Nonhydrostatic Modeling with NICAM

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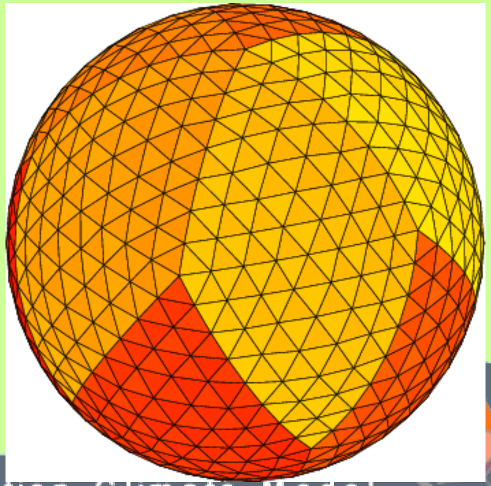
Contents

NICAM project

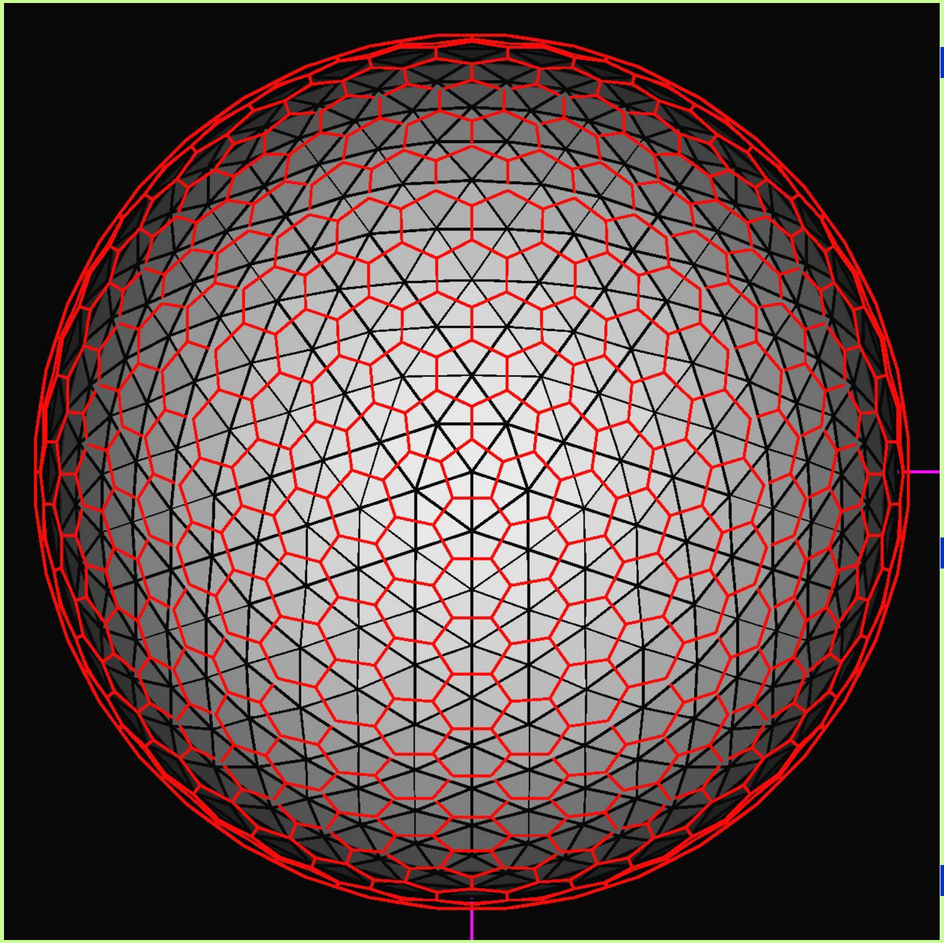
- **NICAM project (~2000)**
  - **Aim :**
    - Construction of GCRM for climate simulation
      - Suitable to the future computer environment
        - Massively parallel supercomputer
        - First target : Earth Simulator 1
          40TFLOPS in peak
          640 computer nodes

  - **Strategy:**
    - Horizontal discretization :
      - Use grid of icosahedarl grid
        (quasi-homogeneous)
      - Anyway, 2nd accuracy over the globe!
    - Dynamics:
      - Non-hydrostatic
        - Mass & total energy conservation
    - Physics :
      - Import from MIROC (one of Japan IPCC models)
        except for microphysics.



Horizontal discretization

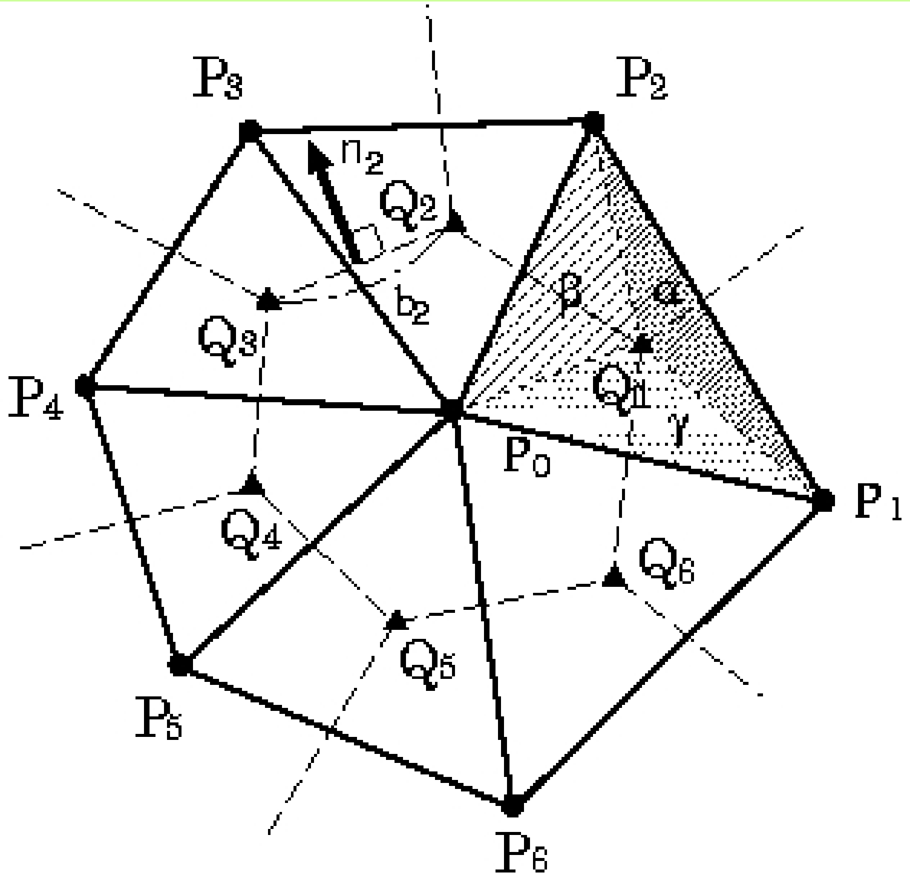
Grid arrangement



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
  - no 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

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

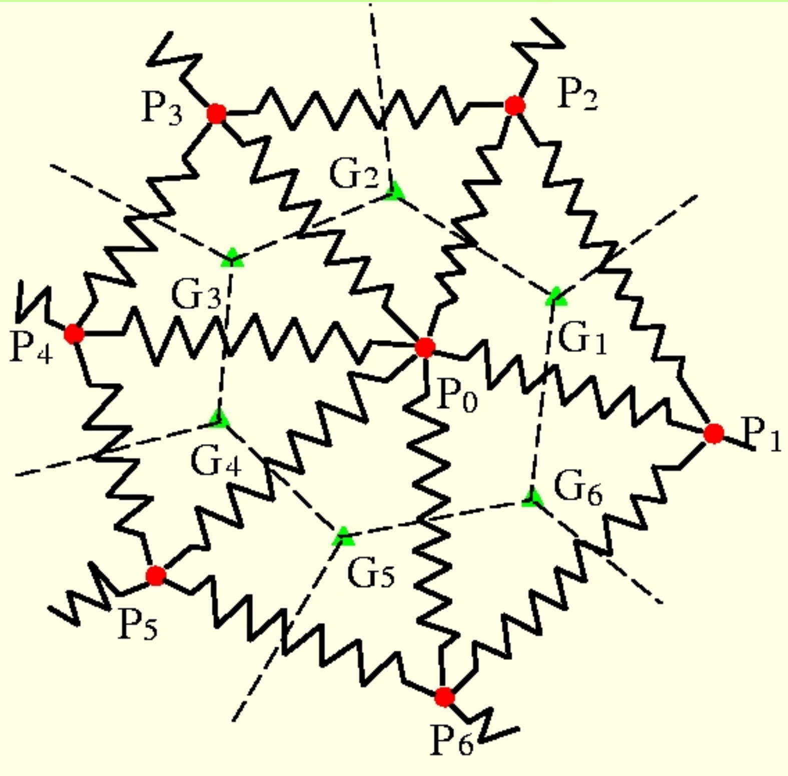
2nd order accuracy?

NO

→ Allocation points is not gravitational center (default grid)

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

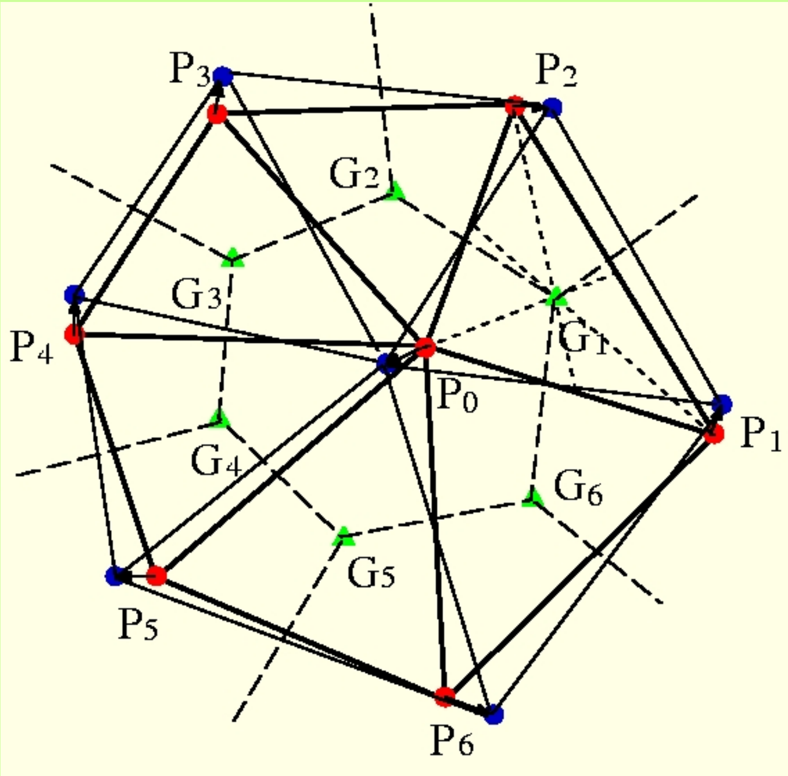
$$\sum_{i=1}^{6} k(d_i - \bar{d})\mathbf{e}_i - \alpha \mathbf{w}_0 = M \frac{d\mathbf{w}_0}{dt}$$

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

SPR-grid:
Solve the spring dynamics
→ The system calms down to the static balance

Modified Icosahedral Grid (2)

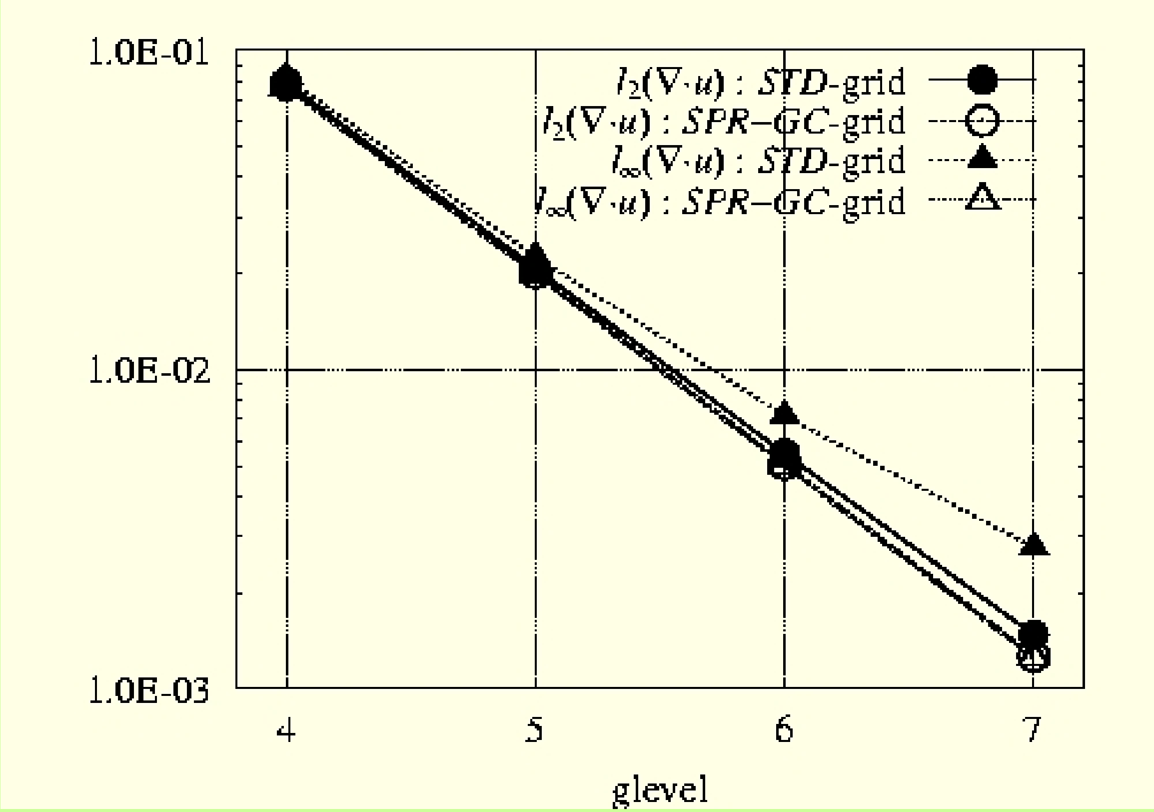
- **Gravitational-Centered Relocation**
  - **To make the accuracy of numerical operators higher**



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 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(△)

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 →

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

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

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

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

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

■ 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** $E=\gamma^2G^{1/2}\rho\,e_{in}$

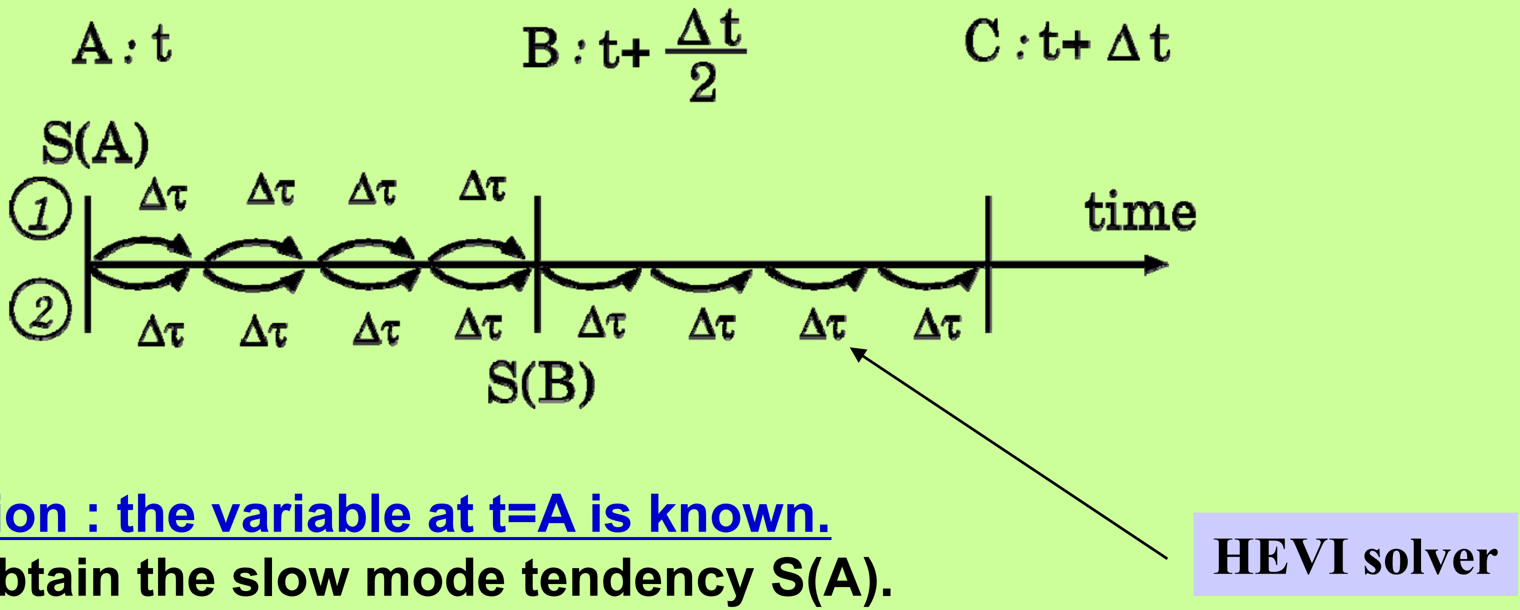
■ Metrics

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

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

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

Temporal Scheme (in the case of 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**

(Steps 1–2: **HEVI**)

Horizontal Explicit Step

- **Horizontal momentum is updated explicitly by**

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

Fast mode

Slow mode : given

Vertical Implicit Step

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

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

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

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

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

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

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

- **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

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

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

- Additionally, Eq.(10) is solved as

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

  – Written by a flux form.

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

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

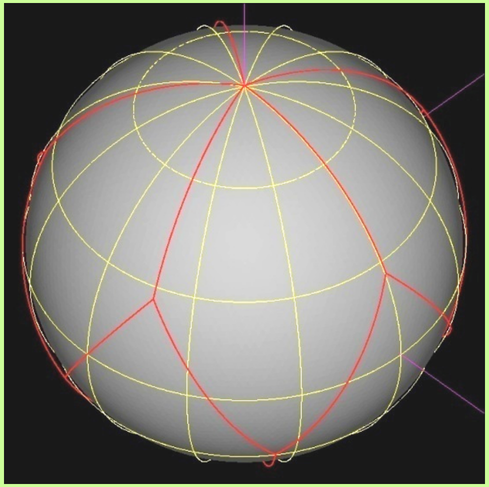
Large Step Integration

- **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**
  - **Use of a catesian coordinate in which the origin is the center of the earth.**
  - **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.
       → $\left(\nabla \cdot v_1 \mathbf{V}, \nabla \cdot v_2 \mathbf{V}, \nabla \cdot v_3 \mathbf{V}\right)$ where $v_i = V_i / \left(G^{1/2} \gamma^2 \rho\right)$
    4. Split again to a horizontal vector and a vertial components.
       → $\mathbf{ADV}_h, ADV_z$

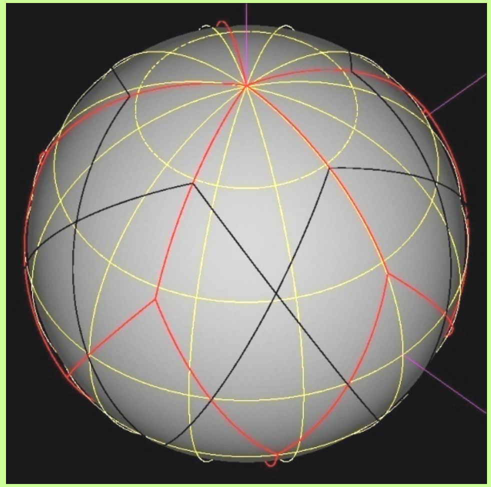
Computational strategy and performance

Computational strategy(1)

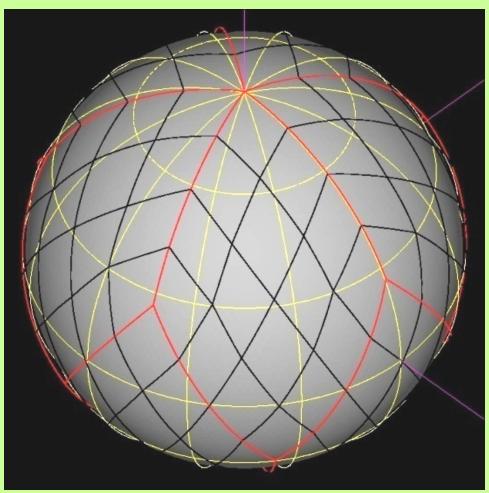
(0) region division level 0



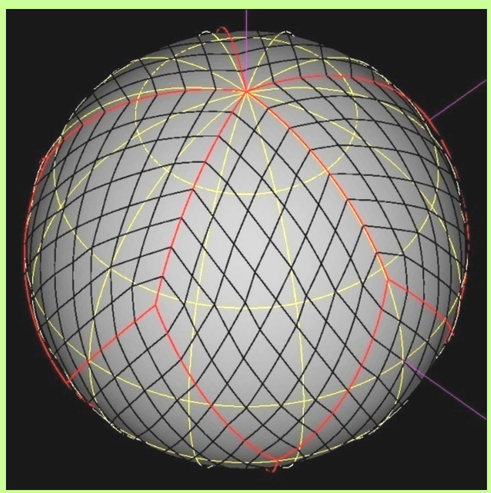
(1) region division level 1



(2) region division level 2



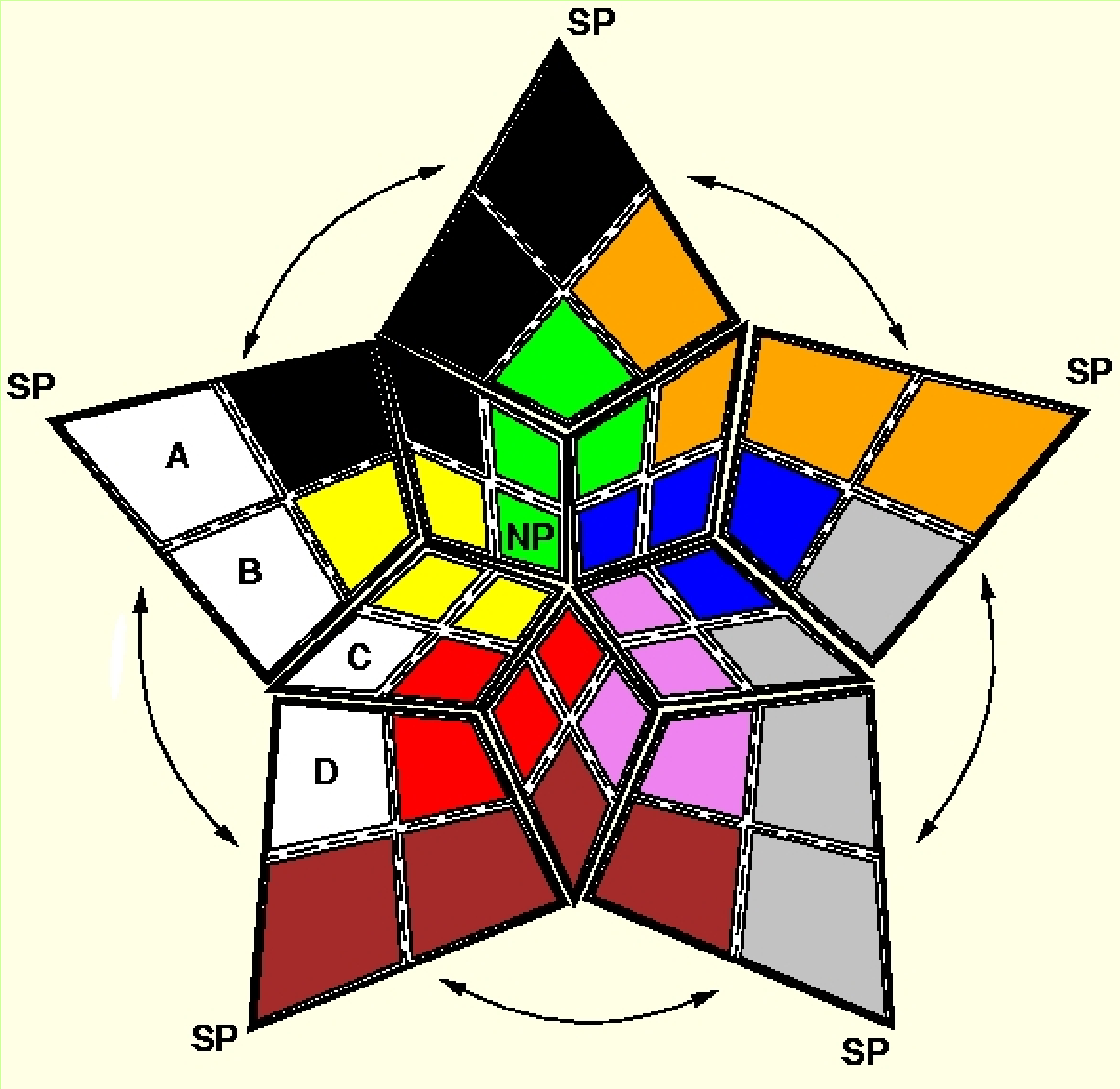
(3) region division level 3



- **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)

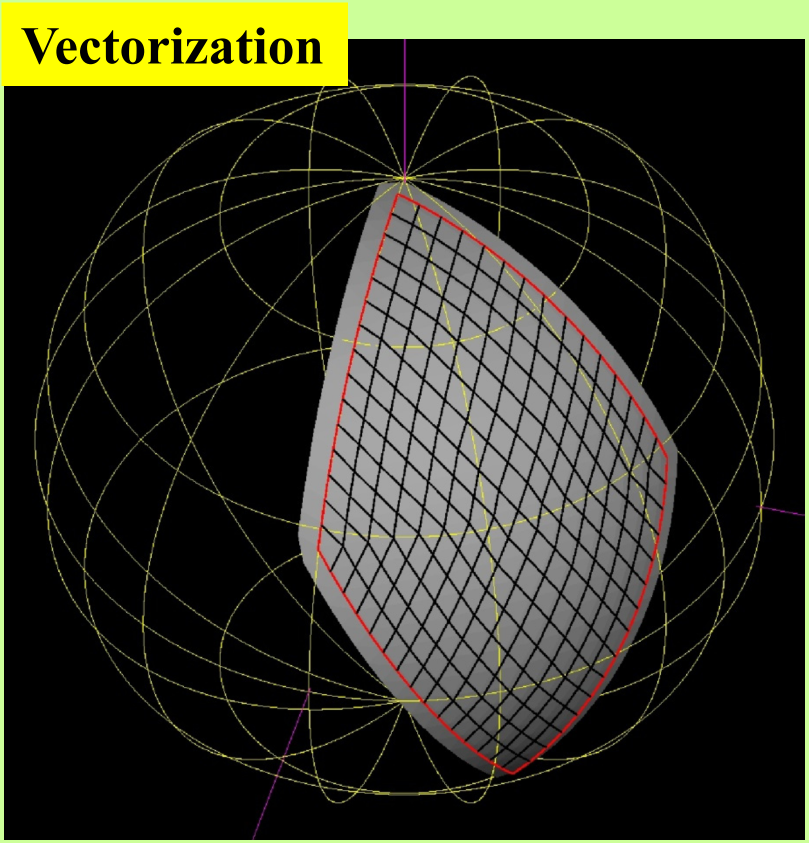
Load balancing

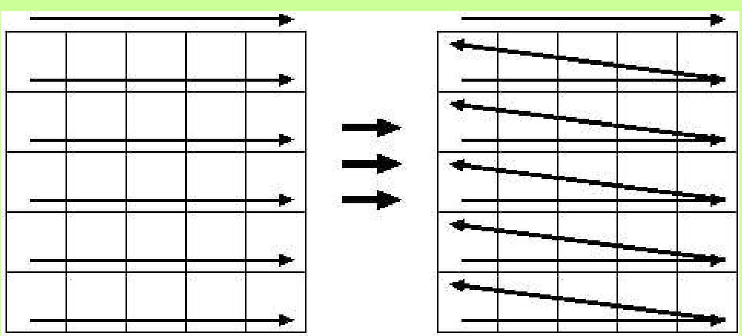


- Example (rlevel-1)
  - # of region : 40
  - # of process : 10
  - Situation:
    - Polar region: Less computation
    - Equatorial region: much computation
- Each process
  - manage same color regions
  - Cover from the polar region and equatorial region.

Avoid the load imbalance

Computational strategy(3)





- **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…

- Computer architecture, degree of code tuning…..

Performance on the old Earth Simulator

Earth Simulator

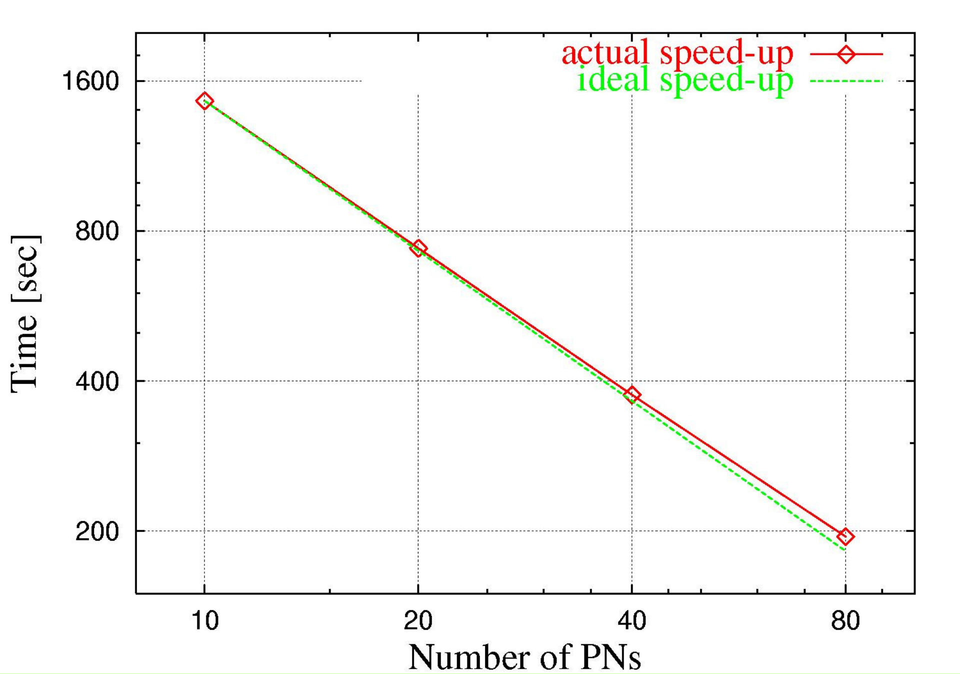
- Massively parallel super-computer based on NEC SX-6 architecture.
  - 640 computational nodes.
  - 8 vector-processors in each of nodes.
  - Peak performance of 1CPU : 8GFLOPS
  - Total peak performance：　8X8X640 = 40TFLOPS
  - Crossbar network

Target simulations for the measurement

- 1 day simulation of Held & Suarez dynamical core experiment

Computational Performance (2)

■ **Scalability of our model (NICAM) --- strong scaling**



Configuration

- Horizontal resolution : glevel-8
  - •30km resolution
- Vertical layers : 100

⇩

Fixed

- Computer nodes :
  increases from 10 to 80.

Results

Green : ideal speed-up line

Red : actual speed-up line

Computational Performance (3)

■ Performance against the horizontal resolution --- weak scaling

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 grid level increases,

# of gridpoints : X 4
# of CPUs : X 4
Time intv. : 1/2

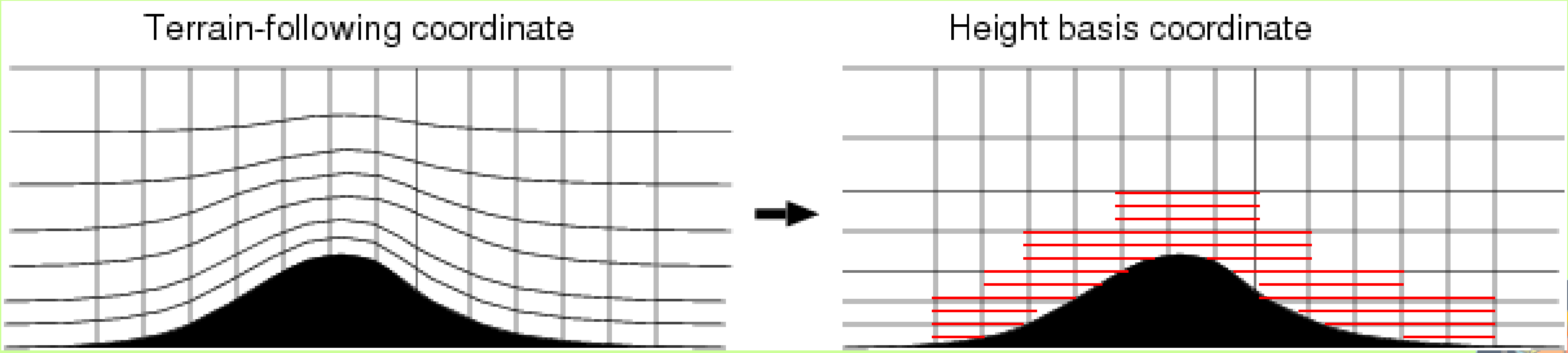
Results

The elapse time increases by a factor of 2.

Problems & subjects

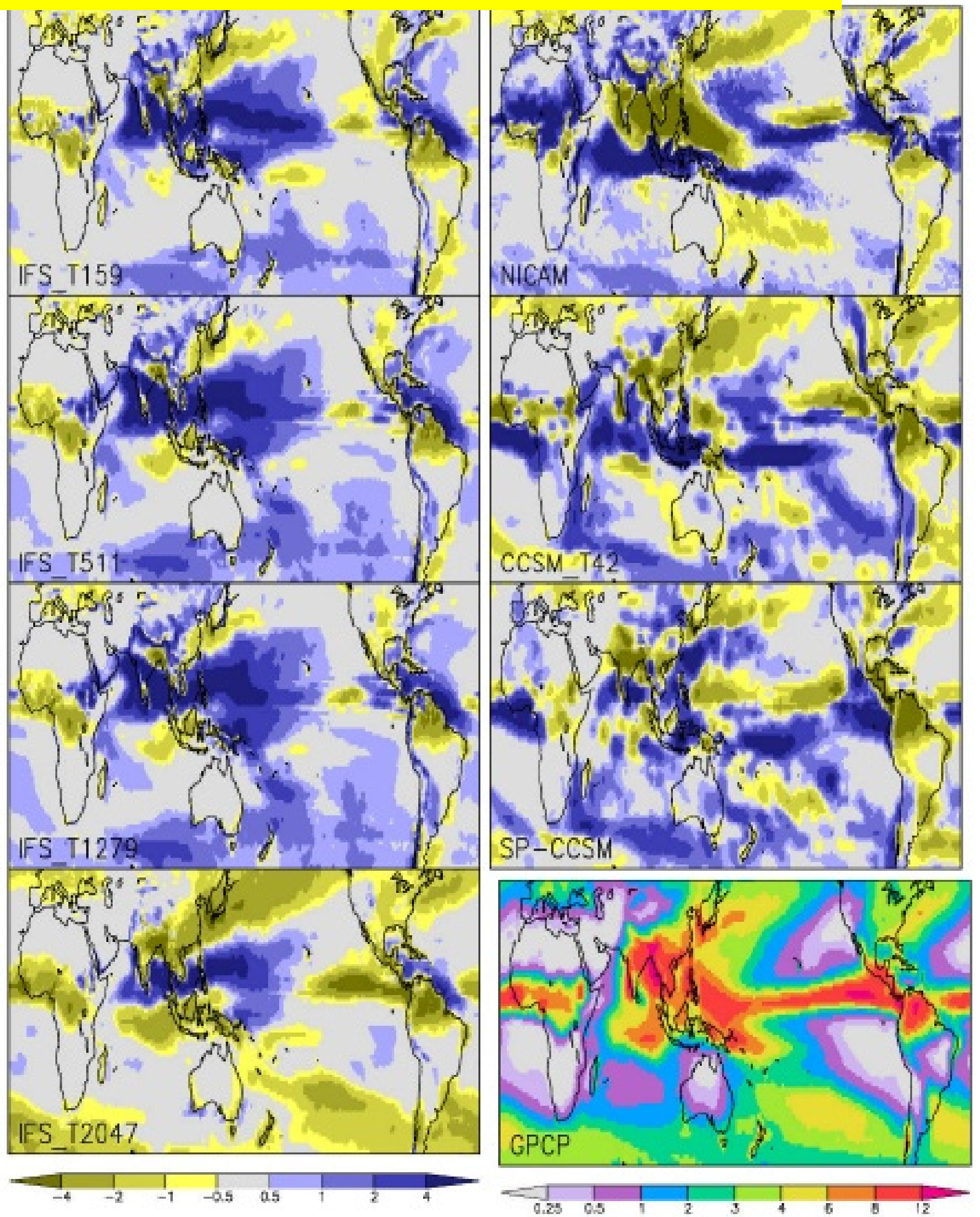
Current problems in NICAM (1)

- **Numerical problem**
  - **3.5km mesh run : sometimes, crash! at the steep mountain area (e.g. Tibetan plateau)**
    - Possible cause
      - The CFL condition in the vertical direction?
        - » Reduction of time step or appication of vertical implicit method?
      - The large Horizontal-PGF error in the terrain-following coordinate.
        - » If the horizontal resolution increases more and more, ….
    - Reconsideration of vertical descritization from the terrain-following coordinate to height basis coordinate.
      - Vertical adaptive mesh for the PBL scheme.



Current problems in NICAM (2)

Dirmeyer et al.(2010,JCLI submitted)



Climatology bias

- **found at the Athena project**
  - IFS : hydrostatic with c.p.
    - TL2047
  - NICAM: nohydro witout c.p.
    - 7km mesh
- **NICAM Bias:**
  - Excessive precipitation
    @ south Indian ocean
    @ SPCZ
  - Little precipitation
    @ storm track area in NH
    @ western pacific ocean
  - Almost same situation as the 14km run.
    → independent of resolution.

**→ basically,
physical scheme problem!**

Future subjects

- **Beyond a simple global cloud-system resolving**
  - **Cloud resolving approach has advantages over the convetional approach.**
    - **Explicit representation of cold pool dynamics**
    - **Well capture the organization of cloud dynamics**
      - **meso-scale cloud system, CC, SCC, MJO and so on.**
- **However,…… climate simulation?**
  - **Physics is not still sufficient!**
- **Radiation-microphysics coupling with aerosol process is a key!**
  - **CURENT :**
    - **Microphysics : one or two moment bulk method**
    - **Radiation: prescribed or assumed diameter of cloud particle**
  - **FUTURE :**
    - **Microphysics : spectral method as regard to the size distribution**
    - **Aerosol : spectral method**
    - **Radiation: estimate the optical depth of cloud and aerosol by tight coupling with microphysics and aerosol models.**

→ **Locality is very important!**

Ocean / Land high latitude/ mid latitude/ tropics

Near future problem　（ computer side ）

- **Exa-FLOPS is coming soon!**
  - **Inner node:**
    - Many-core /Many-socket → Memory bandwidth problem!!
      Bandwidth per core is very narrow (less that 0.1?).
      - Disadvantage for gridpoint method
        - Load/store of memory occures frequently.
        - Short computation
      - But, welcome for complicated physics?
        - Calculation is dominated over the memory load/store.
    - Hybrid architecture with CPU and GPU?
      - Complicated programming?
  - **Outer node:**
    - Commnication is dominated
      - Network topology, speed itself
    - Parallel IO
  - **Coding problem:**
    - What is the standard language?
      - OpenCL, new Fortran?

Summary

- NICAM dynamical core
  - Icosahedral A-grid
    - with grid modification by spring dynamics etc.
  - Coservative nonhydrostatic scheme
    - Mass & total mass
    - CWC
  - Time scheme
    - Split explicit scheme with HEVI for the small step solver.
- Problem
  - Numerically,
    - Steep mountain problem!
    - Need to change from terrain-following approach to height-base approach for vertical discretization.
  - Physically,
    - Precipitation bias still exists.
      - This can be solved by many tuning runs on K-computer(10 PFLOPS) within 1 or 2 years
- Up to date, the parallel efficiency of NICAM is quite good.
  - There is a lot of computer-side problems towards the next-generation supercomputer (ExaFLOPS)
    - Need to construct the model, considering the future evironment.