

- **General problem for current AGCMs**
  - **Cumulus parameterization**
    - **One of ambiguous factors**
    - **Statistical closure of cumulus**
- **Future AGCM**
  - **Explicit treatment of each cloud**
    - **Cumulus parameterization**
      Large scale condensation scheme : not used!
    - **Cloud microphysics : used!**
  - **Explicit treatment of multi-scale interactions**
    - **Each cloud scale → meso-scale → planetary scale**

→ Global Cloud Resolving Model

Motivation (2)

- **Target resolutions**
  - **5 km or less in the horizontal direction**
  - **Several 100 m in the vertical**
- **Strategy of dycore development**
  - **Quasi-uniform grid**
    - **Spectral method :**
      not efficient in high resolution simulations.
      - **Legendre transformation**
      - **Massive data transfer between computer nodes**
    - **Latitude-longitude grid :**
      the pole problem.
      - **Severe limitation of time interval by the CFL condition.**
    - **The icosahedral grid:**
      homogeneous grid over the sphere
      - **To avoid the pole problem.**
  - **Non-hydrostatic equations system**
    - **Very high resolution in horizontal direction.**

Model Hierarchy

Global Shallow Water Model

- To examine the potential of icosahedral grid.

  (Tomita et al. (2001,2002) *J.Compt.Phys.*)

  – Test bed for development of numerical scheme (e.g. advection scheme) on the icosahedral grid.

Regional Non-hydrostatic Model

- To examine a numerical non-hydrostatic scheme suitable to climate model.

  (Satoh(2002,2003) *Mon.Wea.Rev.*)

  – Test bed for development and validation of new physical parameterizations.

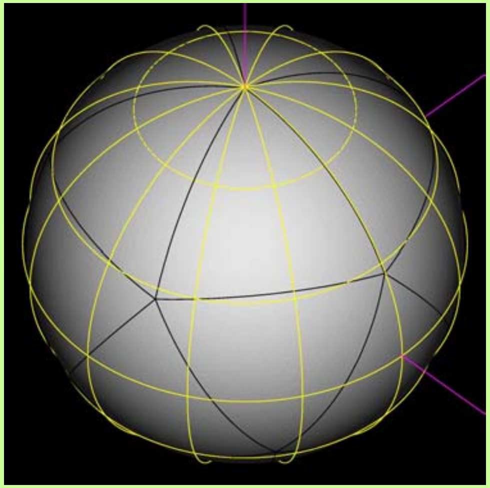
Global Non-hydrostatic Model

- Base on **our non-hydrostatic scheme**
- Using **the icosahedral grid configuration** in the horizontal direction.

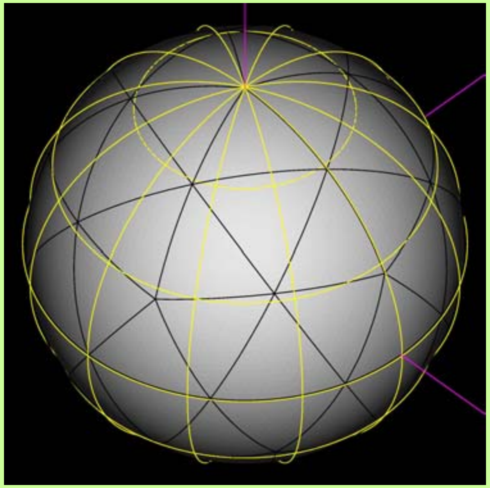
  (Tomita & Satoh (2004) *Fluid Dyn.Res.*)

Grid Generation Method

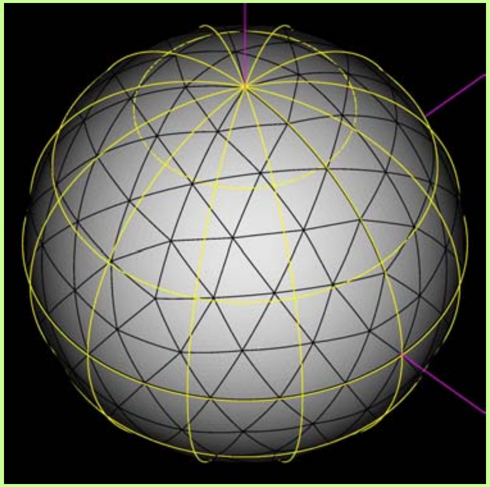
(0) grid division level 0



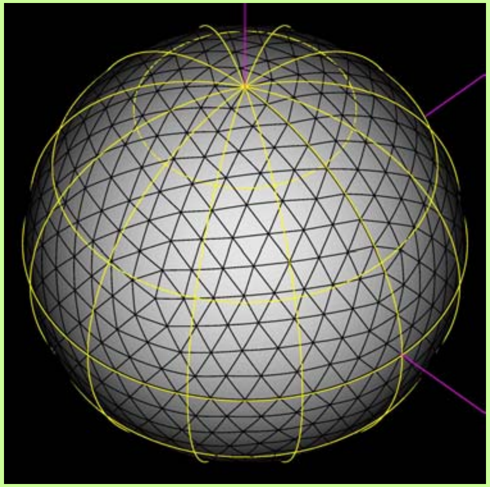
(1) grid division level 1



(2) grid division level 2



(3) grid division level 3

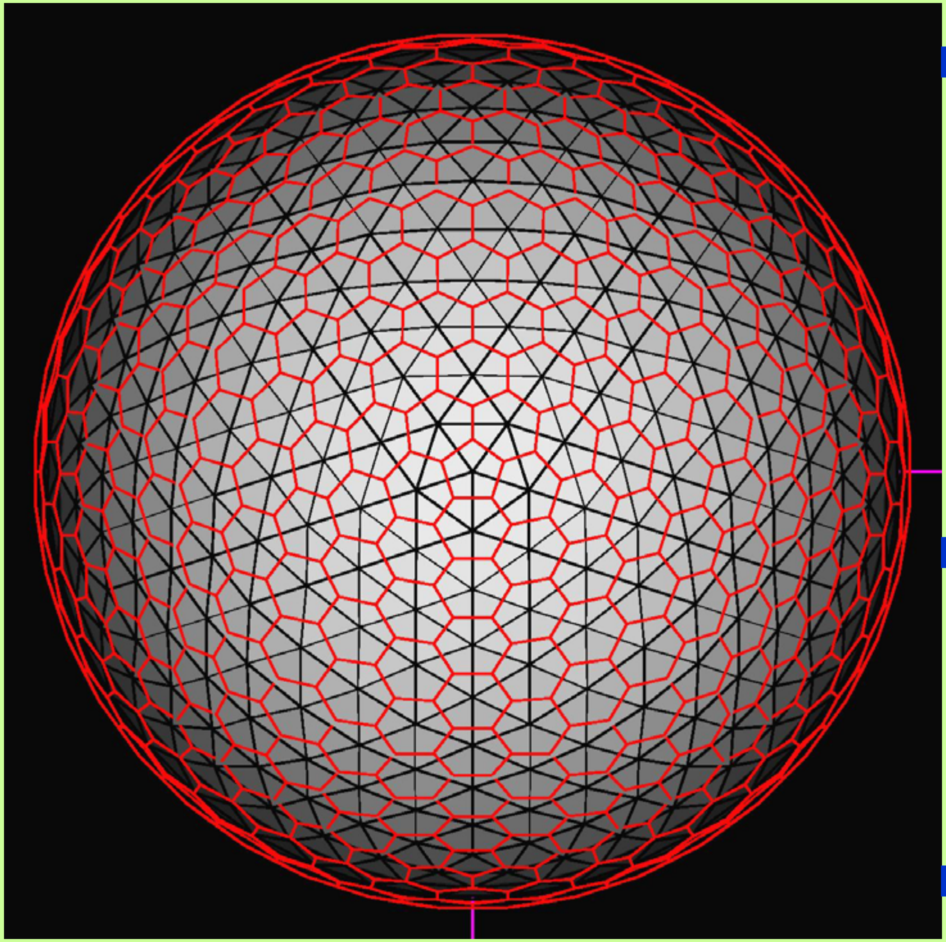


- **Grid generation**
  1. **Start from the spherical icosahedron. (glevel-0)**
  2. **Connection of the mid-points of the geodesic arc → 4 sub-triangle (glevel-1)**
  3. **Iteration of this process → A finer grid structure (glevel-n)**

  STD-grid

- **# of gridpoints**
  - **11 interations are requried to obtain the 5km grid interval.**

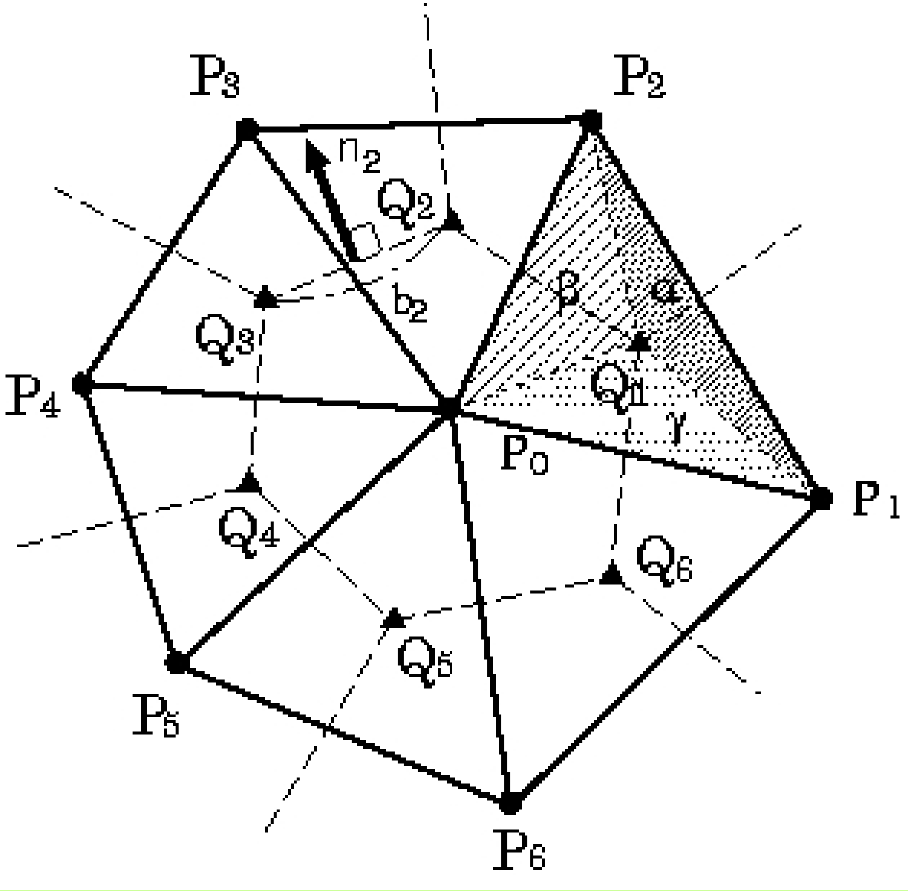
Grid arrangement



Glevel-3 grid & control volume

- **Arakawa A-grid type**
  - **Velocity, mass**
    - triangular vertices
  - **Control volume**
    - Connection of center of triangles
      - Hexagon
      - Pentagon at the icosahedral vertices
- **Advantage**
  - **Easy to implement**
  - **Less computational mode**
    - Same number of grid points for vel. and mass
- **Disadvantage**
  - **Non-physical 2-grid scale structure**
    - E.g. bad geostrophic adjustment

Horizontal differential operator



e.g. Divergence

1. Vector : given at P_i

$$\mathbf{u}(P_i)$$

2. Interpolation of u at Q_i

$$\mathbf{u}(Q_i) \approx \frac{\alpha \mathbf{u}(P_0) + \beta \mathbf{u}(P_i) + \gamma \mathbf{u}(P_{1+\mathrm{mod}(i,6)})}{\alpha + \beta + \gamma}$$

3. Gauss theorem

$$\nabla \bullet \mathbf{u}(P_0) \approx \frac{1}{A(P_0)} \sum_{i=1}^{6} b_i \frac{\mathbf{u}(Q_i) + \mathbf{u}(Q_{1+\mathrm{mod}(i,6)})}{2} \bullet \mathbf{n}_i$$

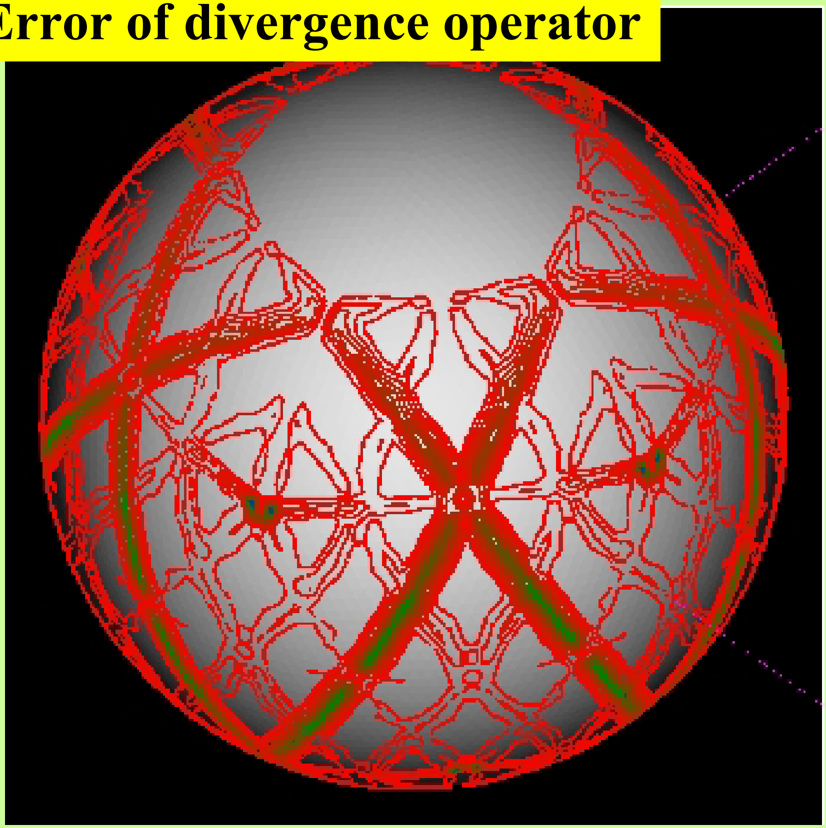
2nd order accuracy?

NO

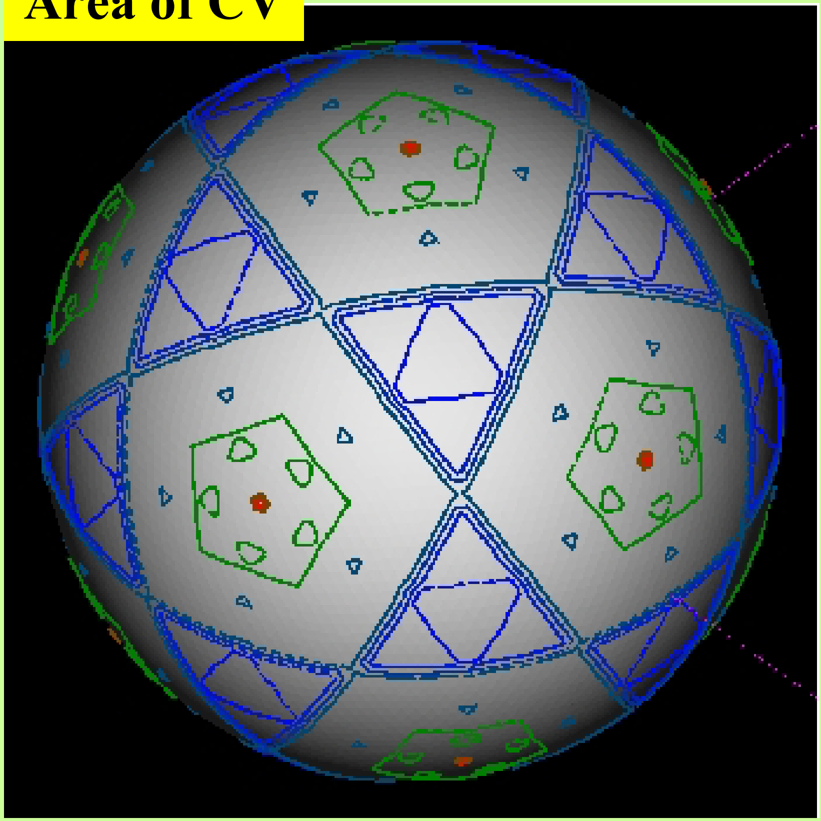
→ **Allocation points is not gravitational center (default grid)**

Error distribution of div U

Error of divergence operator



Area of CV



- Error of div operator
  - Large error on the original icosahedral arc
    - Fractal distribution
  - Generation of grid noise

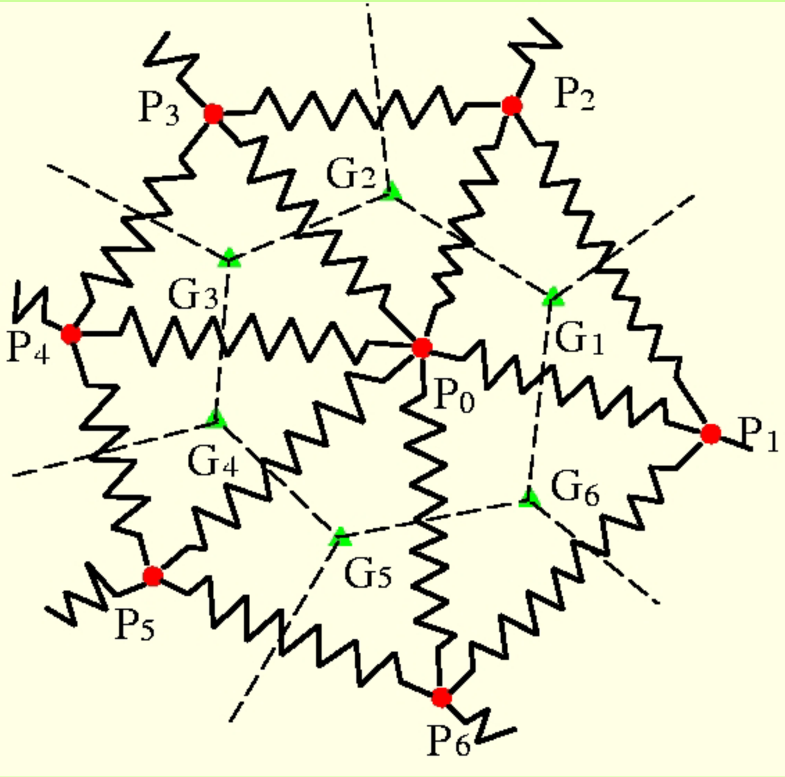
- Distribution of CV area
  - Fractral distribution

GUESS:
smoothness of CV
→ Reduction of grid noise

Modified Icosahedral Grid (1)

Reconstruction of grid by spring dynamics

To reduce the grid-noise



1. STD-grid :
   Generated by the recursive grid division.

2. SPRING DYNAMICS :
   Connection of gridpoints by springs

$$\sum_{i=1}^{6} k(d_i - \bar{d})\mathbf{e}_i - \alpha \mathbf{w}_0 = M \frac{d\mathbf{w}_0}{dt}$$

$$\mathbf{w}_0 = \frac{d\mathbf{r}_0}{dt}$$

Modified Icosahedral Grid (1)

- **SPR-grid**
  - **Solve the spring dynamics**

    → **The system calms down to the static balance**

$$\sum_{i=1}^{6} k(d_i - \bar{d})\mathbf{e}_i = 0$$

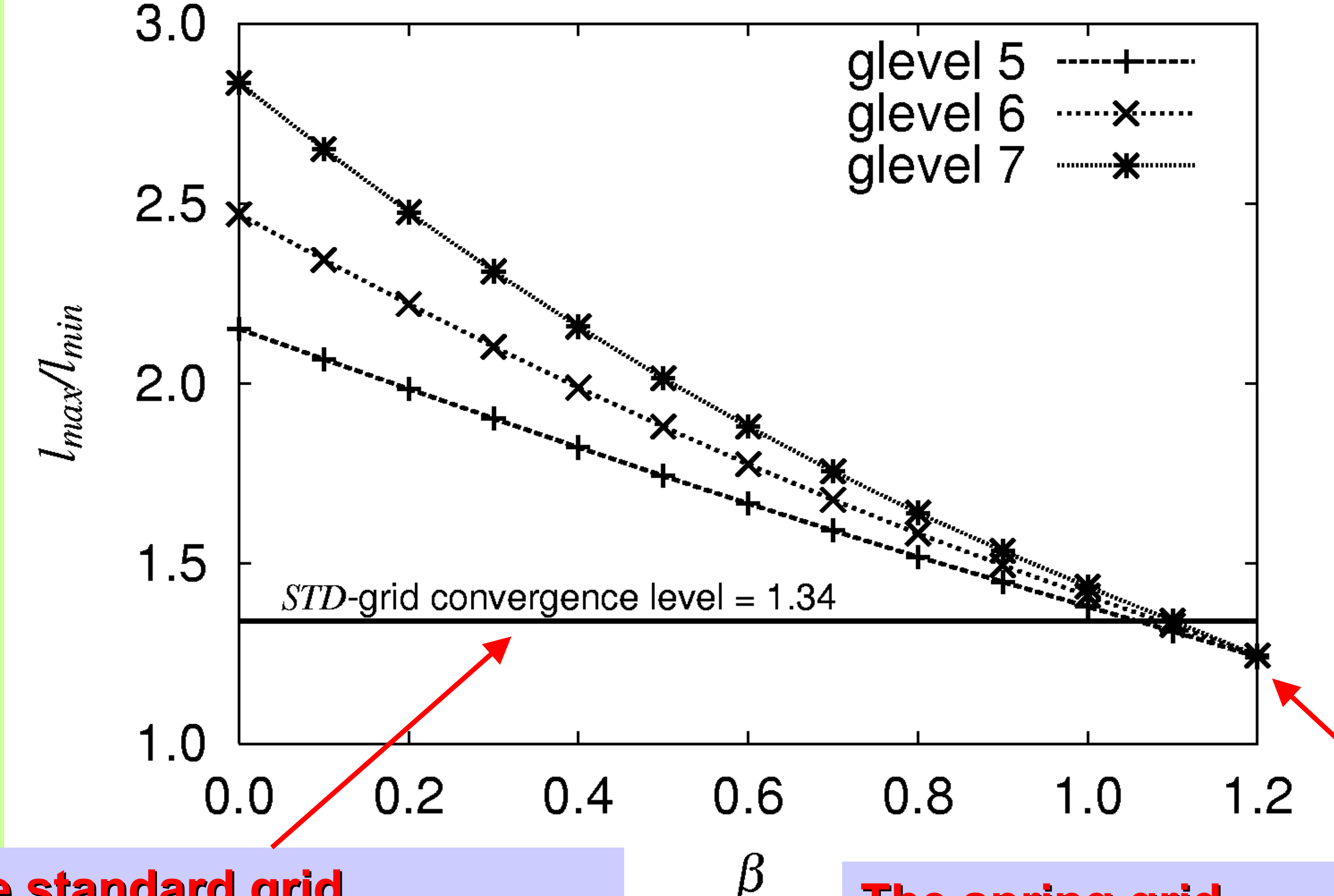
  - **Construction of CV**
    - **Connection of the center of triangles**
- **One non-dimensional parameter β**
  - **Natural length of spring**

$$\bar{d} = \beta \frac{2\pi a}{10 \times 2^{l-1}}$$

    - **Should be tuned!**

Dependency of β on homogeneity

The ratio of *lmax / lmin* against the parameter β



The standard grid

l_{max}/l_{min} → **1.34**.

The spring grid

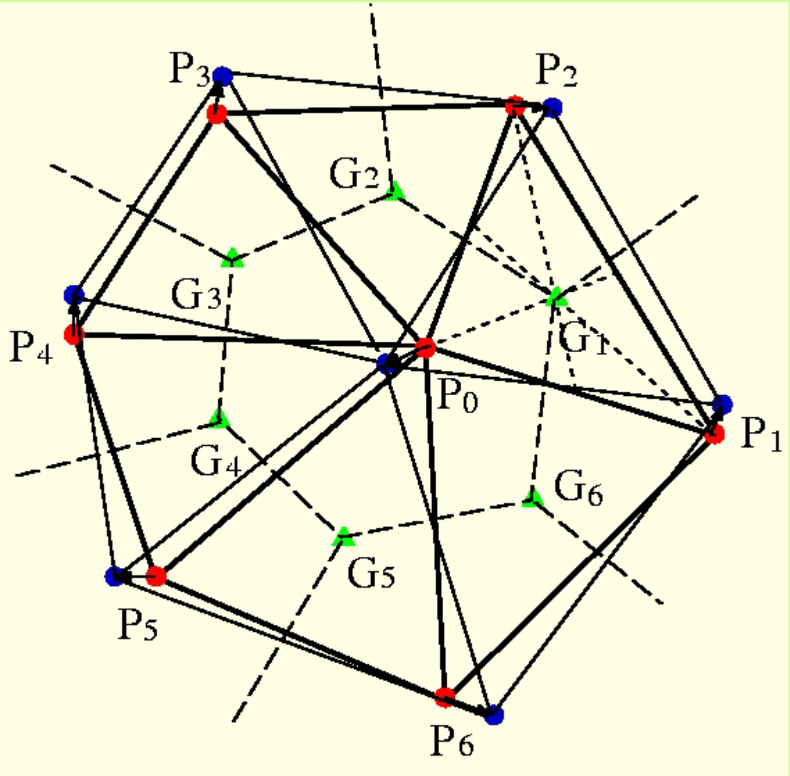
l_{max}/l_{min} **depends on** β **and glevel.**

→**If** β **=1.2,** *lmax/lmin* → **1.24**.

Modified Icosahedral Grid (2)

Gravitational-Centered Relocation

- To make the accuracy of numerical operators higher



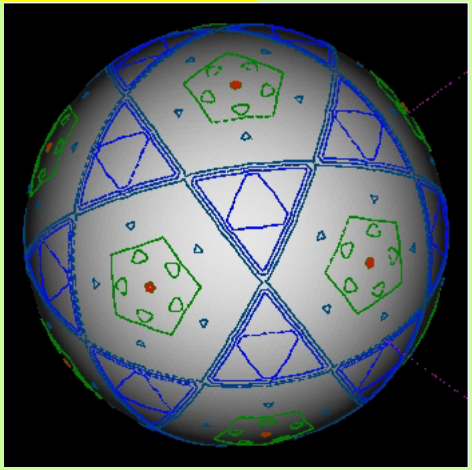
1. **SPR-grid:**
   Generated by the spring dynamics.
   → ●
2. **CV:**
   Defined by connecting the GC of triangle elements.
   → ▲
3. **SPR-GC-grid:**
   The grid points are moved to the GC of CV.
   → ●

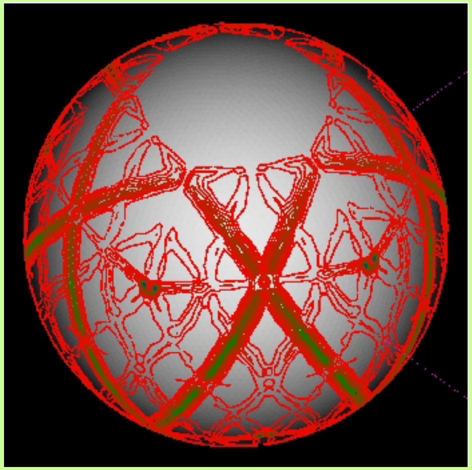
→ The 2nd order accuracy of numerical operator is perfectly guaranteed at all of grid points.

Improvement of error distribution

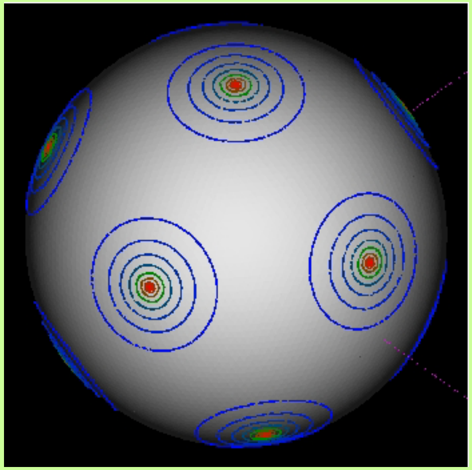
- Area of CV - Error of divergence

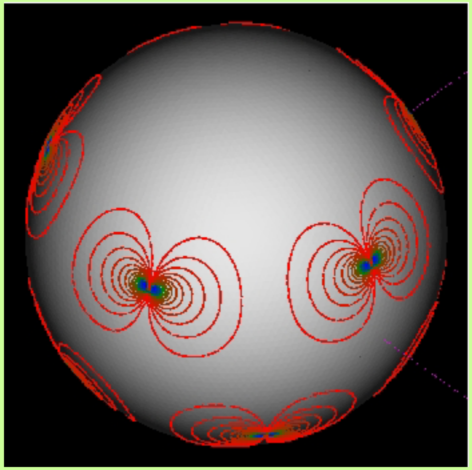
STD-grid





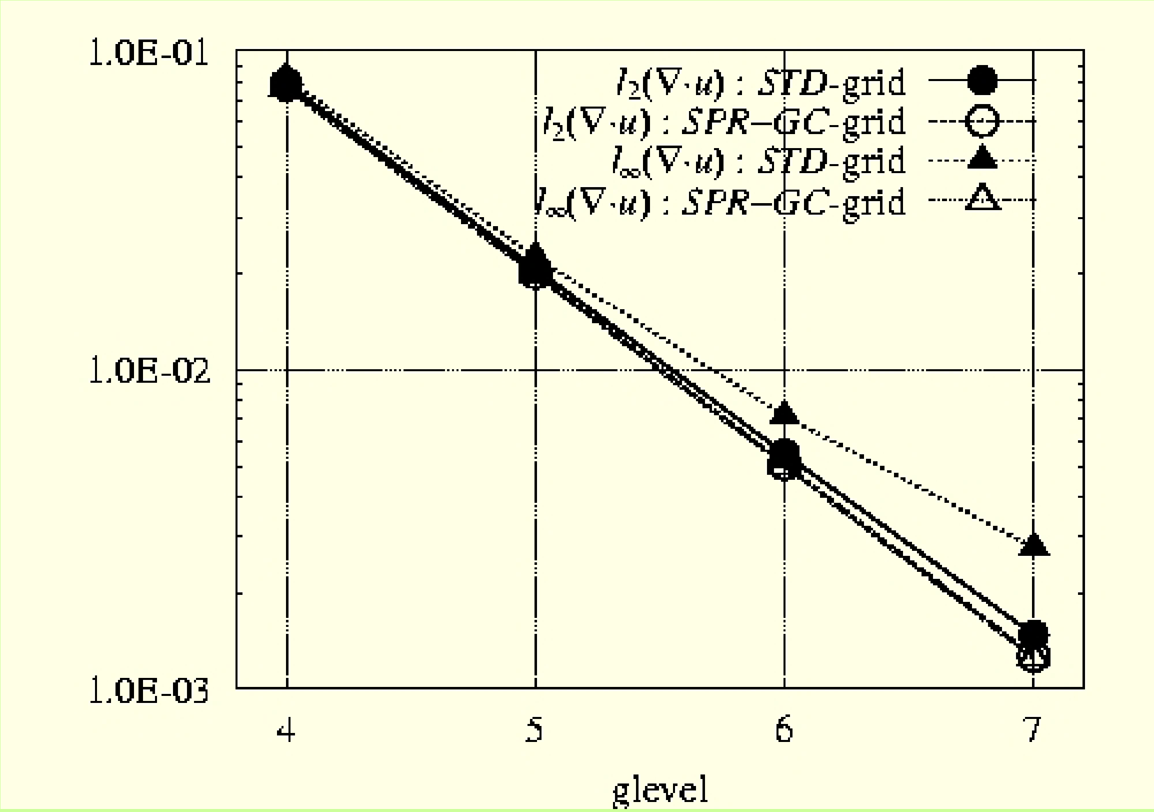
SPR-GC-grid





- **STD-grid**
  - **Area of CV**
    - Fractral distribution due to recursive division
  - **Error of divergence**
    - Fractral distribution error
    - → Generation of grid noise
- **SPR-GC-grid**
  - **Area of CV**
    - Smooth distribution
  - **Error of divergence**
    - Smooth distribution
    - → Reduction of grid noise

Improvement of accuracy of operator



- **Test function**
  - **Heikes & Randall(1995)**
- **Error norm**
  - **Global error**

$$l_2(x)=\frac{\left\{I\left[\left(x(\lambda,\theta)-x_T(\lambda,\theta)\right)^2\right]\right\}^{1/2}}{\left\{I\left[x_T(\lambda,\theta)^2\right]\right\}^{1/2}}$$

  - **Local error**

$$l_\infty(x)=\frac{\max_{all\ \lambda,\theta}\left|x(\lambda,\theta)-x_T(\lambda,\theta)\right|}{\max_{all\ \lambda,\theta}\left|x_T(\lambda,\theta)\right|}$$

	STD-grid	SPR-GC-grid
L_2 norm	Almost 2nd-order(●)	Perfect 2nd-order(○)
l_inf norm	Not 2nd order(▲)	Perfect 2nd-order(△)

Test Case for SWM

Shallow water equations

Vector invariant form

$$\frac{\partial \mathbf{v}}{\partial t} + (\hat{\mathbf{k}} \cdot \nabla \times \mathbf{v} + f)\hat{\mathbf{k}} \times \mathbf{v} = -\nabla\left(gh + \frac{\mathbf{v} \cdot \mathbf{v}}{2}\right) \qquad (1)$$

$$\frac{\partial h^*}{\partial t} + \nabla \cdot (h^* \mathbf{v}) = 0 \qquad (2)$$

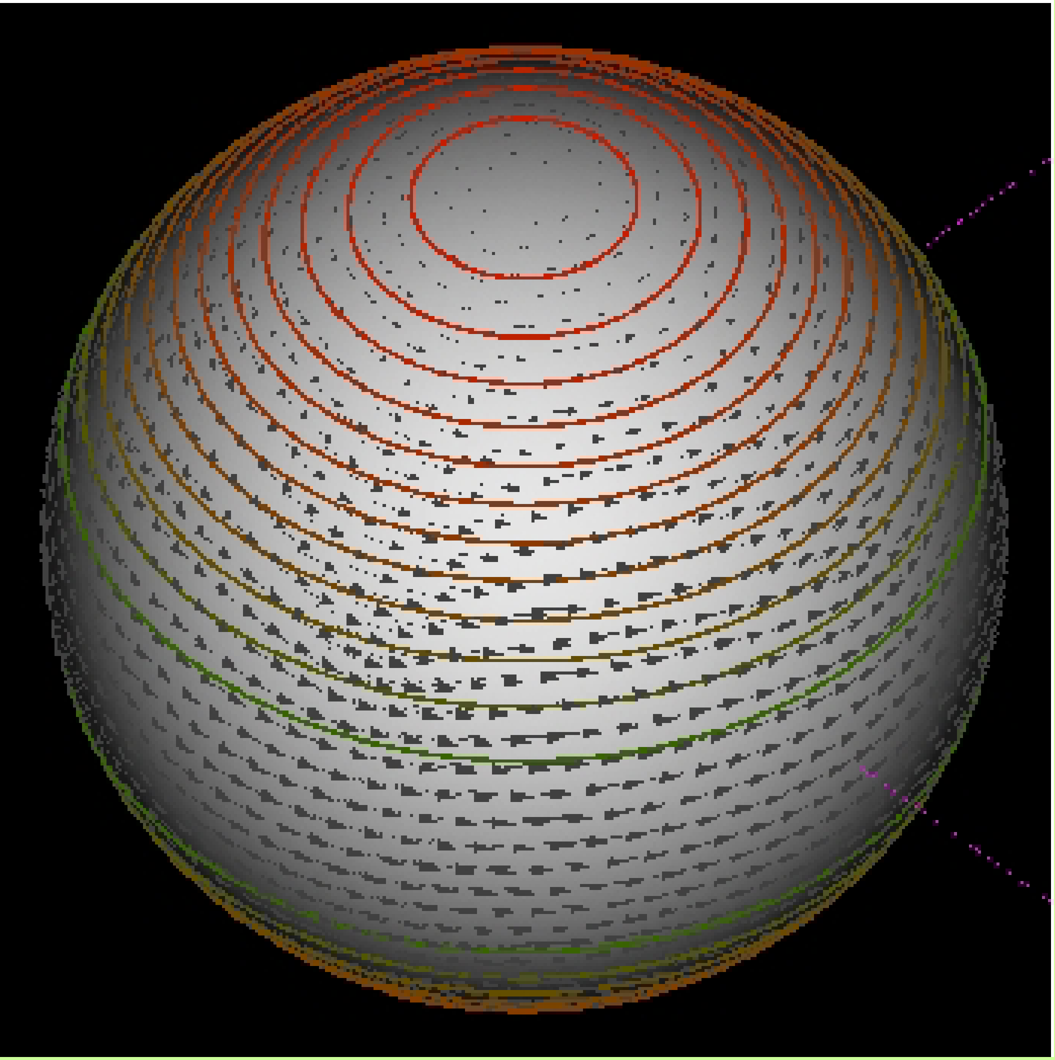
$$\text{where } h = h^* + h_S$$

A Standard Test Case

Williamson et al. (1992, JCP)

- **TEST CASE2**
  - **Solid body rotation test**
- **TEST CASE5**
  - **Unsteady, nonlinear but deterministic test with mountain**

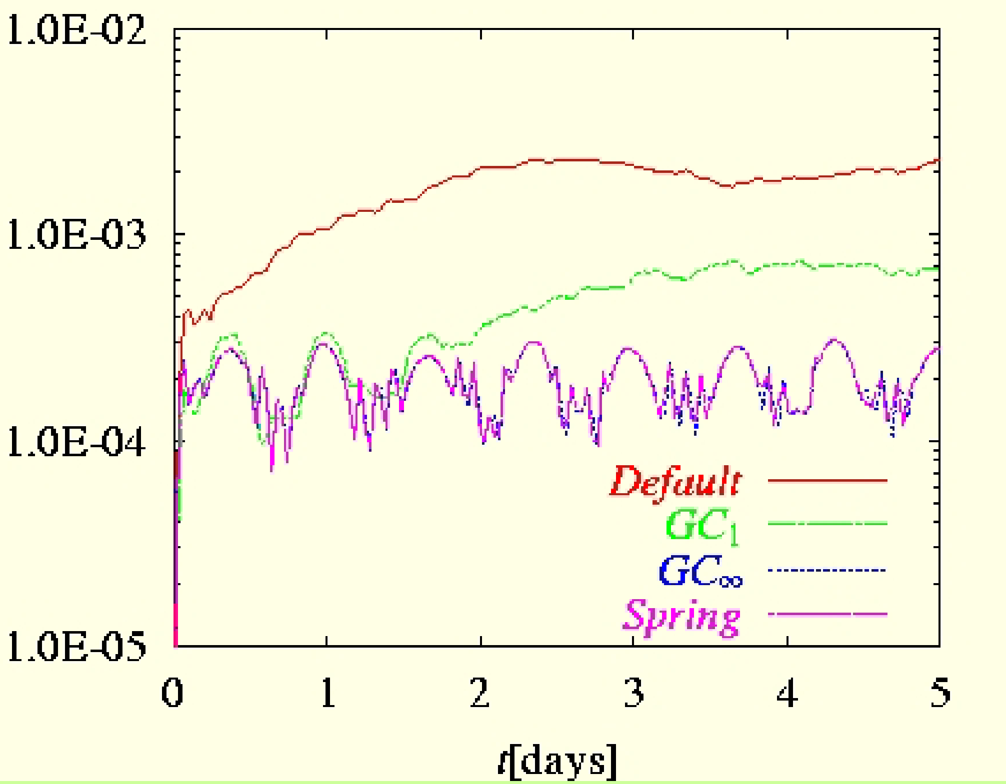
TEST CASE 2 (1)



- **Test configuration**
  - **Initial condition**
    - Solid body rotation
    - Geostrophic balance
  - **Purpose**
    - How does the model maintain the initial state?
  - **Integration time**
    - 5 days
- **Monitor**
  - **Time evolution of L_inf norm of surface height**

TEST CASE 2 (2)

Time evolution l_∞ norm



Numerical condition

- Resolution : glevel-5
- Integration : 5day
- numerical diffusion : none

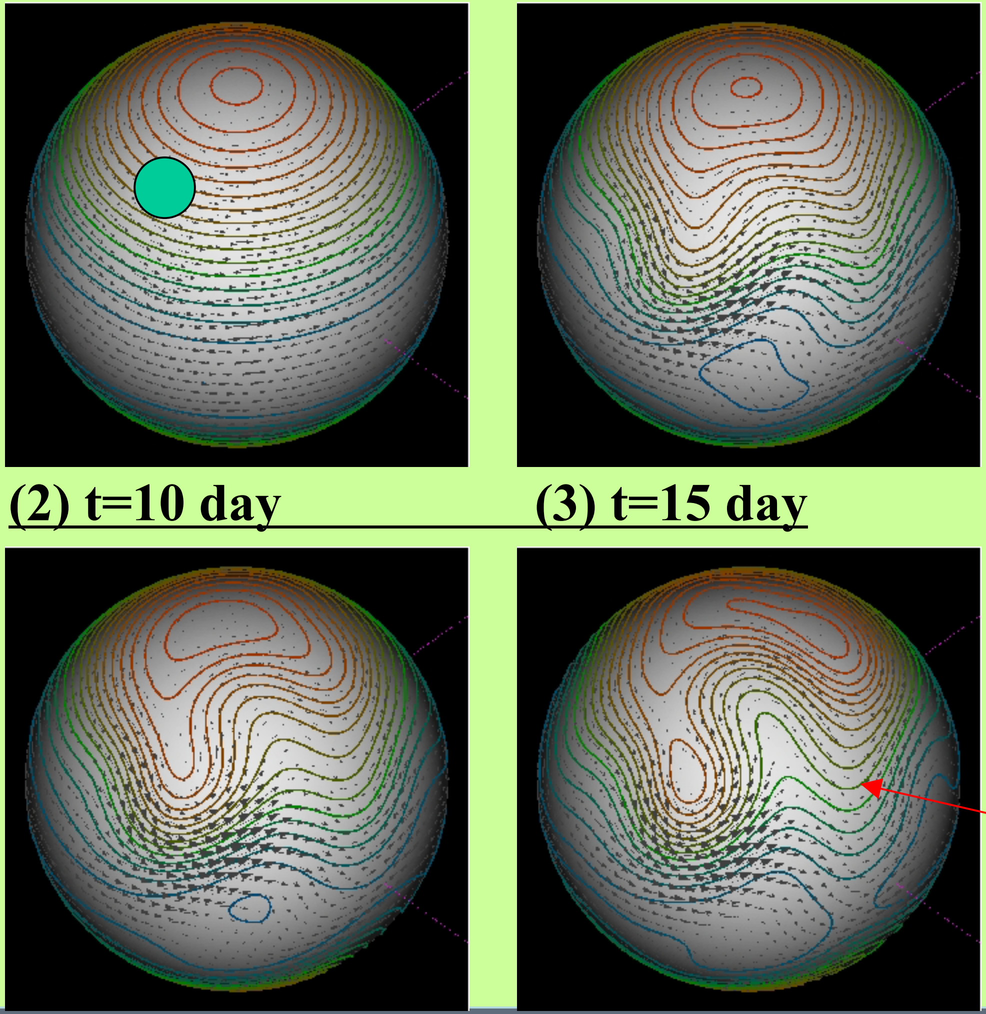
- **STD-grid (---)**
  - No modification of grid
  - **Large error from the initial stage**
- **STD-GC-grid (---)**
  - Only GCR modification
  - **Small error just in 1 day**
  - **Large error from 2 day**
  - → Grid-noise
- **SPR-GC-grid (---)**
  - Spring dyn & GCR
  - **Small error during 5 days**
  - → No grid-noise

TEST CASE 5

Result : glevel5 SPR-GC grid without viscosity

(0) t=0 day (1) t=5 day

(2) t=10 day (3) t=15 day



Test Configuration

- **Initial condition**
  - Solid body rotation
  - Mountain at the mid-latitude
- **Integration**
  - 15 days
- **Purpose**
  - Check the conservation

Total energy

$$TE = \frac{1}{2}h^{*}\mathbf{v}\cdot\mathbf{v} + \frac{1}{2}g(h^{2} - h_{S}^{2})$$

Potential enstrophy

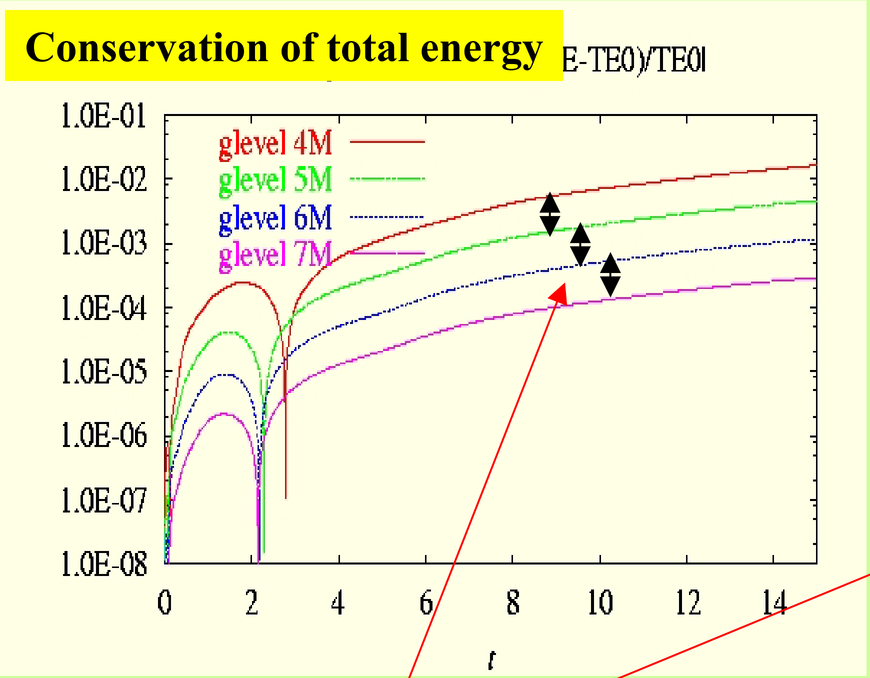
$$PENS = \frac{1}{2h^{*}}(\varsigma + f)^{2}$$

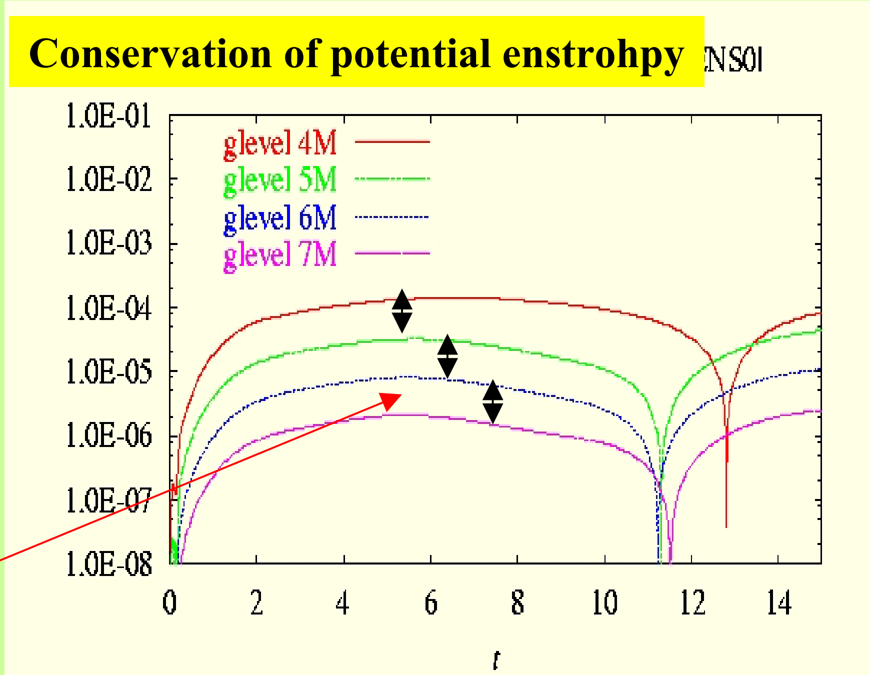
No grid noise

TEST CASE 5 (2)

Grid refinement result (SPR-GC grid)

- Resolution : glevel-4,5,6,7
- Numrical diffusion : NONE





Error : reduction by a factor of 4
→ in the 2nd order

Nonhydrostatic framework

Design of our non-hydrostatic modeling

- **Governing equation**
  - **Full compressible system**
    - Acoustic wave → Planetary wave
  - **Flux form**
    - Finite Volume Method
    - Conservation of mass and energy
  - **Deep atmosphere**
    - Including all metrics terms and Coriolis terms
- **Solver**
  - **Split explicit method**
    - Slow mode : Large time step
    - Fast mode : small time step
  - **HEVI (Horizontal Explicit & Vertical Implicit)**
    - 1D-Helmholtz equation

Governing Equations

← L.H.S. : FAST MODE → ← R.H.S. : SLOW MODE →

$$\frac{\partial}{\partial t}R+\nabla_h\cdot\frac{\mathbf{V}_h}{\gamma}+\frac{\partial}{\partial\xi}\left(\frac{W}{G^{1/2}}+\mathbf{G}^3\cdot\frac{\mathbf{V}_h}{\gamma}\right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\mathbf{V}_h+\nabla_h\frac{P}{\gamma}+\frac{\partial}{\partial\xi}\left(\mathbf{G}^3\frac{P}{\gamma}\right) = \mathbf{ADV}_h+\mathbf{F}_{Coriolis} \qquad (2)$$

$$\frac{\partial}{\partial t}W+\gamma^2\frac{\partial}{\partial\xi}\left(\frac{P}{G^{1/2}\gamma^2}\right)+Rg = ADV_z+F_{Coriollis} \qquad (3)$$

$$\frac{\partial}{\partial t}E+\nabla_h\cdot\left(h\frac{\mathbf{V}_h}{\gamma}\right)+\frac{\partial}{\partial\xi}\left[h\left(\frac{W}{G^{1/2}}+\mathbf{G}^3\cdot\frac{\mathbf{V}_h}{\gamma}\right)\right]$$

$$-\frac{\mathbf{V}_h}{R}\cdot\left[\nabla_h\frac{P}{\gamma}+\frac{\partial}{\partial\xi}\left(\mathbf{G}^3\frac{P}{\gamma}\right)\right]-\frac{W}{R}\gamma^2\frac{\partial}{\partial\xi}\left(\frac{P}{G^{1/2}\gamma^2}\right)+Wg = Q_{heat} \qquad (4)$$

■ Prognostic variables

- density $R=\gamma^2G^{1/2}\rho$
- horizontal momentum $\mathbf{V}_h=\gamma^2G^{1/2}\rho\,\mathbf{v}_h$
- vertical momentum $W=\gamma^2G^{1/2}\rho\,w$
- internal energy $E=\gamma^2G^{1/2}\rho\,e_{in}$

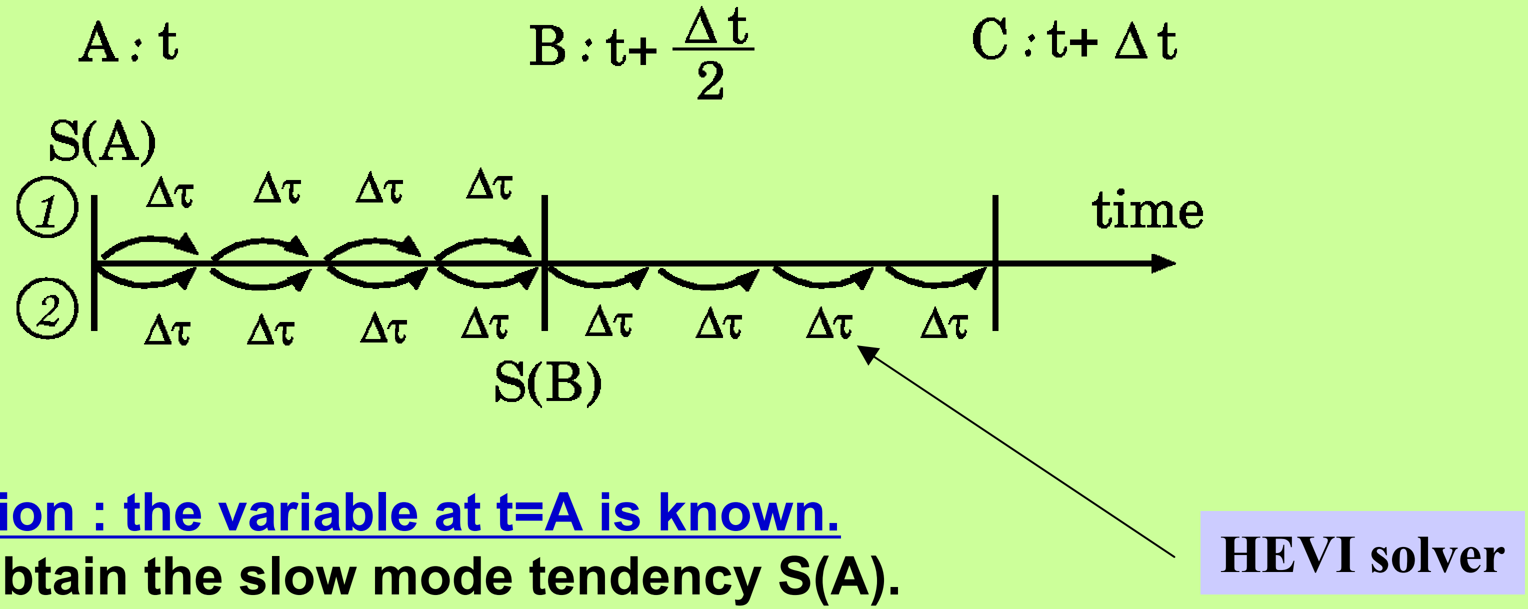
■ Metrics

$$G^{1/2}=\left(\frac{\partial z}{\partial\xi}\right)_{x,y}$$

$$\mathbf{G}^3=\left(\nabla_h\xi\right)_z$$

$$\xi=\frac{H(z-z_s)}{H-z_s}$$

Temporal Scheme (RK2)



Assumption : the variable at t=A is known.

- Obtain the slow mode tendency S(A).

1. **1st step :**
   Integration of the prog. var. by using S(A) from A to B.
   - Obtain the tentative values at t=B.
   - Obtain the slow mode tendency S(B) at t=B.
2. **2nd step :**
   Returning to A, Integration of the prg.var. from A to C by using S(B).

→ **Obtain the variables at t=C**

Small Step Integration

In small step integration, there are 3 steps:

1. **Horizontal Explicit Step**
   - Update of horizontal momentum
2. **Vertical Implicit Step**
   - Updates of vertical momentum and density.
3. **Energy Correction Step**
   - Update of energy

HEVI (steps 1 and 2)

■ Horizontal Explicit Step

- Horizontal momentum is updated explicitly by

$$\mathbf{V}_h^{t+(n+1)\Delta\tau} = \mathbf{V}_h^{t+n\Delta\tau} + \Delta\tau \left[\underbrace{\left(-\nabla_h \frac{P}{\gamma} - \frac{\partial}{\partial\xi}\left(\mathbf{G}^3 \frac{P}{\gamma} \right) \right)^{t+n\Delta\tau}}_{\text{Fast mode}} + \underbrace{\left(\frac{\partial \mathbf{V}_h}{\partial t} \right)_{\text{slow mode}}^{[t,\ or\ t+\Delta t/2]}}_{\text{Slow mode : given}} \right]$$

Small Step Integration (2)

Vertical Implicit Step

- The equations of R,W, and E can be written as:

$$\frac{R^{t+(n+1)\Delta\tau} - R^{t+n\Delta\tau}}{\Delta\tau} + \frac{\partial}{\partial\xi}\left(\frac{W^{t+(n+1)\Delta\tau}}{G^{1/2}}\right) = G_R \qquad (6)$$

$$\frac{W^{t+(n+1)\Delta\tau} - W^{t+n\Delta\tau}}{\Delta\tau} + \gamma^2 \frac{\partial}{\partial\xi}\left(\frac{P^{t+(n+1)\Delta\tau}}{G^{1/2}\gamma^2}\right) + R^{t+(n+1)\Delta\tau} g = G_z \qquad (7)$$

$$\frac{P^{t+(n+1)\Delta\tau} - P^{t+n\Delta\tau}}{\Delta\tau} + \frac{\partial}{\partial\xi}\left[\left(\frac{W^{t+(n+1)\Delta\tau}}{G^{1/2}}\right)c_s^{2t+n\Delta\tau}\right] + \frac{R_d}{C_V} W^{t+(n+1)\Delta\tau}\tilde{g} = \frac{R_d}{C_V} G_E \qquad (8)$$

  – Coupling Eqs.(6), (7), and (8), we can obtain the 1D-Helmholtz equation for W：

$$\frac{W^{t+(n+1)\Delta\tau}}{\gamma^2} - \frac{\partial}{\partial\xi}\left[\frac{1}{G^{1/2}\gamma^2}\frac{\partial}{\partial\xi}\left(\Delta\tau^2 c_s^{2t+n\Delta\tau}\frac{W^{t+(n+1)\Delta\tau}}{G^{1/2}}\right)\right] - \left[\frac{\partial}{\partial\xi}\left(\Delta\tau^2\frac{R_d}{C_V}\tilde{g}\frac{W^{t+(n+1)\Delta\tau}}{G^{1/2}\gamma^2}\right)\right] + \Delta\tau^2\frac{g}{\gamma^2}\frac{\partial}{\partial\xi}\left(\frac{W^{t+(n+1)\Delta\tau}}{G^{1/2}}\right)$$

$$= \text{R.H.S.(source term)} \qquad (9)$$

- **Eq.(9) → W**
- **Eq.(6) → R**
- **Eq.(8) → E**

Small Step Integration (3)

Energy Correction Step

(Total eng.) ＝ (Internal eng.) ＋ (Kinetic eng.) ＋ (Potential eng.)

- We consider the equation of total energy

$$\frac{\partial}{\partial t}E_{total}+\nabla_h\cdot\left[(h+k+\Phi)\frac{\mathbf{V}_h}{\gamma}\right]+\frac{\partial}{\partial\xi}\left[(h+k+\Phi)\left(\frac{W}{G^{1/2}}+\mathbf{G}^3\cdot\frac{\mathbf{V}_h}{\gamma}\right)\right]=0 \quad \textbf{(10)}$$

where $E_{total}=\rho\gamma^2G^{1/2}(e_{in}+k+\Phi)$

- Additionally, Eq.(10) is solved as

$$E_{total}^{t+(n+1)\Delta\tau}=E_{total}^{t+n\Delta\tau}-\Delta\tau\left[\nabla_h\cdot\left[(h+k+\Phi)\frac{\mathbf{V}_h}{\gamma}\right]+\frac{\partial}{\partial\xi}\left[(h+k+\Phi)\left(\frac{W}{G^{1/2}}+\mathbf{G}^3\cdot\frac{\mathbf{V}_h}{\gamma}\right)\right]\right]^{t+(n+1)\Delta\tau}$$

  - Written by a flux form.

- The kinetic energy and potential energy:
  → known by previous step.
- Recalculate the internal energy:

$$E^{t+(n+1)\Delta\tau}=E_{total}^{t+(n+1)\Delta\tau}-\rho^{t+(n+1)\Delta\tau}\gamma^2G^{1/2}\left(k^{t+(n+1)\Delta\tau}+\Phi\right)$$

Large Step Integration

- **Large step tendecy has 2 main parts:**
  1. **Coliolis term**
     - ➢ **Formulated straightforward.**
  2. **Advection term**
     - **We should take some care to this term because of curvature of the earth**
- **Advection of momentum**
  - **The advection term of V_h and W is calculated as follows.**
    1. **Construct the 3-dimensional momentum V using V$_h$ and W.**
    2. **Express this vector as 3 components as (V_1, V_2, V_3) in a fixed coordinate.**
       - ➢ **These components are scalars.**
    3. **Obtain a vector which contains 3 divergences as its components.**

       → $(\nabla \cdot v_1 \mathbf{V}, \nabla \cdot v_2 \mathbf{V}, \nabla \cdot v_3 \mathbf{V})$ where $v_i = V_i / (G^{1/2} \gamma^2 \rho)$
    4. **Split again to a horizontal vector and a vertial components.**

       → $\mathbf{ADV}_h, ADV_z$

Test results of 3D-model

Held & Suarez Dynamical Core Exp.(1)

Test configuration

Radiation

- **We use a simple radiation as Newtonian Cooling of temperature field :**

$$\frac{dT}{dt} = ...-k_T(\phi,\sigma)\left(T-T_{eq}\right) \quad : \quad k_T = k_a + \left(k_s - k_a\right)\max\left(0, \frac{\sigma-\sigma_b}{1-\sigma_b}\right)\cos^4\phi$$

where $\sigma_b = 0.7, k_a = 1/40[/\mathrm{day}], k_s = 1/4[/\mathrm{day}]$

- **Equilibrium temperature is zonally symmetric as:**

$$T_{eq} = \max\left[200\mathrm{K}, \left[315\mathrm{K} - (\Delta T)_y \sin^2\phi - (\Delta\theta)_z \log\left(\frac{p}{p_0}\right)\cos^2\phi\right]\left(\frac{p}{p_0}\right)^{\kappa}\right]$$

where $(\Delta T)_y = 60\mathrm{K}, (\Delta\theta)_z = 10\mathrm{K}$

Surface fricrion

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

$$\frac{d\mathbf{V}}{dt} = ...-k_V(\sigma)\left(T-T_{eq}\right) \quad : \quad k_V = k_f \max\left(0, \frac{\sigma-\sigma_b}{1-\sigma_b}\right)$$

- **where** $k_f = 1/1[/\mathrm{day}]$

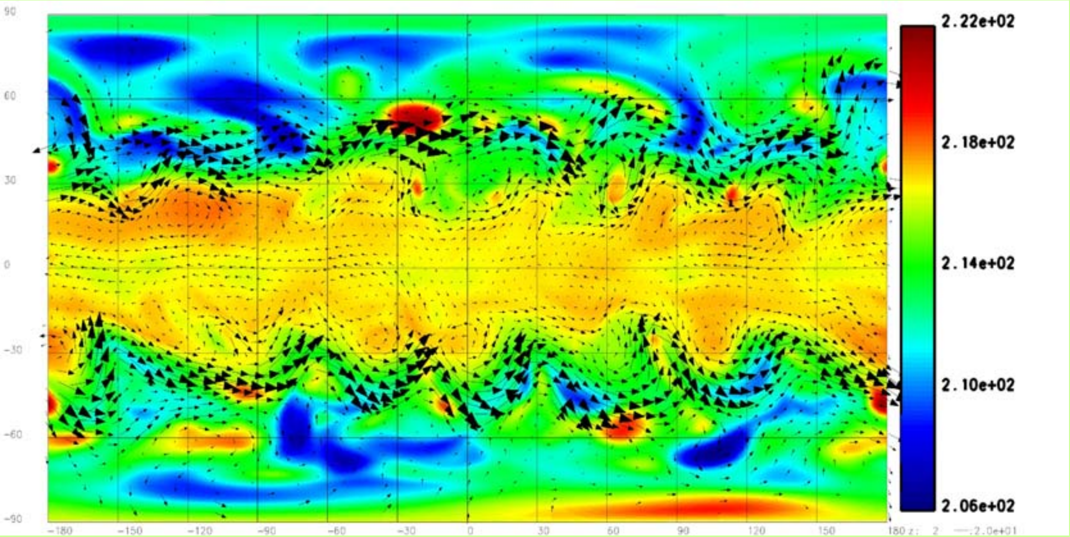
Held & Suarez Dynamical Core Exp.(2)

- **Objective**
  - After 1200 days integration, the climatology in the 1000 days are checked.
  - The results obtained are compared with other models.
- **Model used**
  - AFES(AGCM For Earth Simulator)
    - Based on the CCSR/NIES spectral model.
    - T319L32(resolvable scale = 120km on the equator).
  - NICAM(Nonhydrostatic Icosahedral Atmospheric Model)
    - Glevel-7L32(grid intv. = 60km on the equator)

Resolvable scale (T319←→ Glevel-7) : almost same
Hyper diffusion (4th order) : exactly same

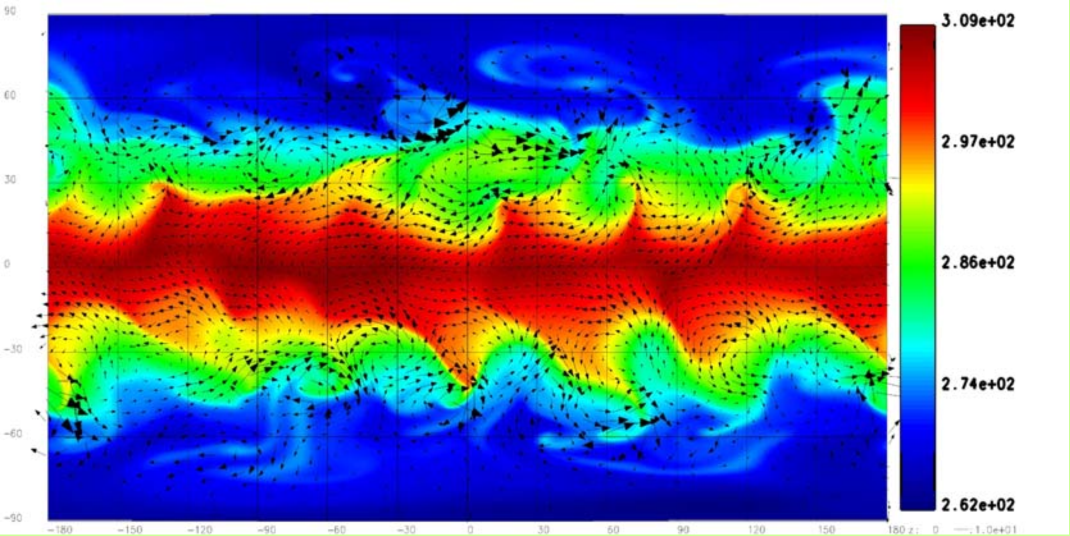
Held & Suarez Dynamical Core Exp.(3)

■ Snapshot results （*T* and v_h fields after 1200 days）



■ Upper atmosphere （z=10.5km)

The westerly jet in the mid-latitude and the baroclinic instability is well simulated



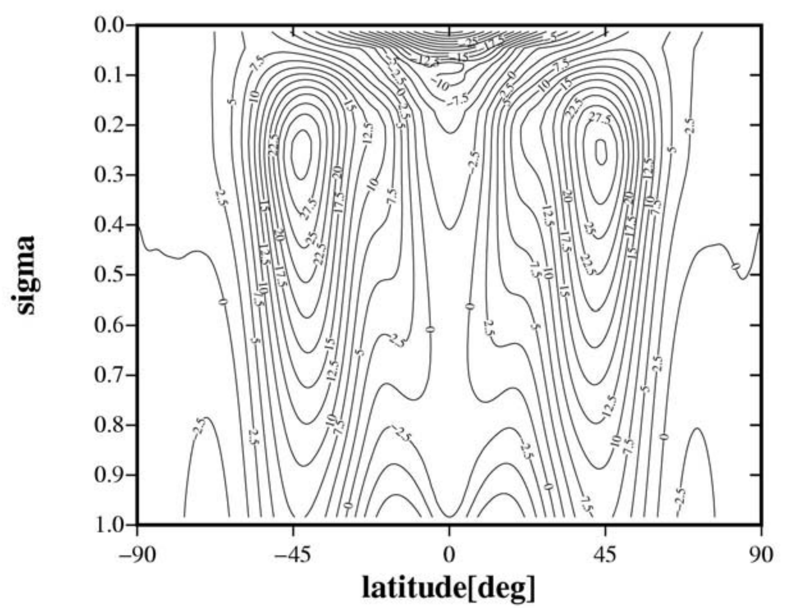
■ Lower atmosphere （z=0.5km)

The easterly wind near the equatorial region is well simulated.

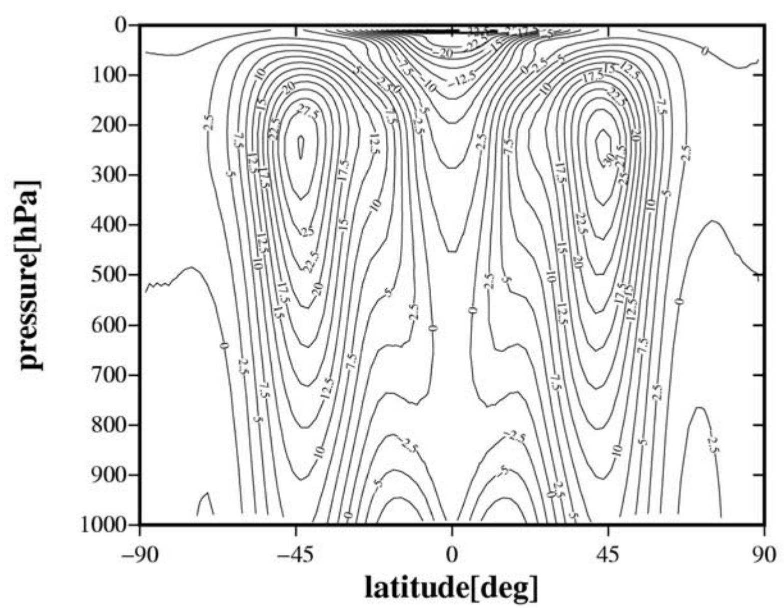
Held & Suarez Dynamical Core Exp.(4)

Zonal mean of zonal wind

AFES(T319L32)



NICAM(glevel7-L32)

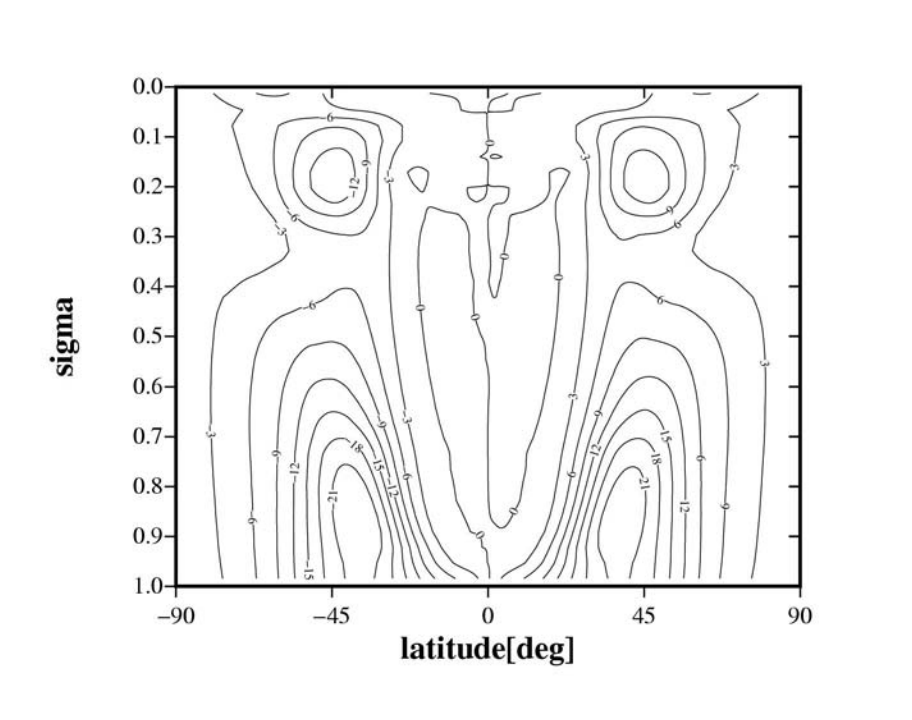


- **No significant difference**
  - **The location & intensity of jet is almost same.**

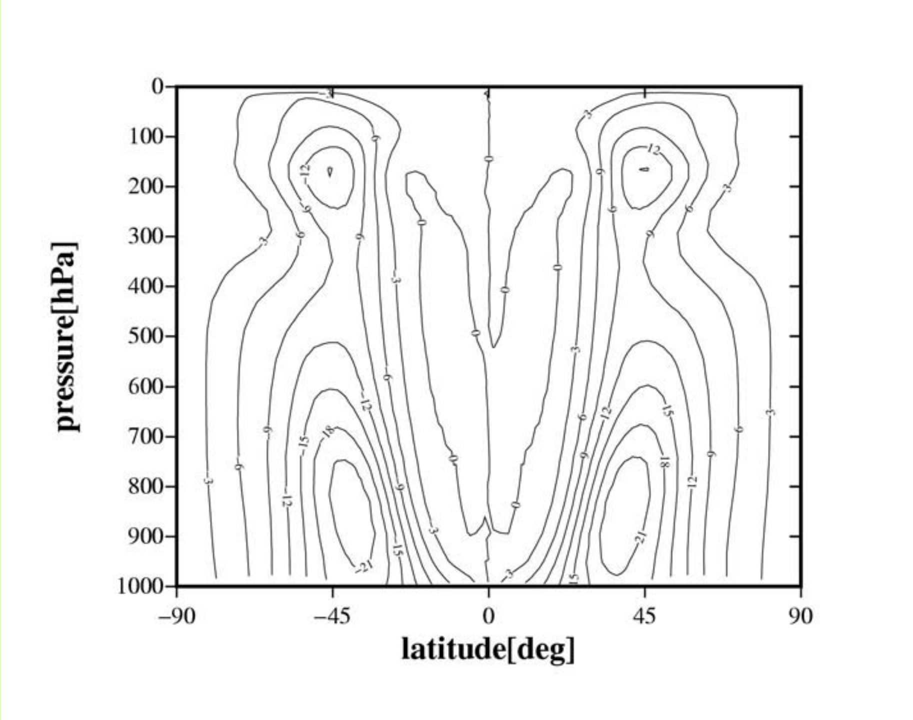
Held & Suarez Dynamical Core Exp.(4)

■ Zonal mean of eddy heat flux(*v'T'*)

AFES(T319L32)

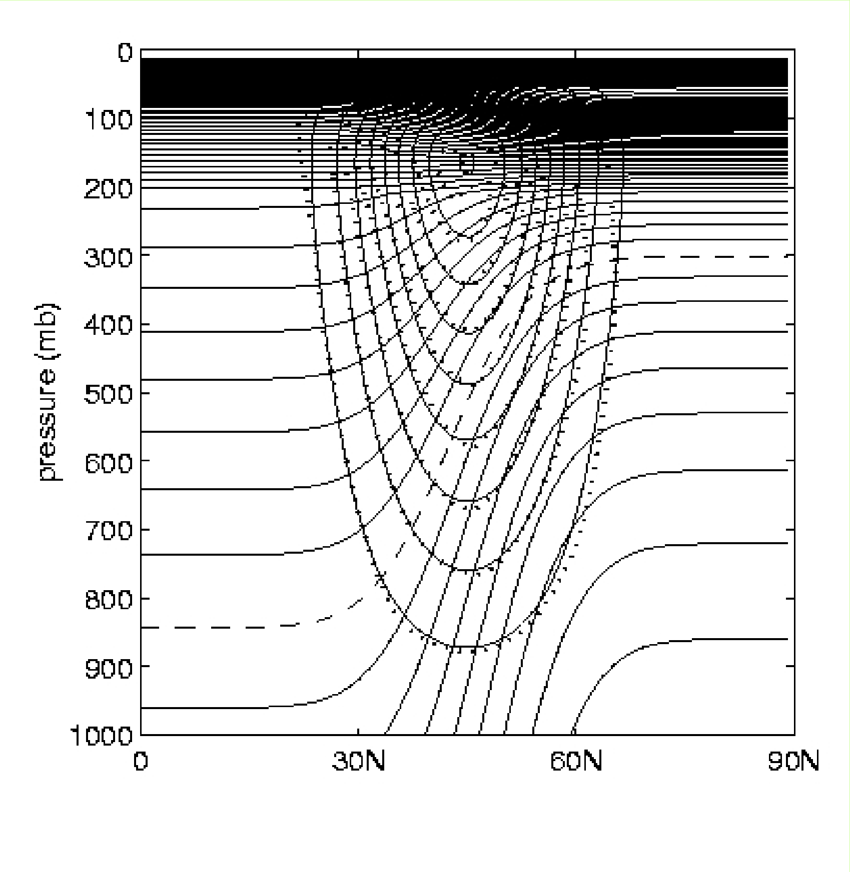


NICAM(glevel7-L32)



- **Almost same intensity for both models**
- **Acceptable difference!**

Lifecycle experiment of baroclinic wave (1)



Initial balance state in the northern hemisphere. Potential temperature & zonal wind profile

- **Test Configuration**

  (Polvani et al, submitted to MWR)

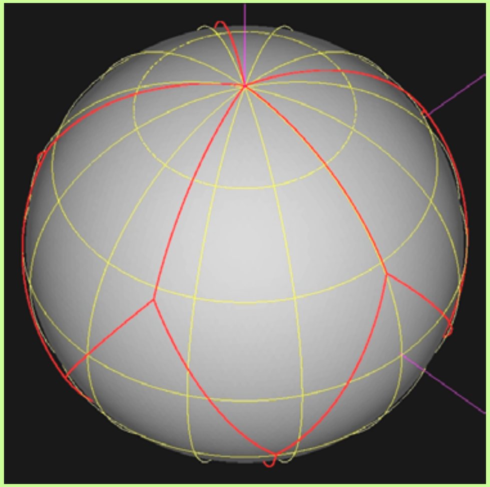
  - Zonal jet in the northern hemisphere

    → max speed : 50 [m/s]

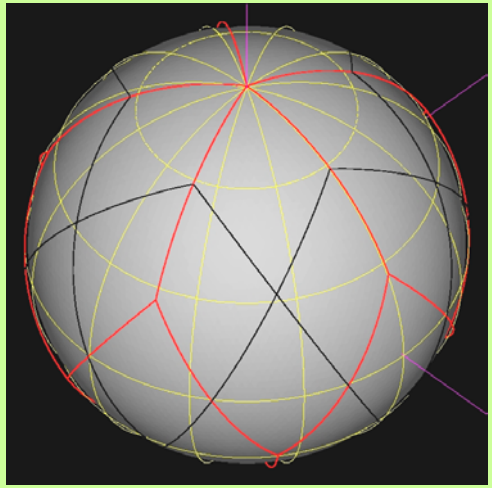
  - Thermal wind balance in the horizontal
  - Hydrostatic balance in the vertical.
  - A thermal disturbance of cosine bell in the mid-latitude.

Computational strategy(1)

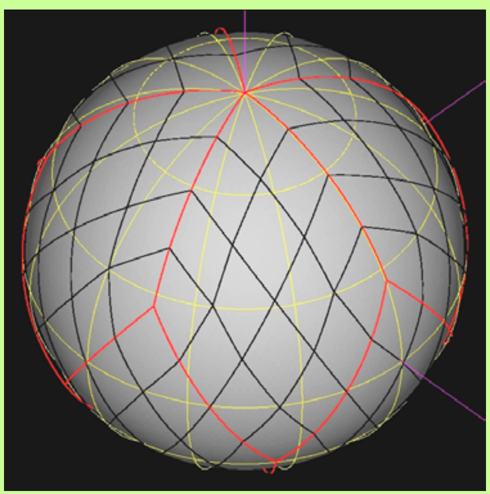
(0) region division level 0



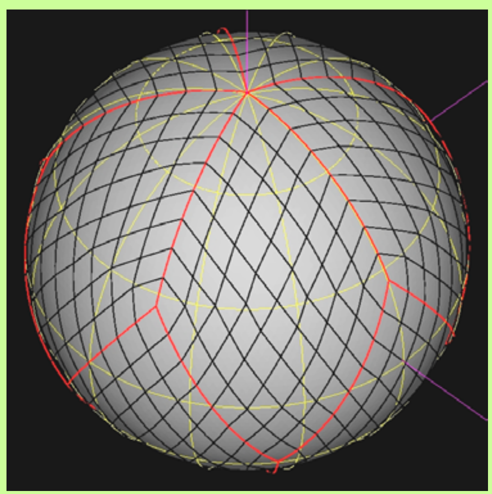
(1) region division level 1



(2) region division level 2



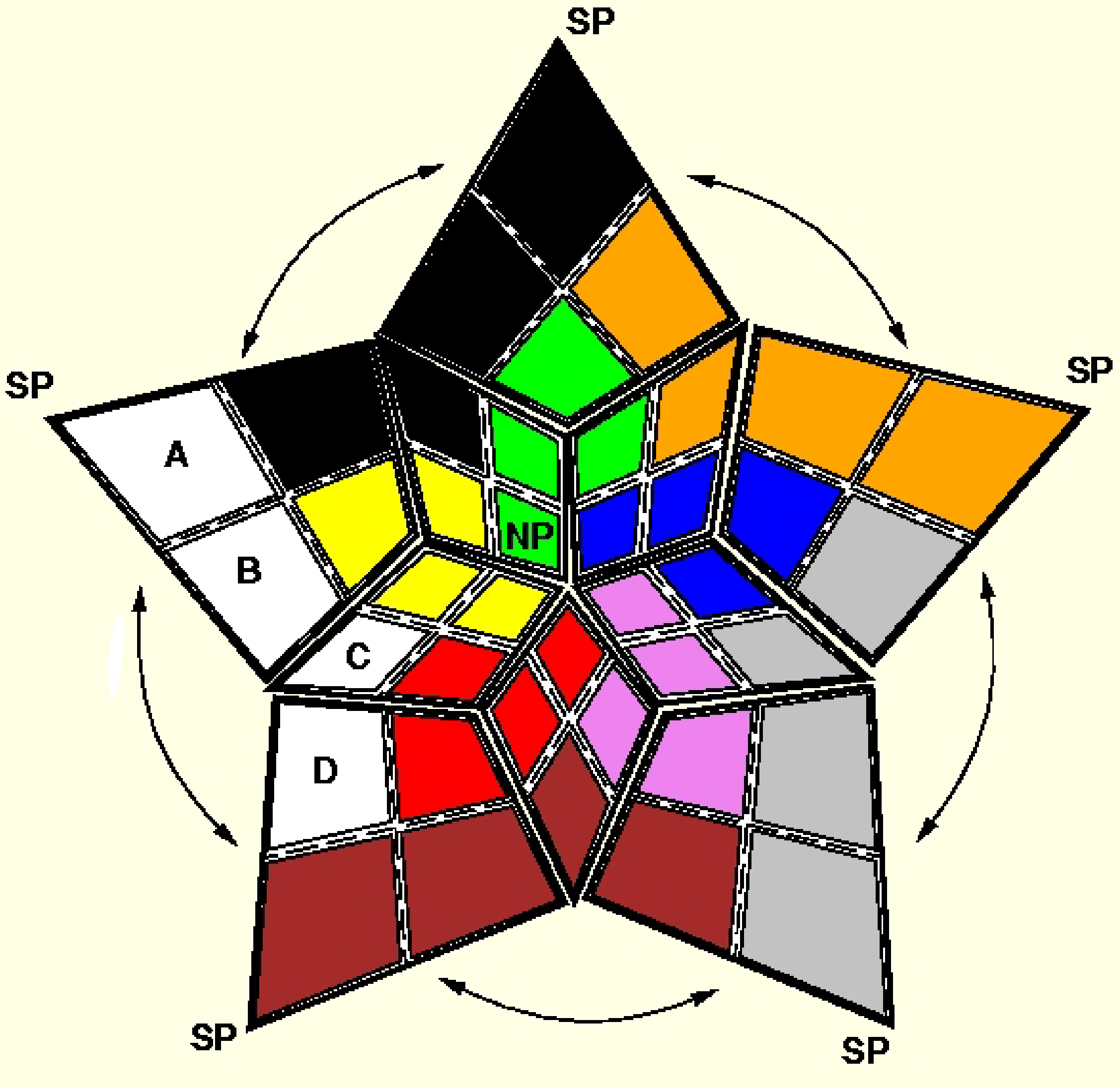
(3) region division level 3



- **Domain decomposition**
  1. By connecting two neighboring icosahedral triangles, 10 rectangles are constructed. (rlevel-0)
  2. For each of rectangles, 4 sub-rectangles are generated by connecting the diagonal mid-points. （rlevel-1)
  3. The process is repeated.
     (rlevel-n)

Computational strategy(2)

Load balancing

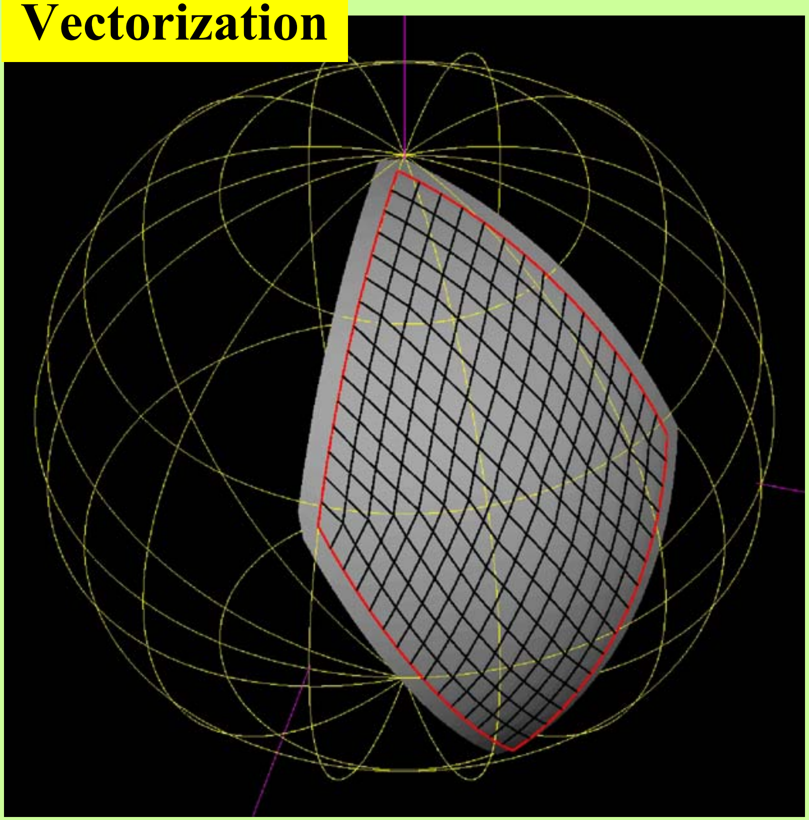


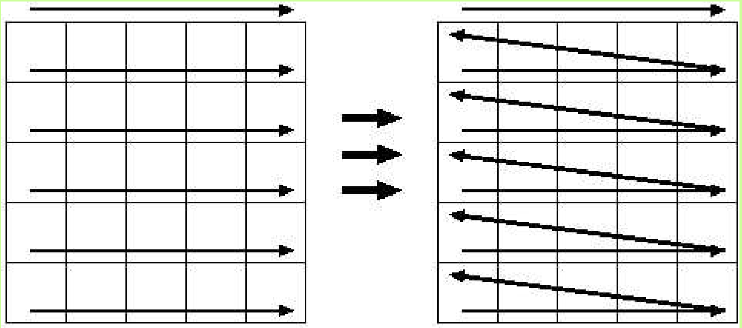
- Example (rlevel-1)
  - # of region : 40
  - # of process : 10
  - Situation:
    - Polar region: Less computation
    - Equatorial region: much computation
- Each process
  - manage same color regions
  - Cover from the polar region and equatorial region.

Avoid the load imbalance

Computational strategy(3)

Vectorization





- Structure in one region
  - Icosahedral grid
    → Unstructured grid?
  - Treatment as structured grid
    → Fortran 2D array
    → vectorized efficiently!
- 2D array → 1D array
  - Higher vector operation length

Computational Performance (1)

Computational performance

Depend on the many things

- Computer architecture, degree of code tuning…..

Rough comparison between GPM & SM

- AFES as one of spectral models
- NICAM as one of gridpoint models
- Both models are well tuned on the Earth Simulator.

Performance on the Earth Simulator

Earth Simulator

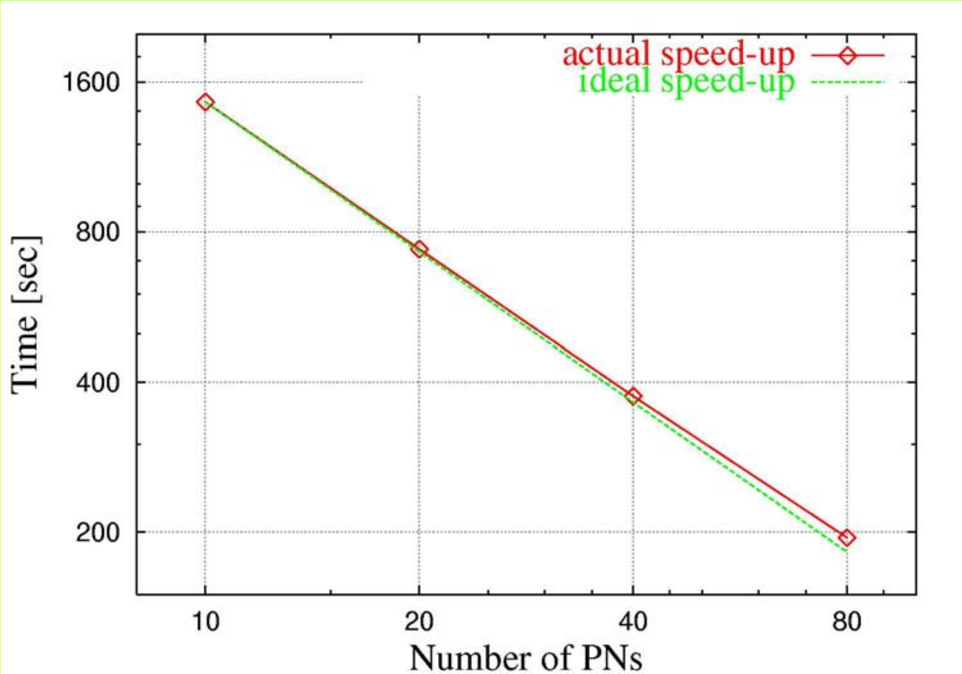
- Massively parallel super-computer based on NEC SX-6 architecture.
  - 640 computational nodes.
  - 8 vector-processors in each of nodes.
  - Peak performance of 1CPU : 8GFLOPS
  - Total peak performance : 8X8X640 = 40TFLOPS

Target simulations for the measurement

- 1 day simulation of Held & Suarez dynamical core experiment

Computational Performance (2)

Scalability of our model (NICAM)



Configuration

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

Fixed

- The used computer nodes increases from 10 to 80.

Results

Green : ideal speed-up line

Red : actual speed-up line

→ good scalability!

Computational Performance (3)

Performance against the horizontal resolution

The elapse time should increase by a factor of 2.

g level (grid intv.)	Number of PNs (peak performance)	Elapse Time [sec]	Average Time [msec]	GFLOPS (ratio to peak[%])
6 (120km)	5 (320GFLOPS)	48.6	169	140 (43.8)
7 (60km)	20 (1280GFLOPS)	97.4	169	558 (43.6)
8 (30km)	80 (5120GFLOPS)	195	169	2229 (43.5)
9 (15km)	**320 (20480GFLOPS)**	**390**	**169**	**8916**

Configuration

As the glevel increases,

# of gridpoints : X 4

# of CPUs : X 4

Time intv. : 1/2

Results

Actually, the elapse time increases by a factor of 2.

Computational Performance (4)

Comparison of performance between SM & GPM

Discussion point

- Which is computationally efficient?
  - Computer performance depends on many things.
  - This attempt is just one example.

Condition

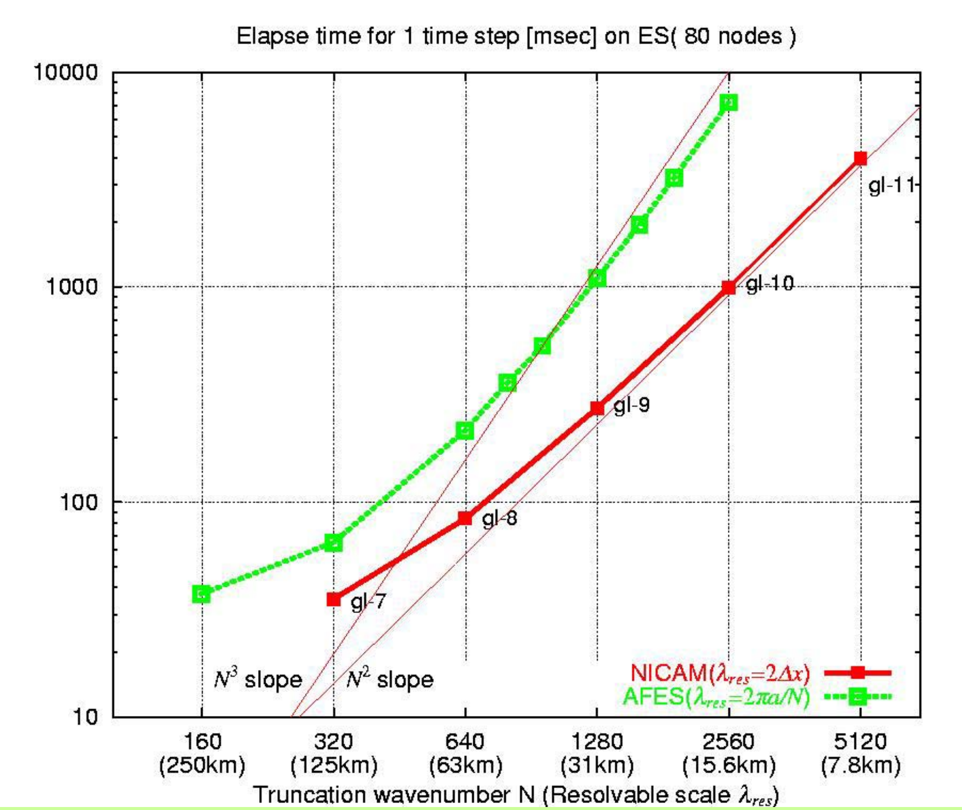
- Vertical layer : 32
- Horizontal resolution : T160 → T2560 (AFES)
  GI-6 → GI-10 (NICAM)
- 80 nodes of ES
- Only dynamical core (without any physical processes)

Estimation method

- There are two factors for estimations.
  - Elapse time of 1 time step
  - Available time step Dt
- By considering two factors,
  Estimation of elapse time of 1 day simulation.

Computational Performance (4)

Elapse time of 1step for NICAM and AFES

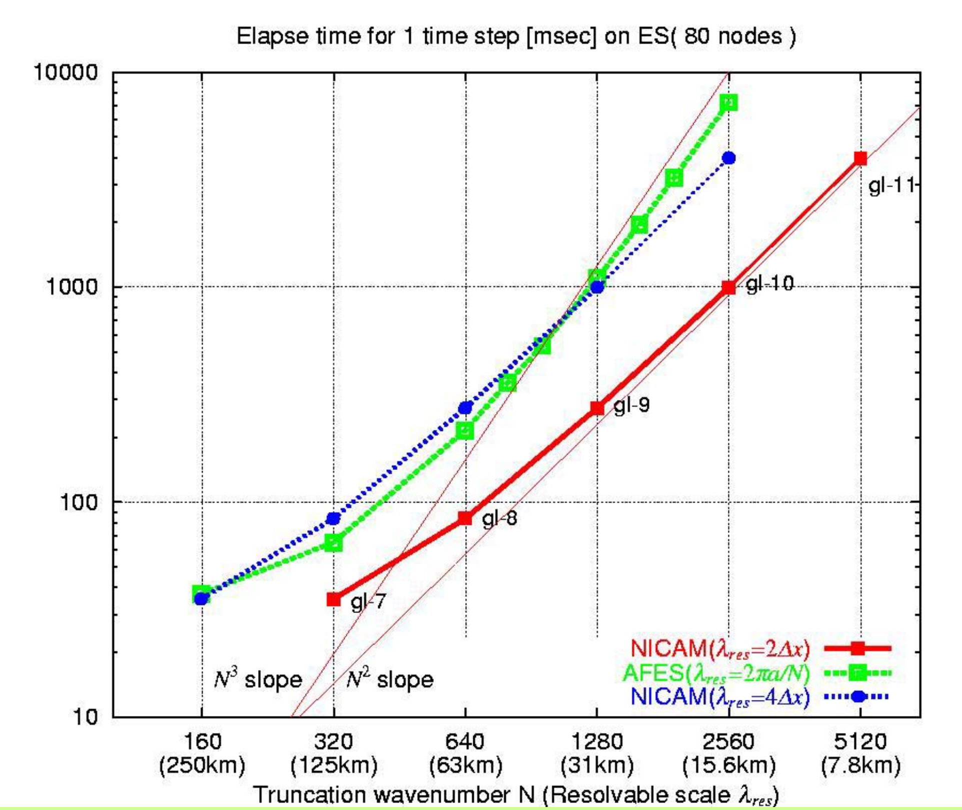


- **AFES (green line)**
  Elapse time increases in the sense O(n^3).
  → Legendre transformation
- **NICAM(red line)**
  Elapse time increases in the sense O(n^2).
- **In all resolutions,**
  NICAM is faster than AFES.

In gridpoint models, 2 grid-scale is the resolvable scale?
→ grid noise?

Computational Performance (5)

■ 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

Even in this consideration,
GPM will be faster than SM in the 30km reslvable scale or less.

Computational Performance (6)

■ Available time step Δt & 1 day simulation time

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

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

- Available Δt : comparable between two model.
- By considering the 1step time measuremet,
  1 day simulation time for GPM
  is much reduced in the higer resolution
  than T1000 for SM.

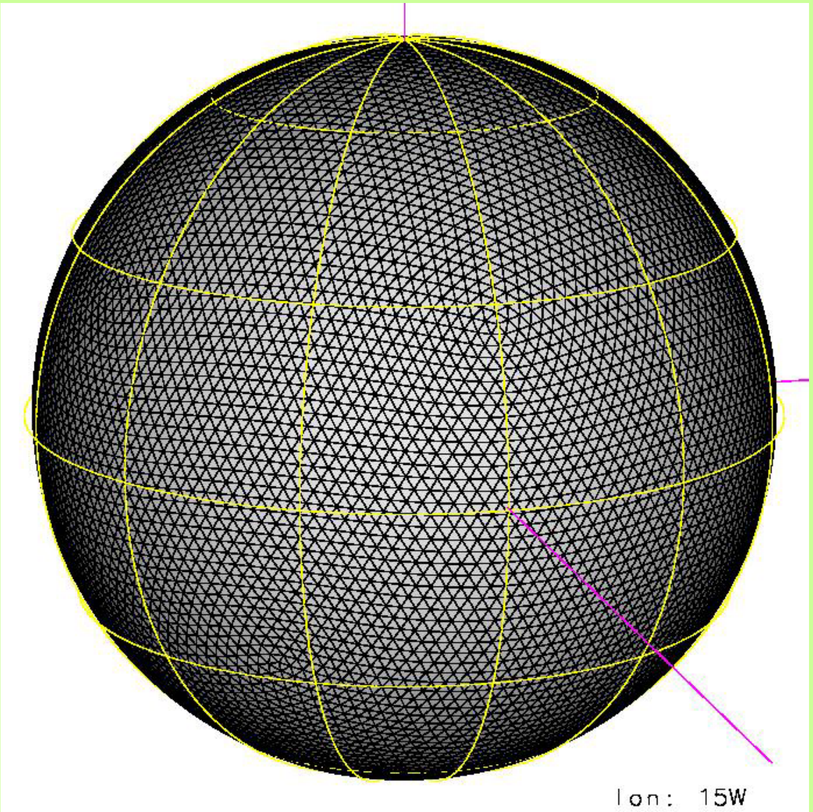
Strategy of development of physics

- **Problem in the early development stage**
  - **Dfficult to do trial and error in 3.5km grid**
    - Limitation of computer resource
- **Solution**
  - **Reduce the earth radius**
    - e.g. R=6400km → 640km
  - **Use a stretched grid**
    - Make the gridpoints clustered in a region intersted by an appropriate transformation function
      - Schmidt transformation
        - » Isotropic transformation

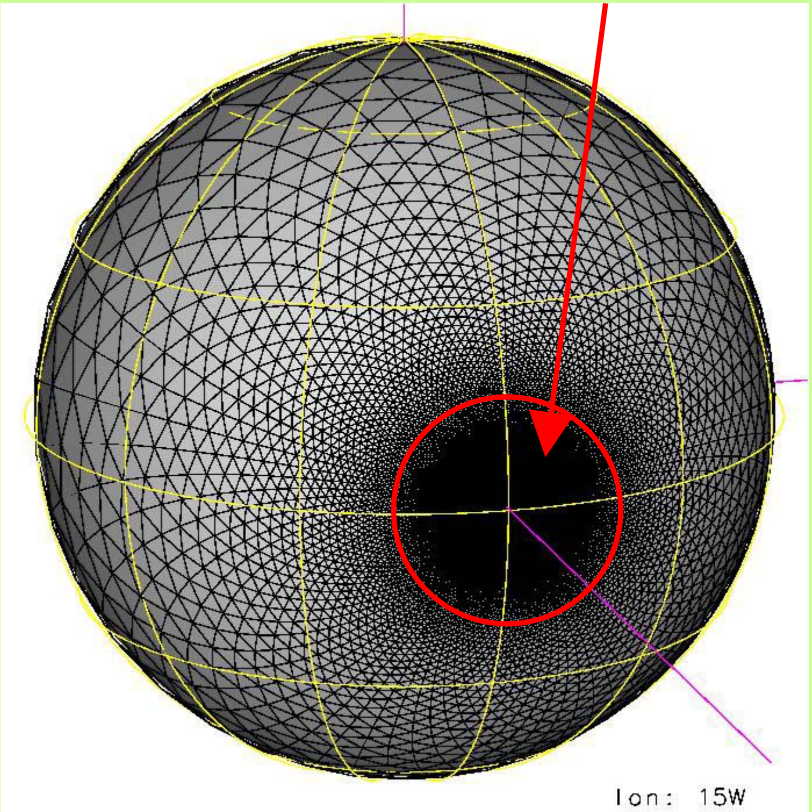
We can fast develop the cloud resolving model by the combination of these strategies.

Example of stretched grid

- Default grid : glevel-6
  - 120km grid intv.
    - Homogenious



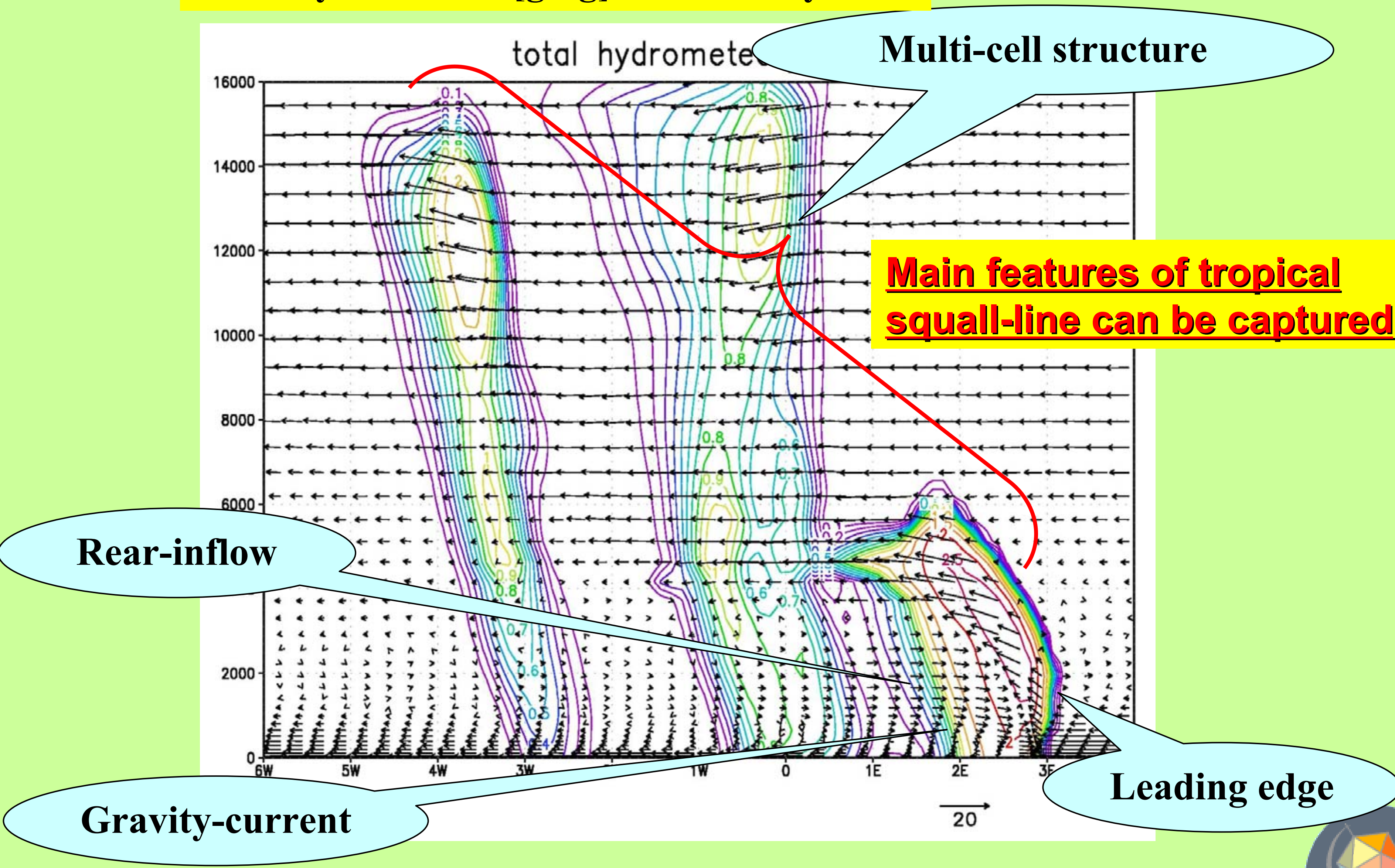
- Stretched grid
  - After the transformation
    - Grid interval :
      - 120km → 12km



Reduction of earth radius : 1/10
1.2km grid interval

Squall-line-experiment by stretched grid

Total hydrometeor[g/kg] and velocity field



Main features of tropical squall-line can be captured

Summary(1)

- **We have developed a new dynamical core based on non-hydrostatic system using the icosahedral grid.**
  - **In this scheme, the mass and total energy are numerically conserved for the long time climate simulations.**
- **We performed many test cases such as the Held & Suarez dynamical core experiment.**
  - **Comparing with the results of the spectral model AFES, our model generated the almost same results.**
- **The computational performance of our model was measured on the Earth Simulator.**
  - **We obtained an ideal scalability and a good sustained performance (40% of peak performance).**
  - **Comparing with the performance of AFES (as one of spectral model), we guess that gridpoint models may be superior to spectral models in the higher resolution than 30km resolvable scale.**

Summary(2)

- It's difficult to do trial and error for tuning the microphysics scheme in the development stage.
  - For this purpose, we use a stretched icosahedral grid by the Schmidt transformation.
- We have shown the application of the stretched grid to the tropical squall line case.
  - Lin et al.(1983) scheme generates the reasonable squall line qualitatively
- After enough assesment of the scheme, we will perform the global cloud resolving runs.
  - Aqua Plant Experiment
  - Realistic topography run